CONGRESS PROGRAM /// TECHNICAL DIGEST

LPM 2010

11th International Symposium
on Laser Precision Microfabrication

June 7-10, 2010
in Stuttgart, Germany

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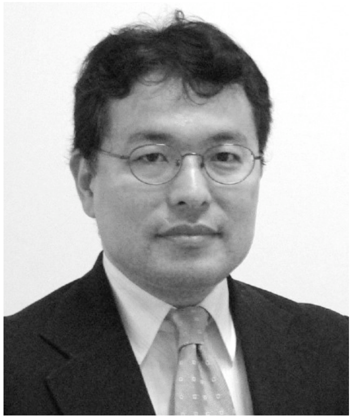
WELCOME TO LPM 2010



It's a pleasure to welcome you to 11th International Symposium on Laser Precision Microfabrication (LPM 2010) held in Stuttgart, Germany. LPM has been initiated at the 2000 Symposium in Omiya, Japan and then has been annually organized in Singapore, Osaka, Munich, Nara, Williamsburg, Kyoto, Vienna, Quebec, and Kobe, and now returns to Germany after an interval of seven years.
The last ten LPM Symposia have won reputation and popularity as one of the most important international events in the field of laser micro and nano processing in the world. LPM continues the tradition inherited from past Symposia and focuses on science and technology of advanced laser processing for precision micro and nano fabrication. The aim of LPM2010 is to provide a forum for discussion of fundamental aspects of laser-matter interaction, the state-of-the-art of laser materials processing, and topics for the next generation by the collaboration among scientists, end users and laser manufactures.

The technical program for a 4-day event includes 18 invited talks, about 140 oral presentations and about 50 posters. In addition to the technical sessions, International Trade Fair for System Solutions in Laser Material Processing (LASYS) is collocated. I do hope that LPM 2010 will stimulate fruitful discussions and useful exchanges and that you will enjoy your stay in Stuttgart, well know as one of the center in the field of manufacturing with lasers as well as car capital.

Dr. Koji Sugioka

杉岡 幸次

RIKEN – Advanced Science Institute, General Chair of LPM 2010

Oragnizers:

JLPS

Japan Laser Processing Society

co-located with:

LASYS

International trade fair for system solutions in laser material processing

Messe Stuttgart
Key to markets

COMMITTEES

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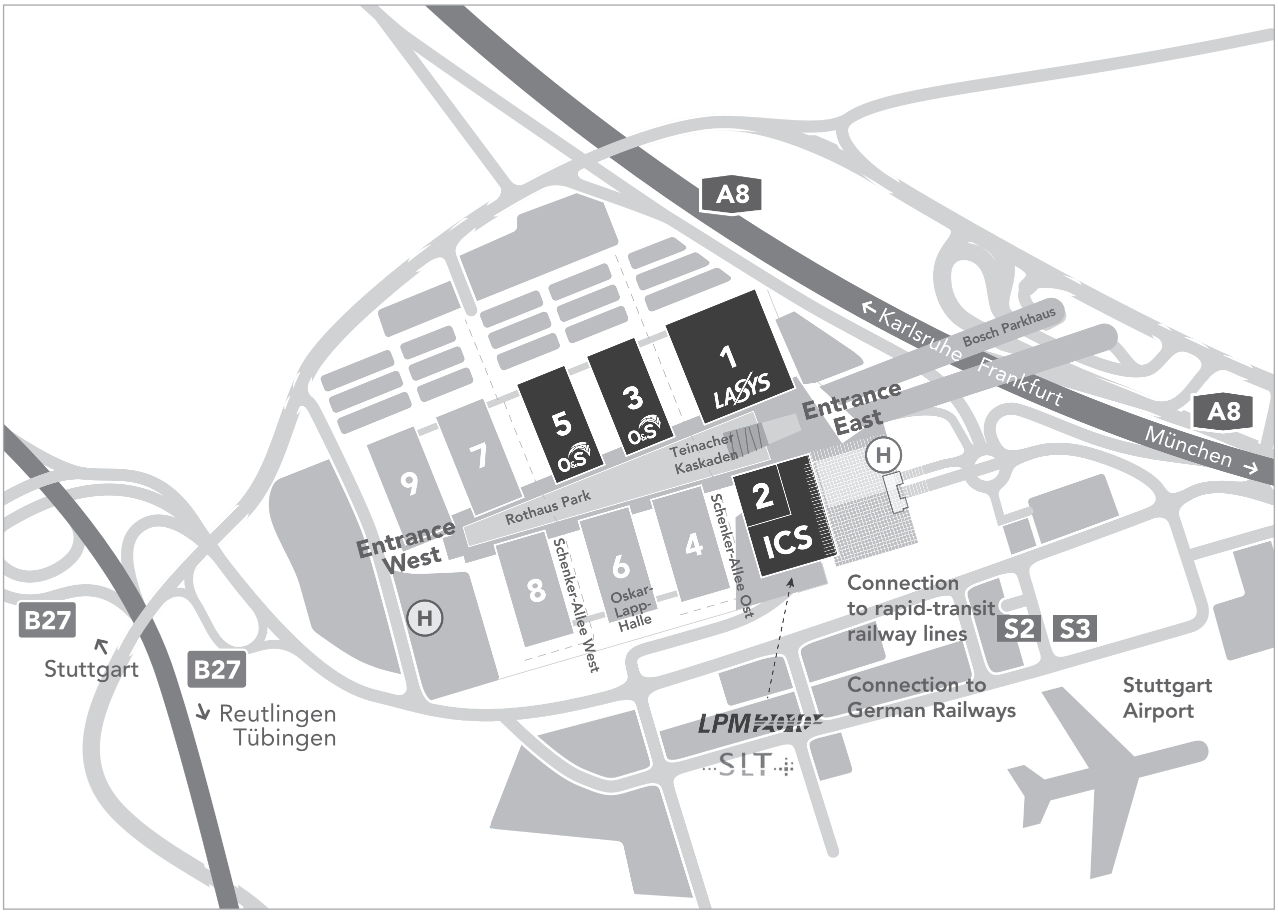
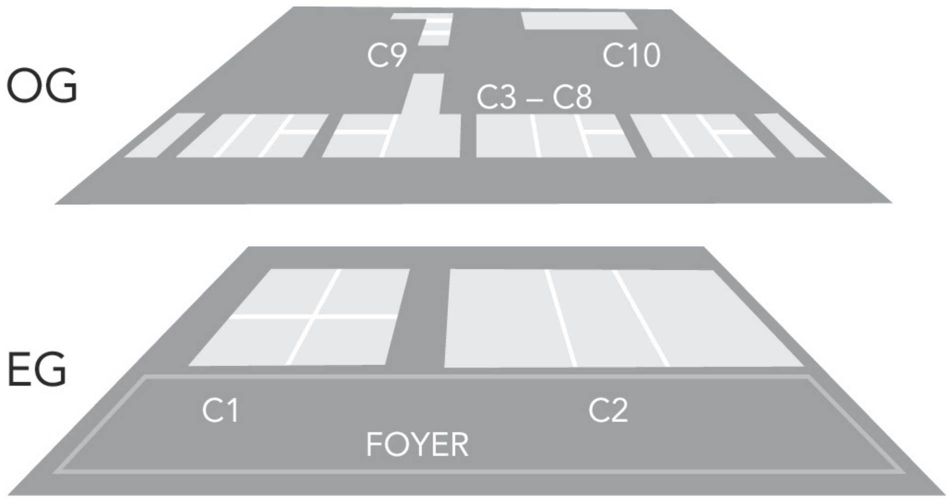
AREA MAP

MESSE STUTTGART



FLOOR PLAN



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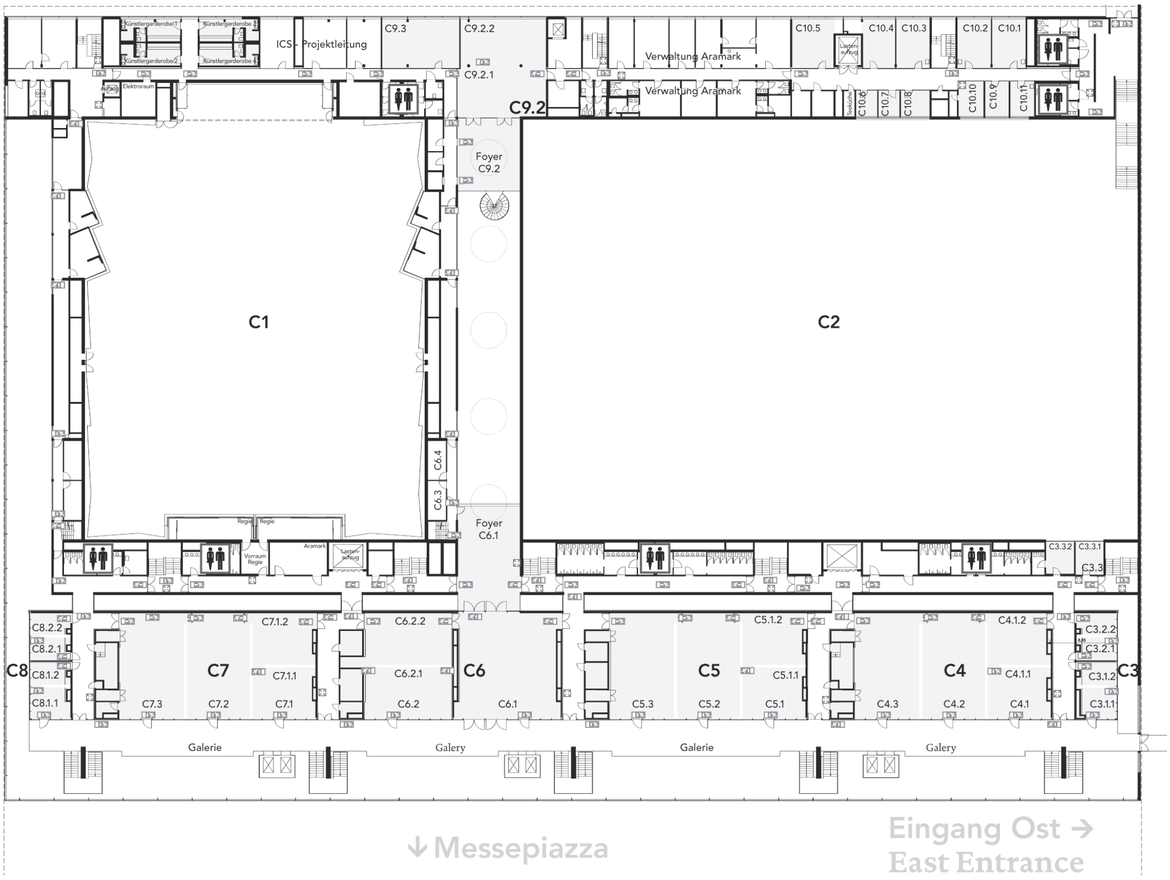

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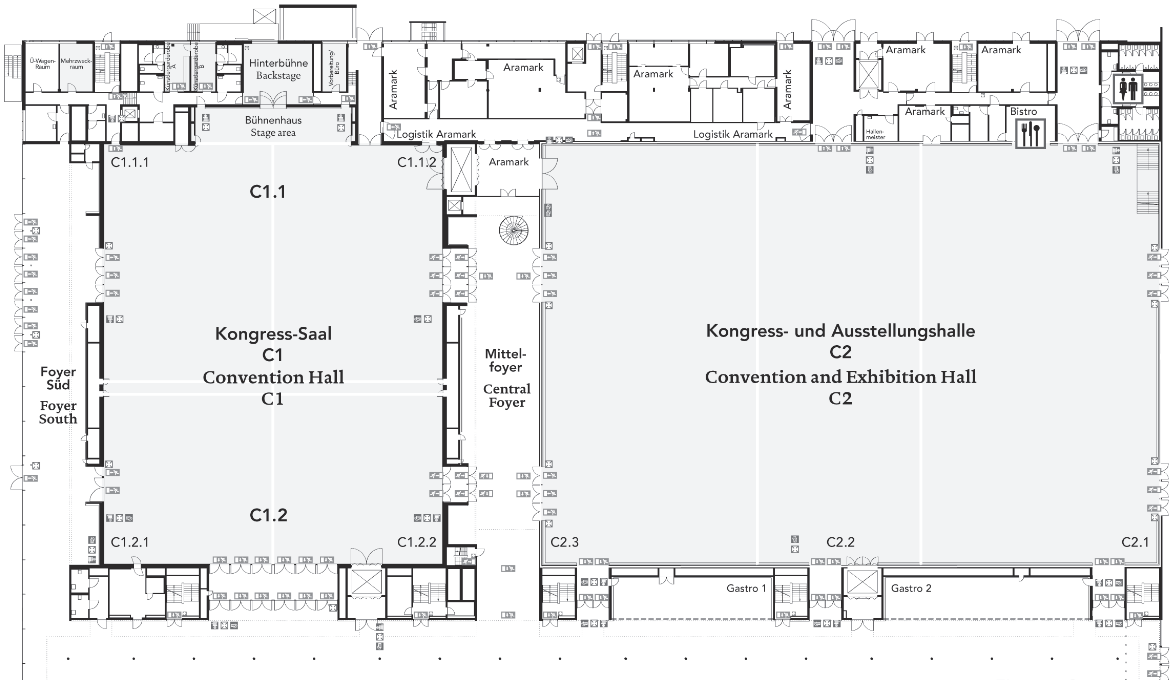

LPM TOPICS

1. Fundamental aspects (dynamic, modeling,simulation, etc.)
2. Process monitoring and control
3. Nano technology
4. Direct write process (MAPLE-DW, LIFT, etc.)
5. Ultra short pulse laser processing
6. VUV laser processing
7. Surface treatment (texturing, cleaning, annealing, modification, etc.)
8. Micro patterning and micro structuring
9. Micro machining
10. 3-D micro and nano fabrication
11. Drilling and cutting
12. Welding and bonding
13. Micro forming
14. Wafer dicing
15. Marking and trimming
16. Packaging and mounting process
17. Lithography (including EUV source and application)
18. Manufacture of micro devices and systems
19. Film deposition and synthesis of advanced materials (PLD, CVD, etc.)
20. Nano and micro particles
21. Medical and biological applications
22. Optics and systems for laser micro processing
23. Laser devices
24. Industrial applications
25. Photochemistry
26. Free electron laser material processing
27. High-power single-mode fiber lasers
28. Glass/ceramic processing
29. Others

JOINT SESSIONS

On overlapping topics joint sessions have been organized together with SLT. These sessions are open for participants of both conferences.

LASERS FOR MICRO FABRICATION

This session co-organized with SLT gives an overview of recent progress and expected developments of laser sources for micro applications.

INDUSTRIAL APPLICATIONS

In this session co-organized with SLT numerous application success stories show the importance of micro fabrication for production of automobile, photovoltaic and electronic products.

INVITED SPEAKERS

Andrew J. Birnbaum	Naval Research Lab Materials Science And Technology - USA *“Laser Printed MEMS and Electronic Devices”*
Heather Booth	Oerlikon Solar - Switzerland *“Laser processing in industrial solar module manufacturing”*
Joachim John	IMEC - Belgium *“Laser based processes in next generation solar cell production, chances and challenges”*
Vitaly Konov	General Physics Institute - Russia *“Role of gas optical breakdown plasma in material ablation by short laser pulses”*
Jochen Löffler	Energy Research Center Of The Netherlands *“Laser processing for advanced solar cells”*
Yongfeng Lu	University of Nebraska - Lincoln - USA *“Controlled Growth of Carbon nanostructures in Laser-assisted Chemical Vapor Deposition”*
Klaus Mann	Laser-Laboratorium Goettingen e.V. - Germany *“Laboratory-scale EUV sources for metrology and material interaction studies”*
Isamu Miyamoto	Osaka University - Japan *“Laser applications in Japan during the first 50 years”*
Minoru Obara	Keio University - Japan *“Nanoablation using 2D Gold and Dielectric Nanosphere Templates Excited by Femtosecond Laser”*
Roberto Osellame	Istituto Di Fotonica E Nanotecnologie (IFN) - CNR - Italy *„Femtosecond laser micromachining enables optofluidic sensing in lab-on-a-chip”*
Rajesh S. Patel	Newport Corp., Spectra-Physics Lasers Division - USA *“Laser - An Enabling Technology in the Photovoltaics Revolution”*
Martin Richardson	University of Central Florida - USA *“Femtosecond laser waveguide writing for customized micro optical elements”*
Michael Schmidt	University of Erlangen - Germany *“Laser-Bonding in high power electronics”*
Godehard Schmitz	Robert Bosch GmbH - Germany *“Introduction of laser manufacturing into mass production”*

Marc Sentis	LP3 Laboratory - France *"Femtosecond laser applied to photovoltaic cell processing"*
Hong-Bo Sun	Jilin University - China *"3D Polymerization for Functional Devices"*
Yasuyuki Tsuboi	Hokkaido University - Japan *"Optical Trapping of Bio-molecules and Nanoparticles Based on Resonance and Surface Plasmon"*
Ernst Wintner	Vienna University Of Technology - Austria *"Laser Ignition of Internal Combustion Engines"*
Luo Xiangang	State Key Lab of Micro-Fabrication and Technology - China *"Meta-materials consisting of plasmonic nanostructures"*

LPM 2010 SESSION CHART – OVERVIEW

MONDAY, JUNE 7, 2010

LOBBY		
Registration 8.00 – 10.00		
COFFEE BREAK		
C5		
Plenary Session 10:10 – 12:30		
LUNCH TIME		
C4.1	**C4.3**	**C5**
Micro machining 1 13:50 – 16:10	VUV laser / direct write 13:40 – 16:00	Ultra-short pulse processing 1 13:40 – 15:50
COFFEE BREAK		
C4.1	**C4.3**	**C5**
Micro machining 2 16:30 – 18:10	Direct write 16:30 – 18:10	Ultra-short pulse processing 2 16:20 – 18:00

TUESDAY, JUNE 8, 2010

C4.1	C4.3	C5
3d processing 1 9:20 – 10:50	Biological and medical applications 9:20 – 11:10	Deposition and synthesis 9:20 – 10:40
COFFEE BREAK		
C4.1	**C4.3**	**C5**
3d processing 2 11:30 – 13:00	Patterning 1 11:30 – 12:50	Fundamentals 11:30 – 12:40
LUNCH TIME		
C4.1	**C4.3**	**C1.1**
Components and systems 14:00 – 16:10	Patterning 2 14:00 – 16:00	Joint session: Industrial applications 1 14:00 – 16:10
COFFEE BREAK		
C4.1	**C4.3**	**C1.1**
Process monitoring 16:30 – 18:30	Patterning 3 16:30 – 18:10	Joint session: Industrial applications 2 16:50 – 18:30

WEDNESDAY, JUNE 9, 2010

C4.1	C4.3	C1.1
Ultra-short pulse processing 3 9:20 – 11:20	Welding and bonding 1 9:20 – 10:40	Joint session: Lasers for micro 8:35 – 11:40
COFFEE BREAK		
		C1.1
		50 years Laser 12:00 – 13:45
LUNCH TIME		
C4.1	C4.3	
Nano structures 1 14:30 – 15:50	Welding and bonding 2 14:00 – 16:10	
COFFEE BREAK		
C4.1	C4.3	C5
Nano structures 2 16:30 – 18:30	Micro devices 16:30 – 18:30	Installation of posters 16:30 – 18:30
TRANSPORT TO BANQUET		
BANQUET		

THURSDAY, JUNE 10, 2010

C4.1		C5
Short presentation of posters 9:20 – 11:10		Installation of posters 9:20 – 11:20
COFFEE BREAK		
		C5
		Poster session 11:30 – 13:00
LUNCH TIME		
C4.1	C4.3	
Photovoltaic applications 1 14:00 – 16:00	Nano structures 3 14:00 – 16:00	
COFFEE BREAK		
C4.1	C4.3	
Photovoltaic applications 2 16:30 – 17:10	Nano structures 4 16:30 – 17:10	
CLOSING REMARKS		

SHORT PRESENTATION OF POSTERS JUNE 10, 2010 – LOCATION: C4.1

P 1: Synthesis of cyclohexanone capped gold nanoparticles by nanosecond pulsed laser ablation

Speaker: Nastaran Mansour
09:20 – 09:22

P 2: Dielectric and Metallic Particles for Sub-Micron Laser Structuring

Speaker: Andreas Kolloch
09:22 – 09:24

P 3: Near-field two-photon absorption in photoresists for nanopatterning

Speaker: Florin Jipa
09:24 – 09:26

P 4: Femtosecond laser shock peening of various carbon steels

Speaker: Hitoshi Nakano
09:26 – 09:28

P 5: Multi Phase D-shape fiber optics localized plasmon resonance sensor realized by femto-second laser engraving

Speaker: Chien-Hsing Chen
09:28 – 09:30

P 6: ???

Speaker: ???
09:30 – 09:32

P 7: Fabrication of microstructures on Foturan glass by femtosecond laser

Speaker: J.S. Chen
09:32 – 09:34

P 8: Femtosecond Laser Anti-Reflection Micro Texturing of Bulk Polycrystalline Silicon Surface

Speaker: Wen-chang Yeh
09:34 – 09:36

P 9: Patterning electrode for cholesteric liquid-crystal display by laser ablation

Speaker: Hsuan-Kai Lin
09:36 – 09:38

P 10: Laser Fabrication for Water Repellent Surface of Micro/Nano Hybrid Structures

Speaker: Minghui Hong
09:38 – 09:40

P 11: Si Anti-Reflection Surface Design and Engineering by Laser Microfabrication

Speaker: Minghui Hong
09:40 – 09:42

P 12: Laser micro-lens array lithography for functional structures fabricated on quartz substrate for chromeless phase mask applications

Speaker: Huang Zhiqiang
09:42 – 09:44

P 13: Pulsed Laser Interference Lithography

Speaker: Stephen Riedel
09:44 – 09:46

P 14: Diffractive Optical Elements in bulk fused silica by nanosecond pulses laser ablation

Speaker: F.J. Torcal-Milla
09:46 – 09:48

P 15: Direct patterning of ITO coating on polymer using a femtosecond laser with 1030 nm wavelength

Speaker: Ik-Bu Sohn
09:48 – 09:50

P 16: UV laser micropatterning of silicone nanofilaments

Speaker: Ana Stojanovic
09:50 – 09:52

P 17: Micromachining of transparent materials with Fresnel diffraction of infrared radiation

Speaker: K.Okazaki
09:52 – 09:54

P 18: Investigations of laser induced periodic structures using tailored femtosecond laser pulses on polymers

Speaker: Magdalena Forster
09:54 – 09:56

P 19: Structure optimization of novel initiators for two-photon polymerization (2PP) process

Speaker: Marton Siklos
09:56 – 09:58

P 20: Short pulse and ultrashort pulse laser machining inside transparent materials: glass and polymer

Speaker: Udo Loeschner
09:58 – 10:00

P 21: Selective Laser Sintering of Magnesium Powder for Fabrication of Dense Structures

Speaker: Ng Chi Chung
10:00 – 10:02

P 22: Micromachining of low-expansion glass by 263 nm Nd-YLF laser for microfluidics applications

Speaker: Pierre-Yves Thro
10:02 – 10:04

P 23: Experimental study of selective laser melting of pure magnesium powders

Speaker: Chi Chung Ng
10:04 – 10:06

P 24: Using Femto-second Laser to Fabricate the Interior 3D Structures of Polymeric Microfluidic Biochips

Speaker: S.C. Wang
10:06 – 10:08

P 25: Multi Phase D-shape Fiber Optics Localized Plasmon Resonance Sensor

Speaker: Chung-Wei Cheng
10:08 – 10:10

P 26: Novel Butterfly Type Laser Module Packaging Employing Nd:YAG Laser and Separated Clip of Stainless Steel

Speaker: Yi-Cheng Hsu
10:10 – 10:12

P 27: Structured photodiodes by means of Laser Ablation over silica diodes

Speaker: Francisco Javier Salgado-Remacha
10:12 – 10:14

P 28: Integrated liquid crystal electro-optic device with surface-induced parallel alignment using a femtosecond laser

Speaker: F. He
10:14 – 10:16

P 29: Fabrication of Multi-level DOE using laser direct write lithography system and CGH technique

Speaker: Sumio Nakahara
10:16 – 10:18

P 30: Micro-Cladding using a pulsed fibre laser and scanner

Speaker: R. Ebert
10:18 – 10:20

P 31: Heat flow investigation of Infrared Semiconductor Laser Rapid Annealing of Silicon

Speaker: Tohiyuki Sameshima
10:20 – 10:22

P 32: Surface modification of Ti-6Al-4V using line beam laser

Speaker: Balaji Mohan
10:22 – 10:24

P 33: CIGS Seed Layer Deposition by Femtosecond Laser

Speaker: Chung-Wei Cheng
10:24 – 10:26

P 34: Ps-laser scribing of CIGS at 1064 nm wavelength

Speaker: Paulius Gecys
10:26 – 10:28

SHORT PRESENTATION OF POSTERS
JUNE 10, 2010 – LOCATION: C4.1

P 35: Pulsed fiber laser based on single crystal photoelastic modulator for photovoltaic industrial processing

Speaker: Rok Petkovšek
10:28 – 10:30

P 36: "Black silicon" formation by Nd:YAG laser radiation

Speaker: Artur Medvid'
10:30 – 10:32

P 37: Direct Laser Writing of Ring-Like Metal Structures

Speaker: Michael Zenou
10:32 – 10:34

P 38: Laser Direct Writing of Photoresist on Si wafers

Speaker: Cinthya Toro
10:34 – 10:36

P 39: Direct Laser Writing System of Mask for Integrated Photonics Devices

Speaker: Slimane Messaoud
10:36 – 10:38

P 40: The electron-phonon coupling constant as a characteristic parameter for the formation of ripples in ultra-short regime

Speaker: Eric Audouard
10:38 – 10:40

P 41: Femto-second laser ablation dynamics of fused silica

Speaker: Hsiang-Chen Wang
10:40 – 10:42

P 42: Impact of nanostructure formed by laser radiation on photo conductivity of CdZnTe solid solution

Speaker: A. Mychko
10:42 – 10:44

P 43: Modeling and Control of Transfer Phenomena in Nanosystems in Field of Resonance Radiation

Speaker: Valeri V. Levdansky
10:44 – 10:46

P 44: Origin of Laser-induced Near-subwavelength Ripples: Interference between Surface Plasmons and Incident Laser

Speaker: Min Huang
10:46 – 10:48

P 45: On-chip Microlens Fabricated by Femtosecond Laser Micromachining for Nonlinear Microscopy Applications

Speaker: Fei He
10:48 – 10:50

P 46: Yb:YAG Ultrashort Pulse Laser for MEMS Applications

Speaker: Akihiro Tanabashi
10:50 – 10:52

P 47: Deep Trenches of Borosilicate Glass by Laser-Induced Backside Wet Etching

Speaker: Hiroyuki Niino
10:52 – 10:54

P 48: Laser Cutting of CFRP by UV Pulsed Laser Ablation

Speaker: Hiroyuki Niino
10:54 – 10:56

P 49: Laser micro machining of ceramics with brilliant cw laser radiation

Speaker: Lars Hartwig
10:56 – 10:58

P 50: Laser Micromachining of Stainless Steel Powder/Polymer Composite

Speaker: D. Ahn
10:58 – 11:00

P 51: Optical coherence tomography for process control of laser micro machining

Speaker: Markus Wiesner
11:00 – 11:02

P 52: Fabrication of nanostructures on Ag surface with infrared femtosecond laser pulses

Speaker: Chung-Wei Cheng
11:02 – 11:04

P 53: Machining of Substances Located at the Back of a Silicon Substrate by Near-Infrared, Ultrashort Pulse Laser Speaker: Rie Tanabe 11:04 – 11:06
P 54: Water-assisted high pulse repetition rate femtosecond micromachining of wide bandgap dielectrics Speaker: Valdas Sirutkaitis 11:06 – 11:08

LPM 2010: TIME SCHEDULE

MONDAY, JUNE 7, 2010

TIME	Event	Location
10:10 – 10:30	**Welcome and opening remarks** *Speaker:* K. Sugioka, F. Dausinger *Session:* Plenary session	C5
10:30 – 11:10 **P. 44**	**Laser applications in Japan during the first 50 years (Invited)** *Speaker:* Isamu Miyamoto *Session:* Plenary session	C5
11:10 – 11:50	**Introduction of laser manufacturing into mass production (Invited)** *Speaker:* Godehard Schmitz *Session:* Plenary session	C5
11:50 – 12:30 **P. 45**	**Laser processing in industrial solar module manufacturing (Invited)** *Speaker:* Heather J. Booth *Session:* Plenary session	C5
13:40 – 14:10 **P. 46**	**Laboratory-scale EUV sources for metrology and material interaction studies (Invited)** *Speaker:* Klaus Mann *Session:* VUV laser / direct write	C4.3
13:40 – 14:10 **P. 47**	**Femtosecond laser waveguide writing for customized micro optical elements (Invited)** *Speaker:* M. Richardson *Session:* Ultra-short pulse processing 1	C5
13:50 – 14:10 **P. 48**	**Gas-assisted microdrilling in steel with ultrashort pulsed laser radiation** *Speaker:* M. Kraus *Session:* Micro machining 1	C4.1
14:10 – 14:30 **P. 49**	**Advanced laser micro machining using a novel trepanning system** *Speaker:* David Ashkenasi *Session:* Micro machining 1	C4.1

TIME	Event	Location
14:10 – 14:30 **P. 50**	**Nano-structures in array generated in liquid process induced by interfering femtosecond laser processing** *Speaker:* Yoshiki Nakata *Session:* Ultra-short pulse processing 1	C5
14:10 – 14:30 **P. 51**	**Modular EUV source for the next generation lithography** *Speaker:* Olivier Sublemontier *Session:* VUV laser / direct write	C4.3
14:30 – 14:50 **P. 52**	**Effect of shot number on femtosecond laser drilling of silicon** *Speaker:* Petri Laakso *Session:* Micro machining 1	C4.1
14:30 – 14:50 **P. 53**	**Adapting Femtosecond Laser Pulses to Ionization Processes in Wide Band Gap Materials: a Route for Nanoscale Laser Processing** *Speaker:* Thomas Baumert *Session:* Ultra-short pulse processing 1	C5
14:30 – 15:00 **P. 54**	**Laser Printed MEMS and Electronic Devices (Invited)** *Speaker:* Andrew J. Birnbaum *Session:* VUV laser / direct write	C4.3
14:50 – 15:10 **P. 55**	**LASER DRILLING with PULSE FIBER LASER** *Speaker:* Michael Stark *Session:* Micro machining 1	C4.1
14:50 – 15:10 **P. 56**	**Femtosecond Laser Irradiation and Hydrothermal-electrochemical Treatment for Improving Bioactivity of the Ti-based Bulk Metallic Glass** *Speaker:* Togo Shinonaga *Session:* Ultra-short pulse processing 1	C5
15:00 – 15:20 **P. 57**	**New laser direct-writing technique for liquids micro-printing** *Speaker:* Pere Serra *Session:* VUV laser / direct write	C4.3

TIME	Event	Location
15:10 – 15:30 P. 58	**Machining hole arrays in polycarbonate sheet using UV solid state laser** *Speaker:* Susumu Nakamura *Session:* Micro machining 1	C4.1
15:10 – 15:30 P. 59	**Laser micromachining of CFRP by ultra-short pulse lasers** *Speaker:* Masayuki Fujita *Session:* Ultra-short pulse processing 1	C5
15:20 – 15:40 P. 60	**Time-resolved imaging of hydrogel transport by laser-induced forward transfer (LIFT)** *Speaker:* Claudia Unger *Session:* VUV laser / direct write	C4.3
15:30 – 15:50	**Strong birefringence in multi-component silica-based glasses with ultrashort laser irradiation** *Speaker:* Fan Chaxing *Session:* Ultra-short pulse processing 1	C5
15:30 – 15:50 P. 61	**Drilling Holes through Cemented Tungsten Carbide Plates by Ultrafast Laser** *Speaker:* Yoshiro Ito *Session:* Micro machining 1	C4.1
15:40 – 16:00 P. 62	**Fabrication of Optical Inter-connects with two photon polymerization** *Speaker:* Klaus Stadlmann *Session:* VUV laser / direct write	C4.3
15:50 – 16:10 P. 63	**High rate laser micro process-ing using high brilliant cw laser radiation** *Speaker:* Horst Exner *Session:* Micro machining 1	C4.1
16:20 – 16:40 P. 64	**Micro-processing of semi-conductors using ultrafast laser radiation at 2 µm wavelength** *Speaker:* M. Ramme *Session:* Ultra-short pulse processing 2	C5
16:30 – 16:50 P. 65	**Laser Decal Transfer of Nano-materials** *Speaker:* Alberto Piqué *Session:* Direct write	C4.3
16:30 – 16:50 P. 66	**Pulsed laser material ablation by contacting optical fiber** *Speaker:* Vitaly I.Konov *Session:* Micro machining 2	C4.1
16:40 – 17:00 P. 67	**Rapid assessment of energy deposition profiles in sub-surface fs laser processing of dielectrics** *Speaker:* A. Ruiz de la Cruz *Session:* Ultra-short pulse processing 2	C5
16:50 – 17:10	**Ablation of grooves in stain-less steel by femtosecond pulses assisted by laser steam cleaning** *Speaker:* Valdas Sirutkaitis *Session:* Micro machining 2	C4.1
16:50 – 17:10 P. 68	**Dynamics of the Laser Decal Transfer Process** *Speaker:* Scott A. Mathews *Session:* Direct write	C4.3
17:00 – 17:20	**Spatiotemporal double pulse method in femtosecond laser processing** *Speaker:* Yoshio Hayasaki *Session:* Ultra-short pulse processing 2	C5
17:10 – 17:30 P. 69	**Engraving of metals using high repetition rate ultrafast lasers** *Speaker:* John Lopez *Session:* Micro machining 2	C4.1
17:10 – 17:30 P. 70	**Optimization of feature resolu-tion, processing window & structuring time for the two-photon polymerization(2PP) process by the use of novel initiators** *Speaker:* Niklas Pucher *Session:* Direct write	C4.3

TIME	Event	Location
17:20 – 17:40 **P. 71**	**Rapid micro processing of metals with a high repetition rate femto second fibre laser** *Speaker:* Joerg Schille *Session:* Ultra-short pulse processing 2	C5
17:30 – 17:50 **P. 72**	**Fabrication of multiple slanted microstructures on silica glass by laser-induced back-side wet etching** *Speaker:* Tadatake Sato *Session:* Micro machining 2	C4.1
17:30 – 17:50 **P. 73**	**Laser Assisted Bioprinting of Cells & Biomaterials: Development of a Dedicated Work-station, Experimental Results and Jet Formation Modeling** *Speaker:* Agnès Souquet *Session:* Direct write	C4.3
17:40 – 18:00 **P. 74**	**Second hermonic optimization method for holographic femtosecond laser processing** *Speaker:* Satoshi Hasegawa *Session:* Ultra-short pulse processing 2	C5
17:50 – 18:10 **P. 75**	**Microstructuring of Various Materials using Femtosecond Laser Pulses** *Speaker:* Andy Engel *Session:* Micro machining 2	C4.1
17:50 – 18:10 **P. 76**	**Laser Induced Forward Transfer: A Compact Machine** *Speaker:* Dominik Riester *Session:* Direct write	C4.3

TUESDAY, JUNE 8, 2010

TIME	Event	Location
09:20 – 09:50 **P. 77**	**Femtosecond laser micro-machining enables optofluidic sensing in lab-on-a-chip (Invited)** *Speaker:* Roberto Osellame *Session:* 3d processing 1	C4.1
09:20 – 09:50 **P. 78**	**Optical Trapping of Bio-molecules and Nanoparticles Based on Resonance and Surface Plasmon (Invited)** *Speaker:* Yasuyuki Tsuboi *Session:* Biological and medical applications	C4.3
09:20 – 09:40 **P. 79**	**Development of a Laser Stabilised Gas Metal Arc Cladding Process** *Speaker:* Alexander Barroi *Session:* Deposition and synthesis	C5
09:50 – 10:10 **P. 80**	**In Vivo Writing using Two-Photon-Polymerization** *Speaker:* Jan Torgersen *Session:* Biological and medical applications	C4.3
09:40 – 10:00 **P. 81**	**A new additive technique for laser precision microfacturing: laser microcladding** *Speaker:* J. del Val *Session:* Deposition and synthesis	C5
09:50 – 10:10 **P. 82**	**3D laser lithography and nanoimprint lithography: versatile methods for the micro- and nano fabrication of photonic structures** *Speaker:* Volker Schmidt *Session:* 3d processing 1	C4.1
10:10 – 10:30 **P. 83**	**Femtosecond laser ablation of dentin: A characterisation study** *Speaker:* Sandra Alves *Session:* Biological and medical applications	C4.3

TIME	Event	Location
10:00 – 10:20 **P. 84**	**Synthesis of ZnO nanowire heterostructures by laser ablation and their optical characteristics** *Speaker:* Daisuke Nakamura *Session:* Deposition and synthesis	C5
10:10 – 10:30 **P. 85**	**Influence of selective laser melting process parameters on morphology of single vectors from metal powder** *Speaker:* Igor Yadroitsev *Session:* 3d processing 1	C4.1
10:20 – 10:40 **P. 86**	**Mechanism study of gliding movement of Phormidium in nano-aquariums integrated with different functions fabricated by femtosecond laser** *Speaker:* Yasutaka Hanada *Session:* Biological and medical applications	C4.3
10:20 – 10:40 **P. 87**	**F2-Laser Formation of Transparent Protective Layer onto Polycarbonate for Lightweight Window** *Speaker:* Masayuki Okoshi *Session:* Deposition and synthesis	C5
10:30 – 10:50 **P. 88**	**3D sub-diffraction-limit patterning of hybrid polymers with visible and infrared laser pulses** *Speaker:* Sönke Steenhusen *Session:* 3d processing 1	C4.1
10:50 – 11:10 **P. 89**	**Laser-controlled Injector for Biological Applications** *Speaker:* Toshihiko Ooie *Session:* Biological and medical applications	C4.3

TUESDAY, JUNE 8, 2010

TIME	Event	Location
11:30 – 12:00 **P. 90**	**3D Polymerization for Functional Devices (Invited)** *Speaker:* Hong-Bo Sun *Session:* 3d processing 2	C4.1
11:30 – 11:50 **P. 91**	**Plasmonics Enhanced Femtosecond Laser Nano-processing: Modeling and application to biology** *Speaker:* Michel Meunier *Session:* Patterning 1	C4.3
11:30 – 12:00 **P. 92**	**Role of gas optical breakdown plasma in material ablation by short laser pulses (Invited)** *Speaker:* V.I.Konov *Session:* Fundamentals	C5
11:50 – 12:10 **P. 93**	**Local oxidation of thin metallic films under short pulse laser action** *Speaker:* Vadim P. Veiko *Session:* Patterning 1	C4.3
12:00 – 12:20 **P. 94**	**Two-photon polymerization as method for the fabrication of large scale biomedical scaffold applications** *Speaker:* Thomas Stichel *Session:* 3d processing 2	C4.1
12:00 – 12:20 **P. 95**	**Modelling Laser Induced Periodic Surface Structures** *Speaker:* Johann Z.P. Skolski *Session:* Fundamentals	C5
12:10 – 12:30 **P. 96**	**Picosecond laser machined designed patterns with anti-ice effect** *Speaker:* Daniel Arnaldo del Cerro *Session:* Patterning 1	C4.3

TIME	Event	Location
12:20 – 12:40 **P. 97**	**Fabrication of 3D Protein Microstructures** *Speaker:* Sascha Engelhardt *Session:* 3d processing 2	C4.1
12:20 – 12:40 **P. 98**	**Fs-Pump-Probe Measurement of the Transient Dielectric Function of Fused Silica** *Speaker:* Maren Hörstmann-Jungemann *Session:* Fundamentals	C5
12:30 – 12:50 **P. 99**	**Patterning of a NiCr-Al2O3 thin film system with picosecond laser pulses** *Speaker:* Oliver Suttmann *Session:* Patterning 1	C4.3
12:40 – 13:00 **P. 100**	**Development of 2D/3D Micro-machining Processes Based on Nanosecond Laser Sources for Industrial Manufacturing** *Speaker:* José L. Ocaña *Session:* 3d processing 2	C4.1
14:00 – 14:20 **P. 101**	**Laser Micro-Patterning by Means of Optical Fibers with Etched Tips or Micro-grinded Lens End Faces** *Speaker:* Sergii Yakunin *Session:* Patterning 2	C4.3
14:00 – 14:30 **P. 102**	**Laser Ignition of Internal Combustion Engines (Invited)** *Speaker:* Ernst Wintner *Session:* Components and systems	C4.1

TIME	Event	Location
14:10 – 14:30 P. 103	**Thin film processing with UV excimer lasers** *Speaker:* Ralph Delmdahl *Session:* Joint session: Industrial aplications 1	C1.1
14:20 – 14:40 P. 104	**Formation and evolution of self-organized patterns in laser irradiation of silicon surface in water** *Speaker:* X. Y. Chen *Session:* Patterning 2	C4.3
14:30 – 14:50 P. 105	**Micromachining Hard Materials with Industrial Picosecond Lasers** *Speaker:*Dirk Müller *Session:* Joint session: Industrial aplications 1	C1.1
14:30 – 14:50 P. 106	**High-end micromachining with >150W average power from a 1MHz 10ps-laser** *Speaker:* Marco Höfer *Session:* Components and systems	C4.1
14:40 – 15:00 P. 107	**Volume Bragg grating formation in fused silica with high repetition rate femtosecond Yb:KGW laser pulses** *Speaker:* Valdas Sirutkaitis *Session:* Patterning 2	C4.3
14:50 – 15:10 P. 108	**Laser Cutting of Electrodes for Advanced Batteries** *Speaker:* Eric Audouard *Session:* Joint session: Industrial aplications 1	C1.1
14:50 – 15:10 P. 109	**Multiple Beam Internal Structuring of PMMA** *Speaker:* Walter Perrie *Session:* Components and systems	C4.1
15:00 – 15:20 P. 110	**Generation of Multi Spot Arrays and In-Process Spot Shaping for Parallel Laser Processing of Microstructures** *Speaker:* M. Schmidt *Session:* Patterning 2	C4.3

TIME	Event	Location
15:10 – 15:30 P. 111	**Thin metal cutting using water jet-guided laser** *Speaker:* Alexandre Pauchard *Session:* Joint session: Industrial aplications 1	C1.1
15:10 – 15:30 P. 112	**Laser processing by using diffractive optical laser beam shaping technique** *Speaker:* Gediminas Raciukaitis *Session:* Ultra-short pulse processing 3	C4.1
15:20 – 15:40 P. 113	**Fabrication of sub-micron Gratings on Silicon by Maskless Exposure of Nanosecond Laser Pulses** *Speaker:* Ravi K. Soni *Session:* Patterning 2	C4.3
15:30 – 15:50 P. 114	**High Precision Machining Powered by UV** *Speaker:* Rainer Paetzel *Session:* Joint session: Industrial aplications 1	C1.1
15:30 – 15:50 P. 115	**Application of spatial light modulator in nanosecond laser machining** *Speaker:* Rainer J. Beck *Session:* Ultra-short pulse processing 3	C4.1
15:40 – 16:00 P. 116	**Laser Patterning of Conformal Electromagnetic Surfaces** *Speaker:* Nicholas A. Charipar *Session:* Patterning 2	C4.3
15:50 – 16:10 P. 117	**Laser Micromachining of Piezoelectric Ceramics** *Speaker:* Xie Qiong *Session:* Joint session: Industrial aplications 1	C1.1
16:30 – 16:50 P. 118	**Enhancement of the hydrophobic properties of metals by femtosecond laser texturing of surfaces** *Speaker:* Stéphane Valette *Session:* Patterning 3	C4.3

TUESDAY, JUNE 8, 2010

TIME	Event	Location
16:30 – 16:50 P. 119	**Quality Aspects in High Power Ultra Short Pulse Laser Ablation** Speaker: S. Eifel Session: Process monitoring	C4.1
16:50 – 17:10 P. 120	**Ultra fast laser machined hydrophobic stainless steel surface for drag reduction in laminar flows** Speaker: R. Jagdheesh Session: Patterning 3	C4.3
16:50 – 17:10 P. 121	**Three-dimensionally Isotropic Resolution of Femtosecond Laser Micromachining Using Spatiotemporally Focused Pulses** Speaker: Fei He Session: Process monitoring	C4.1
16:50 – 17:10 P. 122	**Reliable laser micro-welding of Copper** Speaker: U. Dürr Session: Joint session: Industrial aplications 2	C1.1
17:10 – 17:30 P. 123	**Interferometric in-process measurement of free-form surfaces in laser chemical manufacturing** Speaker: Christoph Gerhard Session: Process monitoring	C4.1
17:10 – 17:30 P. 124	**Generation of periodic micro- and nano-structures by polarization-controlled laser beam interference** Speaker: Stefan Beckemper Session: Patterning 3	C4.3
17:10 – 17:30	**Broadly based micro machining applications for value added production with high power picosecond lasers** Speaker: S. Weiler Session: Joint session: Industrial aplications 2	C1.1

TIME	Event	Location
17:30 – 17:50 P. 125	**Production of Microstructures in wide-band-gap materials using pulsed laser ablation at 157 nm wavelength** *Speaker:* Falk Haehnel *Session:* Patterning 3	C4.3
17:30 – 17:50 P. 126	**Optical system for on-line monitoring in selective laser melting technology** *Speaker:* Maria Doubenskaia *Session:* Process monitoring	C4.1
17:30 – 17:50 P. 127	**Applications and perspectives of ultrashort pulsed lasers** *Speaker:* J. König *Session:* Joint session: Industrial aplications 2	C1.1
17:50 – 18:10 P. 128	**Cu Micropatterns Fabricated by Femtosecond Laser Direct Writing Using Cu Nanoparticle Ink** *Speaker:* Chung-Wei Cheng *Session:* Patterning 3	C4.3
17:50 – 18:10 P. 129	**Laser-induced plasma investigations during material processing** *Speaker:* David Ashkenasi *Session:* Process monitoring	C4.1
17:50 – 18:10	**High-efficiency high-quality carbon machining strategies** *Speaker:* A. Wolynski *Session:* Joint session: Industrial aplications 2	C1.1
18:10 – 18:30 P. 130	**A practical method to determine laser induced refractive index changes in transparent media using a Fourier approach** *Speaker:* Rene Berlich *Session:* Process monitoring	C4.1

TIME	Event	Location
18:10 – 18:30	**Micromachining with pico-second lasers: New results and trends** *Speaker:* A.Nebel *Session:* Joint session: Industrial aplications 2	C1.1

WEDNESDAY, JUNE 9, 2010

TIME	Event	Location
08:35 – 09:00	**KeyNote** *Speaker:* U. Keller *Session:* Joint session: Lasers for micro	C1.1
09:00 – 09:15 **P. 131**	**Frequency-doubled High-power Nanosecond Lasers for Materials Processing** *Speaker:* C. Stolzenburg *Session:* Joint session: Lasers for micro	C1.1
09:15 – 09:30	**Arbitrary sequence ps-ns laser source** *Speaker:* J. Früchtenicht *Session:* Joint session: Lasers for micro	C1.1
09:20 – 09:40 **P. 132**	**Surface ablation of dielectrics with sub-10 fs to 300 fs laser pulses: Aspect ratio and crater shape evolution as a function of laser intensity** *Speaker:* Olivier Utéza *Session:* Ultra-short pulse processing 3	C4.1
09:20 – 09:40 **P. 133**	**Laser-matter interaction in fusion welding of glass using ultrashort laser pulses - Formation mechanism and prevention of weld defects -** *Speaker:* Isamu Miyamoto *Session:* Welding and bonding 1	C4.3
09:30 – 09:45 **P. 134**	**Robust and flexible picosec-ond lasers for industrial micromachining** *Speaker:* K. Weingarten *Session:* Joint session: Lasers for micro	C1.1
09:40 – 10:00 **P. 135**	**Picosecond laser induced colour centres: Stress-free markings and choice of guiding optics** *Speaker:* Andreas Lemke *Session:* Ultra-short pulse processing 3	C4.1

WEDNESDAY, JUNE 9, 2010

TIME	Event	Location
09:40 – 10:00 **P. 136**	**Ultrafast Laser Microwelding of Glass Substrates with High Strength by Sparse Scanning Technique** *Speaker:* Yasuyuki Ozeki *Session:* Welding and bonding 1	C4.3
09:45 – 10:00 **P. 137**	**Recent advances in high power ultrafast thin disk laser oscillators** *Speaker:* T. Südmeyer *Session:* Joint session: Lasers for micro	C1.1
10:00 – 10:20 **P. 138**	**Laser processing of tungsten powder with femto second laser radiation** *Speaker:* Robby Ebert *Session:* Ultra-short pulse processing 3	C4.1
10:00 – 10:20 **P. 139**	**Laser Glass frit Bonding for Hermetic Sealing of Glass Substrates and Sensors** *Speaker:* Heidrun Kind *Session:* Welding and bonding 2	C4.3
10:20 – 10:40 **P. 140**	**Structural arrangement of titanium microcolumnar surface structures induced by femtosecond laser irradiation** *Speaker:* Alexandre Cunha *Session:* Ultra-short pulse processing 3	C4.1
10:20 – 10:40 **P. 141**	**Emission Data and Environ-mental Costs During Laser Joining of Metals** *Speaker:* Jürgen Walter *Session:* Welding and bonding 1	C4.3
10:20 – 10:40 **P. 142**	**High power femtosecond disk laser** *Speaker:* M. Larionov *Session:* Joint session: Lasers for micro	C1.1

TIME	Event	Location
10:40 – 11:00 **P. 143**	**Removal of nano particles on silicon wafer by plasma filament using a femtosecond laser** *Speaker:* Sung-Hak Cho *Session:* Ultra-short pulse processing 3	C4.1
10:40 – 11:00 **P. 144**	**Long Pulse Fiber Lasers and Applications** *Speaker:* Michael Grupp *Session:* Joint session: Lasers for micro	C1.1
11:00 – 11:20	**High Q Laser femtoREGEN™ UC for industrial micro-processing applications** *Speaker:* Martin Kellert *Session:* Joint session: Lasers for micro	C1.1
11:00 – 11:20 **P. 145**	**Polarization sensitive devices using ultrafast laser photoin-scription of nanoscale periodic arrangements** *Speaker:*Razvan Stoian *Session:* Ultra-short pulse processing 3	C4.1
11:20 – 11:40	**Single stage high energy rod-type femtosecond fiber amplifier for micro-processing applications** *Speaker:* Clemens Hönninger *Session:* Joint session: Lasers for micro	C1.1
12:10 – 12:40	**How the Laser Came to Be** *Speaker:* A. E. Siegman *Session:* 50 years Laser	C1.1
12:40 – 13:10	**Laser on their Way to Industrial Applications** *Speaker:* P. Seiler *Session:* 50 years Laser	C1.1
13:10 – 13:45	**An Economic History of Industrial Laser Technology** *Speaker:* D. Belforte *Session:* 50 years Laser	C1.1

TIME	Event	Location
14:00 – 14:30 P. 146	**Laser-Bonding in high power electronics (Invited)** *Speaker:* Michael Schmidt *Session:* Welding and bonding 2	C4.3
14:30 – 15:00 P. 147	**Nanoablation using 2D Gold and Dielectric Nanosphere Templates Excited by Femto-second Laser (Invited)** *Speaker:* Minoru Obara *Session:* Nano structures 1	C4.1
15:00 – 15:30 P. 148	**Controlled Growth of Carbon nanostructures in Laser-assisted Chemical Vapor Deposition (Invited)** *Speaker:* Yongfeng Lu *Session:* Nano structures 1	C4.1
14:30 – 14:50 P. 149	**Effects of Superposed Con-tinuous Diode Laser on Welding Characteristics for Aluminum Alloy in Pulsed Nd:YAG Laser Welding** *Speaker:* Kazuya Miura *Session:* Welding and bonding 2	C4.3
14:50 – 15:10 P. 150	**Laser welding with pulsed solid state lasers: strategies and new developments** *Speaker:* Reiner Witte *Session:* Welding and bonding 2	C4.3
15:10 – 15:30 P. 151	**Laser Beam Micro Welding of DCB Substrates with Fiber Lasers and Thin Disk Lasers** *Speaker:* Jens Gedicke *Session:* Welding and bonding 2	C4.3
15:30 – 15:50 P. 152	**Nanostructuring by infrared fs-laser densification of amorphous dielectrics** *Speaker:* Arkadi Rosenfeld *Session:* Nano structures 1	C4.1
15:30 – 15:50 P. 153	**YAG laser spot welding of PET and metallic materials** *Speaker:* Yusof Farazila *Session:* Welding and bonding 2	C4.3

TIME	Event	Location
15:50 – 16:10 P. 154	**Laser micro joining of thin films on flexible substrates for electrical connection** *Speaker:* Martin Ehrhardt *Session:* Welding and bonding 2	C4.3
16:30 – 16:50 P. 155	**Fabrication of novel nanos-tructures on Silicon with femtosecond laser pulses** *Speaker:* Chung-Wei Cheng *Session:* Nano structures 2	C4.1
16:30 – 16:50 P. 156	**Silica Based Micro- Cantilevers Fabricated Using Direct UV Writting and Micro-Machining For Chemical and Physical Sensing Applications** *Speaker:* Christopher Holmes *Session:* Micro devices	C4.3
16:50 – 17:10 P. 157	**Fabrication of 2D periodic nanoholes on GaN surface using wet-chemical-assisted femtosecond laser ablation** *Speaker:* Seisuke Nakashima *Session:* Nano structures 2	C4.1
16:50 – 17:10 P. 158	**Rotational Magnetic Micro-Viscometer for Blood Viscosity Measurements at the Micro Scale** *Speaker:* Blaz Kavcic *Session:* Micro devices	C4.3
17:10 – 17:30 P. 159	**Characterization of silver nano-particles prepared by laser ablation in water and DMSO** *Speaker:* Nastaran Mansour *Session:* Nano structures 2	C4.1
17:10 – 17:30 P. 160	**Microstructured GRIN lens as an external coupler to thin-film waveguides** *Speaker:* Jürgen Ihlemann *Session:* Micro devices	C4.3

WEDNESDAY, JUNE 9, 2010

TIME	Event	Location
17:30 – 17:50 **P. 161**	**Size-controlled silicon quantum dots synthesis by gated CO2 laser pyrolysis** *Speaker:* Olivier Sublemontier *Session:* Nano structures 2	C4.1
17:30 – 17:50 **P. 162**	**Analysis of Regimes for Short Pulse Laser Shock Micro-Forming of Thin Metal Components for MEMS Manufacturing** Speaker: José L. Ocaña Session: Micro devices	C4.3
17:50 – 18:10 **P. 163**	**Tuning Size Distribution of Gold Nanoparticles Generated by Laser Ablation in Water at Different Repetition Rates** Speaker: Ana Menéndez-Manjón Session: Nano structures 2	C4.1
17:50 – 18:10 **P. 164**	**Thin silicon wafers dicing using line-focused nanosecond-pulse 355nm q-switched laser** Speaker: Rajesh S. Patel Session: Micro devices	C4.3
18:10 – 18:30 **P. 165**	**Formation of Polycrystalline Ge Micropattern by Laser Direct Writing Method Using Germanium Ink Consisting of Organogermanium Nanocluster** Speaker: Akira Watanabe Session: Nano structures 2	C4.1
18:10 – 18:30 **P. 166**	**Laser Based Vacuum Packaging of Micro-Devices Using Localised Heating** Speaker: Norbert Lorenz Session: Micro devices	C4.3

THURSDAY, 10 JUNE 2010

TIME	Event	Location
09:20 – 11:10	**Short presentation of posters**	C4.1
09:20 – 11:20	**Installation of posters**	C5
11:30 – 13:00	**Poster session**	C5
14:00 – 14:30 P. 167	**Femtosecond laser applied to photovoltaic cell processing (Invited)** *Speaker:* Marc Sentis *Session:* Photovoltaic Applications 1	C4.1
14:00 – 14:20 P. 168	**Continuous Fabrication of Colloidal Organic Nano-particles by Laser Ablation of Microcrystals in Liquid** *Speaker:* Philipp Wagener *Session:* Nano structures 3	C4.3
14:20 – 14:40 P. 169	**Synthesis of nanoparticles in solution using femtosecond laser ablation** *Speaker:* Martti Silvennoinen *Session:* Nano structures 3	C4.3
14:30 – 15:00 P. 170	**Laser processing for advanced solar cells (Invited)** *Speaker:* Jochen Löffler *Session:* Photovoltaic Applications 1	C4.1
14:40 – 15:00 P. 171	**Nanojoining of Ag/Au nano-particles by femtosecond laser irradiation** *Speaker:* Anming Hu *Session:* Nano structures 3	C4.3
15:00 – 15:20 P. 172	**Ultraviolet optical near-fields of micro spheres imprinted in phase change films** *Speaker:* Jan Siegel *Session:* Nano structures 3	C4.3

TIME	Event	Location
15:00 – 15:30 P. 173	**Laser based processes in next generation solar cell production, chances and challenges (Invited)** *Speaker:* Joachim John *Session:* Photovoltaic Applications 1	C4.3
15:20 – 15:40 P. 176	**Two dimensional periodic nanostructures with enhanced band-gap emission on ZnO induced by the interference of three femtosecond laser beams** *Speaker:* Tianqing Jia *Session:* Nano structures 3	C4.3
15:30 – 16:00 P. 177	**Laser - An Enabling Technology in the Photovoltaics Revolution (Invited)** *Speaker:* Rajesh S. Patel *Session:* Photovoltaic Applications 1	C4.1
15:40 – 16:00 P. 178	**Design of bioconjugated gold nanoparticles by femtosecond-laser ablation** *Speaker:* Annette Barchanski *Session:* Nano structures 3	C4.3
16:30 – 16:50 P. 179	**Laser processing of thin films for photovoltaic applications** *Speaker:* Aart Schoonderbeek *Session:* Photovoltaic Applications 2	C4.1
16:30 – 16:50 P. 180	**Nanostructures on ITO thin film irradiated by different femtosecond laser wave-lengths** *Speaker:* J.S. Chen *Session:* Nano structures 4	C4.3
16:50 – 17:10 P. 181	**Development and optimization of an industrial laser doping process for crystalline solar cells** *Speaker:* Malte Schulz-Ruhtenberg *Session:* Photovoltaic Applications 2	C4.1
16:50 – 17:10 P. 182	**Femtosecond laser irradiation induced modification of gold nanorods inside silicate glass** *Speaker:* Bertrand Poumellec *Session:* Ultra-short pulse processing 4	C4.3

SESSION LIST – ALPHABETICAL ORDER

3D PROCESSING 1

TIME	Event	DATE
09:20 – 09:50	**Femtosecond laser micromachining enables optofluidic sensing in lab-on-a-chip (Invited)** *Speaker:* Roberto Osellame	June 08
09:50 – 10:10	**3D laser lithography and nanoimprint lithography: versatile methods for the micro- and nano fabrication of photonic structures** *Speaker:* Volker Schmidt	June 08
10:10 – 10:30	**Influence of selective laser melting process parameters on morphology of single vectors from metal powder** *Speaker:* Igor Yadroitsev	June 08
09:20 – 09:50	**3D sub-diffraction-limit patterning of hybrid polymers with visible and infrared laser pulses** *Speaker:* Sönke Steenhusen	June 08
12:40 – 13:00	**Development of 2D/3D Micromachining Processes Based on Nanosecond Laser Sources for Industrial Manufacturing** *Speaker:* José L. Ocaña	June 08
	Location: C 4.1	

3D PROCESSING 2

TIME	Event	DATE
11:30 – 12:00	**3D Polymerization for Functional Devices (Invited)** *Speaker:* Hong-Bo Sun	June 08
12:00 – 12:20	**Two-photon polymerization as method for the fabrication of large scale biomedical scaffold applications** *Speaker:* Thomas Stichel	June 08
12:20 – 12:40	**Fabrication of 3D Protein Microstructures** *Speaker:* Sascha Engelhardt	June 08

50 YEARS LASER

TIME	Event	DATE
12:10 – 12:40	**How the Laser Came to Be** *Speaker:* A. E. Siegmann	June 09
12:40 – 13:10	**Laser on their Way to Industrial Applications** *Speaker:* P. Seiler	June 09
13:10 – 13:45	**An Economic History of Industrial Laser Technolog** *Speaker:* D. Belforte	June 09
	Location: C 1.1	

BIOLOGICAL AND MEDICAL APPLICATIONS

TIME	Event	DATE
	Optical Trapping of Biomolecules and Nanoparticles Based on Resonance and Surface Plasmon (Invited) *Speaker:* Yasuyuki Tsuboi	June 08
09:50 – 10:10	**In Vivo Writing using Two-Photon-Polymerization** *Speaker:* Jan Torgersen	June 08
10:10 – 10:30	**Femtosecond laser ablation of dentin: A characterisation study** *Speaker:* Sandra Alves	June 08

10:20 – 10:40	**Mechanism study of gliding movement of Phormidium in nano-aquariums integrated with different functions fabricated by femtosecond laser** *Speaker:* Yasutaka Hanada	June 08
10:50 – 11:10	**Laser-controlled Injector for Biological Applications** *Speaker:* Toshihiko Ooie	June 08
	Location: C 4.3	

COMPONENTS AND SYSTEMS

TIME	Event	DATE
14:00 – 14:30	**Laser Ignition of Internal Combustion Engines (Invited)** *Speaker:* Ernst Wintner	June 08
14:30 – 14:50	**High-end micromachining with >150W average power from a 1MHz 10ps-laser** *Speaker:* Marco Höfer	June 08
14:50 – 15:10	**Multiple Beam Internal Structuring of PMMA** *Speaker:* Walter Perrie	June 08
	Location: C 4.1	

DEPOSITION AND SYNTHESIS

TIME	Event	DATE
09:20 – 09:40	**Development of a Laser Stabilised Gas Metal Arc Cladding Process** *Speaker:* Alexander Barroi	June 08
09:40 – 10:00	**A new additive technique for laser precision microfacturing: laser microcladding** *Speaker:* J. del Val	June 08
10:00 – 10:20	**Synthesis of ZnO nanowire heterostructures by laser ablation and their optical characteristics** *Speaker:* Daisuke Nakamura	June 08
10:20 – 10:40	**F2-Laser Formation of Transparent Protective Layer onto Polycarbonate for Lightweight Window** *Speaker:* Masayuki Okoshi	June 08
10:40 – 11:00	**Reactive deposition of AlxGa1-xN thin films by hybrid processes of pulsed laser ablation and ECR microwave discharge** *Speaker:* Jiada D. Wu	June 08
	Location: C 5	

DIRECT WRITE

TIME	Event	DATE
16:30 – 16:50	**Laser Decal Transfer of Nanomaterials** *Speaker:* Alberto Piqué	June 07
16:50 – 17:10	**Dynamics of the Laser Decal Transfer Process** *Speaker:* Scott A. Mathews	June 07
17:10 – 17:30	**Optimization of feature resolution, processing window & structuring time for the two-photon polymerization(2PP) process by the use of novel initiators** *Speaker:* Niklas Pucher	June 07
17:30 – 17:50	**Laser Assisted Bioprinting of Cells & Biomaterials: Development of a Dedicated Workstation, Experimental Results and Jet Formation Modeling** *Speaker:* Agnès Souquet	June 07
17:50 – 18:10	**Laser Induced Forward Transfer: A Compact Machine** *Speaker:* Dominik Riester	June 07
	Location: C 4.3	

FUNDAMENTALS

TIME	Event	DATE
11:30 – 12:00	**Role of gas optical breakdown plasma in material ablation by short laser pulses (Invited)** *Speaker:* V.I.Konov	June 08
12:00 – 12:20	**Modelling Laser Induced Periodic Surface Structures** *Speaker:* Johann Z.P. Skolski	June 08
12:20 – 12:40	**Fs-Pump-Probe Measurement of the Transient Dielectric Function of Fused Silica** *Speaker:* Maren Hörstmann-Jungemann	June 08
	Location: C 5	

JOINT SESSION: INDUSTRIAL APPLICATIONS 1

TIME	Event	DATE
14:10 – 14:30	**Thin film processing with UV excimer lasers** *Speaker:* Ralph Delmdahl	June 08
14:30 – 14:50	**Micromachining Hard Materials with Industrial Picosecond Lasers** *Speaker:* Dirk Müller	June 08
14:50 – 15:10	**Industrial Cutting of Electrodes for Advanced Batteries** *Speaker:* Eric Audouard	June 08
15:10 – 15:30	**Thin metal cutting using water jet-guided laser** *Speaker:* Alexandre Pauchard	June 08
15:30 – 15:50	**High Precision Machining Powered by UV** *Speaker:* Rainer Paetzel	June 08
15:50 – 16:10	**Laser Micromachining of Piezoelectric Ceramics** *Speaker:* Xie Qiong	June 08
	Location: C1.1	

JOINT SESSION: INDUSTRIAL APPLICATIONS 2

TIME	Event	DATE
16:50 – 17:10	**Reliable laser micro-welding of Copper** *Speaker:* U. Dürr	June 08
17:10 – 17:30	**Broadly based micro machining applications for value added production with high power picosecond lasers** *Speaker:* S. Weiler	June 08
17:30 – 17:50	**Applications and perspectives of ultrashort pulsed lasers** *Speaker:* J. König	June 08
17:50 – 18:10	**High-efficiency high-quality carbon machining strategies** *Speaker:* A. Wolynski	June 08
18:10 – 18:30	**Micromachining with picosecond lasers: New results and trends** *Speaker:* A.Nebel	June 08
	Location: C 1.1	

JOINT SESSION: LASERS FOR MICRO

TIME	Event	DATE
08:35 – 09:00	**Joint session: Lasers for micro KeyNote** *Speaker:* U. Keller	June 09
09:00 – 09:15	**Frequency-doubled High-power Nanosecond Lasers for Materials Processing** *Speaker:* C. Stolzenburg	June 09
09:15 – 09:30	**Arbitrary sequence ps-ns laser source** *Speaker:* J. Früchtenicht	June 09
09:30 – 09:45	**Robust and flexible picosecond lasers for industrial micromachining** *Speaker:* K. Weingarten	June 09
09:45 – 10:00	**Recent advances in high power ultrafast thin disk laser oscillators** *Speaker:* T. Südmeyer	June 09
10:20 – 10:40	**High power femtosecond disk laser** *Speaker:* M. Larionov	June 09
10:40 – 11:00	**Long Pulse Fiber Lasers and Applications** *Speaker:* Michael Grupp	June 09
11:00 – 11:20	**High Q Laser femtoREGEN™ UC for industrial micro-processing applications** *Speaker:* Martin Kellert	June 09
11:20 – 11:40	**Single stage high energy rod-type femtosecond fiber amplifier for micro-processing applications** *Speaker:* Clemens Hönninger	June 09
	Location: C 1.1	

MICRO DEVICES

TIME	Event	DATE
16:30 – 16:50	**Silica Based Micro- Cantilevers Fabricated Using Direct UV Writting and Micro-Machining For Chemical and Physical Sensing Applications** *Speaker:* Christopher Holmes	June 09
16:50 – 17:10	**Rotational Magnetic Micro-Viscometer for Blood Viscosity Measurements at the Micro Scale** *Speaker:* Blaz Kavcic	June 09
17:10 – 17:30	**Microstructured GRIN lens as an external coupler to thin-film waveguides** *Speaker:* Jürgen Ihlemann	June 09
17:30 – 17:50	**Analysis of Regimes for Short Pulse Laser Shock Micro-Forming of Thin Metal Components for MEMS Manufacturing** *Speaker:* José L. Ocaña	June 09
17:50 – 18:10	**Thin silicon wafers dicing using line-focused nanosecond-pulse 355nm q-switched laser** *Speaker:* Rajesh S. Patel	June 09
18:10 – 18:30	**Laser Based Vacuum Packaging of Micro-Devices Using Localised Heatin** *Speaker:* Norbert Lorenz	June 09
	Location: C 4.3	

MICRO MACHINING 1

TIME	Event	DATE
13:50 – 14:10	**Gas-assisted microdrilling in steel with ultrashort pulsed laser radiation** *Speaker:* M. Kraus	June 07
14:10 – 14:30	**Advanced laser micro machining using a novel trepanning system** *Speaker:* David Ashkenasi	June 07
14:30 – 14:50	**Effect of shot number on femtosecond laser drilling of silicon** *Speaker:* Petri Laakso	June 07
14:50 – 15:10	**LASER DRILLING with PULSE FIBER LASER** *Speaker:* Michael Stark	June 07
15:10 – 15:30	**Machining hole arrays in polycarbonate sheet using UV solid state laser** *Speaker:* Susumu Nakamura	June 07
15:30 – 15:50	**Drilling Holes through Cemented Tungsten Carbide Plates by Ultrafast Laser** *Speaker:* Yoshiro Ito	June 07
15:50 – 16:10	**High rate laser micro processing using high brilliant cw laser radiation** *Speaker:* Horst Exner	June 07
	Location: C 4.1	

MICRO MACHINING 2

TIME	Event	DATE
16:30 – 16:50	**Pulsed laser material ablation by contacting optical fiber** *Speaker:* Vitaly I.Konov	June 07
16:50 – 17:10	**Ablation of grooves in stainless steel by femtosecond pulses assisted by laser steam cleaning** *Speaker:* Valdas Sirutkaitis	June 07
17:30 – 17:50	**Fabrication of multiple slanted microstructures on silica glass by laser-induced backside wet etching** *Speaker:* Tadatake Sato	June 07
17:10 – 17:30	**Engraving of metals using high repetition rate ultrafast lasers** *Speaker:* John Lopez	June 07
17:50 – 18:10	**Microstructuring of Various Materials using Femtosecond Laser Pulses** *Speaker:* Andy Engel	June 07
	Location: C 4.1	

NANO STRUCTURES 1

TIME	Event	DATE
14:30 – 15:00	**Nanoablation using 2D Gold and Dielectric Nanosphere Templates Excited by Femtosecond Laser (Invited)** *Speaker:* Minoru Obara	June 09
15:00 – 15:30	**Meta-material consisting of nanostructure (Invited)** *Speaker:* Luo xiangang	June 09
15:30 – 15:50	**Nanostructuring by infrared fs-laser densification of amorphous dielectris** *Speaker:* Arkadi Rosenfeld	June 09
	Location: C 4.1	

NANO STRUCTURES 2

TIME	Event	DATE
16:30 – 16:50	**Fabrication of novel nanostructures on Silicon with femtosecond laser pulses** *Speaker:* Chung-Wei Cheng	June 09
16:50 – 17:10	**Fabrication of 2D periodic nanoholes on GaN surface using wet-chemical-assisted femtosecond laser ablation Speaker: Seisuke Nakashima** *Speaker:* Seisuke Nakashima	June 09
17:10 – 17:30	**Characterization of silver nanoparticles prepared by laser ablation in water and DMS** *Speaker:* Nastaran Mansour	June 09
17:30 – 17:50	**Size-controlled silicon quantum dots synthesis by gated CO2 laser pyrolysis** *Speaker:* Olivier Sublemontier	June 09
17:50 – 18:10	**Tuning Size Distribution of Gold Nanoparticles Generated by Laser Ablation in Water at Different Repetition Rate** *Speaker:* Ana Menéndez-Manjón	June 09
18:10 – 18:30	**Formation of Polycrystalline Ge Micropattern by Laser Direct Writing Method Using Germanium Ink Consisting of Organogermanium Nanocluster** Speaker: Akira Watanabe	June 09
	Location: C 4.1	

NANO STRUCTURES 3

TIME	Event	DATE
14:00 – 14:20	**Continuous Fabrication of Colloidal Organic Nanoparticles by Laser Ablation of Microcrystals in Liquid** *Speaker:* Philipp Wagener	June 10
14:20 – 14:40	**Synthesis of nanoparticles in solution using femtosecond laser ablation** *Speaker:* Martti Silvennoinen	June 10
14:40 – 15:00	**Nanojoining of Ag/Au nanoparticles by femtosecond laser irradiatio** *Speaker:* Anming Hu	June 10
15:00 – 15:20	**Ultraviolet optical near-fields of micro spheres imprinted in phase change films** *Speaker:* Jan Siegel	June 10
15:20 – 15:40	**Two dimensional periodic nanostructures with enhanced band-gap emission on ZnO induced by the interference of three femtosecond laser beams** *Speaker:* Tianqing Jia	June 10
15:40 – 16:00	**Design of bioconjugated gold nanoparticles by femtosecond-laser ablation** *Speaker:* Annette Barchanski	June 10
	Location: C 4.3	

NANO STRUCTURES 4

TIME	Event	DATE
16:30 – 16:50	**Nanostructures on ITO thin film irradiated by different femtosecond laser wave-lengths** *Speaker:* J.S. Chen	June 10
	Location: C 4.3	

PATTERNING 1

TIME	Event	DATE
11:30 – 11:50	**Plasmonics Enhanced Femto-second Laser Nanoprocessing: Modeling and application to biology** *Speaker:* Michel Meunier	June 08
11:50 – 12:10	**Local oxidation of thin metallic films under short pulse laser action** *Speaker:* Vadim P. Veiko	June 08
12:10 – 12:30	**Picosecond laser machined designed patterns with anti-ice effect** *Speaker:* Daniel Arnaldo del Cerro	June 08
12:30 – 12:50	**Patterning of a NiCr-Al2O3 thin film system with picosecond laser pulses** *Speaker:* Oliver Suttmann	June 08
	Location: C 4.3	

PATTERNING 2

TIME	Event	DATE
14:00 – 14:20	**Laser Micro-Patterning by Means of Optical Fibers with Etched Tips or Micro-grinded Lens End Faces** *Speaker:* Sergii Yakunin	June 08
14:20 – 14:40	**Formation and evolution of self-organized patterns in laser irradiation of silicon surface in water** *Speaker:* X. Y. Chen	June 08
14:40 – 15:00	**Volume Bragg grating forma-tion in fused silica with high repetition rate femtosecond Yb:KGW laser pulses** *Speaker:* Valdas Sirutkaitis	June 08
15:00 – 15:20	**Generation of Multi Spot Arrays and In-Process Spot Shaping for Parallel Laser Processing of Microstructures** *Speaker:* M. Schmidt	June 08
15:20 – 15:40	**Fabrication of sub-micron Gratings on Silicon by Mask-less Exposure of Nanosecond Laser Pulses** *Speaker:* Ravi K. Soni	June 08
15:40 – 16:00	**Laser Patterning of Conformal Electromagnetic Surfaces** *Speaker:* Nicholas A. Charipar	June 08
	Location: C 4.3	

PATTERNING 3

TIME	Event	DATE
16:30 – 16:50	**Enhancement of the hydrophobic properties of metals by femtosecond laser texturing of surfaces** *Speaker:* Stéphane Valette	June 08
16:50 – 17:10	**Ultra fast laser machined hydrophobic stainless steel surface for drag reduction in laminar flows** *Speaker:* R.Jagdheesh	June 08
17:10 – 17:30	**Generation of periodic micro- and nano-structures by polarization-controlled laser beam interference** *Speaker:* Stefan Beckemper	June 08
17:30 – 17:50	**Production of Microstructures in wide-band-gap materials using pulsed laser ablation at 157 nm wavelength** *Speaker:* Falk Haehnel	June 08
17:50 – 18:10	**Cu Micropatterns Fabricated by Femtosecond Laser Direct Writing Using Cu Nanoparticle Ink** *Speaker:* Chung-Wei Cheng	June 08
	Location: C 4.3	

PHOTOVOLTAIC APPLICATIONS 1

TIME	Event	DATE
14:00 – 14:30	**Femtosecond laser applied to photovoltaic cell processing (Invited)** *Speaker:* Marc Sentis	June 10
14:30 – 15:00	**Laser processing for advanced solar cells (Invited)** *Speaker:* Jochen Löffler *Session:* Photovoltaic Applications 1	June 10
15:00 – 15:30	**Laser based processes in next generation solar cell production, chances and challenges (Invited)** *Speaker:* Joachim John	June 10
15:30 – 16:00	**Laser - An Enabling Technology in the Photovoltaics Revolution (Invited)** *Speaker:* Rajesh S. Patel	June 10
	Location: C 4.1	

PHOTOVOLTAIC APPLICATIONS 2

TIME	Event	DATE
16:30 – 16:50	**Laser processing of thin films for photovoltaic applications** *Speaker:* Aart Schoonderbeek	June 10
16:50 – 17:10	**Development and optimization of an industrial laser doping process for crystalline solar cells** *Speaker:* Malte Schulz-Ruhtenberg	June 10
	Location: C 4.1	

PLENARY SESSION

TIME	Event	DATE
10:10 – 10:30	**Welcome and opening remarks** *Speaker:* K. Sugioka, F. Dausinger	June 07
10:30 – 11:10	**Laser applications in Japan during the first 50 years (Invited)** *Speaker:* Isamu Miyamoto	June 07
11:10 – 11:50	**Introduction of laser manu-facturing into mass production (Invited)** *Speaker:* Godehard Schmitz	June 07
11:50 – 12:30	**Laser processing in industrial solar module manufacturing (Invited)** *Speaker:* Heather J. Booth	June 07
	Location: C 5	

POSTER SESSION

TIME	Event	DATE
09:20 – 11:10	**Short presentation of posters**	June 10
	Location: C 4.1	
09:20 – 11:20	**Installation of Posters**	June 10
11:30 – 13:00	**Poster session**	June 10
	Location: C 5	

PROCESS MONITORING

TIME	Event	DATE
16:30 – 16:50	**Quality Aspects in High Power Ultra Short Pulse Laser Ablation** *Speaker:* S. Eifel	June 08
16:50 – 17:10	**Three-dimensionally Isotropic Resolution of Femtosecond Laser Micromachining Using Spatiotemporally Focused Pulses** *Speaker:* Fei He	June 08
17:10 – 17:30	**Interferometric in-process measurement of free-form surfaces in laser chemical manufacturing** *Speaker:* Christoph Gerhard	June 08
17:30 – 17:50	**Optical system for on-line monitoring in selective laser melting technology** *Speaker:* Maria Doubenskaia	June 08
17:50 – 18:10	**Laser-induced plasma investigations during material processing** *Speaker:* David Ashkenasi	June 08
18:10 – 18:30	**A practical method to deter-mine laser induced refractive index changes in transparent media using a Fourier approach** *Speaker:* Rene Berlich	June 08
	Location: C 4.1	

ULTRA-SHORT PULSE PROCESSING 1

TIME	Event	DATE
13:40 – 14:10	**Femtosecond laser wave-guide writing for customized micro optical elements (Invited)** *Speaker:* M. Richardson	June 07
14:10 – 14:30	**Nano-structures in array generated in liquid process induced by interfering femto-second laser processing** *Speaker:* Yoshiki Nakata	June 07
14:30 – 14:50	**Adapting Femtosecond Laser Pulses to Ionization Processes in Wide Band Gap Materials: a Route for Nanoscale Laser Processing** *Speaker:* Thomas Baumert	June 07
14:50 – 15:10	**Femtosecond Laser Irradiation and Hydrothermal–electro-chemical Treatment for Improv-ing Bioactivity of the Ti-based Bulk Metallic Glass** *Speaker:* Togo Shinonaga	June 07
15:10 – 15:30	**Laser micromachining of CFRP by ultra-short pulse lasers** *Speaker:* Masayuki Fujita	June 07
15:30 – 15:50	**Strong birefringence in multi-component silica-based glasses with ultrashort laser irradiation** *Speaker:* Fan Chaxing	June 07
	Location: C 5	

ULTRA-SHORT PULSE PROCESSING 2

TIME	Event	DATE
16:20 – 16:40	**Micro-processing of semicon-ductors using ultrafast laser radiation at 2 µm wavelength** *Speaker:* M. Ramme	June 07
16:40 – 17:00	**Rapid assessment of energy deposition profiles in sub-surface fs laser processing of dielectrics** *Speaker:* A. Ruiz de la Cru	June 07
17:00 – 17:20	**Spatiotemporal double pulse method in femtosecond laser processing** *Speaker:* Yoshio Hayasaki	June 07
17:20 – 17:40	**Rapid micro processing of metals with a high repetition rate femto second fibre laser** *Speaker:* Joerg Schille	June 07
17:40 – 18:00	**Second hermonic optimization method for holographic femtosecond laser processing** *Speaker:* Satoshi Hasegawa	June 07
	Location: C 5	

ULTRA-SHORT PULSE PROCESSING 3

TIME	Event	DATE
15:10 – 15:30	**Laser processing by using diffractive optical laser beam shaping technique** *Speaker:* Gediminas Raciukaitis	June 08
15:30 – 15:50	**Application of spatial light modulator in nanosecond laser machining** *Speaker:* Rainer J. Beck	June 08

TIME	Event	DATE
09:20 – 09:40	**Surface ablation of dielectrics with sub-10 fs to 300 fs laser pulses: Aspect ratio and crater shape evolution as a function of laser intensity** *Speaker:* Olivier Utéza	June 09
09:40 – 10:00	**Picosecond laser induced colour centres: Stress-free markings and choice of guiding optics** *Speaker:* Andreas Lemke	June 09
10:00 – 10:20	**Laser processing of tungsten powder with femto second laser radiation** *Speaker:* Robby Ebert	June 09
10:20 – 10:40	**Structural arrangement of titanium microcolumnar surface structures induced by femtosecond laser irradiation** *Speaker:* Alexandre Cunha	June 09
10:40 – 11:00	**Removal of nano particles on silicon wafer by plasma filament using a femto-second laser** *Speaker:* Sung-Hak Cho	June 09
11:00 – 11:20	**Polarization sensitive devices using ultrafast laser photoin-scription of nanoscale periodic arrangements** *Speaker:* Razvan Stoian	June 09
	Location: C 4.1	

ULTRA-SHORT PULSE PROCESSING 4

TIME	Event	DATE
16:50 – 17:10	**Femtosecond laser irradiation induced modification of gold nanorods inside silicate glass** *Speaker:* Bertrand Poumellec	June 10
	Location: C 4.3	

VUV LASER / DIRECT WRITE

TIME	Event	DATE
13:40 – 14:10	**Laboratory-scale EUV sources for metrology and material interaction studies (Invited)** *Speaker:* Klaus Mann	June 07
14:10 – 14:30	**Modular EUV source for the next generation lithography** *Speaker:* Olivier Sublemontier	June 07
14:30 – 15:00	**Laser Printed MEMS and Electronic Devices (Invited)** *Speaker:* Andrew J. Birnbaum	June 07
15:00 – 15:20	**New laser direct-writing technique for liquids microprinting** *Speaker:* Pere Serra	June 07
15:20 – 15:40	**Time-resolved imaging of hydrogel transport by laser-induced forward transfer (LIFT)** *Speaker:* Claudia Unger	June 07
15:40 – 16:00	**Fabrication of Optical Inter-connects with two photon polymerization** *Speaker:* Klaus Stadlmann	June 07
	Location: C 4.3	

WELDING AND BONDING 1

TIME	Event	DATE
09:20 – 09:40	**Laser-matter interaction in fusion welding of glass using ultrashort laser pulses - Formation mechanism and prevention of weld defects** *Speaker:* Isamu Miyamoto	June 09
09:40 – 10:00	**Ultrafast Laser Microwelding Strength by Sparse Scanning Technique** *Speaker:* Yasuyuki Ozeki	June 09
10:20 – 10:40	**Emission Data and Environ-mental Costs During Laser Joining of Metals** *Speaker:* Jürgen Walter	June 09
	Location: C 4.3	

WELDING AND BONDING 2

TIME	Event	DATE
10:00 – 10:20	**Laser Glass frit Bonding for Hermetic Sealing of Glass Substrates and Sensors** *Speaker:* Heidrun Kind	June 09
14:00 – 14:30	**Laser-Bonding in high power electronics (Invited)** *Speaker:* Michael Schmidt	June 09
14:30 – 14:50	**Effects of Superposed Continuous Diode Laser on Welding Characteristics for Aluminum Alloy in Pulsed Nd:YAG Laser Welding** *Speaker:* Kazuya Miura	June 09
14:50 – 15:10	**Laser welding with pulsed solid state lasers: strategies and new developments** *Speaker:* Reiner Witte	June 09
15:10 – 15:30	**Laser Beam Micro Welding of DCB Substrates with Fiber Lasers and Thin Disk Lasers** *Speaker:* Jens Gedicke	June 09
15:30 – 15:50	**YAG laser spot welding of PET and metallic materials** *Speaker:* Yusof Farazila	June 09
15:50 – 16:10	**Laser micro joining of thin films on flexible substrates or electrical connection** *Speaker:* Martin Ehrhardt	June 09
	Location: C 4.3	

Laser applications in Japan during the first 50 years

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Lasers have played an important role in manufacturing technology in Japanese industry since the first delivery of commercial solid-state laser and CO_2 laser in 1968 and 1979, respectively. Japanese industry also played an important role in the world laser market providing a world share of approximately 40% in the beginning of 1990's. Unfortunately, however, the laser technology slowed down suddenly due to economical recession continued for approximately 10 years in Japan from the mid-1990's. Nevertheless it is believed that Japan stays as one of the most important countries in laser application technology, where the technology is strongly supported by the steady improving effort of engineers in the production floor.

Different types of lasers have been used in industry for different purposes. Figure 1 shows the ratio of major lasers appeared in LAMP (International Congress on Laser Advanced Materials Processing), which represents the trend of lasers for materials processing in Japan. Whereas CO_2 laser dominated in 1987 decreases monotonically down to approximately 6% in 2009, YAG laser became largest in 2002. Excimer laser reached as large as 20% in 1992 due to the effect of Japanese national project, and decreases down to similar level of CO_2 laser. High rightness lasers such as fiber and disk lasers have been increasing rapidly in 21st century due to advances of the semiconductor laser technology. It is noted that ultrashort laser is increasing rapidly reaching over 40%, showing the strong anticipation as the new precision microfabrication tool in the next generation, although there exist actually only small industrial applications at the moment.

The présentation also includes (1) contributions of three main national projects of laser R&D in Japan, which initiated from 1977 with total budget of 37 billion yen, (2) historical overview of laser materials processing in Japan through the life cycle of selected laser materials processing technologies, and (3) recent topics of laser materials processing, some problems to be overcome and future prospects.

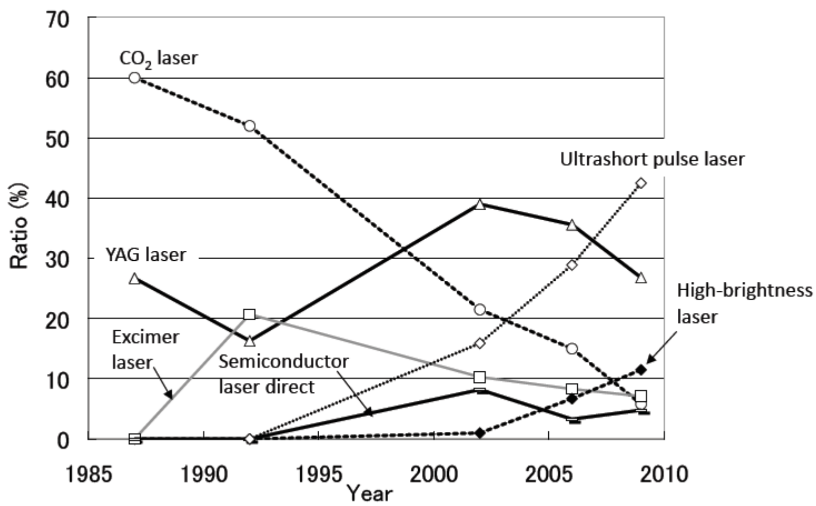

Fig. 1 Ratio of lasers for materials processing appeared in the proceedings of LAMP Congress (1987~2009).

Laser processing in industrial solar module manufacturing

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The use of lasers in the processing of solar cell structures has been known for many years both for c-Si and thin-film solar technologies. The maturity of the laser technology, the increase in scale of solar module production and the pressures to drive down cost of ownership and increase cell efficiencies have all contributed to the adoption of laser processes in industrial manufacturing. Where laser processes have been adopted in production they exploit the advantages of selective machining, a well defined interaction region, high precision and cost effective processing.

Today laser systems are the tool of choice in thin-film module manufacturing both for scribing the cell interconnects and for the module edge isolation. In thin-film module scribing, lasers are used for all of the technologies; amorphous and microcrystalline silicon, CdTe, CIS and CIGS in various patterning steps. For thin-film silicon and CdTe modules lasers are used in each of the P1, P2 and P3 cell interconnections, see Fig.1a, 1b for a typical industrial production tool. For CIS and CIGS modules lasers are widely used for P1 processes; P2 and P3 processes are possible with short-pulse lasers however adoption is limited. The use of lasers is common in all thin-film technologies for the clearing of the border region of the panel to electrically isolate the active area from the module edges.

For c-Si solar cells the primary laser application today is edge isolation and this is well-established in industrial production of most wafer-based cells. Other laser processes which are used in the production of advanced high-efficiency cell designs are laser grooved buried contacts (LGBC), see Fig. 1c, emitter wrap-through (EWT) or metal wrap-through (MWT) interconnects from the front side to the rear side of the wafer, selective emitters (SE) on the front side of the wafer or laser fired contacts (LFC) on the rear side of the wafer. Laser texturing processes are also being developed for enhanced cell efficiency. Although ‘standard’ cell designs characterized by discrete front and back contacts deposited via screen-printing and firing constitute over 90% of c-Si cell production today, the enhanced efficiency cells utilizing laser technologies are becoming produced more widely and will grow in market share in the years to come.

In the mission of the solar industry to reduce the cost of electricity generation there are increasing opportunities for laser processing to contribute to the goal of low cost of ownership in industrial manufacturing through improved module efficiencies, higher throughput and reduced process costs.

(a) (b) (c)

Figure 1: Lasers in industrial manufacturing of solar modules: (a) Multiple-beam processing of thin-film solar modules. (b) Scribe tools in an Oerlikon thin-film silicon end-to-end line. (c) Dual laser processing of LGBC in c-Si wafers.

Laboratory-scale EUV sources for metrology and material interaction studies

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Triggered by the roadmap of the semiconductor industry, tremendous progress has been achieved in the development of Extreme Ultraviolet (EUV) sources and high-quality EUV optical elements in recent years. Currently, the application of EUV radiation apart from microlithography comes more and more into focus. In this contribution we report on table-top laser-produced plasma sources capable of generating and focusing soft x-rays in the wavelength range from 2 - 20 nm. Main goal of our research is to utilize the uniquely strong interaction between EUV radiation and any kind of matter for probing, modifying, and high-resolution structuring of solid surfaces.

In most of our applications a highly excited plasma is generated by focusing a Nd:YAG laser (1064 nm, 800 mJ, 6 ns) into a pulsed gas target at power densities > 10^{12} W/cm². Depending on the employed target gas, broad-band as well as narrow-band characteristic emission in the EUV (~ 10 – 20nm) or XUV (~ 2 – 10nm) spectral range can be obtained. Instead of gaseous also solid state targets are employed, accomplishing a smaller plasma of higher brilliance. In order to generate a high fluence for interaction studies in the EUV at λ=13.5nm, a Schwarzschild objective consisting of two spherical mirrors with Mo/Si multilayer coatings is adapted to the source. Demagnified imaging of the plasma yields a small EUV writing spot (5µm dia.) with fluences of up to 7J/cm². Moreover, the device accomplishes a spatial resolution of ~130nm.

We present first applications of this integrated EUV source and optics system, demonstrating its potential for high-resolution modification and structuring of solid surfaces. The system has been employed e.g. for structured color center formation in LiF and for EUV ablation studies of various materials (cf. Fig.1) [1,2]. Ablation rates were determined for PMMA, PC and PTFE as a function of EUV fluence, yielding etch rates of up to 100 nm/pulse without any incubation effects. All investigated polymers as well as fused silica exhibit very smooth ablation craters, indicating a direct photon-induced bond breaking process, whereas for metal surfaces a thermal interaction process is observed. Silicon shows the highest ablation threshold of all investigated materials.

In addition, damage threshold measurements on EUV optics [2] as well as metrological applications are presented, in particular NEXAFS spectroscopy in the ´water window´ (λ= 2 – 4nm) [3].

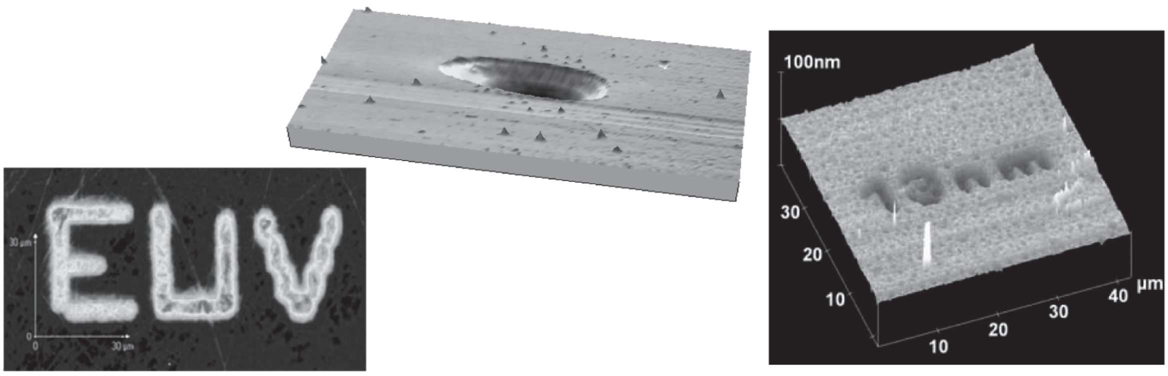

Figure 1 : Modification of different materials with EUV radiation (13.5nm, 6ns); left: color center formation in LiF, middle: ablation of PMMA using single EUV pulse of 1.1J/cm², right: structuring of PMMA using writing spot of 1µm dia.

[1] F. Barkusky, A. Bayer, C. Peth, K. Mann: Direct photo-etching of various polymers using high fluence radiation from a table-top extreme ultraviolet plasma source, J. Appl. Phys. **105**, 1 (2009)

[2] F. Barkusky, A. Bayer, S. Döring, P. Grossmann, K. Mann: Damage threshold measurements on EUV optics using focused radiation from a table-top laser produced plasma source, Optics Express **18**, No. 5, 4347 (2010)

[3] C. Peth, F. Barkusky, K. Mann: Near-edge X-ray absorption fine structure measurements using a laboratory-scale XUV source, Journal of Physics D: Applied Physics, **41** 105202 (2008)

Femtosecond laser waveguide writing for customized micro optical elements

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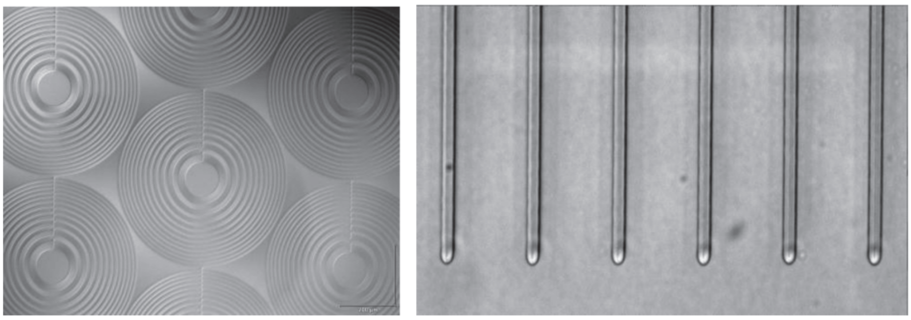
Femtosecond laser direct writing (FLDW) has drawn much attention for its ability to inscribe waveguide structures in a variety of optical glasses [1]. These waveguide structures are produced by laser-induced nonlinear optical processes such as multiphoton absorption resulting in localized refractive index changes in the transparent media. Laser-written waveguides can be the building-blocks of micro-optical elements such as directional couplers, gratings, and diffractive optical elements [2-4]. FLDW is therefore becoming a promising technique for micro-optical device fabrication, especially for 3D integration of customized optical structures [4,5].

This talk reviews the state-of-the-art of femtosecond laser direct writing and envisions future applications that can benefit from this technique. First, various waveguide writing techniques and associated optical glass research are presented. Characterization techniques to evaluate the properties and performance of laser-written waveguides are also shown. Examples of laser-written waveguides fabricated in various commercial and tailored glasses are shown with the evaluation of their performance. Second, some examples of 3D integration schemes for femtosecond laser-written structures are demonstrated. These will include volumetric Fresnel zone plates and their integration with other laser-written structures (fig.1). Characterization of the integrated devices will be presented including an estimation of coupling efficiency and propagation loss.



(a) (b)

Figure 1 Microscope image of (a) a micro diffractive optical lens array (b) a waveguide array.

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Gas-assisted microdrilling in steel with ultrashort pulsed laser radiation

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Ultrashort laser pulses enable the fabrication of high-precision microholes in metals without post processing, due to the minimization of thermal effects such as melt generation and recast formation [1,2]. The use of high pulse energies and high repetition rates, however, usually results in a strong ionization of the gas atmosphere inside the capillary. A considerable part of the pulse energy is transferred to the comparatively long-living laser-induced plasma and subsequently redistributed to the workpiece, causing a radial expansion of the capillary and the formation of melt due to prolonged surface heating. Using appropriate shielding gases for beam delivery and processing, plasma-induced effects such as beam distortion, defocusing or plasma shielding can be significantly reduced, whereas precision and ablation rate can be enhanced [3,4].
In the present work we have studied the influence of assist gas type and pressure on ablation velocity, borehole morphology and machining quality at microdrilling in X5CrNi18-10 austenitic steel. The drilling experiments were carried out in ambient air and under compressed air, nitrogen, argon and helium, the latter being delivered by a coaxial conical nozzle.
Microholes with a diameter in the range of 100 µm were fabricated in 1 mm sheets (see Figure 1), utilizing a helical drilling process without core. In order to analyze the ionization behaviour of the atmosphere inside the capillary, the optical plasma emissions were recorded using a fast Si photodiode [5].

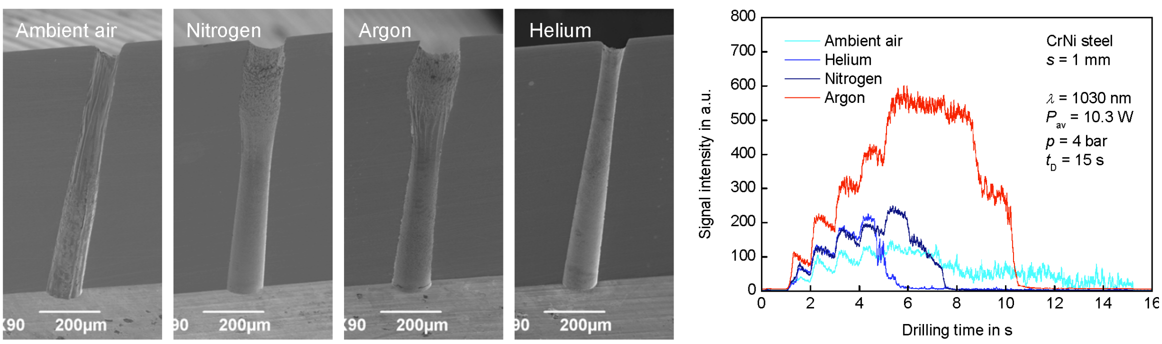

Figure 1. Left: Transverse sections of microholes in 1 mm CrNi steel, drilled in ambient air and under nitrogen, argon and helium atmosphere. Right: Intensity evolution of the optical process emissions. t_H = 6 ps, l = 1030 nm, processing time 15 s, helical drilling.

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Advanced laser micro machining using a novel trepanning system

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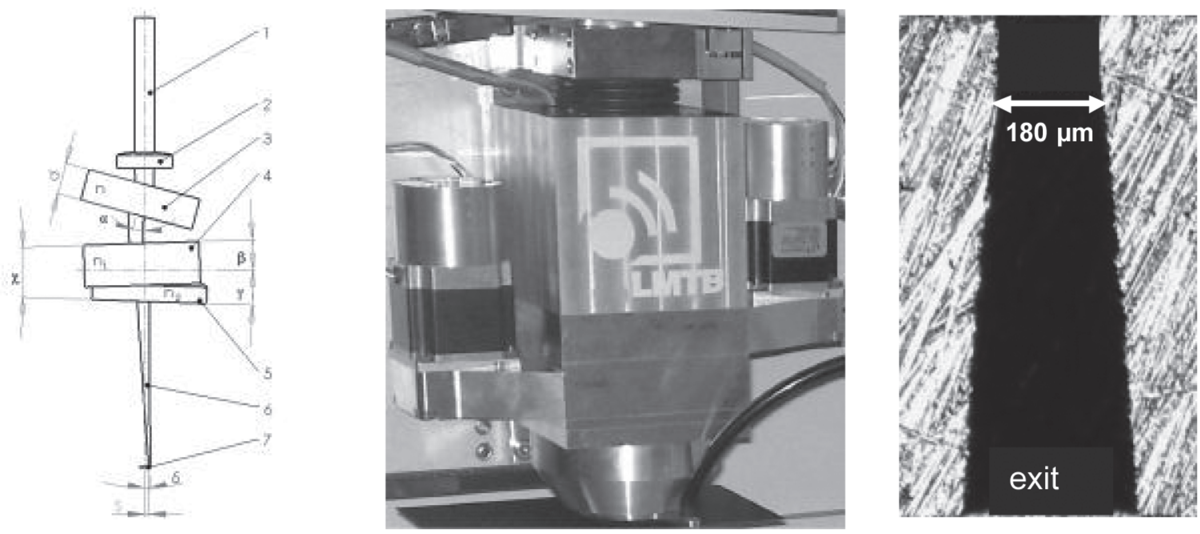
Laser induced micro ablation using diode-pumped pulsed solid-state lasers offers the possibility to machine and structure a whole range of different materials at adequate speed and high precision. To avoid negative thermal and mechanical effects at given laser parameters that obstruct the precision, LMTB has developed new concepts in optical trepanning. The resulting systems allow for a fast distribution of laser pulses, and they are implemented to process through-holes, pockets and grooves.

In conventional laser trepanning the ablation groove width decreases at progressing depth. Therefore, laser machined through-holes usually demonstrate a positive conicity. However, in many industrial applications, e.g. fabrication of combustion nozzles, even a **negative** conicity of the through-hole is required. To solve this problem, the LMTB designed and implemented a novel optical concept for the development of a versatile trepanning system, see Fig. 1, enabling the adjustment of the displacement **and** the inclination angle during circular rotation of even 20000 r.p.m. The presented trepanning systems are able to laser machine through-holes diameters < 100 µm with a negative conicity of up to 5°. Starting from an early stage of implementation, the novel trepanning system has been customized for two different industrial partners. The presentation outlines the development steps and advanced performance, accenting laser micro machining results utilizing the novel LMTB trepanning system in operation at different laser parameters [1].



(a) (b) (c)

Figure 1: LMTB trepanning system. (a) optical design (patent pending [2]): 1: laser beam, 2: focusing lens, 3: tilted plate, 4 and 5: lens pair, 6: displaced laser beam, 7: focal position. (b) Mounted trepanning system with three motor stages: 1. hollow shaft for the rotation (up to 20000 r.p.m.) of the optical elements, 2. step motor to alter the tilt angle of the plate during rotation and 3. step motor to alter the relative position of two optical elements to change the inclination angle (c) Laser processed tapered through-hole into a 0.8 mm Al plate with the novel LMTB trepanning system.

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Nano-structures in array generated in liquid process induced by interfering femtosecond laser processing

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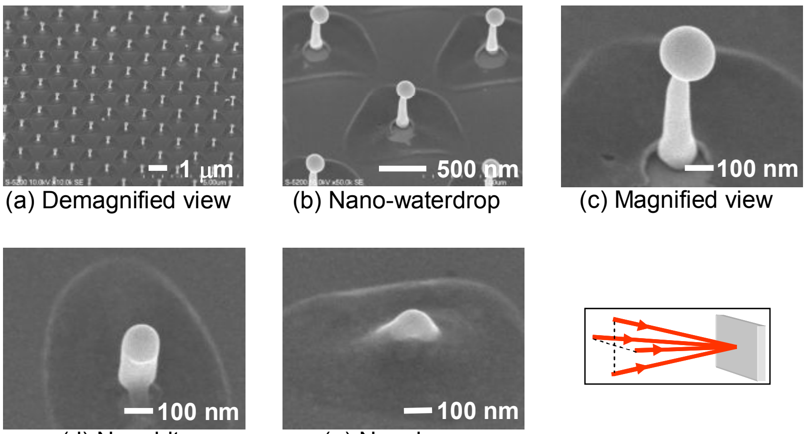
Interfering ultra-short pulse laser processing have been applied to generate nanostructures on metallic thin films [1-3]. The nanostructures are nano-waterdrop, nanobit, and nanobump etc.. They are generated by thermally process such as melting, inflation of solute film due to vapour pressure, etc.. Example structures generated on 10 nm thick Au film evaporated on sapphire (0001) substrate is shown in figure 1. The pulse width of the laser was 150 fs, and the wavelength was 785 nm. The correlation is illustrated in the bottom right inset, and the correlation angle between a beam and the target normal was about 25 degree. All the structures were generated in a single shot of laser irradiation, at room temperature, and without any evacuation.
As shown in the demagnified view of figure 1 (a), nanostructures were in matrix according to the interference pattern of four beams. The period was about 1.3 μm, which reflects the interference pattern. The fluence in average was about 103 mJ/cm^2. In the magnified view of (b) and (c), waterdrop-like structure was generated, and we named this structure “nano-waterdrop” [3]. The height including the top ellipsoidal bead was about 730 nm. The bead size was about 220 nm in long axis and 180 nm in short axis. The radius of the bottom was about 65 nm, and the neck was about 30 nm, which is far smaller than the wavelength, and resolution of normal fs laser processing. The shape is similar to that of normal waterdrop taken by a high-speed camera. In our case, liquid process, which is induced periodically by interference pattern, freezes by thermal radiation and conduction. In (d) at 69 mJ/cm^2, “nanobit” structure was generated. The height is about 330 nm, and the radius is about 70 nm. In (e) at 59 mJ/cm^2, nanobump structure was generated [1].
In the presentation, quite sharp structures having curvature radius smaller than 10 nm will be also presented.



(a) Demagnified view (b) Nano-waterdrop (c) Magnified view
(d) Nanobit (e) Nanobump

Figure 1 Nano-structures in array generated at different fluences. (a), (b) and (c) at 103 mJ/cm^2, (d) 69 mJ/cm^2, (e) 59 mJ/cm^2. The bottom right inset explains four beam correlation

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Modular EUV Source for the Next Generation Lithography

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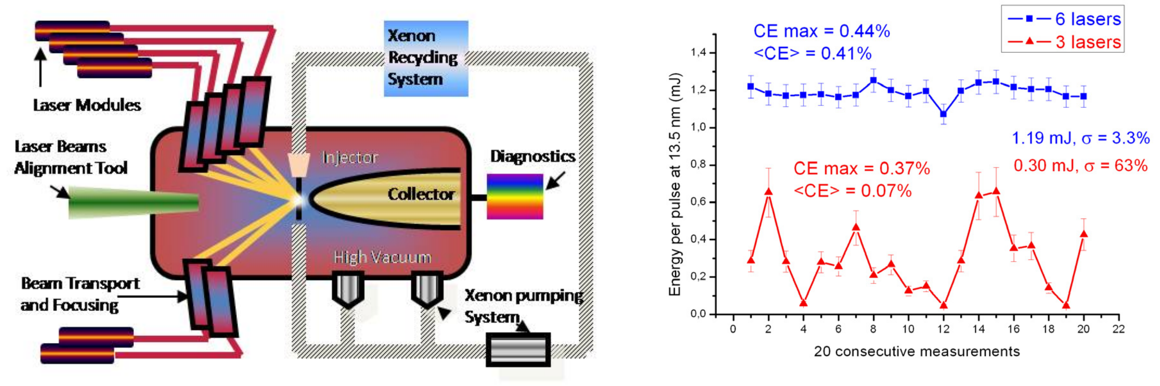
The EXULITE national-funded project was dedicated to the design and characterization of a laser-plasma-produced EUV power source at 13.5 nm for the next generation lithography. It was conducted in cooperation with two laboratories from CEA, ALCATEL and THALES and had received the Medea[+] label from the European Union.

One of our approach originalities was the laser scheme modularity [1] illustrated on Fig. 1(a). Six Nd:YAG laser beams were focused at the same time on a liquid xenon target to generate the EUV emitting plasma. In the first part of the project, a dense and collimated spray of micrometric xenon droplets was used. We finally used a filament xenon jet, with which best results were obtained. The "spider-like" attack had important industrial advantages and led to interesting source performances in terms of in band power, stability and isotropic properties with the filament jet target [2]. A maximum coefficient of efficiency (CE) of 0.44% in 2pi sr and 2% band width was measured with xenon and with six 6 kHz repetition rate lasers, which corresponds to a maximum in band EUV mean power of 7.7 W. The EUV emission was found to be stable and isotropic in these conditions.



(a) (b)

Fig. 1. Spider-like scheme of the EUV source (a) and source stability in 20 shots with 3 and 6 lasers (b).

In parallel to the experimental work, numerical studies were performed to model nanosecond laser interaction with xenon micro-sized droplets and sprays [3].

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Effect of shot number on femtosecond laser drilling of silicon

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Silicon wafer drilling has been under heavy investigation for some time already. Several different laser types and methods have been introduced to different applications. In the industry usually the ns lasers are used. Femtosecond lasers have been seen as high cost and not suitable for industrial production. Nowadays femtosecond lasers offer really high pulse energies and good reliability and also high repetition rates and relatively high pulse energies are possible with sub picosecond range. Processing accuracy with fs laser is really good and heat input is negligible to processed surface [1, 2, 3].

In this paper we demonstrate the effect of number of pulses in silicon wafer drilling with a femtosecond laser in free air. Silicon wafer was p–type, [100] oriented and it was polished on both sides. Targeted hole diameters were 50µm with f100 and 30 µm with the f50 optic. Hole diameters were adjusted by using proper pulse energy. Study shows that penetration through the 500µm thick wafer is obtained with quite low amount of pulses but making the hole conical takes a lot more pulses. This can be seen from figure 1 in which all the holes are drilled through using 2000 – 16000 pulses.

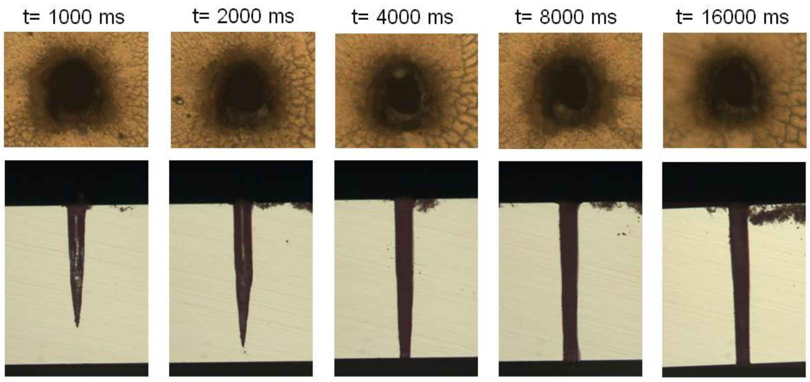

Figure 1 Holes drilled using 244µJ pulse energy with f50 optic in focus. Pulse count from left to right 1000, 2000, 4000, 8000 and 16000 pulses per hole.

From the experiments we can see that hole depth increases rapidly until a turning point is reached, where the ablation rate becomes much smaller. The transition shot number occurs at around several hundreds to 1000 shots. This is confirmed by other authors also [4].

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Adapting Femtosecond Laser Pulses to Ionization Processes in Wide Band Gap Materials: a Route for Nanoscale Laser Processing

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Ultrashort laser pulses are a promising tool for processing wide band gap materials even below the wavelength of light. It is the transient free-electron density in the conduction band playing a fundamental role for sub picosecond pulses [1] [2] [3] that after coupling to the lattice lead to phase transitions or the creation of voids. In our work we make use of temporally asymmetric femtosecond pulses of identical fluence and identical statistical pulse duration in order to control two distinct ionization processes, i.e. photoionization and electron-electron impact ionization. Control leads to different final electron densities / energies as the direct temporal intensity-profile and the time inverted intensity-profile address the two ionization processes in a different fashion. This results in observed different thresholds for material modification in fused silica as well as in reproducible lateral structures being an order of magnitude below the diffraction limit (down to 100 nm at a NA of 0.5) [4] [5]. These findings are supported by our recent experiments: we used chirped pulses with comparable pulse duration and observed that the asymmetric temporal frequency ordering had no significant influence.

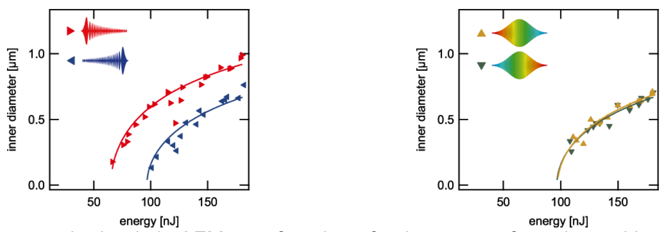

Figure 1: Structure diameter obtained via AFM as a function of pulse energy for pulses with a statistical pulse duration of about 1 ps. Left: temporal asymmetric pulses with constant instantaneous frequency Right: temporal symmetric pulses with asymmetric frequency sweep, i.e. up chirp and down chirp

In addition, experiments with geometrically overlapping focal regions did not show incubation effects on the creation of the nanostructures. In order to get a conclusive picture we currently extend our studies on time resolved plasma dynamics [6] to spectral interference measurements with shaped laser pulses. Aiming at optimizing the temporal pulse shapes further, we started to simulate the free electron creation under the constraint of minimizing the spatial structure. Minimizing the spatial structure and at the same time maximizing the spectrochemical sensitivity for fs-LIBS [7] completes our experiments exploiting temporal pulse tailoring for material processing.

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Laser Printed MEMS and Electronic Devices

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Interest in digital printing techniques for generating patterns or structures non-lithographically continues to grow due to their relatively low cost and potential for scalability as well as inherent flexibility in terms of compatibility with low temperature and non-planar substrates. Recent advances in laser forward transfer techniques have provided a pathway for the fabrication of arrays of structured geometries and device architectures relevant for electronics and MEMS applications. Through the utilization of the Laser Decal Transfer (LDT) process, as-deposited free-standing structures [1] for sensing/actuation without the use of sacrificial release layers on pre-patterned channels and cavities have been demonstrated. In addition, the ability to simultaneously deposit spatially resolved polymer/metal multi-layer heterostructures [2] has also been developed and used for printing functioning micro-scale capacitors as well as three-layer architectures under development for the fabrication of organic thin film transistors. This presentation will discuss the latest results achieved with LDT and also describe efforts at scaling up the laser printing process using single pulses for parallel processing features in the form of large area arrays.

This work was sponsored by the Office of Naval Research.

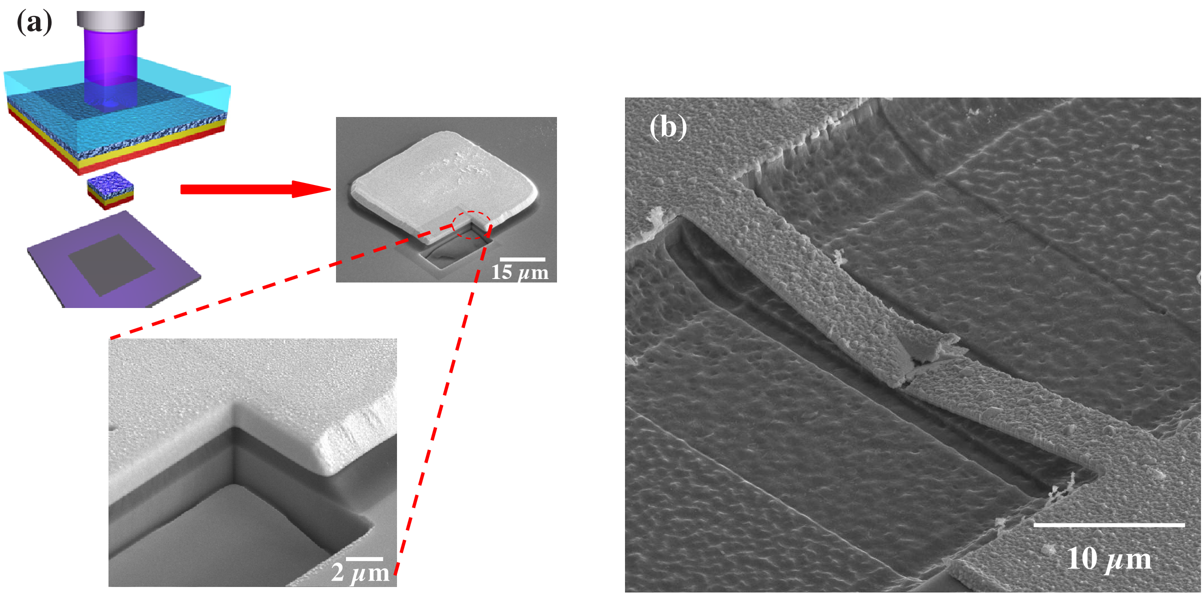

Figure 1 SEM images revealing examples of realizable geometries and configurations of laser printed structures **(a)** schematic of the multi-layer laser printing process as well as micrographs of the 40 μm transferred and cross-section revealing well defined layer interfaces and **(b)** nanoindented micro-bridge deposited via release layer-free laser printing technique.

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LASER DRILLING with PULSE FIBER LASER

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Laser drilling with high drill rates and small holes diameters are required in a white range of industrial applications for printed circuit board, nozzles, cooling boreholes for turbine blade and in the production of solar panels. There are three general types of Laser drilling in industrial application: It is “one pulse drilling”, percussion drilling and trepanning. With a new generation of fiber laser it is possible to drill with new scan strategy like “on the fly percussion drilling” which allows the drilling of a very narrow pattern with minimum thermal distortion, Fig. 1(a). Fig. 1(b) shows an example of percussion drilling of a 0.3mm thick metal sheet with a 2 mJ fiber laser.

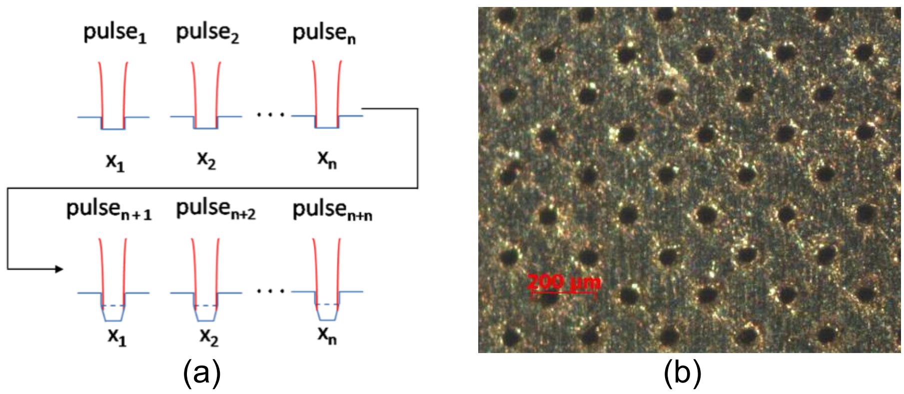

Figure 1 (a) Principle of “on the fly percussion drilling” (b) Example of a percussion drilling thin metal sheet.

The paper shows the advantage of different laser drill strategy with new pulsed fiber lasers from nanoseconds to milliseconds for various materials like steel, aluminum, silicon and ceramics.

Femtosecond Laser Irradiation and Hydrothermal-electrochemical Treatment for Improving Bioactivity of the Ti-based Bulk Metallic Glass

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Ti-based bulk metallic glasses (BMGs) are expected to be used as new biomaterials owing to their high strength, low Young's modulus, and excellent corrosion resistance. Recently, Zhu et al. developed Ti-based BMGs, Ti-Zr-Cu-Pd, without toxic elements, such as Ni, Be and Al [1]. But, these may not be directly joined to human bones due to their high chemical stability and bioinertness. It can be improved by surface modification of BMGs [2] and microstructure formation on BMGs [3]. For the surface modification and the microstructure formation of BMGs, low temperature processes are more desirable because such processes maintain BMGs' excellent properties. If not, these BMGs will crystallize, resulting in degradation of their properties. For the surface modification of BMGs, it is reported that bioactive titanate nanomesh layers were coated on Ti-based BMGs by hydrothermal-electrochemical treatment [2]. This nanomesh layer can induce the growth of hydroxyapatite (HAp), which has good biocompability, in simulated body fluid (SBF). For microstructures formation on BMGs, the femtosecond laser is a useful tool since it provides considerable advantages for precision material processing, such as drilling, cutting and grooving into the metal [4] in comparison with nanosecond lasers [5]. The advantages are based on very rapid creation of vapor and plasma phase, negligible heat conduction, and the absence of liquid phase. It is reported that various microstructures, such as periodic nanostructures, periodic microstructures and microstructures which were the broken periodic microstructures, were formed on the Ti-based BMGs by femtosecond laser irradiation [6]. However, optimum microstructures formed by femtosecond laser irradiation for improving bioactivity of Ti-based BMGs have not been investigated yet.

In this study, we reported the various microstructures formation on the Ti-based BMGs, $Ti_{40}Zr_{10}Cu_{36}Pd_{14}$, by femtosecond laser irradiation. After microstructures formation, they were treated by hydrothermal-electrochemical treatment, and they were immersed in SBF to evaluate their bioactivity. In the experiment, the wavelength, pulse duration, repetition rate, and beam diameter of the femtosecond laser were 775 nm, 150 fs, 1 kHz, and approximately 5 mm, respectively. The laser beam was focused onto the BMG surface by a lens with a 100 mm focal length. The laser spot was scanned on the Ti-based BMG surface in the area 5 mm×5 mm. Titanate nanomesh layers were created on the microstructures by hydrothermal-electrochemical treatment. After immersion test in the SBF, HAp was deposited on titanate nanomesh layers.

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New laser direct-writing technique for liquids microprinting

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Laser direct-writing appears to be a very interesting tool for microfabrication, with applications ranging from the well established microelectronics industry to more emerging fields like lab-on-a-chip manufacturing. Although in most direct-writing techniques lasers are used for material removal, they can also be used for material addition. The best known additive laser-direct writing technique is possibly laser-induced forward transfer (LIFT). In LIFT, small amounts of material are transferred under the action of a laser pulse from a previously prepared donor thin film to a receptor substrate, placed parallel and at a short distance from the film. The application of LIFT to liquid donor films allows the deposition of complex and fragile materials in solution or suspension without compromising the integrity of the deposited material [1]. In this case, LIFT acts as a microprinting technique, in a very similar way to inkjet printing, but with clear advantages over it, like a potentially higher resolution or a much wider range of printable rheologies. However, the LIFT of liquids is not free from drawbacks, being the preparation of the donor material in thin film form the main obstacle for its further implementation in an industrial process. Indeed, it is hard obtaining reproducible thin films with thickness uniformity and good stability. Furthermore, the preparation of a liquid film requires of good wettability, which is usually achieved through the addition of surfactants, but this is detrimental for printing droplets with very small diameters. Finally, the film preparation not only constitutes an additional step in the printing process, but also increases the risk of contamination of the material to be printed.

In this work, a new laser microprinting technique is presented [2]. It allows printing transparent liquids avoiding the drawbacks associated with the preparation of the liquids in thin film form. The principle of operation consists in strongly focusing a very short laser pulse underneath the free surface of the liquid, which is contained in a reservoir. Subsurface absorption of the laser radiation results in the propulsion of liquid away the free surface, leading to material deposition on a substrate facing that surface. It is demonstrated that the technique results in the deposition of uniform circular droplets with excellent reproducibility and resolution (see Figure), and that it is feasible for printing fragile materials without harm.

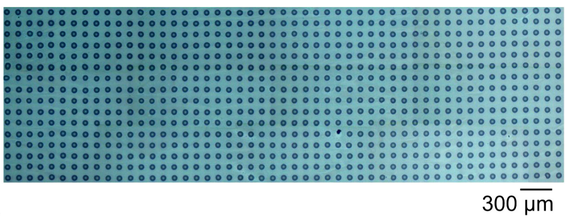

Figure: Large microarray of 750 microdrolets printed with the new technique.

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Machining hole arrays in polycarbonate sheet using UV solid state laser

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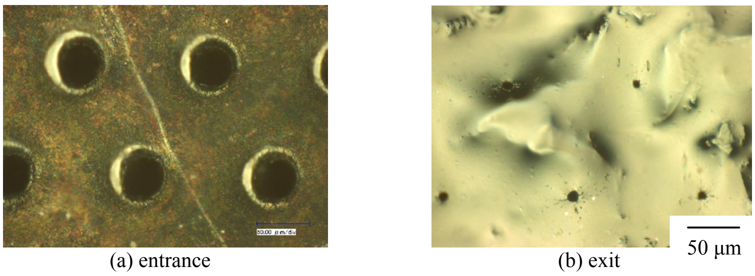
Recently, the design trend of small electronics devices such as personal digital assistants, cellular phones and so on is flattening the front panel. Therefore, for aesthetic reason, small holes are better for speaker and microphone. The body of digital gadgets is commonly made of engineering plastic. The traditional laser drilling of the engineering plastic used CO_2 laser with 10.6 μm wavelength. However, a hole diameter which is less than 100 μm is difficult for CO_2 laser drilling due to the major problems of the material surface deformation and burnt deposit.

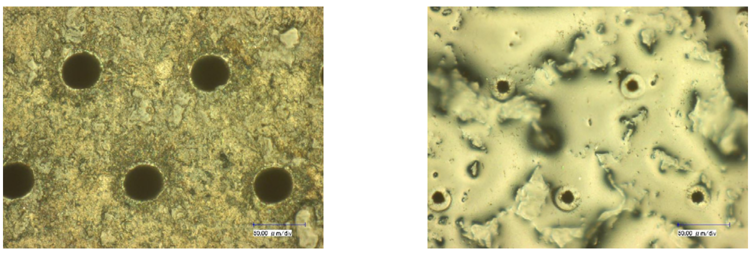
To make arrays of reproducible percussion-drilled holes of several tens of micrometer in polycarbonate, UV solid state laser is used in this work. The UV laser used is the Spectra-Physics Explorer, a DPSS Q-switched Nd :YLF laser with a third harmonic wavelength of 349 nm. Since this laser is operated in TEM00 mode, the beam has a Gaussian-distributed intensity profile. The pulse duration is less than 5 ns and the maximum pulse energy that can be achieved at the target surface in our setup is approximately 100 μJ at 1 kHz pulse repetition rate. To machine an array of holes, we use galvanometer scanner system with full digital control and a fθ lens which has a focal length of 200 mm.

Figure 1 shows optical photographs of entrance and exit holes made with a repetition rate of 5 kHz, 20 μJ per pulse and 200 pulses per hole. This figure is hard for us to understand, however the surface deformation is actually occurred by the cumulative heating. On the other hand, in Figure 2, we can see there is no surface deformation on the hole arrays made with a repetition rate of 0.5 kHz. In conclusion, this paper shows us the relationship between the repetition rate and the thermal effects and also how the thermal effects can be overcome by exploring the processing parameters.



(a) entrance (b) exit

Figure 1 Optical photographs of (a) entrance and (b) exit holes made with a repetition rate of 5 kHz , 20 μJ per pulse and 200 pulses per hole. Polycarbonate (t=0.25mm)



(a) entrance (b) exit

Figure 2 Optical photographs of (a) entrance and (b) exit holes made with a repetition rate of 0.5 Hz , 20 μJ per pulse and 200 pulses per hole. Polycarbonate (t=0.25mm)

Laser micromachining of CFRP by ultra-short pulse lasers

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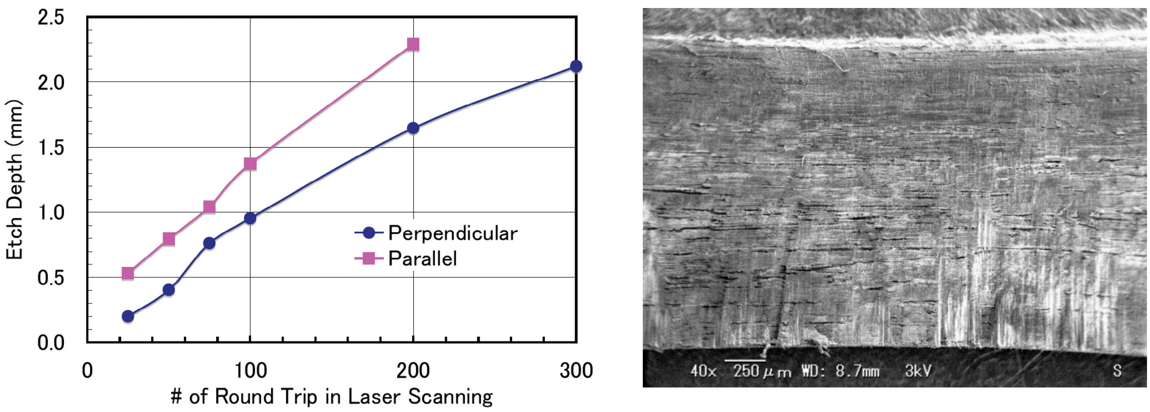
CFRP (Carbon Fiber-Reinforced Plastic), which is a composite material consisted of carbon fiber and polymer matrix, has attractive features like high strength and light weight. It is expected to realize higher energy efficiency and hence lower carbon emission in transportations by using CFRP as a body material of aircrafts, automobiles, and so on. Laser processing of CFRP had been studied by various kinds of lasers such as CW disk lasers, quasi-CW CO_2 lasers, several 10s μs pulsed Nd:YAG lasers [1] and 10s ns pulsed UV $Nd:YVO_4$ lasers [2], where laser cutting quality, thermal damages and possible changes of strength were investigated.

We have been investigating micromachining of CFRP by ultra-short laser pulses in order to minimize material damages and HAZ. The laser system used in this study was a commercially available Ti:Sapphire laser (Spectra Physics, Hurricane). The fundamental wavelength, pulsewidth, rep. rate were 800nm, 100fs and 1kHz, respectively. For comparison, we also used 200ps stretched pulses from the Ti:Sap. laser and output from a CW fiber laser. Various samples of CFRP were supplied by Toray Industries, Inc. and Mitsubishi Chemical Corp., which included uni-directional and cross-ply composite laminates, short and long carbon fiber pellet composites. Figure 1 shows examples of our experimental results, which shows dependences of laser scanning with respect to the fiber direction and a SEM image of the kerf. Optimizations of the laser parameters were explored.



(a) (b)

Figure 1 (a) Dependences of etching depth on the number of laser scanning. Laser scanning perpendicular to the fiber direction showed slower and saturated processing speed. Laser pulse energy, pulsewidth, rep. rate and scanning speed were 0.4mJ, 200ps, 1kHz and 1m/min, respectively. (b) SEM image of the kerf, 200ps laser cutting parallel to the fiber direction.

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Time-resolved imaging of hydrogel transport by laser-induced forward transfer (LIFT)

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Laser-induced forward transfer (LIFT) is a direct-write technique that allows printing of different materials to form high-resolved structures. For LIFT, donor and collector glass substrates are arranged parallel and in close proximity to each other. The transparent donor slide is coated with a thin gold layer and subsequently a layer of the transfer material, which in our case is a hydrogel. The donor substrate is arranged upside down with the layer of hydrogel facing the collector slide. For the material transfer, a pulsed laser beam is focused through the donor glass substrate onto the gold layer. The gold at the point of interaction is vaporized locally and the vapor pressure transfers the hydrogel onto the collector slide. When liquids or hydrogels are transferred by LIFT, the generation of a jet instead of a droplet transfer has been observed.
With a self-developed stroboscopic imaging system, the jet generation and the jet impingement onto the collector slide were investigated in detail (spatial resolution: 2 µm, temporal resolution: 10 ns).

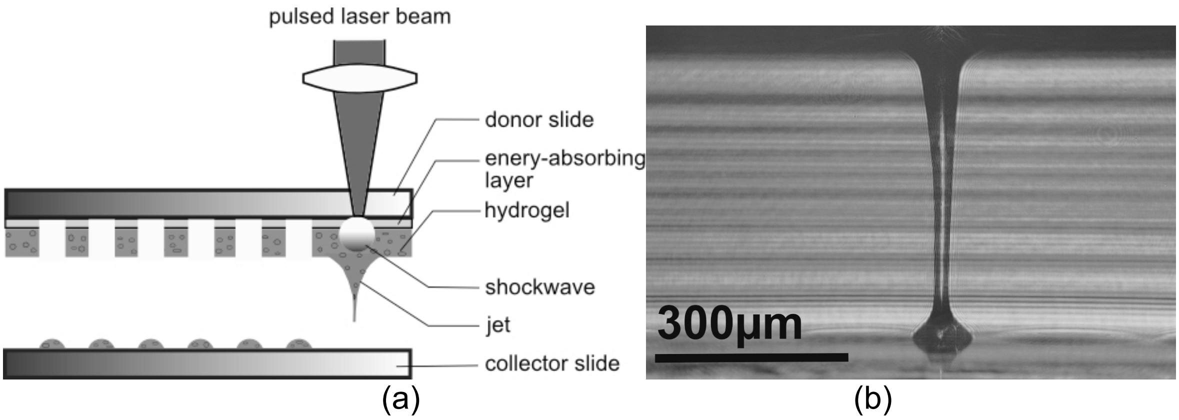

Figure 1 (a) Schematic overview of LIFT. (b) Hydrogel jet between donor and collector slide 80 µs after laser pulse impact. The laser fluence of the LIFT laser is 1.2 J/cm². The horizontal black lines between the two slides originate from interference phenomena of the laser light used for stroboscopic illumination.

As a result of the captured images, a better understanding of the jet formation process has been obtained. Furthermore, dependencies of the transfer process on the laser fluence and the viscosity of the hydrogel have been examined.

Drilling Holes through Cemented Tungsten Carbide Plates by Ultrafast Laser

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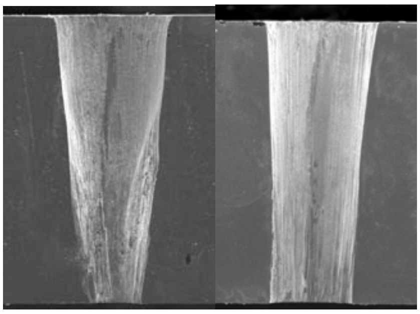
Holes of about 300 μm in radius are drilled through plates of cemented tungsten carbide of 0.5 and 1 mm thick by a femtosecond laser. The laser delivered 150 fs pulses at 1 kHz repetition rate at 785 nm. The laser was scanned circularly by a galvanometer scanner equipped with an fθ lens of about 80mm focal length in air. Effects of the scanning speed and polarization of the laser on the quality of drilled hole, such as the side taper, machining speed and evenness of the sectional diameters, are examined. It is demonstrated that the circularly polarized beam results in smaller taper than linearly polarized beam, as shown in the figure 1. Machining time for circularly polarized beam is about 200 s in case of figure 1 (b) and is faster than linear one. Central part of machined volume was ejected as bulk during the laser irradiation.



(a) (b)

Figure 1 Cross section of holes open through 1 mm thick WC-Co plate by (a) linearly polarized beam and (b) circularly polarized beam. Scan speed was 35mm/s. Laser pulse energy was 800 μJ.

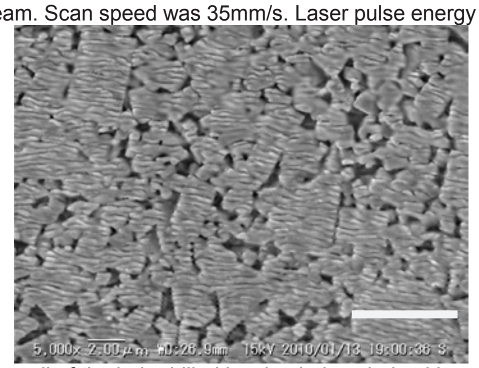


Figure 2 Magnified image of the side wall of the hole drilled by circularly polarized beam. LIPSS is seen of the grain of WC. White bar indicates 4 μm.

It is found that laser induced periodic surface structure is formed on the side surface of the hole. The LIPSS is formed by both lie\nearly and circularly polarized beam in horizontal direction (perpendicular to the laser incident axis) but their periods are different: about 320 nm for linearly polarized beam and about 260 nm for circularly polarized one. Shape and machining speed are dependent on other parameters such as scanning speed and focus position. Effects of these parameters will be discussed.

Fabrication of Optical Interconnects with two photon polymerization

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Two photon polymerization (2PP) is a direct 3D structuring technique based on femtosecond laser technology. In the focus of a high numerical aperture microscope objective a polymerized voxel is generated. Depending on the voxel size and shape, single lines can be polymerized showing a line width in the range of 100 nm. By using 2PP instead of one photon lithography processes, three dimensional nano-scaled structures can be written directly into a photo curable resin, without stacking up layer by layer.

This work presents a method to create optical interconnects using 2PP. Waveguides structured directly into to the matrix material have a potential for a future industrial application. The 2PP process allows us to write waveguides directly into a matrix material made out of polydimethylsiloxane (PDMS). Polydimethylsiloxane is a cost effective, mechanically flexible and temperature-resistant material with a low attenuation in optical applications (smaller than 0.1 dB/cm at 850 nm wavelength).

Various approaches to simplify the preparation of the sample and reducing the pre-process steps using PDMS are also presented in this work.

Hence we developed different chemical compositions, which could be swollen by a monomer containing a dissolved photoinitiator. Another chemical concept allows us to directly be mix the uncured matrix material with a special resolved monomer. The photoinitiator as well as the matrix material and waveguide material were tuned to facilitate easy processing and achieve low damping in combination with high refractive index changes ($\Delta n = 0.04$) in combination with high writing speeds up to 2 mm/s.

The waveguides were examined using phase contrast and optical transmission microscopy, showing a guiding region with a significant diameter around 20µm. By cutting the waveguide and coupling light from the microscope condenser directly into the waveguide the cross section of the optical interconnects were estimated.

High rate laser micro processing using high brilliant cw laser radiation

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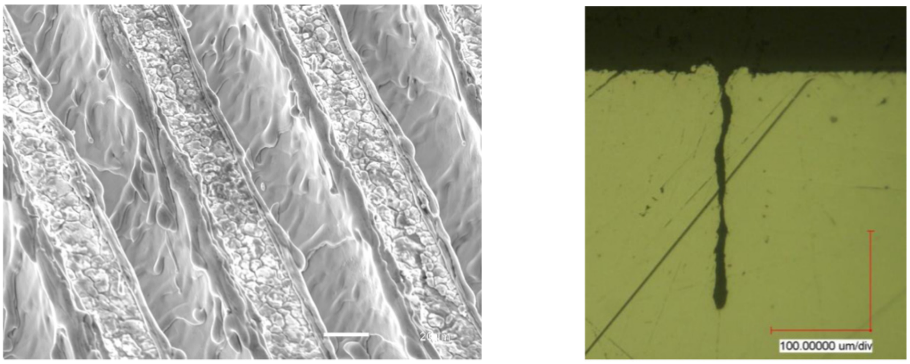
In this study laser machining using a combination of a high power mono mode fibre laser and a polygon scanning system as an innovative key technology in high rate laser ablation cutting and structuring was investigated. Therefore maximum cw laser power up to 3 kW at scanning velocities up to 9000 m/min was applied. Focusing the laser beam into a laser spot of 21 µm diameter resulted in a laser dwell time less than 140 nanoseconds. Consequently laser intensities comparable to q-switched ns laser technology were irradiated onto stainless steel 1.4301, copper, and tungsten.
The paper discusses the influence of significant laser processing parameters, such as laser power and scanning velocity, onto ablation rate and machining qualities. Furthermore first ablation structures and micro-slits will be presented.



(a) (b)

Figure 1: Machining examples in high rate micro processing of stainless steel 1.430; (a) micro ablation structure with 30 µm width and 100 µm depths; (b) micro-slit (depth: 270µm, width: 20µm) obtained after 25 over scans and 0.43 kW laser power at processing speed of 1200m/min.

Micro-processing of semiconductors using ultrafast laser radiation at 2 µm wavelength

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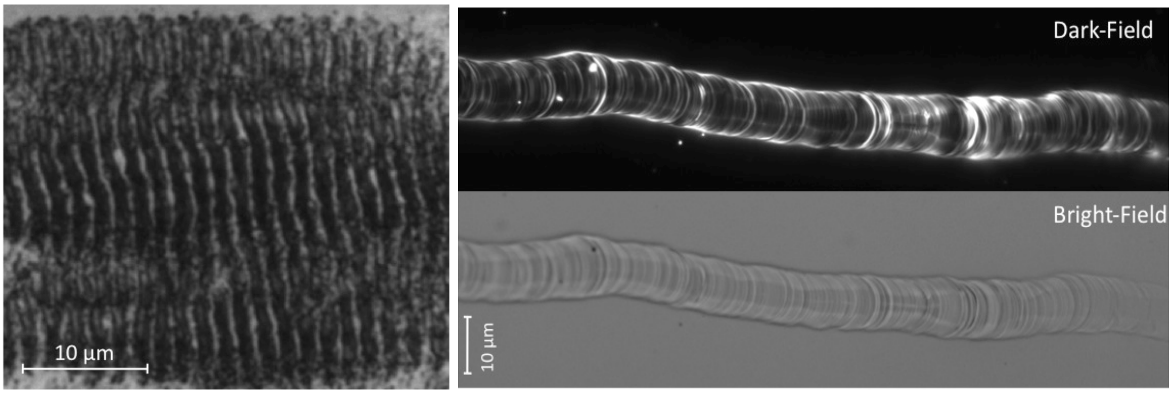
In recent years, a major interest in surface and bulk processing of semiconductors using ultrafast laser radiation has grown [1]. With the development of ultrafast mid-IR laser sources, a new avenue of irradiation can be established in a spectral region where the semiconductor material is highly transparent to the laser radiation [2]. A variety of applications featuring optical waveguide capability and combining microfluidics and electronics can be developed using this approach.

Irradiation of Si and GaAs with ultrafast laser radiation (t_p≤150 fs) at the wavelength λ=2 µm has been matter of the presented research. Surface ablation threshold, ripples formation (**Figure 1**) and radiation penetration depth have been studied by variation of the dopant concentration of the material and the processing parameters such as irradiation intensity, translation velocity and focusing conditions. Laser induced modifications in surface and bulk have been investigated by means of optical microscopy, SEM and TEM. The achieved results of the ultrafast irradiation were compared to ablation processes in the ns pulse regime using a wavelength λ=2 µm.



(a) (b)

Figure 1 (a) Microscope image of ripples formation on c:Si surface after fs laser irradiation close to the ablation threshold at f_{rep} = 1 kHz. (b) Microscope image of ablation track formed by ns irradiation close to the ablation threshold.

First results on selective laser etching of semiconductors are reported. Laser radiation is used to selectively change the crystalline properties of semiconductors in surface and bulk leading to a significant change in the wet etching rate as it has been demonstrated in sapphire [3]. The feasibility of the selective etching technique and the potential for applications in integrated optics and fluidics has been studied.

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Laser Decal Transfer of Nanomaterials

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Laser direct-write processes such as laser induced forward transfer or LIFT offer unique advantages and capabilities for digital microfabrication. Overall, laser direct-write or LDW is perhaps the most flexible digital microfabrication process available in terms of materials versatility, substrate compatibility and ranges of speed, scale and resolution. At NRL, we have developed various LDW processes from the laser transfer of semi-dry complex fluids or inks [1], to the “Lase-and-Place” of entire semiconductor devices [2]. These processes have been demonstrated in the fabrication of a variety of microelectronic elements such as interconnects, passives, antennas, sensors, power sources and embedded circuits. Recently, laser forward transfer of thin film-like structures with excellent lateral resolution and thickness uniformity using metallic nanoinks has been shown at NRL using a technique named laser decal transfer [3]. The high degree of control in size and shape achievable with laser decal transfer has been applied to the digital microfabrication of 3-dimensional stacked assemblies and freestanding structures for MEMS applications [4]. Examples of some of the structures produced by laser decal transfer are shown in figure 1. This talk will discuss the unique advantages and capabilities of laser decal transfer of nanomaterials such as metallic nanoinks and dielectric nanopastes, and describe the various types of structures produced to date.

This work was sponsored by the Office of Naval Research.

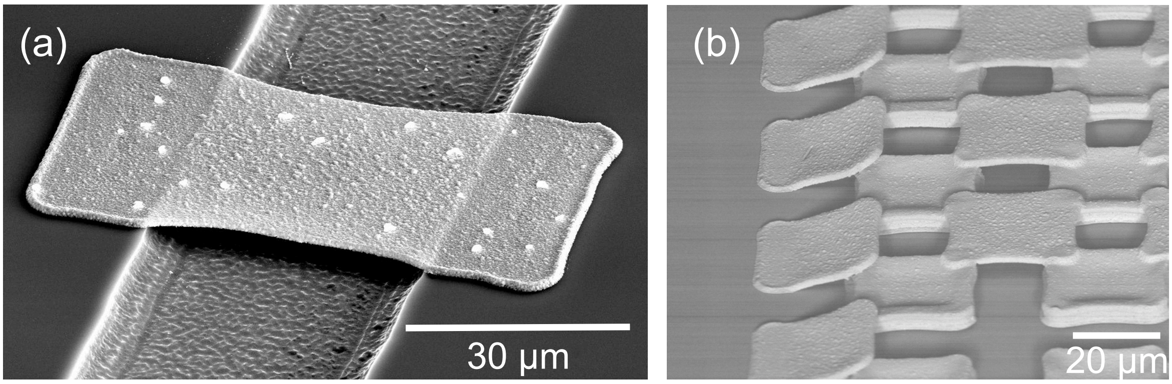

Figure 1 SEM images showing sample structures produced by laser decal transfer of silver nanoinks on Si substrates. (a) Silver microbridge made by LDT across a 30 µm wide trench on silicon without the use of any sacrificial layers. (b) 3-D stacked structures fabricated by LDT of square voxels on top of each other to form the bottom column array and the top freestanding and edge inclined plates.

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Pulsed laser material ablation by contacting optical fiber

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The aim of this work was to find microsecond-pulsed Nd:YAG laser parameters that would allow fast material ablation by contacting quartz fiber without a catastrophic damage of its tip by laser beam and ablation products. By catastrophic damage we assume situation when single or several laser pulses destroy the tip in such a way that further material ablation by subsequent pulses in no longer possible. The choice of laser pulse duration τ=1.3μs is explained by two reasons. First, in this case highly productive (up to 10μm/pulse or even higher) material ablation takes place at fluencies E>10J/cm^2 which is much lower than the measured optical damage threshold 400-600J/cm^2 for free-standing fiber tip. Second, for most of materials investigated the quality of craters produced by microsecond pulses can be quite good.

Different ceramics, composites, polymers, carbon materials and metals were used as targets in atmospheric air. Fiber core diameter was 300μm, pulse repetition rate < 10Hz. The gap between the fiber tip and target surfaces was Δ=0-1mm. Dynamics of materials ablation and fiber destruction were studied by pump-probe shadowgraphy with temporal resolution 100 ns.

It is shown that the action of expanding vapor plume and particles on the fiber tip depend on the target material and Δ. At E=30-40J/cm^2, when productive ablation of all materials was observed, and pulse number N=1-3 a catastrophic fiber damage was observed only for metals and Δ<20μm. We explain this effect by the action of fast liquid droplets that are expelled at small angles to the target surface. For metals at higher Δ and other materials for all Δ values ablation with stable rate took place for multiple-pulsed irradiation. At the same time, we found that in this general case part of the ablated material is deposited on the fiber tip. Moreover, this thin film can be also ablated by subsequent laser pulses. The deposited film and its vapor plume do not shield the main target from the laser beam, but result in gradual removal of quartz and formation of shallow crater on the fiber tip surface. The rate of quartz etching was about 0.01μm/pulse. This effect did not essentially influence target ablation for all Δ studied and laser pulse number $N<5\cdot10^3$.

Thus we have demonstrated that at fluencies E≈30-40J/cm^2 of microsecond-pulsed Nd:YAG laser, high rate ablation of different materials in contacting mode without a catastrophic damage of quartz fiber tip can be realized. Applications of contacting fiber ablation technique in dentistry will be presented.

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Rapid assessment of energy deposition profiles in sub-surface fs laser processing of dielectrics

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The shape and dimensions of subsurface structures written inside dielectric materials with fs laser pulses are defined by the energy deposition profile of the focused writing beam. This profile is given by the beam wave-front and the NA of the focusing optics, and is influenced by linear and nonlinear propagation effects inside the material (aberrations, self-focusing, nonlinear absorption, …) that can substantially distort the desired shape and size of the transformed region. These effects are particularly relevant in the case of light guiding structures as the size and shape of the transformed region will crucially affect the light guiding properties of the fs-laser written waveguide. The usual approach to find a set of optimized 'writing' parameters (pulse energy, duration, processing depth, beam ellipticity, etc.) is to make a systematic experimental study, trying several combinations of parameters to find those ones yielding the best performing waveguides.

Obviously, the use of numerical models capable to predict with sufficient precision the energy deposition profile inside the material enables accurately estimating *a priori* the optimal writing parameters before processing. Still, a precise numerical calculation to determine the energy deposition profile usually requires solving the nonlinear Schrödinger equation using the split-step propagation technique or similar calculation procedures [1,2]. However, the sampling requirements to fully determine the field during the propagation using these *traditional* approaches makes the calculations very time consuming and computationally demanding. Recently, a generalized adaptive fast-Fourier evolver (GAFFE) has been realized [3, 4]. It dynamically resizes in the space and spectral domain the grid that describes the propagated field as well as the propagation step.

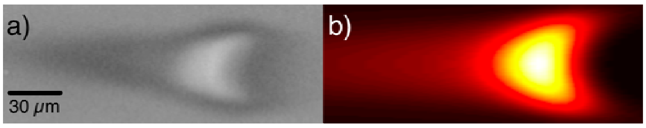

Figure 1 (a) Transillumination microscopy image of the cross-section of a waveguide produced by direct laser writing with a slit-shaped beam. (b) Energy deposition profile calculated using GAFFE with irradiation parameters similar to those of Fig. 1(a).

By using this evolver with a propagation model considering the most relevant linear and nonlinear propagation effects [5] we have been able to make rapid calculations of the expected energy deposition profile in realistic writing conditions. Figure 1(a) illustrates this for a waveguide written using the slit shaping technique [6] at a depth z =1.56 mm, with an energy E =9.6 μJ (to force the appearance of non-linear propagation effects) and a pulse duration t_p =200 fs. The material is an Er-Yb co-doped phosphate glass. In Figure 1(b) we present the resulting calculated energy deposition profile using similar parameters as the ones of Fig. 1(a). The numerical results reproduce quite well the shape and size of the finally produced structure. By using GAFFE [4] we were able to obtain this result in some tens of seconds using a laptop computer. This shows the potential of this approach for the rapid assessment of the final structures produced by fs-laser writing in dielectrics.

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Dynamics of the Laser Decal Transfer Process

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Laser forward transfer of high viscosity or semi-solid nanoparticle suspensions can be used for printing highly uniform and well-defined patterns, which are spatially identical to the size and shape of the laser transfer pulse. This non-lithographic patterning technique, termed Laser Decal Transfer or LDT, has been used to directly print thin film-like patterns such as lines and interconnects [1], microbridges and microcantilevers [2] and various free-standing 3-D structures. With LDT, patterns or structures with edge definition and thickness uniformity far superior than previously achievable with traditional LIFT techniques have been demonstrated. The primary difference between LDT and other laser transfer processes can be found in how the material leaves the donor substrate. With LDT, the material is transferred as a single contiguous voxel which travels across the gap and lands on the receiving substrate without changing its size or shape. To study the dynamics of the LDT process, we have evaluated the effect of size and fluence of the laser transfer pulse, donor ink composition, its thickness and viscosity on the quality of the transfer. Furthermore, using a high speed digital camera, imaging of the voxels as they are released from the donor substrate and travel across the gap towards the receiving substrate should be possible. This presentation will discuss the results form these studies in order to better understand the LDT process.

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Engraving of metals using high repetition rate ultrafast lasers

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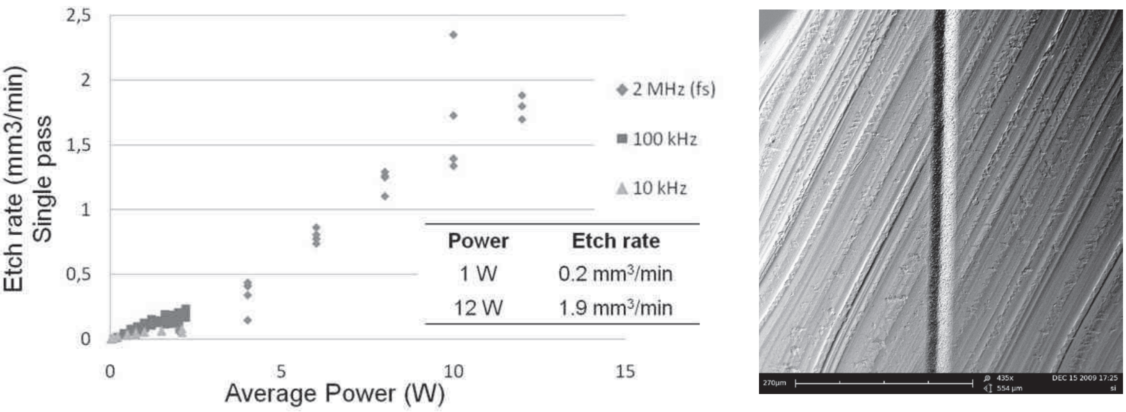
Since 1996, ultrafast laser micromachining has been widely proven to be a high quality [1], high flexibility process, with numerous potential, industrial applications. Indeed, femtosecond lasers are a key technology for micro processing since they combine the unique capability to process any material with a reduced heat affected zone. Until recently, a main drawback was the low processing speed due to the limited average power available from ultrafast lasers. Recent advances in commercial ultrafast lasers enable us to overcome this limitation since there is a significant increase of the average power available to the user and of the repetition rate (up to 5MHz). Moreover, recent papers have shown that in specific operating conditions (pulse energy <70µJ) the femtosecond regime can be more efficient, in terms of removal rate, than the picosecond regime [2,3].



(a) (b)

Figure 1 Micro processing using 500fs / 1030nm ultrafast laser (a) Etch rate in mm3/min versus average power at 2MHz (losange), 100kHz (square) and 10kHz (triangle) on Molybdenum target. (b) Burr-free groove engraved on Brass target at 10µJ / 300kHz, width 29µm depth 14µm.

In this paper, we report on comparative results on micromachining and engraving of metal (Molybdenum, Aluminum, Copper, Brass, Nickel, Silicon) using both crystal-based systems (8W@300kHz) and fiber lasers (15W@2MHz), operating in the femtosecond regime. We have obtained removal rates of up to 2mm^3/min on metal without any burr.

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Optimization of feature resolution, processing window & structuring time for the two-photon polymerization (2PP) process by the use of novel initiators

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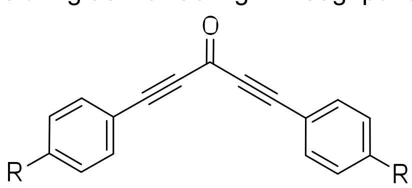
Two-photon polymerization (2PP) is currently one of the hot topics of Additive Manufacturing Technology (AMT) because it is a suitable technique for structuring complicated 3D (sub)micrometer shapes. These parts can be used in various future applications such as different mechanical, electronic and optical micro devices, high-density 3D optical data storage, photonic crystals and the like.[1] Researchers are still trying to improve this novel technique. Higher resolutions, faster writing speeds, improved processing windows, the possibility of using multiple exposure spots and so one are the goals to reach in order to push 2PP into the commercial market. To achieve good results an appropriate laser system and structuring device are necessary as well as a reactive formulation, consisting of appropriate monomers and a photoinitiator (PI).
The selection rules for the excitation process of the PI are different in 2PP compared to classical AMT methods such as µ-stereo lithography using a one-photon polymerization technique, so that special optimized PIs are necessary in order to fulfill the requirements for high resolution structuring.
We have synthesized a series of different novel PIs (figure 1 – left) and tested them concerning their two-photon absorption cross-section values at 800 nm using open aperture Z-scan analysis as well as performing 2PP structuring tests under the same conditions.[2] So we were able obtain structure-reactivity relationship. We compared the results with highly active PIs from literature[3] as well as commercially available one photon initiators such as Irgacure 369 and Michlers ketone, which are still often used for the 2PP process, indicating that the novel initiators are highly active. Nicely shaped structures at very low intensities and initiator concentrations as low as 0.05 wt% were obtained over a broad intensity and writing speed area in various resins making these PIs perfectly suitable for high resolution structuring as well as high throughput applications (figure 1 – right).



H3K R = H
O3K R = OMe
M3K R = NMe_2
P3K R = NPh_2
B3K R = $N(n\text{-}Bu)_2$

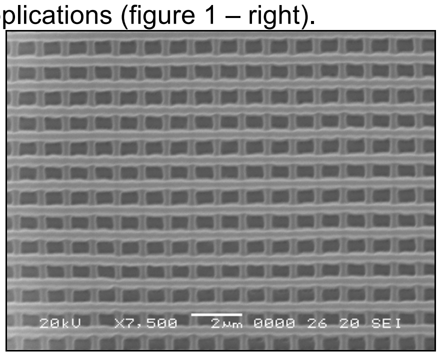


Figure 1 Novel highly active TPIs (left); High-resolution photonic crystal(right)

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Rapid micro processing of metals with a high repetition rate femto second fibre laser

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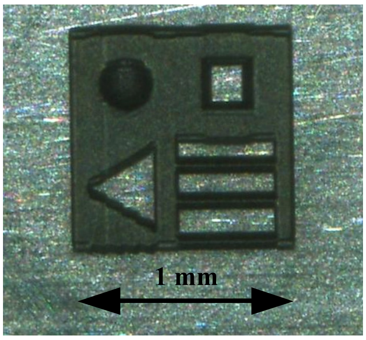
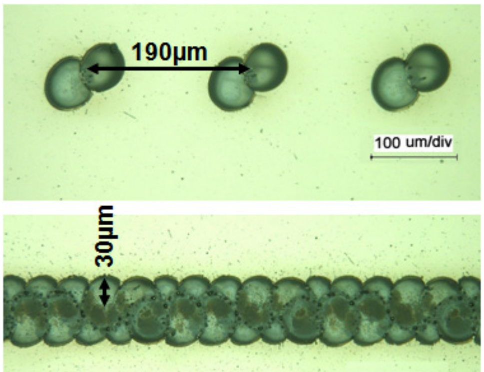
This study aims to investigate innovative rapid micro processing technologies by implementation of a high repetition rate femto second fibre laser and novel scanning systems.
First experiments in femto second laser machining with high repetition rates have shown new mechanisms in laser matter interaction with the repetition rate as one of the mainly influencing parameter. Depending on temporal distances between the laser pulses considerable changes of obtained ablation depths have been detected, caused by heat accumulation or particle shielding effects. Heat accumulation causes locally a rise in temperature encircled the laser working zone accompanied by better absorption conditions and lowered ablation thresholds. For laser processing with repetition rates in ranges of some 100 kHz phenomena of particle shielding and plasma shielding have been reported.
However, utilising high repetition rate laser technologies in 3d micro structuring the machining times have been reduced more than 40 times compared to fs laser processing with repetition rates of some kHz. A further reduction of processing times or irradiation with the full available laser energy is limited by insufficient scanning speed of commercial available galvo scanning systems. Hence implementation of novel scanning systems, such as resonance scanning technology with processing speed up to 95m/s, is the challenge for a further reduction of laser processing times.
In the work results of rapid micro processing of metals, e.g. steel, copper and aluminium, with both, a resonance scanner and a fast galvo scanner will be presented to demonstrate the possibilities and limits of the new technology in laser micro machining and mechanism of laser matter interaction will be discussed.



(a)



(b)

Figure 1: (a) 3d test structure in stainless steel machined with galvo scanner shows a hemisphere, pyramidal frustum, triangle and rectangular prism; ablation depth: 100µm; processing speed: 4000m/s; processing time: 350 sec.
(b) resonance scanner ablation at a thin stainless steel layer; above: lateral pulse distance of 190µm at 500kHz results in 95m/s processing speed; below: lateral ablation shift due to sinusoidal oscillating of the scanner

Fabrication of multiple slanted microstructures on silica glass by laser-induced backside wet etching

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Towards flexible fabrication of components for micro electro-optical-mechanical system (MEOMS) and microfluidic devices, several techniques for micromachining of glass materials has been proposed. Among them, we have developed a laser-induced backside wet etching (LIBWE) [1, 2], that is an indirect laser processing technique employing organic dye solution as laser-absorbing media. By using this technique, deep trenches with high aspect ratios could be fabricated on silica glass [3]. We have succeeded to fabricate a microtrench with an aspect ratio of 102 (width: 9.7 μm, depth: 986 μm). Moreover, inclined features could be flexibly fabricated by shifting the irradiated area in the lateral direction during the etching. Such structures were formed as a result of both lateral and vertical etching at the etch front. Inclined features with tilting angles up to about 30 degrees could be fabricated.

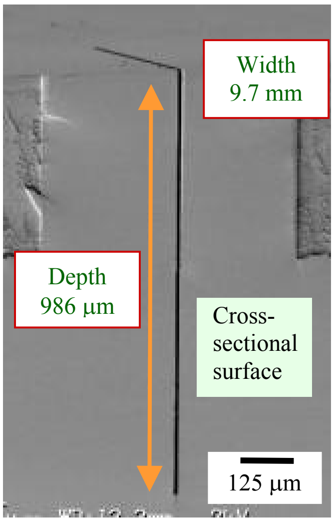

Figure 1 cross-sectional SEM image of the deep microtrench with an aspect ratio of 102

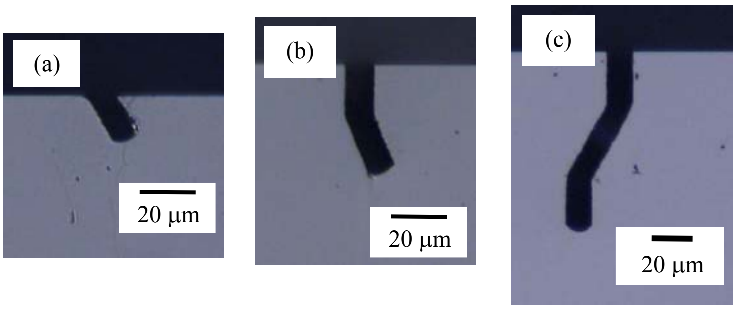

Figure 2 Optical micrographs of the cross-sectional surface of the trenches with Inclined features. Inclined sections were fabricated from (a) surface and (b), (c) from the bottom of the trenches by shifting the irradiated area in the lateral direction with a speed of 0,3 μm/s.

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Laser Assisted Bioprinting of Cells & Biomaterials: Development of a Dedicated Workstation, Experimental Results and Jet Formation Modeling

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Parallel to inkjet printing and bioplotting, Laser Assisted Bioprinting (LAB) using Laser-Induced Forward Transfer (LIFT) is emerging as an alternative method to assembly and micropatterning of biomaterials and cells. LAB specificities concern mainly the absence of clogging and the capacity of printing fluids with a wide range of viscosity. In addition, as an optics-based method, a laser printing device can also be set up for targeting and shooting as well as marking, cutting, exciting, photo-polymerizing or else foaming materials. In this paper, we present results on LAB of human cells (osteoblasts, endothelial cells) as well as biomaterials (nano-sized HA synthesized by wet precipitation) giving an interest for 3D bone-like tissue building in combination with the physical phenomena of droplet ejection by LIFT.

First a rapid prototyping workstation (NovaLase, S.A., Canéjan, France) equipped with an infra-red pulsed laser (30 ns pulse duration, 1064 nm wavelength, 1–100 kHz repetition rate) has been set up. A sophisticated 5–axe positioning system has been integrated to the workstation with the purpose of printing multi-color patterns and building 3D biostructures. The substrate is held with a (x, y, z) motorized micrometric translation stage whose resolution is 1 µm for (x, y) axis and 5 µm for the z axis. In order to achieve multi-color printing, a high resolution (1° angular resolution) motorized carousel with a loading capacity of 5 different ribbons has been designed. Substrate positioning system and carousel are held on the same vertical axis in the aim of varying focusing conditions without changing the gap distance between each other. Droplet generation from the ribbon surface is performed by driving the laser beam by means of a high speed scanning system composed of two galvanometric mirrors with a scanning speed reaching 2,000 mm/s, and a large field optical F-theta lens (F = 58 mm). Focal setting in the ribbon and (x, y, z) substrate positioning are carried out thanks to a CCD camera through the optical scanning system. Substrate positioning, carousel driving, video observation and pattern designs are monitored with dedicated software developed with Delphi® software.

Based on experiments, we propose a model to explain the ejection phenomena. According to the laser energy release in the absorbing layer we differentiate three ejection regimes which can be distinguished using a dimensionless parameter Γ. In each case a vapor bubble is formed at bioink – absorbing layer interface. Its expansion generates the bioink – air interface deformation and putting in motion. If the laser energy is not sufficient enough ($\Gamma > \Gamma_2$) transfers could not occur unless the substrate is close to the target. This is defined as the subthreshold regime. If the laser energy is slightly higher ($\Gamma_1 < \Gamma < \Gamma_2$) the bubble expands, then collapses and finally a jet is formed. This regime is hence called jetting regime. The third regime which occurs when the laser fluence is much higher ($\Gamma < \Gamma_1$) is the plume regime. The vapor bubble expands until it bursts. The ejection mode is closely related to the laser pulse energy and the vapor cavity dynamics, which depends on the bioink surface tension and kinematic viscosity and which can be described by the Rayleigh – Plesset equation.

Finally, droplets size (from 20 µm to 100 µm) has been controlled by monitoring laser focusing conditions and ink rheological properties (viscosity, surface tension). Droplets of 70 µm in diameter containing around 5–7 living cells per droplet has been obtained minimizing the dead volume of hydrogel around cells. We have shown LAB is suitable to print cells in close contact to each other, with a high cell concentration, according to a desired spatial organization. The printing resolution achievable by the LAB is consistent with the study of cell-to-cell, or cell-to-material interactions as well. In addition to cell transfer, we demonstrate the potential of LAB for creating well defined patterns of nano-sized HA. Three dimensional sequential printing of nHA and HOPs illustrated the possibility to build composite biological structures in 3D with a high resolution with the maintenance of osteoblastic cells biological properties after printing.

To conclude, LAB seems to be a suitable technique for printing cells and biomaterials and we have shown new insights about the ejection mechanism, what allows improving printing results (cell viability, resolution…).

Second hermonic optimization method for holographic femtosecond laser processing

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Femtosecond laser processing implemented a computer-generated hologram (CGH) on a spatial light modulator (SLM), called holographic femtosecond laser processing, has advantages of high throughput and high light-use efficiency of the laser pulse energy [1-3] . The precise control of the diffraction peaks is essential in fabricating enormous numbers of nanometer-scale structures simultaneously. To obtain a CGH with high quallity in the optical system, an adaptive scheme has been proposed for optimizing the CGH using the diffraction peak intensities measured in its optical reconstruction.[2] The adaptive optimization is iteratively implemented by taking advantage of the rewritable capability of the SLM, while automatically incorporating spatial properties of the optical system into the CGH. The past method we developed cannot respond to temporal properties of a pulse[3]. In this study, we demonstrate a new optimization method of a CGH to improve a uniformity of the diffraction peaks. The CGH is optimized on the basis of a second-harmonic pattern excited by reconstruction pattern of the CGH. The CGH incorporated the temporal property of the pulse in addition with its spatial property; therefore the laser processing can perform further precise control of the processing size.

An experimental system was mainly composed of a regeneratively-amplified Ti:sapphire laser, a liquid-crystal SLM (LCSLM), a second-harmonic generation optics, a relay optics, and a control computer. The femtosecond pulse was diffracted by a CGH formed on the LCSLM, was converted to a spatially shaped pattern, and was focused on the sample. At the same time, the second harmonic pattern was generated by the spatially shaped pattern on a barium borate (BBO) crystal and imaged by a charge-coupled device (CCD) camera.

The second harmonic optimization method of a CGH is a modification based on the optimal rotation angle (ORA) method [4]. This may have applicability to not only the ORA method but also any other optimization methods. A weight w_m for controlling the diffraction peaks is updated as $w_m(n+1)=w_m(n)[I^{(d)}_m/I_m(n)]^{\alpha}$, where I_m is the m-th second harmonic peak intensity and $I^{(d)}_m$ is the desired intensity. The exponent α should be small enough to avoid instability. $I_m = \eta(I_{avg}/Sf\tau)^2$ where an average light intensity I_{avg}, a focus area S, a repetition f, a pulse duration τ, and η is a conversion effciency. It is important that I_m depends on τ.

Figure 1(a) shows an intensity image of the reconstruction of the CGH optimized only in a computer and Fig. 1(b) shows the second harmonic image. The CGH was designed by the original ORA method. The diffraction intensity at the high spatial frequency region was low because of the spatial frequency response of the LCSLM[3]. The second harmonic image had a narrower peak width and a larger spatial frequency dependence and enabled to detect the differences between diffraction peaks with a high sensitivity. Figures 1(c) and 1(d) show the intensity image and the second harmonic image after the second harmonic optimization. In each optimization step, the second harmonic image was the average of 30 images. α=0.125. The uniformities were 0.66 and 0.97, respectively, where the uniformity is defined as the ratio of the minimum peak intensity to the maximum peak intensity in the reconstruction. The peak value of the diffraction in the optimization process was detected, therefore the peak intensity was uniformized.

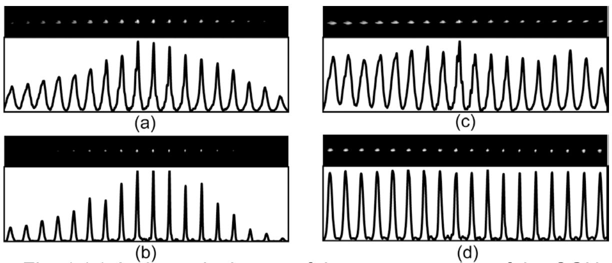

Fig. 1 (a) An intensity image of the reconstruction of the CGH optimized only in a computer and (b) the second harmonic image. (c) The intensity image and (d) the second harmonic image after the second harmonic optimization.

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Microstructuring of Various Materials using Femtosecond Laser Pulses

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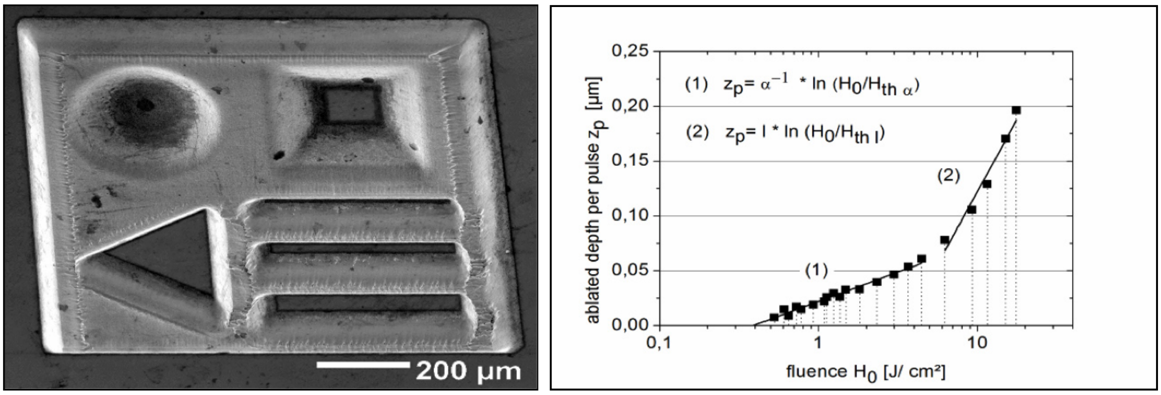
New results on three-dimensional micro-structuring of tungsten carbide hard metal, steel, copper and brass using femtosecond laser pulses will be presented. For the investigations, a largely automated high-precision fs-laser micromachining station was used. The fs-laser beam is focussed onto the sample surface using different objectives. The investigations of the ablation behaviour of the various materials in dependence of the laser processing parameters will be presented in the first part of the presentation. In the second part, complex 3D microstructures with a variety of geometries and resolutions down to a few micrometers showing smooth side walls as well as steep wall angles and the parameters which were found to be optimum for the micro-structuring of each material will be presented. It will be shown that ultrashort laser pulses are suitable for high-precision micromachining of metals. Nearly no heat affected zones next to the laser processed microstructures and, in the case of the sintered hard metal, no decomposition or segregation due to the fs-laser action was observed.



(a) (b)

Figure 1: (a) SEM micrographs of 3D microstructures with a depth of 100 µm in tungsten carbide (microstructuring parameters: 27 µm Gaussian radius of the focused laser beam on the sample, ablation of 100 layers with focus setpoint tracing of 1 µm from layer to layer, fluences: 1.37 J/cm², pulse to pulse distances: 8 µm, post-treatment in a ultrasonic alcohol bath and with cellulose acetate to remove some debris).
(b) Ablated depth per pulse for tungsten carbide as a function of laser fluence (structuring parameters: 400 µm x 400 µm ablated area, 27 µm Gaussian radius of the focused laser beam on the sample surface, beam scanning with 7 µm pulse to pulse distance, ablation of 4 layers without focus setpoint tracing).

Laser Induced Forward Transfer: A Compact Machine

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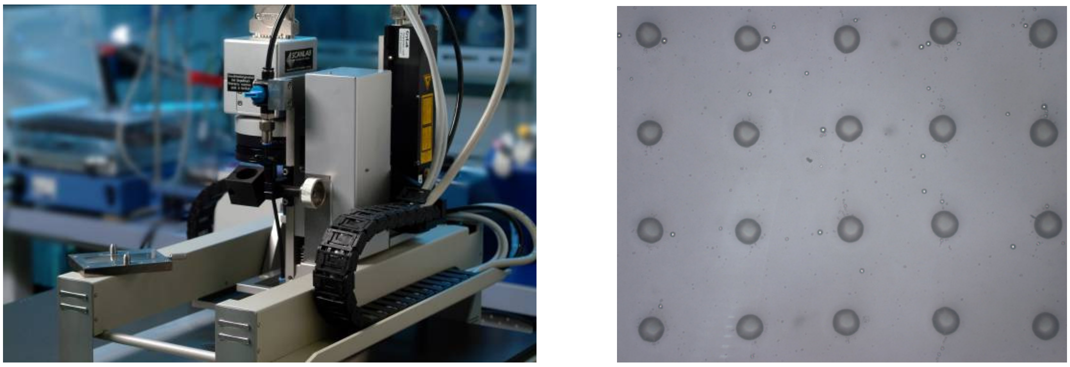
In applications of medical engineering (e.g. microarray production) and polymer electronics, highly viscous or solid, expensive substances are to be transferred. Procedures like inkjet-printing impose strict requirements on the ink. Furthermore, a lot of material is wasted due to dead volumes.
By means of the LIFT-process, high viscous or solid substances can be transferred without any damage and with minimal loss of material, at a spot size of 10 µm.



(a) (b)

Figure 1 (a) Machine for LIFT. 355 nm Microchiplaser (CryLas) and laser scanner (ScanLab) integrated
(b) microarray of a protein solution (50 µg/mL Laminin in 80% Glycerin-Water solution (v/v))

The LIFT-machine meets the following specifications:
It is compact and easy to transport. Hence it is usable in a flow-box. Ink carriers can be processed automatically. Furthermore the print surface is automatically positioned. Target and substrate are moveable towards each other. As a result it has been ensured that the carrier for materials to be transferred can be processed entirely, and that the carrier and the surface to be coated can be positioned relative to each other. Thus any outline is fashionable and complex structures are coatable with a minimal loss of coating substance.

Femtosecond laser micromachining enables optofluidic sensing in lab-on-a-chip

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Permanent modifications of the refractive index in transparent materials can be obtained by tightly focusing femtosecond laser pulses. Exploiting this index gradient, a wide variety of waveguide devices can be produced [1,2]. Advantages of femtosecond laser micromachining, with respect to standard techniques, are the capability of direct device writing without any photolithographic process and the possibility of fabricating three-dimensional waveguide in the volume of the substrate.
In addition, femtosecond-laser irradiation of fused silica followed by chemical etching in HF solution allows the manufacturing of directly buried microfluidic channels, due to the enhanced (by up to two orders of magnitude) etching rate of the irradiated material with respect to the pristine one. This opens the possibility of using a single femtosecond laser system for the production and the integration of microfluidic channels and optical waveguides [3].

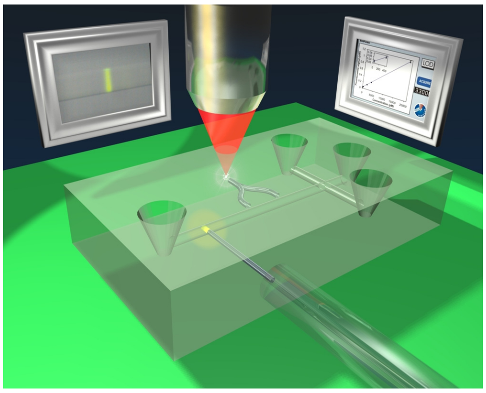

Figure 1 Scheme of femtosecond laser direct writing of photonic devices (waveguides, splitters,…) in a lab-on-a-chip for fluorescent sensing of the biomolecules flowing in the microchannel.

A lab-on-chip (LOC) is a device that squeezes onto a single glass substrate the functionalities of a biological laboratory. Femtosecond-laser micromachining is particularly suited for the integration of optical waveguides (or more complex photonic devices such as splitters and interferometers) inside a pre-existing LOC (Fig. 1)[4,5] or even to fabricate the whole optofluidic chip [5,6]. We exploit this technology to integrate both fluorescent [4] and label-free [5] detection in capillary electrophoresis microchips; as well as to produce all-femtosecond-laser-fabricated biochips for cell analysis [6].

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Optical Trapping of Bio-molecules and Nanoparticles Based on Resonance and Surface Plasmon

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Optical tweezers, which are using a tightly focused laser beam, have been used to manipulate microparticles (e. g. polymer beads, living cells). We and other groups have demonstrated that optical tweezers can trap not only such microparticles but also individual polymer chains with nanometer dimension, resulting in molecular assembling. In this study, we demonstrate that photon force can trap small nanometer-sized particles: amino acids, proteins, and other dielectric nanoparticles in aqueous solutions. The present trapping mechanisms falls in the two categories: resonant optical trapping and plasmon-based trapping, we believe Molecular manipulation possibly provides a significant impact on chemistry as well as bioscience.

Details of the former type trapping (resonant trapping) were described in our previous papers [1-5]. Here, we focus our attention to the latter case, plasmon-based optical trapping. When nano-particles of a noble metal such as gold or silver are irradiated with visible light, a localized surface plasmon (LSP) would be excited and the electromagnetic field of the light would be strongly localized around the nano-structures of a metal, resulting in the enhancement of an electromagnetic field. Such enhanced electromagnetic field is applicable not only to SERS but also to chemical reaction promotion [6], and also even to optical trapping. Plasmon-based optical trapping is quite intriguing and is currently attracting much attention in nano-photonics and related research fields, since optical trapping based on surface plasmon can potentially overcome several disadvantages of conventional optical trapping technique, (i) the conventional technique requires an intense focused laser light and a complicated optical set up to manipulate a small nanoparticle [1], and (ii) the spatial resolution in the trapping is, as a matter of course, regulated to be more than several hundreds nanometers by a diffraction limit of a incident light.

As has been predicted theoretically and verified experimentally, an electromagnetic field of incident light should be considerably localized and enhanced at a nano-junction or a nano-gap between metal nanoparticles, so called gap-mode excitation. In the present study, we have succeeded in optically trap a very small nanoparticle (diameter ~ 10 nm) utilizing gap mode excitation of surface plasmon. The light intensity to induce the plasmon-based optical trapping was much smaller than that used in conventional optical trapping with a factor of 0.001-0.0001. Characteristic features involving energetic balance, spectroscopic and dynamic behavior of such plasmon-based optical trapping, i.e., nanoparticle around the metallic nano-gap, will be discussed in details on the basis of microscopic measurements and theoretical analysis.

Acknowledgement

This work was financially supported by by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan for the Priority Area "Strong Photon-Molecule Coupling Fields (470)" (No. 19049004) and No. 20550002. The author is grateful to all the collaborators: Dr. Tatsuya Shoji, Prof. Noboru Kitamura, Dr. Mai Takase, Prof. Kei Murakoshi (Hokkaido Univ.), and Prof. Hajime Ishihara (Osaka Prefecture Univ.)

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Development of a Laser-stabilised Gas Metal Arc Cladding Process

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In industries where tools and mechanical parts experience wear or corrosion, effective coating techniques are required that are accurate, energy efficient, cheap and fast. To satisfy this requirement we are developing a process that uses a diode laser with a wavelength of 811 nm for stabilisation of a gas metal arc cladding process (LSGMA cladding). The potential of high-contour accuracy, for example, will lead to decreased effort in form finishing.

In previous studies, guidance and stabilisation of the gas metal electric arc using low-power Nd:YAG laser radiation has been shown. Basic process parameters for enhancing the electric arc were obtained. This paper shows new results using a diode laser with an optimized wavelength of 811 nm. Results with hard steel metals are presented concerning a change in GMA technology reducing the induced thermal stress within the material.

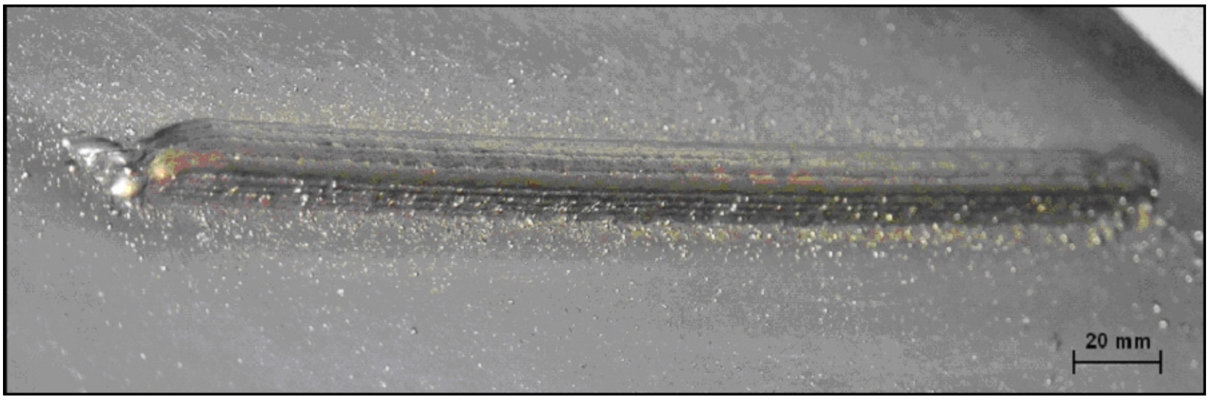

Figure 1: Diode-laser-stabilised multi-layer hard steel clad with a length of 200 mm and a section of 6.5 mm x 6.5 mm

Investigations on clads as pictured in Fig. 1 covering seam geometry, heat-affected zone, deposition rate and increase of travelling speed of over 100% compared to the unstabilized process will be presented.

In Vivo Writing using Two-Photon-Polymerization

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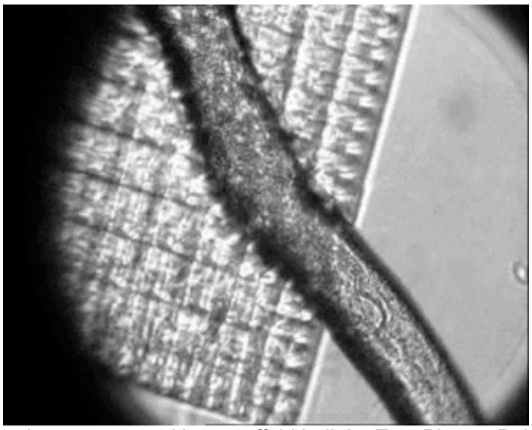

Figure 1: *C. elegans* captured in a scaffold built by Two-Photon-Polymerization

Two-Photon-Polymerization (2PP) is a fast developing method for the micro- and nanostructuring of three-dimensional parts. The manufacturing of biocompatible structures using this technique is a promising field as it fulfills the demand for parts with high feature resolution. This paper reports the fabrication of scaffolds using methacrylate-based photopolymers with embedded living organisms (*Caenorhabditis elegans*). The structuring was performed with a pulsed near-infrared laser with a wavelength of 810nm and adjustable power up to 160mW. Using a 20x magnification microscope objective with a numerical aperture of 0.4, a high resolution scaffold with a base area of 300x300µm and a height of 80µm could be fabricated (see figure). Taking advantage of high laser intensities (writing speed: 300µm/s) the structuring process took only 12 minutes.
The required laser intensities do not cause damage at the cellular level for the model organism since biological tissues are very transparent to red and infrared light. Due to the high transparency, environmental stress for the organism is of chemical origin only. The limiting factor for in-vivo-writing is therefore the toxicity of the resin. The toxicity increases with the reactivity of the resin; therefore there is a trade-off between polymerization time and toxicity in the in-vivo-writing process. As the resin used for the fabrication of the scaffold was rather reactive, polymerization time in this work was kept short (<30min). To optimize the conditions we tested the toxicity and reactivity of different resins with a focus on water-based, biocompatible and biodegradable hydrogels together with water soluble, near-infrared initiators suitable for 2PP.

A new additive technique for laser precision microfacturing: laser microcladding

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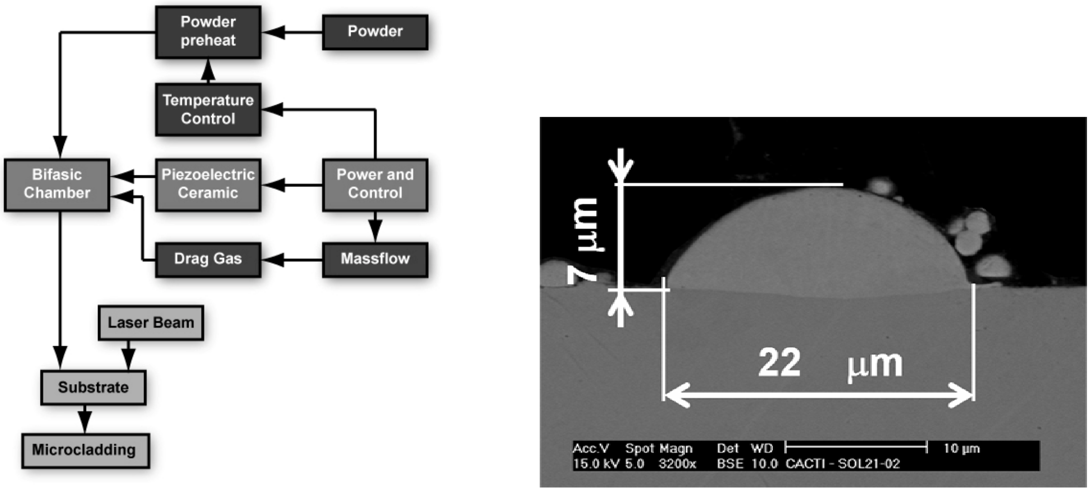
The technologies used for manufacturing metallic products within the field of microproducts show a relatively limited development compared to silicon technologies [1]. In the world of the industrial laser technologies, examples of micro-technologies can be found mainly within the subtractive techniques category, such as microcutting and microdrilling. The challenge is to adapt the laser surface cladding technique, an additive technique, to the scale of micro engineering [2]. In conventional laser cladding technique applied on macro-processing, the heat affected zone and the distortion of the substrate, are not a main concern as a general rule. However some applications exist where these parameters are critical because of the laser interaction zone is closed to sensitive elements or the geometrical requirements are highly demanding. In order to provide an adequate response to this challenge, a new experimental configuration has to be developed based on a highly stable high laser power, with high beam quality and a powder stream carrying micron and submicron particles. This works collects our efforts to make this new concept real extending the operation range of the laser cladding in order to produce microcoatings. The feasibility of this new technique has been tested with a systematic study of different precursor materials to create a hard coating whose geometrical and mechanical properties have been evaluated.



(a) (b)

Figure 1. (a) Block diagram of the new experimental system. (b) Representative example of a track cross section obtained by laser micro-cladding.

The clads obtained will face up to the production of large area coating with low thermal loading. In addition, fabrication of pieces with high dimensional accuracy and low dimensions can be dealt with this new micro-cladding technique. Reparation of defective microparts, surface functionalisation of small areas, or rapid fabrication of prototypes are areas of application of this rapid one step microcoating technique.

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3D laser lithography and nanoimprint lithography: versatile methods for the micro- and nano fabrication of photonic structures

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The development of optical micro systems requires sophisticated methods for the fabrication of prototypes and small series. Starting from the scratch, an optical design is usually developed by means of optical simulations that result in a CAD design of a prototype. This prototype is fabricated at very high precision by means of a laser direct writing method such as the two-photon based 3D laser lithography. The flexibility of this method supports the optical design in every sense, since nearly arbitrary complex shapes are fabricated and the time from the design to the physical structure is rather short. The applications in micro systems range from *e.g.* diffractive structures (flat optics) for beam shaping, micro refractive optics, coupling structures for organic LEDs, photo diodes and waveguides to master structures for organic electronics as alternative to electron beam lithography, which are used for replication by means of nanoimprint lithography.

We use a direct laser writing system from Nanoscribe [1] for the fabrication of 3D photonic prototypes. This system is build up on an inverted microscope and is equipped with a coarse motor stage and a piezo stage for accurate positioning. This combination enables the fabrication of structures with dimensions from several microns up to several centimetres without changes in the setup. The achievable spatial resolution is given by the smallest voxel diameter of the tightly focused laser beam (100x microscope oil immersion objective, NA=1.4), which is approx. 100-150nm in SU-8.

We report the fabrication of photonic structures in SU-8 (cf. Fig. 1), which are directly used in optical micro systems or act as master structures for nanoimprint replicas via a PDMS mold.

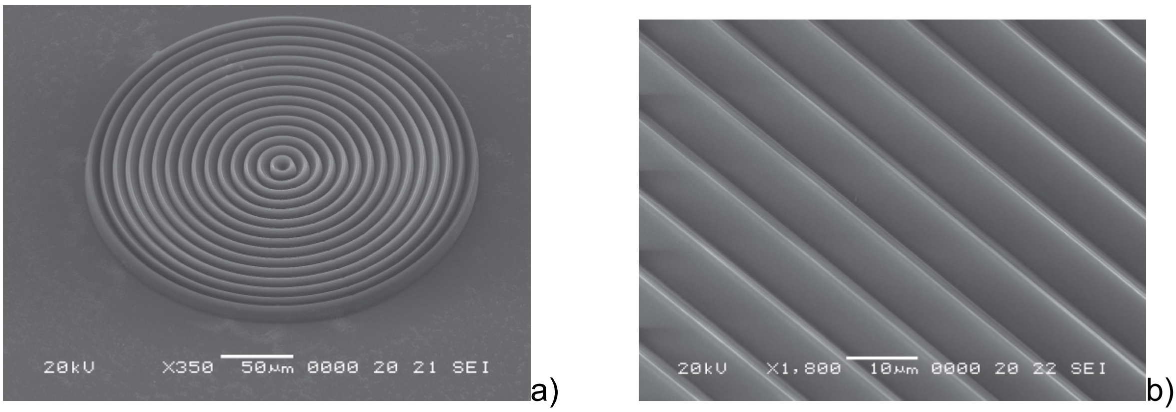

Figure 1 a) round sawtooth structure made from SU-8 by means of two photon based laser lithography; b) detail of a linear sawtooth structure with similar geometry showing a very smooth surface, which is required for high quality micro optics.

[1] www.nanoscribe.de

Femtosecond laser ablation of dentin: A characterisation study

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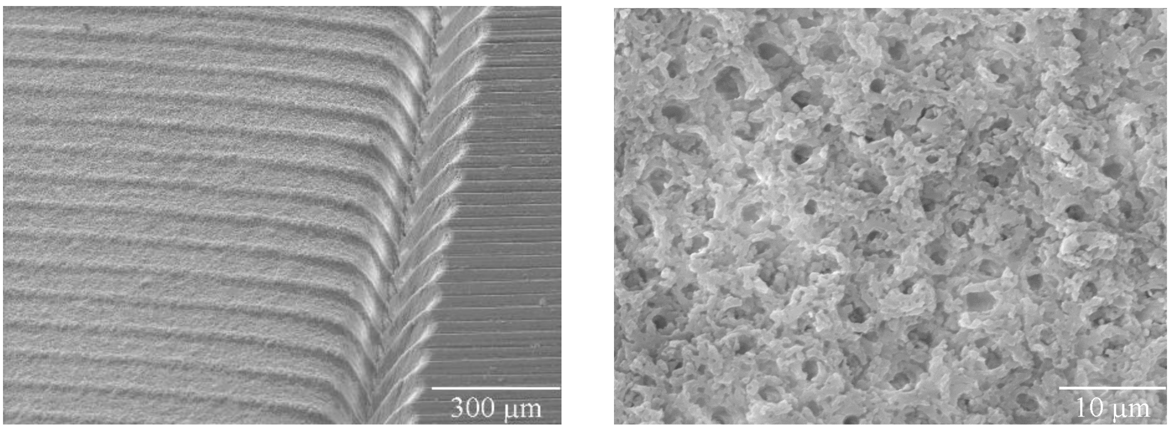
Ultrafast lasers seem to be able to overcome some of the detrimental effects of conventional lasers and dental drills for hard dental tissues removal applications.[1,2] They are fast, efficient and do not have significant thermal effects on teeth.[3]
The main purpose of this study is to evaluate the changes in surface structure, constitution and chemical composition induced in human dentin by irradiation with an ultrafast laser (Yb:KYW chirped-pulse-regenerative amplification infrared laser system) with pulse duration of about 500 fs at a wavelength of 1030 nm, using fluences ranging from 2 to 8 J/cm^2 .
The ablation threshold for non-carious dentin was determined by submitting samples to increasing fluences. The surface topography of the ablated areas was observed by scanning electron microscopy (SEM) in order to choose the processing parameter ranges that were used to prepare samples for systematic characterisation.
The chemical alterations of the dentin surface layer were investigated by X-ray photoelectron spectroscopy, Fourier transform infrared spectroscopy and Raman spectroscopy.



(a) (b)

Scanning electron micrographs showing the dentin surface after laser treatment (a) and the induced morphological changes (b)

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Synthesis of ZnO nanowire heterostructures by laser ablation and their optical characteristics

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Zinc oxide (ZnO), a II–VI semiconductor, which has a direct wide band-gap of 3.37 eV at room temperature and a relatively large exciton binding energy of 60 meV, is one of the promising materials in UV optoelectronic applications. In addition, ZnO nanowire has attracted a great attention for next generation nanodevices because it has a superior crystalline quality, a better electrical/optical quality, a freedom to choose substrate and a large surface area to volume ratio. For the practical optoelectronic applications based on the ZnO nanowires, however, three important tissues are essentially required: p-type doping, growth control and fabrication of heterostructures. Synthesis of phosphorus- and nitrogen-doped ZnO nanowires, have shown p-type conductivity[1], and core-shell ZnO/ZnMgO quantum well heterostructure[2] by PLD using a target manipulator have been reported in these years. On the other hand, we have been succeeded in growing ZnO nanostructures, such as vertically-aligned ZnO nanowires, by nanoparticle-assisted pulsed-laser deposition (NAPLD) without using any catalyst. In this paper, we describe progresses of synthesis of ZnO nanowire heterostructure by NAPLD using a multi-target changer system. In the use of the multi-target changer system, sintered ZnO targets can be changed without disturbing chamber condition during synthesis of ZnO nanowires. Furthermore, we recently found that several ZnO nanostructures such as a film, nanowires and nanowalls can be synthesized in the same chamber. Thus, it is expected to fabricate various ZnO nanowire Heterostructures.

In the experiment, sintered cylindrical ZnO source targets were used in synthesizing ZnO nanowires. An c-plane sapphire substrate was put on a SiC heater and heated to 600-800 ºC in a vacuum chamber filled with a background gas of argon or oxygen. The ZnO target was ablated with third harmonic generation (THG) of a Q-switched Nd:YAG laser at 355 nm with a repetition rate of 10 Hz and a fluence of about 1.3 J/cm^2, in the chamber for around 30 min. The morphology of the as-deposited products was analyzed by scanning electron microscopy (SEM). The optical properties of the ZnO nanowires were investigated by observing the photoluminescence (PL) with THG of other Q-switched Nd:YAG laser.

As an initial demonstration of fabricating the film-wire heterostructure, ZnO nanowires were synthesized after deposit a ZnO film. The film was deposited at a substrate temperature of 650 ºC and oxygen gas pressure of 26 mTorr. Then, the nanowires were synthesized on the film at the temperature of 750 ºC and argon gas of 200 Torr in the same chamber. Fig.1 shows the SEM image of the ZnO nanowires on the film. It was found that the vertically aligned low density ZnO nanowires with average length of about 2 mm. With respect to PL characteristic, the UV emission centered at 390 nm, which is the contribution of the near band edge emission of the wide band-gap ZnO, and no visible light emission at green emission band were observed from the synthesized nanowires. This indicates a very low concentration of deep-level defects inside ZnO lattices. We are trying to fabricate the heterostructure such as p-n junction and core/shellstructure using the multi-target changer system.

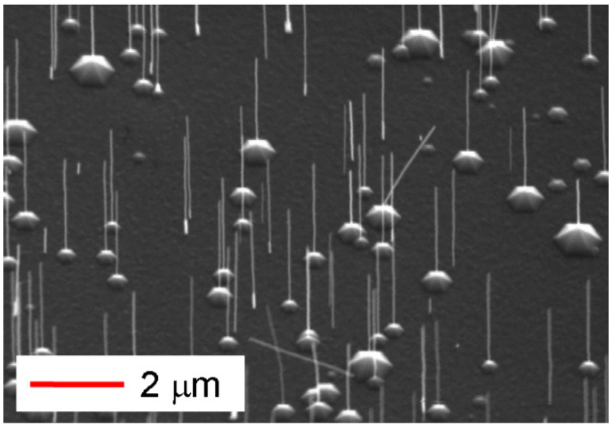

Figure.1 SEM image of ZnO nanowires grown on ZnO thin film.

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Influence of selective laser melting process parameters on morphology of single vectors from metal powders

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Selective Laser Melting (SLM) is a powder-based additive manufacturing capable to produce parts layer-by-layer from a 3D CAD model. Currently there is a growing interest in industry (from aerospace to biomedical) for applying this technology [1, 2]. SLM has a strong miniaturization potential while maintaining high geometrical complexity of the parts since it uses small-diameter laser beams and fine powders. Properties of the manufactured parts depend strongly on the quality of each single laser-melted track ("vector") and each single layer [3, 4]. Statistical relations between the principal SLM parameters (laser power, scanning speed, powder layer thickness, powder particle size) and geometrical characteristics of the synthesized single vectors are subject of this study. For stainless steel (SS) grade 904L –16 µm and –7 µm powders, three layer thicknesses are chosen: 60, 90 and 120 µm. A Greco-Latin square design (Tab. 1) is used to control characteristics of the sintered vectors: width and height of vector (*w1, h1*), width of contact zone (*w2*), ratio (*w2/w1*), remelting depth (*h2*), ratio (*h2/h1*), average value of the contact angle (α). For each case, three-by-three vectors in each series are sintered (laser power is 50, 37.5, and 25 W; scanning speed is 0.05, 0.10, and 0.15 m/s). Descriptive statistics are calculated for 108 single vectors. Analysis of variance (ANOVA) has permitted to establish a hierarchy of the process parameters for SS grade 904L powders with different particle size (–7 µm and –16 µm) listing them in descending order of importance as follows: laser power, powder layer thickness, scanning speed and, finally, powder particle size (Fig. 1).

Table 1. Test plan with four factors and three levels (Greco-Latin square)

	Layer thickness 60 µm	Layer thickness 90 µm	Layer thickness 120 µm
Power 25 W	Scanning speed 0.15 m/s	Scanning speed 0.10 m/s	Scanning speed 0.05 m/s
Power 37.5 W	Scanning speed 0.05 m/s	Scanning speed 0.15 m/s	Scanning speed 0.10 m/s
Power 50 W	Scanning speed 0.10 m/s	Scanning speed 0.05 m/s	Scanning speed 0.15 m/s

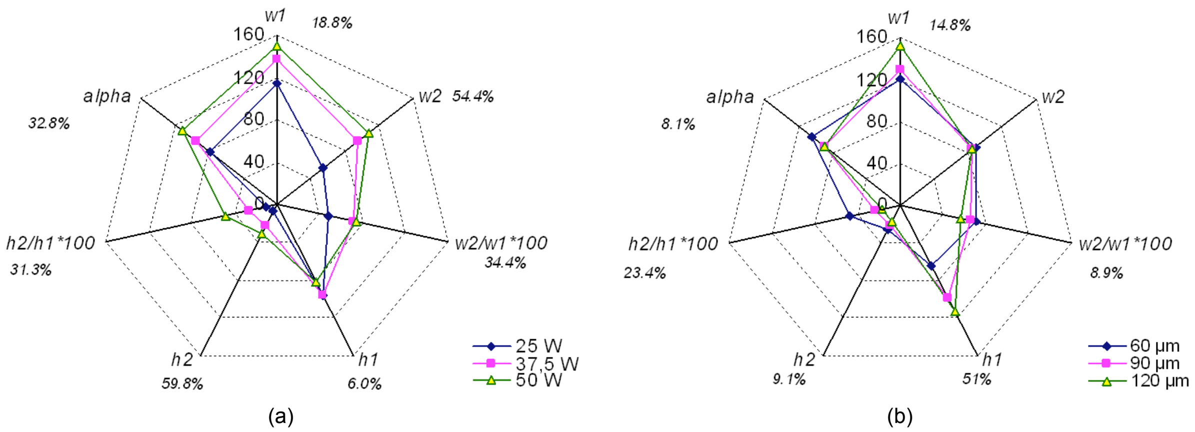

Figure 1. The effect of laser power (a) and powder layer thickness (b) on geometrical characteristics of single vectors (significance level p<0.05)

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Mechanism study of gliding movement of *Phormidium* in nano-aquariums integrated with different functions fabricated by femtosecond laser

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We demonstrate fabrication of nano-aquarium microchips integrated with functional microcomponents for mechanism study of *Phormidium* gliding to a seedling root using a femtosecond (fs) laser. Fs laser direct writing followed by annealing and successive wet etching in dilute hydrofluoric (HF) acid solution resulted in formation of three dimensional (3D) hollow microstructures embedded in photostructurable glass (FOTURAN™). Last year, we succeeded in extraordinally shortening observation time of unique phenomenon of *Phormidium* gliding to the seedling root, resulted in *Phormidium* assemblage for growth acceleration of seedling using nano-aquarium possessing simple microfluidic structures. In addition, integration of optical filter in the nano-aquarium revealed that light illumination is required for the gliding movement of *Phormidium*. The optical filter was realized by the fs laser exposure followed by thermal treatment, since the processed regions became lithium metasilicate crystallite which has brown color. Figure 1 shows sequential microscopic images of *Phormidium* in the microchannel, part of which is covered with optical filters.

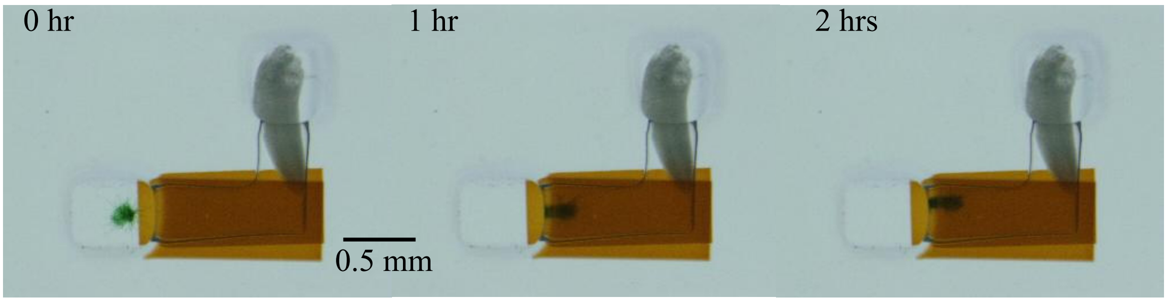

Figure 1 Sequential microscopic images of *Phormidium* in the microchannel covered by fabricated optical filters.

From Fig. 1, one can see that *Phormidium* doesn't glide to the seedling root within 2 hrs, while it glides to the root in the microchannel with no optical filters around the microchannel. In this talk, we will discuss the light intensity required for gliding movement of *Phormidium* using fabricated nano-aquarium integrated with optical filters of various transmissions. In addition, identification of attractant secreted from the root, which also needs for the gliding movement of *Phormidium*, is carried out using nano-aquarium integrated with different functions.

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F_2-Laser Formation of Transparent Protective Layer onto Polycarbonate for Lightweight Window

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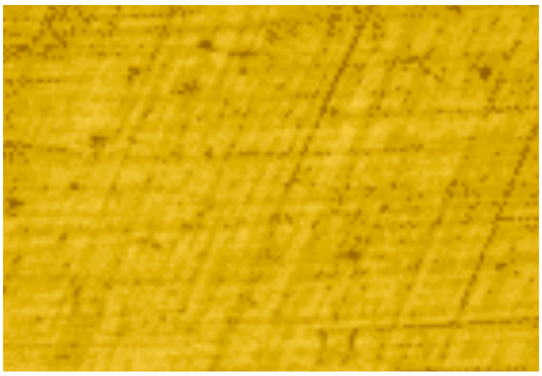
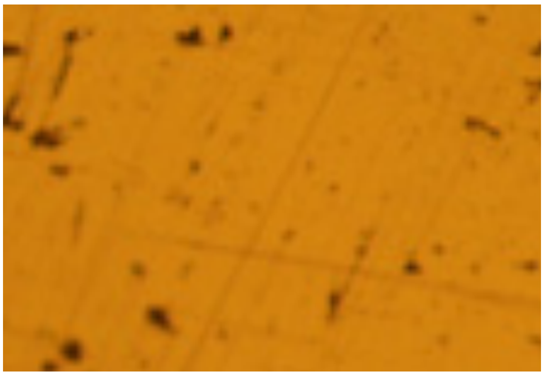
The window material of car, bus, truck, train, ship, plane, and so on is usually made of silica glass (SiO_2) because of its high optical transparency, high scratch-resistance, and high chemical stability. However, the windowpane is basically heavy and fragile. Transparent, light polycarbonate (PC) is one of the leading candidates for lightweight window material. However, PC shows a poor scratch-resistance; conventionally a protective coat is formed on PC before practical uses. The protective coat is made of polymer, which is composed of silicone ($[SiO(CH_3)_2]_n$) resin, acrylic resin, or melamine resin. In general, the protective coat made of silicone is the best for the scratch- and chemicals-resistances, but the scratch-resistance is still not sufficient as an alternative material of automobile windowpane.

In this paper, a transparent SiO_2 protective layer was formed on the protective coat made of silicone on PC by the irradiation of a 157 nm F_2 laser. In our previous work, silicone rubber surface was photochemically modified into carbon-free SiO_2, accompanied by swelling of the F_2 laser-irradiated area [1,2]. Thus, we have thought out that the conventional silicone-protective coat on PC can be modified into SiO_2 by the F_2 laser irradiation for improving the scratch-resistance of the silicone-protective coat, for developing the lightweight automobile window.

Figure 1 shows the optical microscope photographs of the samples after the Taber abrasion test. The scratches were clearly observed in the case of a bare PC plate (Fig.1(a)). After the F_2 laser irradiation, the scratch-resistance of the sample is quite high ((Fig.1(b))). As a result, the haze value of the F_2-laser irradiated sample was successfully reduced from 41.3 to 3.6, compared with the case in a bare PC.



(a)



(b)

Figure 1 Optical microscope photographs of the surfaces of (a) a bare PC and (b) the F_2-laser irradiated samples after the Taber abrasion test.

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3D sub-diffraction-limit patterning of hybrid polymers with visible and infrared laser pulses

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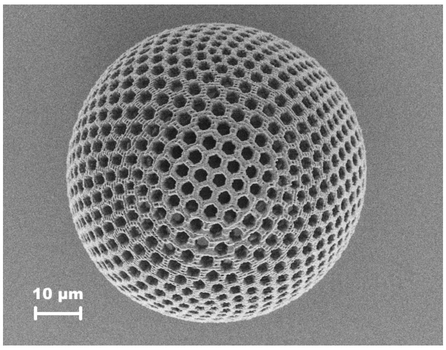
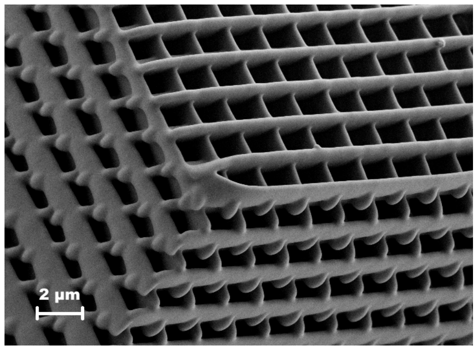
The use of visible and infrared femtosecond laser pulses for the patterning of inorganic-organic hybrid polymers (ORMOCER®s) will be presented and discussed. Laser pulses are obtained from a low-cost diode-pumped Ytterbium laser system emitting at 1030 nm with optional second harmonic generation. By using suitable photoinitiators, two types of patterning strategies are enabled: a three-photon absorption process at 1030 nm, and a two-photon absorption process when using the second harmonic at 515 nm. For the latter, we will present high quality 3D photonic crystal structures and arbitrary microstructures (Figure 1 (a)). In comparison to formerly presented studies on two-photon polymerization (2PP) initiated at 800 nm [1], the process efficiency is significantly higher when using visible light. Besides, a study on volume pixel (voxel) sizes is performed and discussed with respect to the underlying photochemical parameters such as two-photon-absorption cross-section, radical diffusion, quenching, and the choice of polymerizable moieties of the hybrid polymer.
Furthermore, a z-scan experiment was established to investigate the non-linear properties of the photoinitiators [2]. Although there are pioneering publications for 2PP with visible fs pulses [3,4], this is, to our knowledge, the first comprehensive study on voxel growth mechanisms at this wavelength.



(a)



(b)

Figure 1: (a) Hollow ball (source file after [5]) fabricated in ORMOCER® with an average power of 34 µW and 515 nm laser pulses (repetition rate 10.1 MHz, pulse duration 350 fs). (b) High aspect ratio photonic crystal structure created with three-photon-polymerization (3PP) at 1030 nm. An average power of 6 mW was necessary to exceed the polymerization threshold.

Additionally, microstructures fabricated by 3PP such as, for example, the photonic crystal structure (Figure 1(b)), are presented. The fabrication of these structures requires a significantly higher pulse energy indicating a non-linear absorption process of higher order. For both processes, the 2PP and the 3PP process, a spatial resolution beyond the diffraction limit can be easily achieved.

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[5] http://www.georgehart.com/rp/rp.html

Laser-controlled Injector for Biological Applications

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Laser controlled injector has a simple driving unit and work with less buffer volume. We have developed a disposable injector head driven by a pulsed laser [1]. It is a drop-on-demand head, applicable to laser-transparent liquid. It requires only 5μl of sample for normal operation. The speed and volume of ejected droplets depend on the pulse energy of the laser and the nozzle diameter, respectively.
By using the injector, small immobilized antibody dots for P1CP (procollagen I carboxyterminal propeptide) [2] antigen, of which detection sensitivity was comparable to that formed by an injector driven by piezo-electric unit, on PMMA and COC plates were successfully formed.

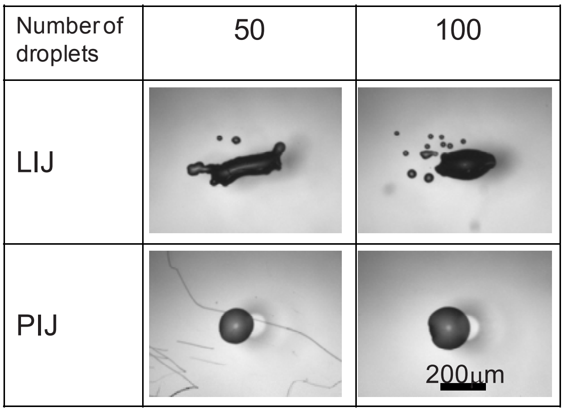

Figure 1 Photographs of immobilized antibody dots on COC plate by laser-controlled injector (LIJ) and piezo-electric injector (PIJ), respectivily.

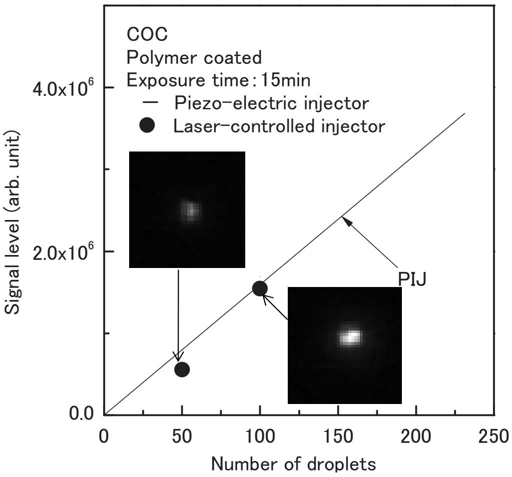

Figure 2 Results of antigen detection by the antibody dots formed by laser-controlled injector.

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3D Polymerization for Functional Devices

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Since the first application the two-photon photopolymerization technology on fabrication of three-dimensional (3D) photonic crystal structures [1], the method has attracted a lot of research efforts because of its unique merits like the high fabrication resolution down to nanometers and the 3D prototyping capability [2-15]. Various exquisite structures such as a sculpture of micro-bull, spring, and rotating wheels have been demonstrated. However, an open problem is, is that all? In order to answer this question, our group in the passed several years has been focused on the practical use of the technology on micro-optics, micromachines, microfluids and microsensors. In this presentation, we will present our recent progress along this line. Shown in Fig. 1 is an aspheric microlens [Fig. 1(a)], an aspheric microlens array and its use for high-resolution imaging. [Fig. 1(b)].

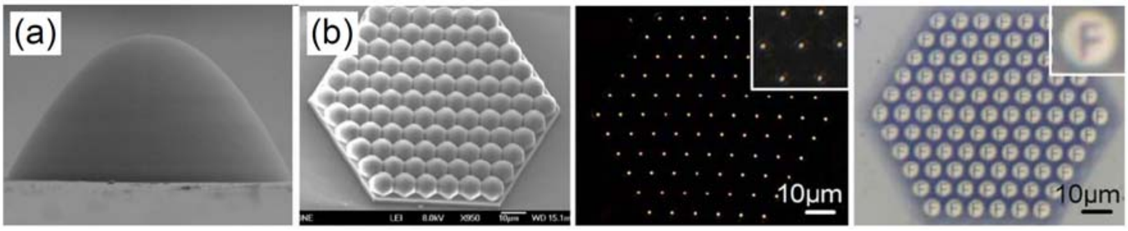

Figure 1 Examples of micro-optical components: (a) a scanning electronic microscope side view of a aspheric micro lens; and (b) a micro lens array (left), the focal spot image (middle) and its use for high resolution (NA=0.52) imaging.

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Plasmonics Enhanced Femtosecond Laser Nanoprocessing: Modeling and application to biology

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When an electromagnetic wave hits a metallic nanostructure of a size less than its wavelength, the wave's energy is absorbed and locally reemitted as near field in close proximity to the nanostructure, but with a multiplied intensity. This local field enhancement is mainly attributed to the surface plasmon resonance of the nanostructures and can be used to perform nanoprocessing of the medium. The irradiation of a nanostructure imbedded in a biological media by a femtosecond (fs) laser could results in a highly localized plasma and /or heat production yielding to the nanosurgery of cells. To understand the basic mechanism of plasmonic enhanced fs laser nanoprocessing in a biological tissue, we performed three dimensional simulations to obtain the electromagnetic field distribution, the plasma production and tissue transient temperature distribution and thermodynamic state surrounding the gold nanostructure irradiated by a fs laser beam. The electromagnetic field distribution is calculated directly from the Maxwell equations using a finite-element based method. Transient temperature distribution inside the nanostructure is determined through a two-temperature model. Significant gold parameters, including heat capacity, thermal conductivity and electron-phonon coupling constant, are calculated using full quantum treatment. Biological tissue is then modeled using the Pennes equation. Cavitation and hydrodynamics phenomena are simulated using Navier-Stokes equations. As an example, we are considering Au nanorods (10 x 41 nm) irradiated by a 800nm 45 fs laser pulse at 100 $\mu J/cm^2$, just under the permanent deformation fluence threshold Simulation results indicate a temperature rise of ΔT ~ 370K in the medium, while the corresponding ΔT is negligibly small (< 0.1K) when nanorods are absent. Plasma is created around the nanostructure and diffuses deep in the medium, creating a several hundred nanometers radius damage zone. Laser interaction also creates strong thermomechanical effects on the surrounding area. A pressure shockwave of ~200MPa is generated along with a 8nm radius cavitation bubble. Using pump-probe experiments, variations of the transmitted probe irradiation of the gold nanorods immersed in water were study in details as a function of the pump laser fluence and polarization. There is a good agreement between the pump-probe and the simulation results.

When the gold nanorods are located in close proximity to a cell membrane, it will induce transient pores due to the plasmonic effects during laser irradiation, which permit macromolecules, e.g. DNA, to enter the cell. Gene transfer (transfection) has become a very important tool in biomedical research. The transfection methods developed in the past are unsatisfactory in terms of efficiency and viability, strongly depending on the cell type used. The combination of fs-laser pulses and nanostructures is a very promising tool for a highly efficient, high throughput solution for transfection. Preliminary results indicate that approximately 400 human melanoma cells per minute were treated in presence of the membrane impermeable fluorescent dye Lucifer Yellow (LY) at a fluence of 80 to 100 mJ/cm^2. A perforation efficiency of up to 45% was obtained with a very high viability of ~ 90%.

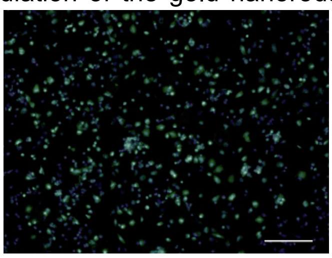

Figure 1: WM793B melanoma cells perforated in presence of Lucifer Yellow (green) and a 6.5 µg/ml gold nanorod concentration (41x10 nm) using a laser fluence of 100 mJ/cm^2. After the treatment, the cells were labelled with Propidium Iodide (red) to show dead cells and DAPI (blue) to show all present cells. Scale bar: 200 µm.

Role of gas optical breakdown plasma in material ablation by short laser pulses.

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It will be shown that optical breakdown of gas (air), surrounding the sample, can play an important (sometimes vital) role in material ablation by intense laser pulses.
Three particular problems will be discussed.

1. Catastrophic beam profile transformation and high (up to 70%) scattering losses, induced by dense electron cloud that is produced in the gas during the femtosecond laser pulse action, will be considered. Corresponding experimental data, including fast pump-probe interferometric studies of the air breakdown kinetics, will be presented. The effect is described as a result of the so called "conical emission". The means of minimizing gas breakdown effect on ablation rates and quality, such as variation of pulse duration and wavelength, gas type and pressure will be discussed.
2. The effect of picosecond laser gas breakdown plasma ignition by microparticles, produced in the cause of material ablation by the previous pulses and floating (up to few seconds) inside the beam caustic, will be outlined. It will be shown that such plasma can shield the target from the incident radiation. It was found that majority of these microparticles are charged and application of electrical fields can drastically increase gas breakdown threshold.
3. The attention will be paid to the late stages of vapour plasma, expanding into the gas and the formation of long-living plasma volume – "fire ball". Such plasma has density much lower than the atmospheric one and can intensify materials ablation for ultra-high ($\geq 10^5$Hz) pulse repetition rates.

Local oxidation of thin metallic films under short pulse laser action

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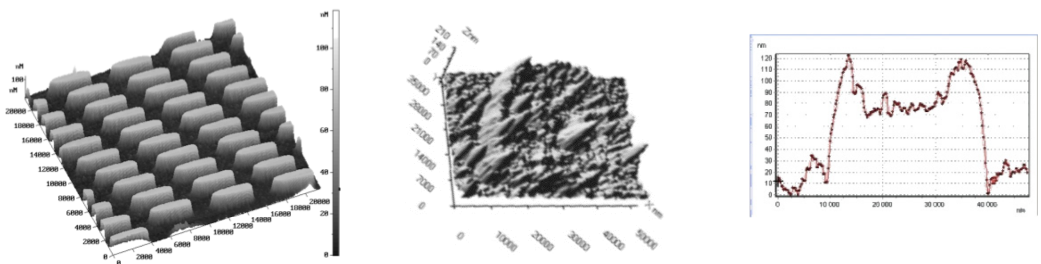
Laser–induced oxidation on thin metallic films with following selective etching is a powerful method for micropatterning of different structures like photomasks, diffractive optical elements etc.
Nowadays the most important question is how small could be structures produced by this technology, what are the experimental methods to realize it and what is the nature of theoretical limitations for space resolution
Under this research will be shown that Arrhenius dependence of oxidation speed from temperature raises this limit on some orders of magnitude higher then the resolution of thermal image. Corresponding calculation will be done and will be verified experimentally. From the other hand régimes of laser irradiation (power density, time of irradiation etc) as well as régimes of selective etching (type of etchant and its concentration), material of thin film and its thickness have also big influence on the final results.
Most interesting problem in this area now is to check is it possible to oxidize or to modify metallic films (or surfases) structure under short (nsec) and ultrashort (pcsec, fsec) laser pulses action. The experiments has been carried out shown selective etching after such kind of laser action. Experimental and practical results for fabrication of some specific components and devices as different diffraction components, synthesized holograms will be demonstrated.



(a) (b) (c)

Figure.1. a – AFM–image of thermochemical recordinmg on Cr films (exposition time τ = 2.6 mks, width of the recorded line < 600 nm), b, c – Femtosecond laser dot on Cr film after etching (3D image (b) and cross–section (c)).

Finally it is proved theoretically and experimentally that resolution of above mentioned technology can reach hundreds of nanometers and even less.

This work was supported by RFBR grant 09-02-01065.

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Two-photon polymerization as method for the fabrication of large scale biomedical scaffold applications

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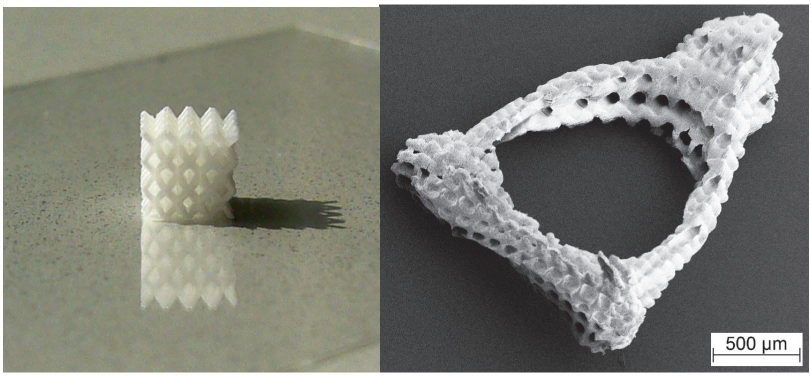
Two-photon polymerization (2PP) using ultra-short laser pulses is already well-known in research especially for 3D free-form fabrication of optical devices with resolutions down to 100 nm [1-3]. However, the structure dimensions have been restricted to quite small sizes, mainly related to the focussing optics and to the very long fabrication times. In order to create large patterned samples, these limitations have to be overcome which is challenging for both, the exposure strategy and the employed material systems. Up to now, only little is published concerning 2PP as method for a large-scale fabrication of patterned structures which might be applied as biomedical scaffold structures.

We will present a novel setup for which allows one to create arbitrary 3D structures using a diode-pumped Ytterbium laser system emitting 325 fs laser pulses at 515 nm after second harmonic generation using inorganic-organic hybrid polymers (ORMOCER®s). The exposure setup enables the production of large structures which can be in the cm region with a resolution of a few microns. In addition, a 3D porous inner structure can be provided (Figure 1 (a)), which is required for three-dimensional cell growth to support cell adhesion and proliferation. The pore size can be adjusted from a few microns to hundreds of microns, and different pore shapes as well as distinct sample shapes can be realized to adapt to individual preferences of certain cell types or applications. In Figure 1 (b), a real scale stapes (smallest human bone) implant with porous inner structure fabricated by 2PP is displayed.



(a) (b)

Figure 1 : 3D structures in ORMOCER®. (a) Macro image of a 3 x 3 x 3 mm^3 scaffold structure (re-design from a design of Phoenix GmbH & Co. KG). (b) SEM image of porous real scale stapes implant.

In addition to the fabrication method, the underlying materials play an important role in the fabrication process. Thus, the degree of organic cross-linking of inorganic-organic hybrid materials is investigated by high resolution µ-Raman spectroscopy for differently processed 3D structures which will be correlated to the structure quality, and their mechanical stability.

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Modelling Laser Induced Periodic Surface Structures

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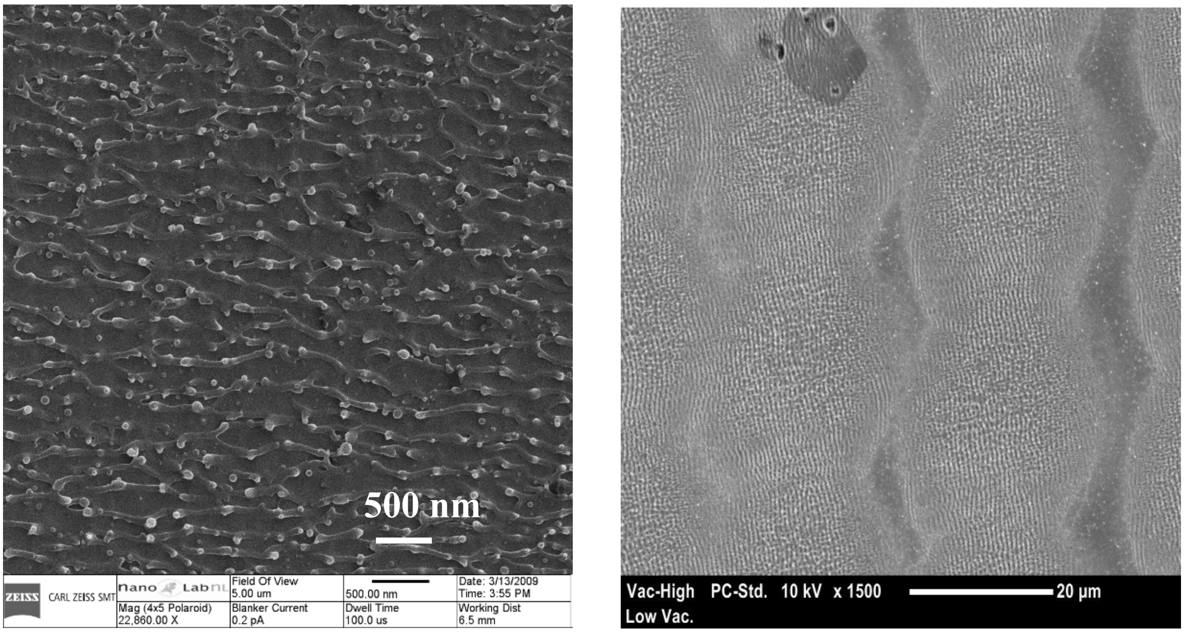
In surfaces irradiated by short laser pulses, Laser Induced Periodic Surface Structures (LIPSS) have been observed for over forty years on all kind of materials. These LIPSS are also referred to as “self organizing structures”, or ripples, consist of wavy surfaces, with periodicity and amplitude equal or smaller than the wavelength of the laser. Unfortunately, the physical phenomena explaining ripple initiation, growth and transitions toward other patterns are still not fully understood. Models, explaining ripple initiation and growth, based on the (laser) parameters, such as fluence and polarization, are frequently discussed in literature. This paper presents the most promising models, their ability and limits to predict experimental results.



(a) (b)

Figure 1 : (a) Scanning helium ion microscopy (SHIM) image of LIPSS on stainless steel treated by normal incidence, linear polarization, 800 nm laser with ~ 13 mJ/cm^2, 5 pulses. High spatial frequency LIPSS with a wavelength of ~ 170 nm, parallel to the polarization of the laser beam are visible with bubbles mainly on top of them [1]. (b) Scanning electron microscopy (SEM) photos of LIPSS on stainless steel treated by normal incidence, linear polarization, 800 nm laser with ~ 0.6 J/cm^2, 2 pulses. Low spatial frequency LIPSS with a wavelength of ~ 675 nm, orthogonal to the polarization of the laser beam are visible [2].

Figure 1 shows two different kinds of LIPSS obtained on stainless steel. On (a) high spatial frequency LIPSS are produced at low fluence and parallel to the laser beam polarization. If the fluence is increased these structures are often washed out and low spatial frequency LIPSS perpendicular to the laser beam polarization can be obtained (b). The angle of incidence, the laser beam polarization, the shape of this beam, the pulse duration, the number of pulses, the repetition rate, the energy per pulse and a lot of material parameters are governing the observed phenomena. Due to this large number of parameters a modeling approach is suited.

[1] B. Huis in ’t Veld and H. van der Veer, submitted to Journal of Laser Micro/Nano Engineering (JLMN)
[2] Internal report Univerty of Twente

Picosecond laser machined designed patterns with anti-ice effect

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Micromachining using ultra short pulse lasers (USPL) has evolved over the past years as a versatile tool for introducing functional features in surfaces at a micrometric and even at a subwavelength scale. Being able to control the surface topography at this level provides a method to change the wetting behavior of a great number of materials. In most cases, when a surface has a natural tendency to be wetted (high surface energy), increasing its roughness will increase the spreading of water over it, and when it is naturally hydrophobic this roughness can dramatically enhance the water repellency. In this study, anti-ice properties of water repellent laser machined materials are investigated.

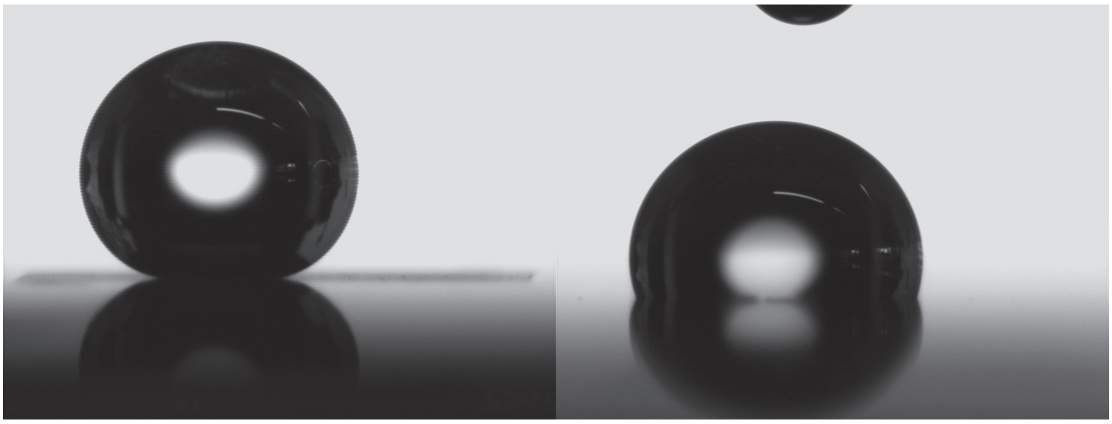

Figure 1. Effect of a laser texture on a stainless steel sample. The left drop on top of a laser micro structured surface exhibits a high contact angle; the surface on the right is smooth and wets the surface.

Therefore, stainless steel (AISI 321), titanium alloy (Ti6Al4V) and Al 2024T3 alloy have been textured with regular hatched, as well as non-uniform patterns, using UV and green laser pulses of 6.7ps. In order to decrease the surface energy, a thin hydrophobic coating has been applied on top of these structures. Super-hydrophobic state has been reached for many of the samples, and small hysteresis values have also been measured to confirm the so-called, self-cleaning, or "lotus effect" properties of the engineered surfaces. Finally, the performance of the surfaces was evaluated in an ice-chamber. These "smart" materials repel water; remain clean and prevent ice accumulation under certain (environmental) conditions. The potential applications include automotive and aircraft industries, where the development of an anti-ice coating is highly desired in order to increase in-flight safety and to reduce fuel consumption.

3D-Microstructuring of Protein and Polymer Networks

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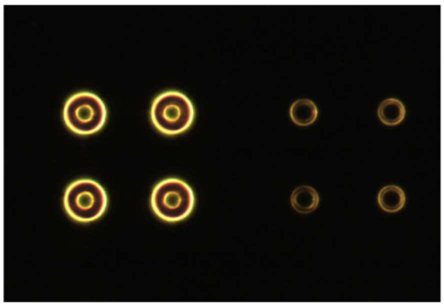
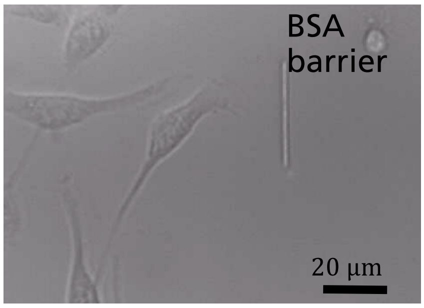
Multiphoton Polymerisation (MPP) is a high resolution stereolithographic process able to create complex three-dimensional structures.[1] Normally, a photoinitiator simultaneously absorbs two or more photons of a tightly focused, ultrashort pulsed laser beam, thus serving as an initiator for a polymerisation chain reaction of a pre-polymer. The same procedure can be applied to biopolymers such as extracellular matrix proteins, where the development of cystin bridges between different proteins form a stable connection.[2] Some proteins, such as Serum Albumin (Figure 1(b)) can be crosslinked without the use of an additional, mostly toxic photoinitiator. Here, protein inherent aromatic amino acids (Phenylalanin, Tyrosin, Tryptophan) show a pronounced two photon absorption ability.[3]



(a)



(b)

Figure 1 (a) Darkfield image of tubes made of pTHF containing a specialy designed photoinitiator. The inner diameter of the tubes is 20 µm, the wall thickness is 10 µm and 4 µm respectively and the height is 50 µm. (b) A µ-barrier formed from bovine serum albumin in the presence of live nerve cells

In order to use this process for the creation of three-dimensional cell scaffolds we built a cost efficient and highly flexible MPP-machine, including a small footprint, turn-key laser source, capable of creating complex microstructures.

Apart from biopolymers, such as proteins, a range of photosensitive artificial polymer can be manufactured as well. In cooperation with the Fraunhofer Institute for Applied Polymer Research (IAP) we use specially designed polymer compositions to enhance polymerisation efficiency and scaffold properties. The artificial polymer structures, having more mechanical stability than protein structures surf as a robust backbone for the cell scaffolds.

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Fs-pump-probe measurement of the transient dielectric function of fused silica

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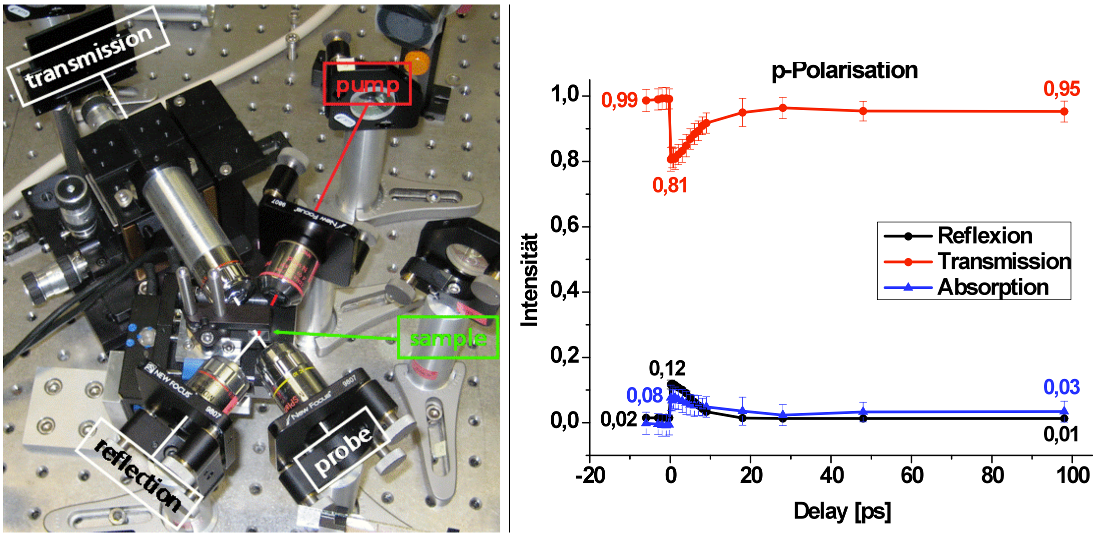
Periodical surface nanostructures (ripples) are fabricated on the surface of dielectric materials with fs-laser direct writing. Using high repetition rate fs-laser radiation with a wavelength of 1045 nm ripples with periods of 200-350 nm are obtained on dielectrics. The periodical nanostructures are aligned perpendicular to the polarisation of the laser radiation.
The period of the ripples does not depend on the focussing optics and the pulse overlap but it depend on the laser wavelength and the material. No simple correlation between the period of the ripples and materials properties like refractive index or band gap has been found. Therefore, a dependence on transient material properties modified during the fs-laser pulse has been proposed [1].
In this paper a pump-probe technique is used for time-and spectrally resolved investigations of the reflection and transmission during and up to 100 ps after the fs-laser pulse. The transient dielectric function is derived from the pump-probe measurements and will give a hint for the metallic behaviour of the dielectric material during and after the fs-laser pulse.
Furthermore the dependence of the ripples period on the repetition rate, the pulse duration, the pulse energy and the sample temperature is investigated.



(a) (b)

Figure 1 Transient dielectric function. (a) Pump-probe set up for the measurement of the transient dielectric function. (b) Measured transmission and reflection of the probe pulse over 110 ps for parallel polarised white light.

[1] J. Gottmann, D. Wortmann, M. Hörstmann-Jungemann, Appl. Surf. Sci., doi:10.1016/j.apsusc.2008.10.097

Patterning of a NiCr-Al_2O_3 thin film system with picosecond laser pulses

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Strain measurement is an important task for the automation of many manufacturing processes. Most strain gages need to be glued onto the tool to be measured. Glued strain gages suffer from the negative properties of the adhesives used. Creeping and swelling through harsh conditions are the consequence and limitation for such strain gages.

Metal thin film sensors are a promising approach to overcome the disadvantages of the adhesives. An insulating layer and a sensing metal layer are sputtered directly on to the surface of the tool to be measured. The patterning of the sensor elements can be performed by means of laser ablation. Using laser ablation instead of photolithography for the patterning process has two advantages. Firstly laser ablation enables patterning in the third dimension; the limitation to planar work pieces is overcome. Secondly, laser ablation is a flexible process that allows in situ trimming of the sensors and thus increases the signal/noise ratio of the measured signals.

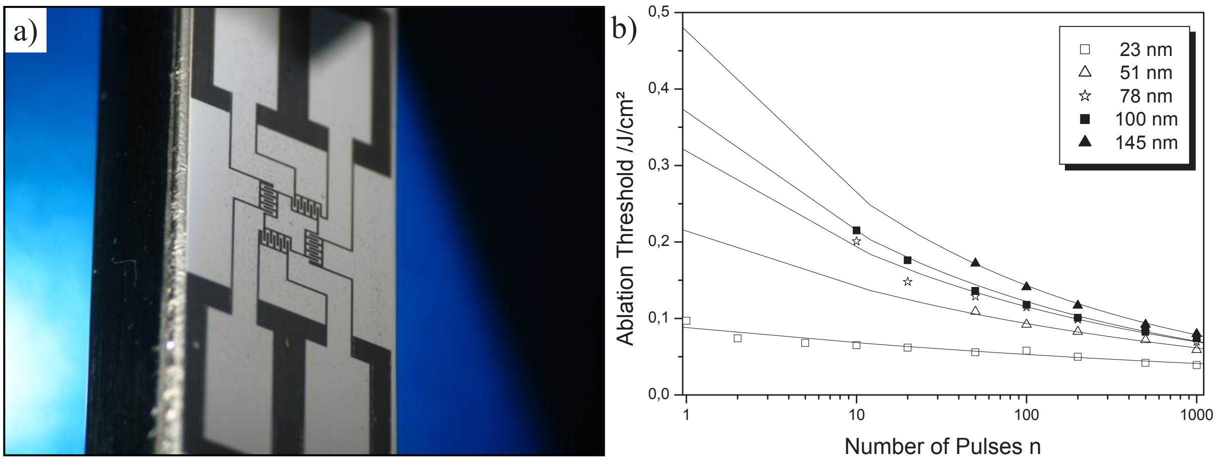

Figure 1 a) Patterned sensors in a full bridge design (b) Ablation thresholds of NiCr films with different film thicknesses as a function of number of pulses

This paper concentrates on the characterisation of the ablation process of thin NiCr films deposited on metal work pieces with an Al_2O_3 layer for galvanic insulation in between. The used laser source is a mode-locked DPSSL with pulse duration of 15 ps and a wavelength of 532 nm.

Due to the deposition process, uniform film thicknesses on 3D work pieces cannot be ensured. Thus, the laser ablation process has to be robust against variations of the film thickness. Our investigations reveal that ablation thresholds for high number of pulses differ much less than the ablation thresholds for low number of pulses (Fig. 1 b). This is caused by thickness dependent incubation. Therefore a time efficient and robust processing strategy will in fact depend more on high repetition rates than on high energy per pulse.

Ablation thresholds of single and multiple pulse ablations are compared with ablation thresholds of line ablations realised with high repetition rates. Scanning speed and repetition rate are varied to identify useful patterning parameters. Damage behaviour and thresholds like delamination and cracking of the Al_2O_3 film are identified and discussed. Delamination of the Al_2O_3 film can partly be accepted in some areas, e.g. at the soldering pads. Consequently, cracking has to be avoided to ensure the galvanic isolation between sensing layer and work piece. Based on these damage thresholds a processing strategy is derived which allows for fast processing of precise strain sensors which are free of creeping and swelling.

Development of 2D/3D Micromachining Processes Based on Nanosecond Laser Sources for Industrial Manufacturing

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The current availability of different short and ultra-short laser sources are extending the applications fields of laser microprocessing. Nowadays MEMSs, fluidic devices, advanced sensors and biomedical devices and instruments are among the most significant developments of this technology. The fast development in the understanding and implementation of micromachining process has easily led to the expectation of industrial scale production of different relevant components and to the consequent attempt for the building up of specific laser based machines for each process of interest.

However most of these new facilities easily work strictly in the 2D frame, while a much more difficult task is to setup experimental equipments for filling the gap existing from the fabrication point of view for fully 3D micromachining applications. Even more for the development of micromanufacturing systems exportable to industry.

At the UPM Laser Centre, the task of micromachining processes design and implementation from an industrially exportable point of view has been undertaken in view of the needs expressed by different application actors and the corresponding manufacturing aids and quality control procedures have been setup as required by industrial practice.

In this paper, the conception, design and first results of a fully automatized 2D/3D laser micromachining workstation based on the main concepts of accuracy, flexibility and process quality control is presented. This system integrates two UV laser sources, excimer and DPSS in ns pulse regime and an advanced positioning system (with six degrees of freedom) for complex parts machining. Additionally, the appropriate (dimensional) quality control procedures have been implemented. Several examples of first results obtained with this system, including processing of semiconductors for sensoring and photovoltaic applications, organic materials for biomedical devices and metallic materials for different strategic industrial sectors are presented. In figure 1, two sample components showing the possibilities of the developed system are displayed.

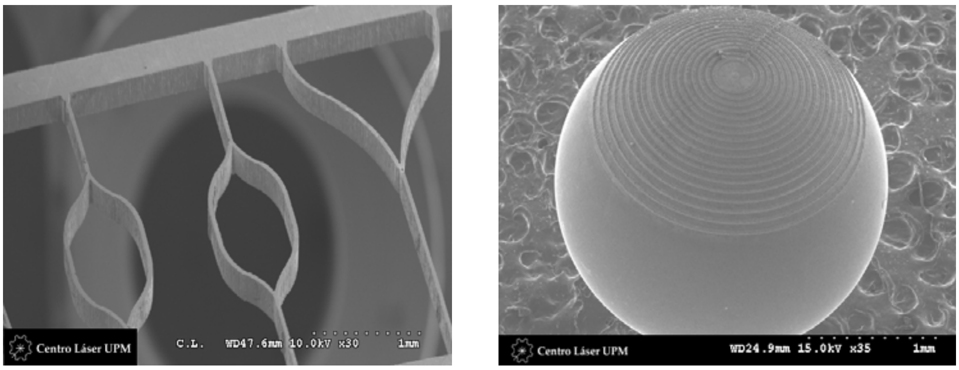

Figure 1: Scanning electron microscope images of negative photo-mask and textured microshpere in AISI 304 micromanufactured at UPM Laser Centre

Laser Micro-Patterning by Means of Optical Fibers with Etched Tips or Micro-grinded Lens End Faces

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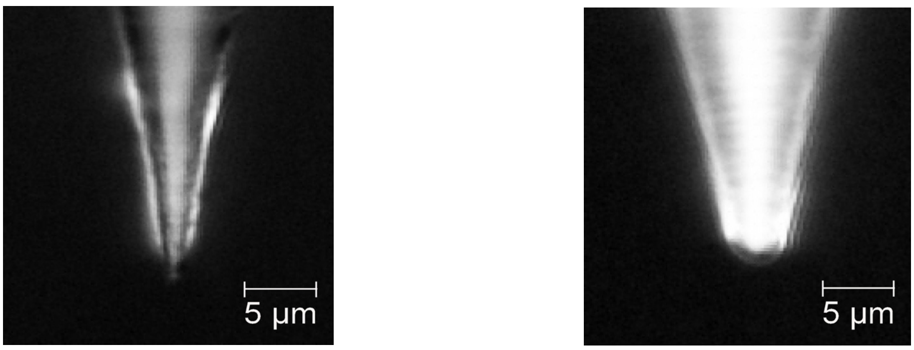
We have developed a scanning optical near-field microscopic (SNOM) setup allowing to produce sub-micrometer patterns by laser induced processes and to perform atomic force microscope (AFM) investigation in the same setup [1]. The laser light for processing is delivered to the sample surface by a tapered optical fiber tip produced by chemical etching (Fig.1a). The same fiber tip is used as probe for AFM analysis. Similar as in a SNOM, the distance between tip and surface is controlled using a piezoelectric quartz tuning fork as shear-force sensor. We demonstrated that the same setup can also be employed for analysis of the chemical surface composition by laser-induced break-down spectroscopy (LIBS). In the present contribution, we concentrate on laser-patterning of polymer surfaces. By UV light emitted in the near-field of the optical fiber tip, we are able to produce features in spin-coated poly(methyl-methacrylate) layers with a lateral size of about 100 nm and a depth of several tens nm. However, the low transmission efficiency of the fiber tip and the direct tip-sample contact result in a relative slow writing speed and the risk of tip damage due to thermo-mechanical effects.

We show that it is possible to overcome the limits of writing speed and to extend the tip durability considerably by keeping a certain distance between the tip and the sample during the patterning process. In this operation mode, we use fiber probes with polished hemispherical end face of several µm curvature radius (Fig. 1b). These micro-lensed fibers were produced by grinding in the same setup [2]. The light propagating through the lensed fiber is focused at the distance of about 1 µm from the fiber end face. With 266 nm Nd:YAG laser radiation, we can produce features in the order of about 100 nm corresponding to about half of the wavelength. Additionally, we are still able to measure the AFM topography with reasonable sensitivity and to perform also micro-LIBS analysis of the surface by using these tips.



(a) (b)

Figure 1 (a) Tapered optical fiber tip. (b) Fiber tip polished to hemispherical lens end face.

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Laser Ignition of Internal Combustion Engines

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The idea of laser ignition of engines was attempted to be realized for the first time in 1978 [1], although with inadequate tools like a CO_2 laser. After a long time of inactivity in this field, about 10 years ago a few institutions like Vienna University of Technology resumed this approach with the help of modern type solid-state lasers and started systematic investigations around the idea of laser ignition of internal combustion engines. Now, this technique has reached a high degree of maturity on the level of basic research as it can be carried out e.g. at universities; the remaining problems lie on the product development level and cannot be treated adequately any more by such institutions. On the other hand, ambitious product development by the leading engine producers or ignition equipment suppliers has been started worldwide and, as seen from today, in a few years laser ignition will probably be implemented into high power gas engines or high priced automotive engines. This talk will provide an overview on advantages and critical issues of laser ignition, different system concepts and alternative approaches which are considered to be less advantageous or even unrealistic. Figure 1 shows the front end of a laser spark plug as it has been developed by the author's group.

Figure 1 Plasma spark emitted from a laser spark plug developed at Vienna University of Technology. The heart of this device is a compact monolithic diode-pumped passively Q-switched Nd:YAG laser. Pulse duration ~1 ns, pulse energy >10 mJ.

As a perspective for the future, laser ignition is considered to be an indispensable process for the ignition of chemical reactions in general [2], and it will with high likeliness be implemented e.g. into rocket engine ignition (attitude control in the first place) and jet engine (re)ignition.

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Thin Film Processing with UV Excimer Lasers

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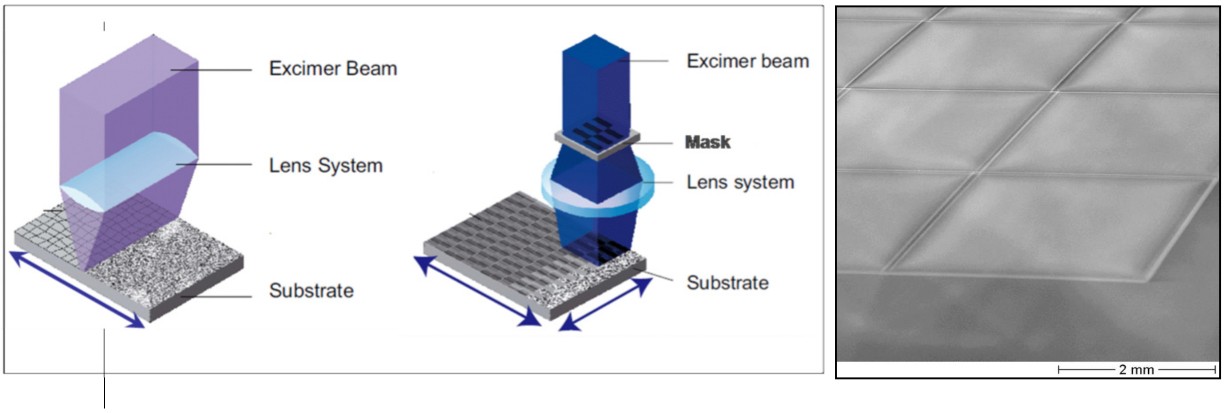
Driving cost-efficient material and process development in display and microelectronics industries Coherent has launched the VarioLas family of excimer surface processing systems. Two processing approaches, line-beam scanning or large-area square-field step and repeat processing as shown in figure 1 (a) can be chosen supporting selective layer annealing as well as various lift-off tasks [1,2]. Shrinking structures in microelectronics put UV excimer lasers in the forefront as to the formation of ultra shallow junctions (USJ) for ever smaller CMOS logic devices such as CPUs and memory chips, of power devices such as insulated gate bipolar transistors (IGBTs) and of advanced CCD or CMOS based image sensors [3]. The respective functional structures are activated by diffusion-controlled, 308nm excimer annealing with low-thermal-budget. Excimer laser wavelength, repetition rate, fluence and pulse width can be flexibly adapted to match the device-specific process window.



(a) (b)

Figure 1 (a) Thin film excimer laser processing schemes using scanned homogeneous lines or rectangular fields.
(b) Micrograph of an annealed silicon wafer surface using square field beam step and repeat processing.

Laser lift-off (LLO) using excimer lasers is an enabling step in producing high-brightness LEDs (light emitting diodes) based on e.g. GaN. GaN-LEDs are commonly fabricated on sapphire substrates due to good lattice match for the growth of GaN crystals [4]. However, sapphire limits LED output power because of its poor electrical and thermal conductivity. Using LLO, absorption of the 248 nm excimer photons occurs at the interface between GaN and sapphire layers resulting in thermally induced debonding. Large field sizes of up to 2mm x 2mm as employed in figure 1 (b) are advantageous for LLO in that many LED dies can be covered at the same time thereby ensuring uniform delamination over individual dies.

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Formation and evolution of self-organized patterns in laser irradiation of silicon surface in water

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The formation and the evolution of the patterns formed in nanosecond laser irradiation of silicon surface in water were investigated. It was found that axisymmetric, network- or maze-like and linear structures could be formed at short evolution times and all these patterns were finally turned into hexagonal patterns with period of about 10 μm. The behaviors of these patterns were compared both theoretically and experimentally with those appeared in the Rayleigh-Taylor instability system of a suspended thin liquid film under gravity, indicating the highly consistencies between the two systems. So it was concluded that the underlying mechanism for the patterns observed here was the Rayleigh-Taylor instability of the melted surface layer of the silicon wafer formed by laser irradiation. The instability driving force was the expansion of the interfacial vapor layer formed by the boiling of the layer of water adjacent to the hot silicon surface. The effective acceleration involved was estimated to be above 10^8 m/s^2.

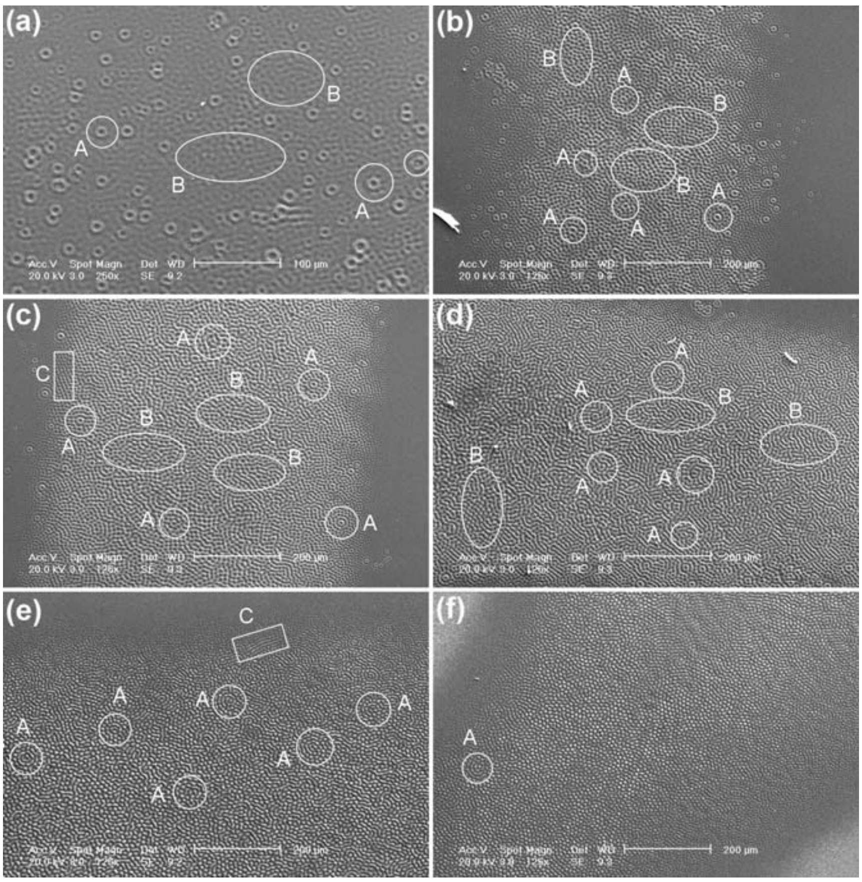

Figure 1 SEM images of the silicon surfaces after irradiated by a ~2 J/cm^2 laser beam with pulses of (a) 100, (b) 300, (c) 600, (d) 900, (e) 3000, (f) 6000, respectively. Three kinds of patterns can be distinguished, which are marked with A, B and C, respectively.

Micromachining Hard Materials with Industrial Picosecond Lasers

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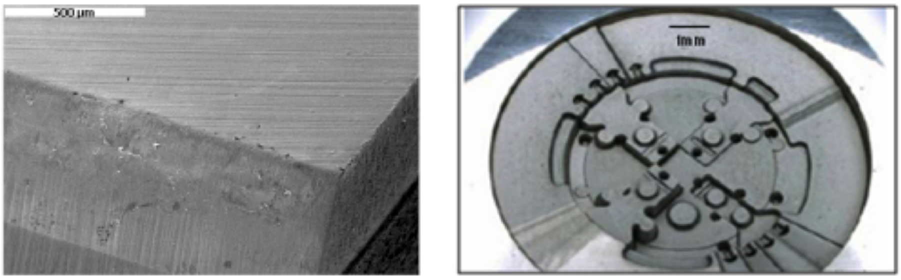
As material requirements are pushed further and further to their limits in terms of hardness, stiffness, and temperature tolerance, it also becomes more and more difficult to machine such materials to their desired shapes. Conventional machining of the hardest materials requires even harder mechanical tools which can become prohibitively expensive as well as very slow at machining. We report on machining results of tungsten carbide, hard metals, polycrystalline diamond (PCD), and cubic boron nitride (CBN) using industrial grade high-power ps-laser systems. Our results show that these very hard materials can be machined cost effectively with high power ps-lasers and that the machining quality exceeds what has been achieved by conventional methods such as milling and grinding. Often times the edge quality is key to the utility and longevity of the material (Fig.1a). Micromachining with a ps-laser does not only allow for much faster machining speeds, but also allows for edge rounding which again leads to longer tool life. We have demonstrated ablation rates of up to 25mm^3/min for CBN and up to 8mm^3/min for tungsten carbide and hard metal (Fig 1b)[1]. These ablation rates have been facilitated by the use of a special burst mode in the ns time scale.



(a) (b)

Figure 1 Material Images. (a) The picture shows CBN on top of hard metal, which can be seen by the different shading. (b) Micromold out of hard metal machined with burst mode @ 1064nm.

Many laser systems are capable of producing a sequence of intense ps pulses in a burst, but only pulses in a fast time sequence in the ns scale can achieve these high ablation rates. Aside from the burst mode capability, high repetition rates up to 1MHz are key to large ablation rates. High ablation rates again are imperative when looking for an economic machining process that requires micro structuring large surfaces such as printing drums.

We will present multiple examples of machining hard materials and discuss the challenges encountered as well as contrast our machining results with conventional methods. Among other samples, we have machined drilling heads, pill molds and high aspect ratio cooling holes into nickel alloys.

[1] Sample machined with HYPER RAPID50 laser in a Lasertec40 machine by DMG.

High-end micromachining with >150W average power from a 1MHz 10ps-laser

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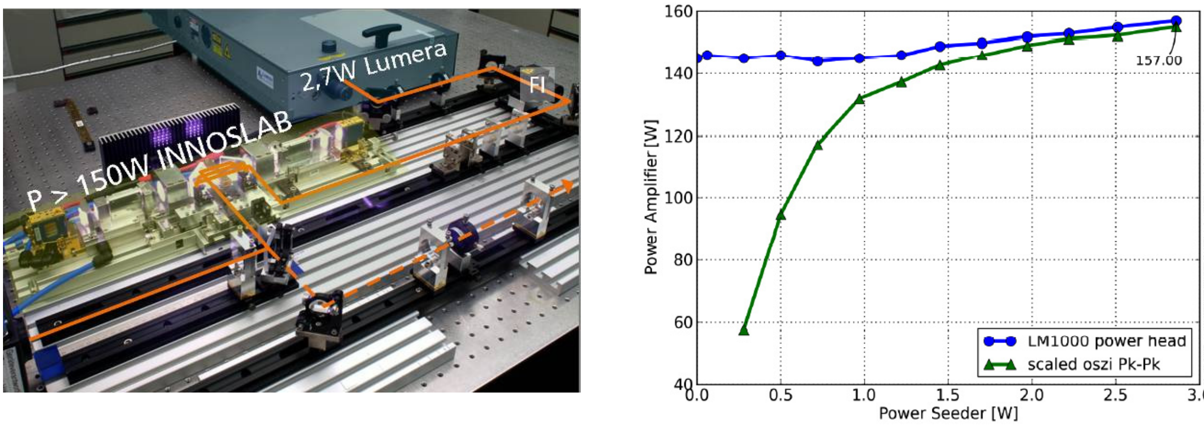
High-end micromachining with picosecond lasers became an established process during the recent years. Power scaling led to industrial lasers, generating average power levels well above 50W. Such lasers are routinely used in applications like machining turbine blades, micro moulds, and semiconductors [1]. In addition to high average power, a smart distribution of energy into groups of pulses significantly improves ablation rates for some materials, also providing a better surface quality.

In this paper we describe further power scaling, achieved by combining a state-of-the-art industrial LUMERA picosecond laser with Fraunhofer ILT INNOSLAB amplifier technology (figure 1 b). Pulses with 10ps-duration and a wavelength of 1064 nm were generated from a LUMERA RAPID laser in MOPA configuration [2]. These pulses with an average power of 2.8W at a pulse repetition frequency (PRF) as high as 1MHz were further amplified in a multi-pass INNOSLAB amplifier [3]. The slab amplifier consisted of a 1mm thick Nd:YVO_4 crystal, 10mm long and 24mm wide, which was end pumped from two faces by 2x 250W. The input beam was shaped to an elliptical profile and folded through the amplifier crystal with seven passes. The output power was as high as 157W, corresponding to a pulse energy of ~160µJ (figure 1 b). Measured M² was <1.5.



(a) (b)

Figure 1 : (a) laboratory setup (b) power (blue) and pulse energy (green) vs. seed power at 1 MHz PRF

The amplified beam was passing scanners and optical isolators, so that an average power of >137W was available on the probe for micromachining. Glass machining with full average power was possible, doing surface modifications, cutting, and volume ablation. Machining results and ablation rates will be presented, as well as for ceramics and steel, which benefits from higher throughput provided by high average laser power.

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Volume Bragg grating formation in fused silica with high repetition rate femtosecond Yb:KGW laser pulses

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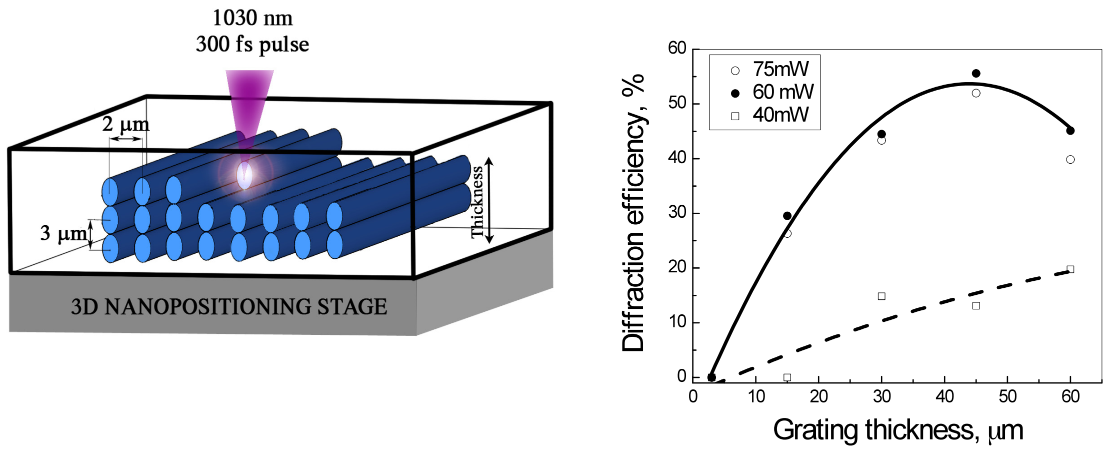
The capability to locally alter the optical properties of transparent material with femtosecond laser radiation opened the doors to many new and unique applications. Already more than a decade, this technique is successfully applied in creation of photonic devices such as waveguides [1], splitters, active elements [2] and etc. Volume phase Bragg Gratings (VBGs) and the possibilities to fabricate them in various glasses are also extensively studied [3]. Because of their high diffraction efficiency these gratings have more advantages compared with amplitude gratings. They are essential in optical systems where high spectral and angular selectivity is needed. Though highly efficient VBGs have been demonstrated also in photosensitive materials, the manipulation of the refractive index by means of femtosecond radiation allows to form these structures in more common materials such as fused silica. On the other hand the efficiencies of these gratings yet are not satisfying, because the physics of the refractive index modification is still not well understood and requires additional study.



(a) (b)

Figure 1 (a) Schematic layout of fabrication of volume phase grating. (b) Bragg diffraction efficiency dependence on the grating thickness with different laser writing powers at 300 kHz pulse repetition rate.

In this work we present results on VBG formation in fused silica with the Yb:KGW femtosecond laser (Pharos, "Light Conversion Ltd.") pulses, operating at 300 kHz repetition rate and having pulse duration of 300 fs. Gratings were created by direct laser writing technique, translating the sample perpendicular to the focused (0.42 NA) laser beam and forming several grating layers (Figure 1(a)). The VPG's diffraction efficiencies up to 57 % were reached and its efficiency dependence on the thickness is shown in Figure 1(b). We demonstrate that high repetition rate helps to increase the manufacturing speed of such devices: 1×1 mm grating with thicknesses up to 60 µm was written in less than an hour.

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Industrial production with ultra fast laser workstations

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Femtosecond lasers have proved to be great tools for precise, accurate and high quality micro- but also nano-machining. Numerous works have been carried out to study laser-matter interaction mechanisms on the one hand, and laser machining processes on the other hand.

Very naïve first industrial approaches, such as “ultra fast machining is interesting because it’s not a thermal process”, are only used by manufacturers who do not really want to sell workstations for industrial use. Technical development and good knowledge of the process have to be simultaneously settled to allow a real practical application.

In this work, we will underline some practical applications and the link between a better knowledge of physical mechanisms and the development of industrial processes. Of course, we have to pay attention to typical parameters of industrial development, such as the processing time. With the knowledge of an “efficient” ablation rate, the physical time can be easily calculated, using the total length of the machining, speed and laser parameters. This calculated physical process time can be compared to the effective time needed to machine the sample. This kind of information can evidence the possible improvement to be done on the mechanical and computer environment to reach this minimum process time.

Femtosecond technology has now proven its capacity to lead innovative production, even if it’s still in some well defined fields, but its contribution is non negligible in a context of economical crisis.

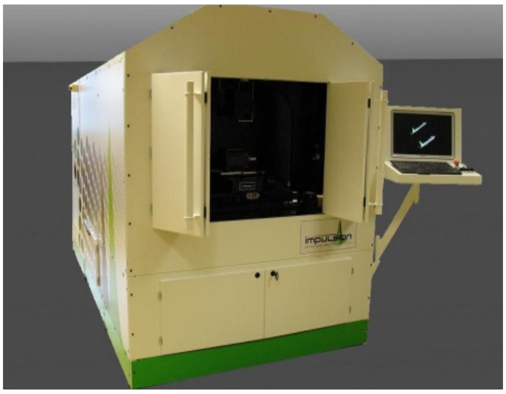

Figure 1 : Photo of the first fs workstation from IMPULSION company used for production (field of automotive industry)

Keyword : Ultrafast processing, Industrial applications.

Multiple Beam Internal Structuring of PMMA

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A Spatial Light Modulator addressed with Computer Generated Holograms is used to diffract femtosecond laser pulses into > 15 parallel beams and focussed simultaneously inside poly(methyl methacrylate) (PMMA) for high throughput 3D refractive index modification, (Fig.1 (a)). Highly uniform modification throughout the entire structure is demonstrated and used to create 19μm pitch, 5 x 5 x 2mm thick volume gratings in < 30minutes with 1st order diffraction efficiency > 65%. In PMMA, diffraction efficiency is highly order and time dependent, and remarkably different with NIR (775nm) exposure compared to second harmonic NUV (387nm) indicating different photochemical mechanisms, probably related to three photon (NIR) and two photon (NUV) absorption processes [1]. The benefits and current limitations of this technique are discussed in detail.

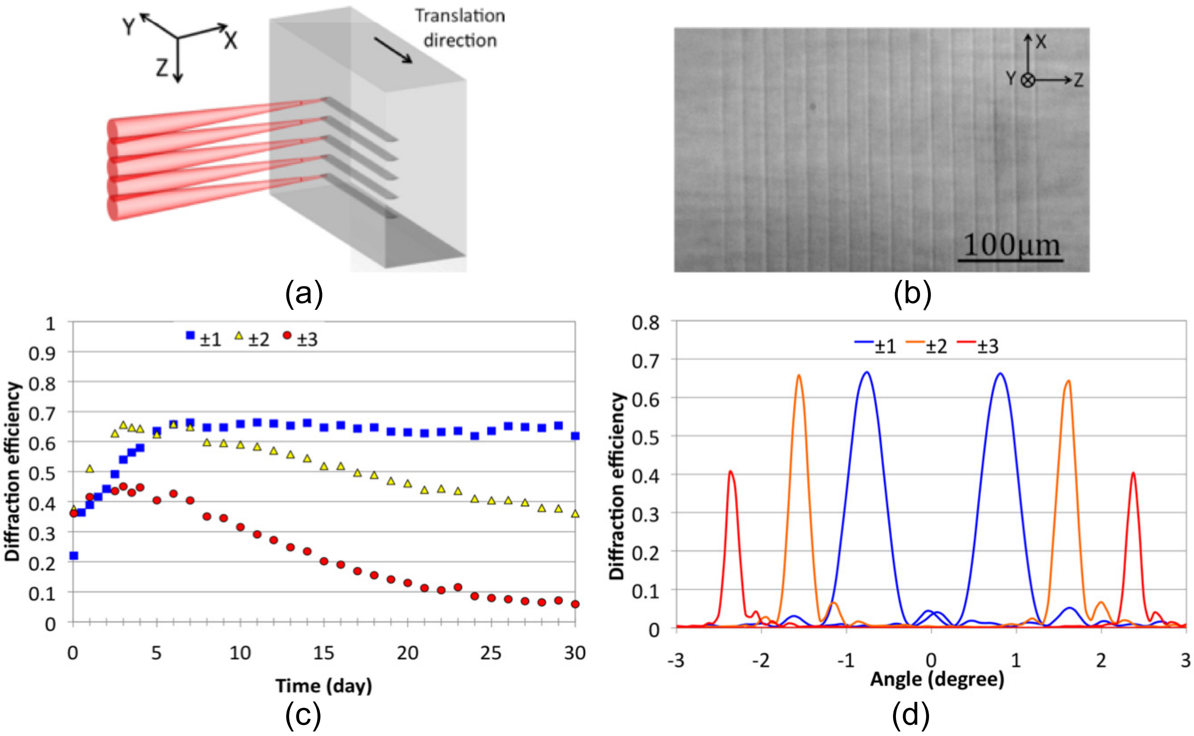

Figure 1 (a) Schematics of multi-beam internal structuring. (b) Modified cross section of PMMA. (c) Temporal behaviour of NIR written volume grating diffraction efficiency at 1st, 2nd and 3rd order and (d) Angular sensitivity of volume grating.

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Generation of Multi Spot Arrays and In-Process Spot Shaping for Parallel Laser Processing of Microstructures

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The processing of microstructures with a single focus is feasible and well known. Multi-spot optics are applied for parallelizing production if the demands on throughput in mass production rises or micromachining of large-scale materials have to be processed. These elements split the beam into a periodic spot pattern where each spot has the same shape and energy. This allows the simultaneous manufacturing of several equal shaped structures at the same time. For patterning a surface this is a good technique to reduce processing time and to receive a high lateral resolution as well as a good relative position of the structures.

This paper shows the investigation of microlens arrays in combination with different optical elements like axicons for forming an arbitrary shaped laser beam into a spot-, line- or ring array pattern. The principal functionality of the multi-spot generator is shown by wave optical simulation and principles of fourier optics. We show a method for parallel processing of three dimensional microstructures without a lateral scan of the beam or work piece during process. By adapting the spot shape in process it is possible to perform for each scan step in depth a different spot. By applying this method the time consuming lateral displacement could be avoided and a fast patterning of a complex microstructure becomes feasible. This paper shows experimental results of generated microstructures realized with a nanosecond and picosecond laser.

Thin metal cutting using water jet-guided laser

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This paper presents the latest results of thin metal cutting using the water jet-guided laser technology [1,2]. This technique has found a broad range of applications in the precision micromachining field. The water jet-guided laser is used today in several industrial fields, such as semiconductor, solar, electronics, medical, tooling [3], LED [4], watch and automotive industries.

The water jet-guided laser technology was recently implemented to cut 100 µm thick CuBe sheet. A Q-switched frequency-doubled Nd:YAG DPSS laser operating at a wavelength of 532 nm was coupled inside the water jet. Cutting tests were performed using a 40 mm nozzle, delivering a water-jet diameter of 36 µm. A laser repetition rate of 8 kHz and an average power of 20 W were used. The water pressure was 400 bar. A single pass at a speed of 1 mm/s was sufficient to cut the CuBe sheet. The obtained results are shown in Figure 1. Complex shapes were cut in the 100µm thick CuBe sheet, with no burrs and no heat affected zone.

Another recent application is shown in Figure 2. In this case the water jet-guided laser technology was implemented for the cutting of springs from 150 *µ*m thick annealed stainless steel sheet. A Q-switched Nd:YAG DPSS laser operating at a wavelength of 1064 nm was coupled inside the water jet. Cutting tests were performed using a 40 mm nozzle. A laser repetition rate of 0.5 kHz, a pulse duration of 60 µs and an average power of 5.5 W was used. The water pressure was 400 bar. A single pass was performed at a speed of 3 mm/s. As shown in Figure 2, the spring structure is very symmetric. Spring twisting issue, due to residual stress inside the spring, could be resolved by improving the cutting strategy. The picture was taken right after cutting, without any post cleaning treatment. The width of the metal lines in the spring structure is only 40 µm.

Other challenging thin metal cutting applications, such as the drilling of injection nozzles with an angle, will be presented in the paper.

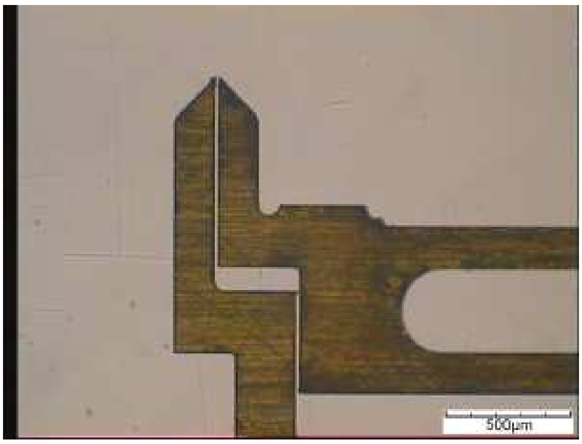

Figure 1: cut of a 100µm CuBe sheet

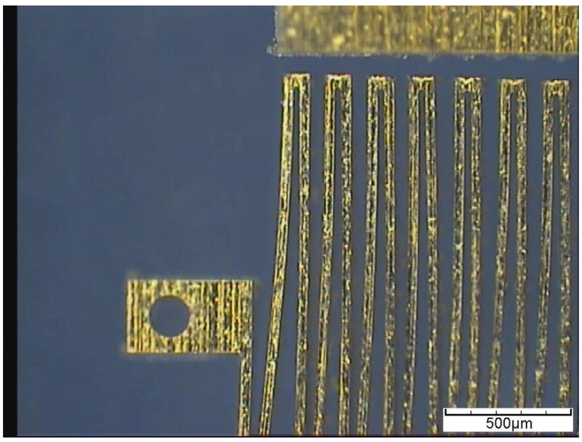

Figure 2: cut of a 150 µm Cu annealed stainless steel spring

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Laser processing by using diffractive optical laser beam shaping technique

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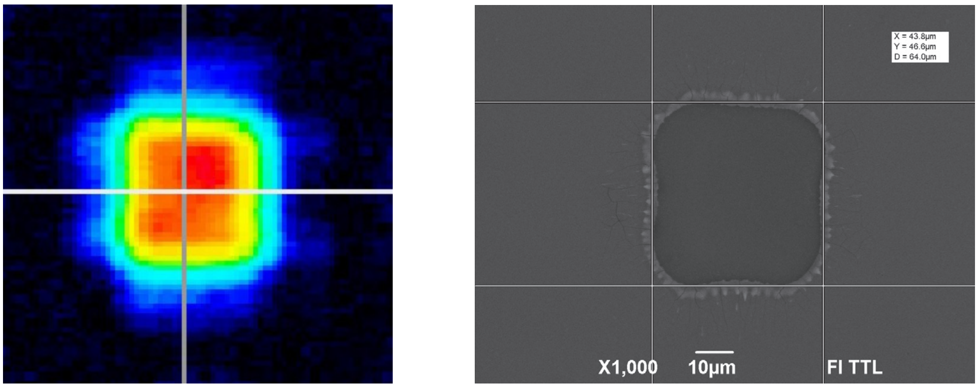
Laser beam shaping and homogenization techniques are substantial to optimize a large number of laser-material processing applications and laser-material interaction studies [1]. Diffractive optical elements (DOE) play important role in provision of the process-adapted laser beam shaping. In this paper, we present an approach for laser beam shaping by using innovative DOE [2]. Experimental results have been achieved by applying the shaped beam for laser microfabrication.
The nanosecond laser NL640 (EKSPLA Ltd.) working at fundamental wavelength with moderate beam quality (M^2=1.5) was used in the experiment. The circular Gaussian beam was transformed to square flat-top intensity profile in the focal plane of the objective lens by using novel DOE from TOPAG Lasertechnik GmbH. The intensity distribution of the focused laser beam is shown in Figure 1 (a). About 95% of the laser energy was coupled in the main beam with a nearly perfect rectangular shape.
The shaped laser beam was applied for direct laser ablation of metal film on the glass substrate, drilling in silicon wafer, scribing of thin-film solar cells and other technical materials. The Scanning Electron Microscope (SEM) image of square-shaped hole ablated by using single laser pulse in chromium thin film (100 nm) is shown in Figure 1 (b).



(a) (b)

Figure 1 (a) square shaped flat-top laser beam intensity distribution formed by using DOE and spherical lens measured by using CCD camera. (b) SEM image of square-shaped hole ablated with the single laser pulse in a chromium thin film on the glass substrate.

We have proposed a beam shaping technique by using DOE and a spherical lens. This technique allows creating rectangular shaped flat-top intensity profile in the focal plane that shows distinct advantages in laser material processing.

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Fabrication of sub-micron Gratings on Silicon by Maskless Exposure of Nanosecond Laser Pulses

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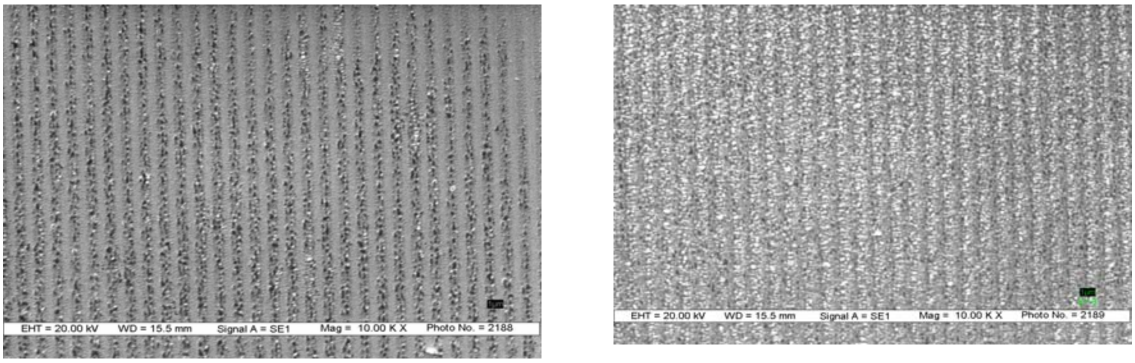
Maskless submicron grating structures on silicon surface are fabricated with two-beam holography exposure of second harmonic wavelength (532 nm) and fourth harmonic wavelength (266 nm) of a nanosecond pulsed Nd: YAG laser. Laser interference lithography or holography lithography is the preferred method for fabricating periodic pattern, as it is a relatively simple and maskless method, utilizing the interference of two or more coherent beams, and ideal for low cost and large area exposure. It has advantage over other techniques, provides flexibility in grating period and depth by changing the incident angles and irradiation time. Thus the interference method using beam holography has great potential for fabricating gratings with fine periods [1,2]. The grating structures fabricated with fourth harmonic beam are more regular, uniform and well-controlled periodicities than structures fabricated with second harmonic beam. We have investigated the grating surface by Fourier method to understand the wavelengths dependence of two-beam holography patterning on the surface gratings. RMS roughness, power spectral density (PSD) and cross-sectional analysis have been carried out to understand the effect of increasing number of shots of fourth harmonic beam on patterned surface morphologies. It is found that with increasing the number of shots, valley depth of grating pattern increases alongside many spatial frequency components other than the fundamental frequency of the structure due to increase in extreme amount of interfacial roughness. AFM analyses reveal gratings fabricated with fourth harmonic beam have only fewer frequency components other than fundamental frequency of the structures. Cross-sectional depth profiles of the AFM investigated gratings display a periodic line valley with a regular spacing of 1.1 μm for number of shots 600 and 900, 1500. Figure 1 shows periodic grating on silicon at laser fluence of 232 mJ/cm^2 with number of laser pulses.



(a) (b)

Figure 1 SEM images of submicron gratings on Si (100) for laser fluence 232 mJ/ cm^2 of second harmonic beam with (a) 2400 and (b) 3000 pulses.

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High-Precision Machining Powered by UV

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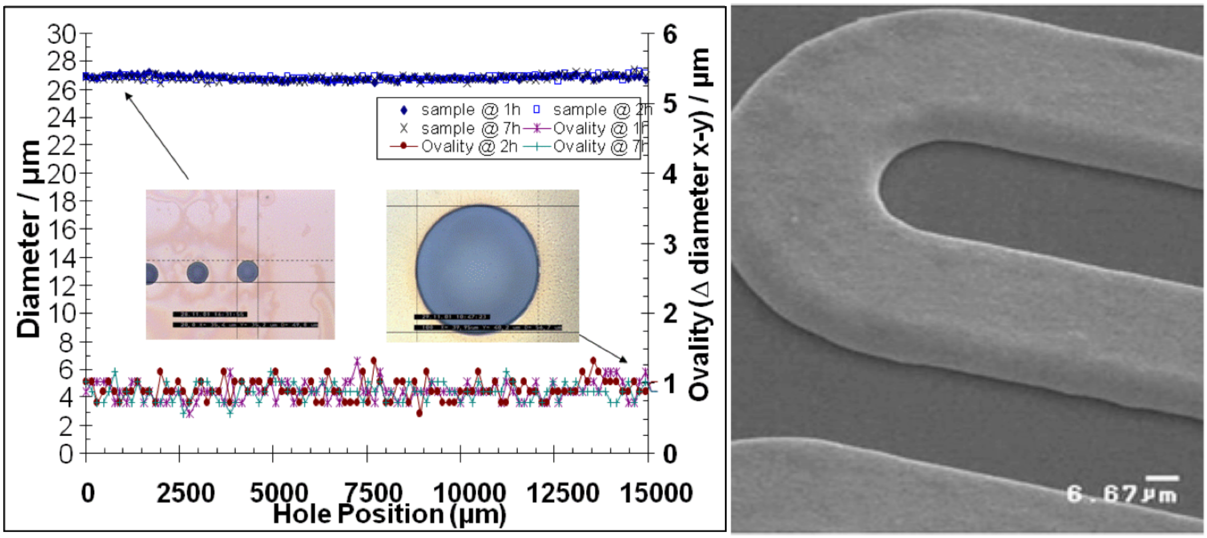
The capability of producing ever more accurate microstructures is pivotal for the production of increasingly capable micromechanical and microoptical systems (MEMS/MOEMS) as well as for downscaling biotechnological analysis devices (BioMEMS) [1]. Both quality and longevity of the functional microstructures acting e.g. as sensors, actuators, bioreactors or information transmitters strongly depend on the degree of accuracy achieved in the fabrication process [2].
Excimer lasers emitting in the UV to far UV region are by nature the laser sources enabling the highest optical resolution and strongest material-photon interaction. At the same time, excimer lasers deliver unmatched UV pulse energies up to 1000 mJ and output powers up to several hundred watts. Thus, they are the key to fast and effective large area processing of smallest structures with micron precision [3]. As a consequence, excimer lasers are the UV technology of choice when it comes to high-performance microstructuring with unsurpassed quality and process repeatability in applications such as drilling advanced ink jet nozzles shown in figure 1 (a) or patterning biomedical sensors shown in figure 1 (b).
Recent progress in excimer laser design and UV optical performance will be introduced enabling fast, high-precision UV manufacturing in cost-sensitive applications.



(a) (b)

Figure 1 (a) Typical repeatability of ink jet nozzles of 27 µm diameter drilled in polymer with excimer laser mask projection processing . (b) Micrograph of metal circuit structures on polymer substrate obtained at a wavelength of 308 nm.

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Application of spatial light modulator in nanosecond laser machining

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Nanosecond lasers enable high-precision machining of a wide range of materials with a comparatively high throughput. The typical Gaussian intensity distribution generated at focus is not always ideal for the application. Spatial light modulators (SLM) based on liquid crystal displays are widely used for different beam shaping applications as variable diffractive optical elements. To date, for applications in laser materials processing, SLMs have been mainly used for changing the beam shape of femtosecond [1] and picosecond [2] laser pulses. We present in this paper the application of the spatial light modulator LC-R 2500 manufactured by Holoeye for high power nanosecond laser machining. In this context, the power handling capabilities of the device, i.e.
1-2W/cm^2 average power specified by the manufacturer, are the limiting factor for most laser machining applications in the nanosecond regime. Additionally, the display of the SLM has a curvature of the silicon backplane due to manufacturing process. This can be compensated for by addressing a Fresnel-lens to the display [3] but is still not ideal for beam shaping applications.

We developed a custom-designed mount to address both issues: The mount consists of a copper block which acts as a heat sink and enables additional water cooling. Also, by providing an optically flat surface, the copper block can be used to flatten the inherently curved SLM display by applying strain to it. We demonstrated that the cooled display can withstand nanosecond laser pulses (wavelength 532nm, pulse length 65nm) with an average power of 14.7W (laser repetition rate 30kHz) over a timescale of more than 60 minutes without significant change in the diffraction efficiency and without any damage of the display. This corresponds to a power density of ~5W/cm^2. The increased power handling capabilities provide sufficient intensity for laser machining when using computer generated holograms to modify the spatial intensity distribution at the focus of the system (figure 1).

It was found that the display shows a periodic flickering due to the way it is electronically addressed as reported by [4] and [5]. This flickering potentially has a negative impact on the quality of the laser machining outcome as demonstrated in this paper (figure 2a). We present strategies to overcome the flickering problem (figure 2b).

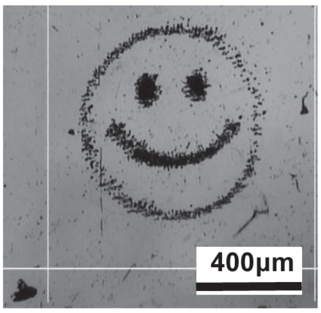

Figure 1: Laser machining result on metal coated glass slide using SLM and computer generated hologram (zero order bottom left corner)

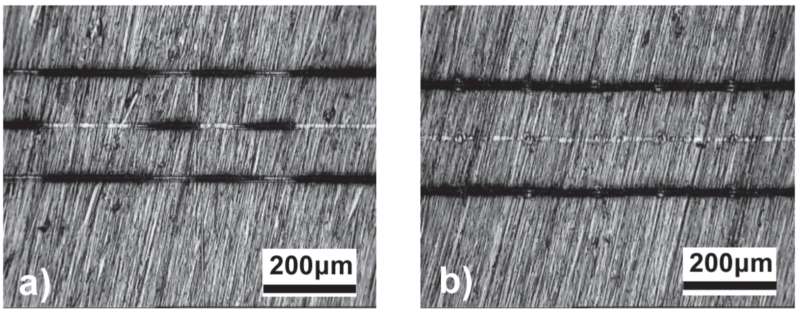

Figure 2: a) Discontinuous lines arise when scanning the laser beam across the work piece (stainless steel) due to flickering of the SLM (binary grating addressed); b) result using flickering compensation based on process synchronisation between laser machining workstation and graphics card

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Laser Patterning of Conformal Electromagnetic Surfaces

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The development of conformal electromagnetic surfaces has been hampered by difficulties in their fabrication with traditional lithographic techniques. Use of these surfaces is required in order to incorporate the RF structure to a host platform with minimal impact on the platform's weight, aerodynamics and aesthetics. Examples of these surfaces include conformal antennas and artificial impedance surfaces. Artificial impedance surfaces are comprised of sub-wavelength metal patches patterned on a grounded dielectric surface. These patterned surfaces provide a method to control the propagation of surface waves, thus controlling their radiation properties. In general, artificial impedance surfaces have been limited to planar geometries and are difficult to incorporate onto curved surfaces. The ability to laser pattern doubly curved surfaces allows for the realization of the above described complex electromagnetic structures. At NRL, we have developed a combination of direct-write processes that allow for the metallization, laser patterning and room temperature curing of electromagnetic patterns on doubly curved surfaces such as radomes. The metallization step dispenses a conformal metallic nanoink layer over the surface and then the pattern is generated by laser ablating the excess nanoink prior to its curing with a high intensity light source. Laser patterning of the metallic nanoink utilizes a 5-axis motion system to maintain normal incidence to the surface. This presentation will provide examples of the conformal electromagnetic surfaces fabricated using these techniques and will examine their future impact.

Laser Micromachining of Piezoelectric Ceramics

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Piezoelectric ceramics are widely used in sensors, actuators and transducers. The laser/material interaction PZT ceramic PIC 151 (PI) was investigated using Q-Switched DPSS lasers operating at Green (532 nm, <20 ns) and UV (355 nm, <20 ns). 61-hole with 90 μm diameter array on PZT ceramics was drilled using a trepanning technique in air by green laser with clean edge periphery. The hole circularity at exit and the hole taper was discussed. 200 um width trench with ±2.5um max peak-peak roughness has also been achieved using galvanometric UV laser scanning system. The clean edge with good bottom roughness and negligible microcracks has made it applicable in device.

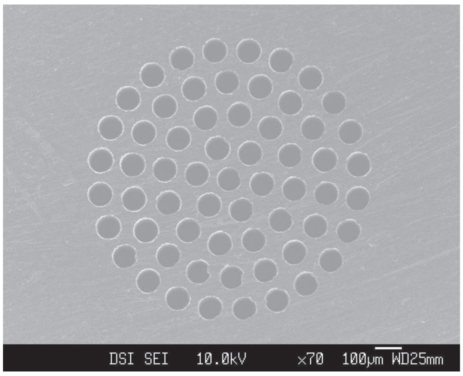

Figure 1 Laser micro- hole drilling by green laser.

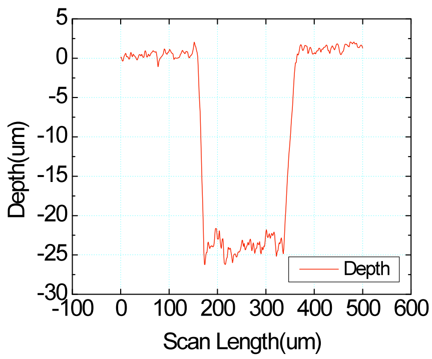

Figure 2 Laser micro-trench etching by UV laser.

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Enhancement of the hydrophobic properties of metals by femtosecond laser texturing of surfaces

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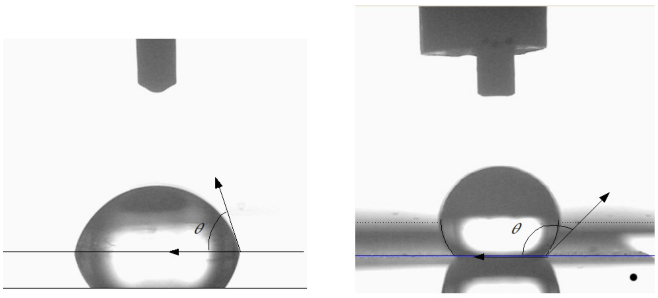
Fabrication of hydrophobic and superhydrophobic surfaces presents many advantages in different domains of applications like surface auto-cleaning, biomimetics, micro-fluidics lab-on-chip devices...[1-3]. We present here some results allowing to put in evidence the strong link between surface topography and surface energy. Indeed, femtosecond laser irradiation of metallic samples is performed to modify the topography of the surface. Multiscale roughness effects are obtained, like ripples and spikes. We study the relation between the generation of such topographic systems and the response of the materials on the wettability point of view. Results show the possibility to largely enhance the wettability response of the femtosecond irradiated surfaces compared to the flatten surfaces. Contact Angle (CA) measurements are performed. They are related to topographic analyses by atomic force microscopy (AFM) and optical interferometry.
Within this work, we put in evidence the possibility to generate highly hydrophobic, or even superhydrophobic metallic surfaces with femtosecond laser irradiation.
Figure 1 gives an example of such a behavior. Before and after the femtosecond laser irradiation, the contact angle varies from $\boldsymbol{\theta} = \mathbf{75.4}°$ to $\boldsymbol{\theta} = \mathbf{129.8}°$. That is to say, the metallic surface goes from an hydrophilic behavior to a highly hydrophobic behavior.
This approach allows thinking the femtosecond laser irradiation of surfaces like a promising tool to functionalize surfaces.



a) non treated sample
θ = 75.4°

b) Femtosecond laser nano textured surface
θ = 129.8°

Figure 1 : Contact angle measurments. a) Before femtosecond laser texturing : hydrophilic character. b) After femtosecond laser texturing : high hydrophobic character due to multi-scale topography

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Quality Aspects in High Power Ultra Short Pulse Laser Ablation

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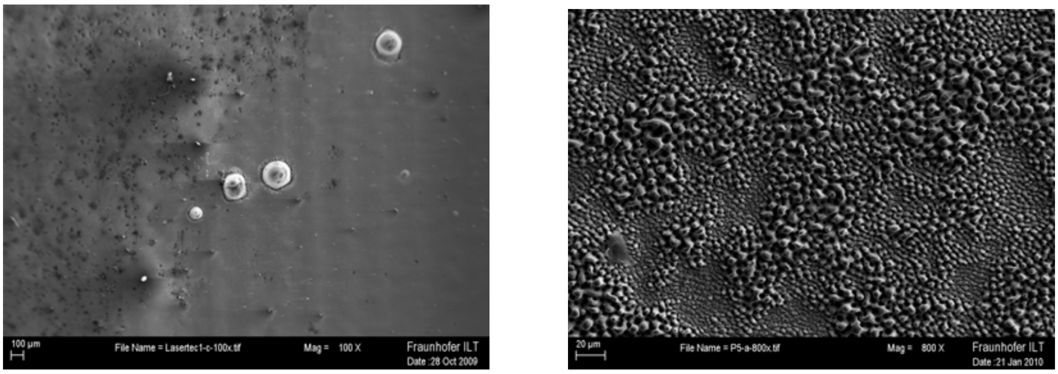
In the production of micro structures and micro replication tools, laser ablation becomes a more and more important tool which is able to generate structure sizes in the range of 10 – 100 µm. Especially with ultra short pulsed lasers with pulse durations in the range of 10 ps, a new and flexible tool is available, which allows the processing of standard tool steel materials as well as hard and ultra hard materials. Compared to conventional EDM-processing, laser manufacturing of parts and tools can be performed without additional working tools at reasonable times directly from the CAD-CAM-System. Using this new laser ablation technology opens a new field of micro processing of tools, which allows the generation of even nano-scaled functional structures in tools, which can be replicated on polymers, metals and glass components. With ultra short pulse laser ablation, pulse bursts of several pulses with a time spacing of 20 ns each and adapted pulse energies accuracies < 1 µm and slicing depths of 100 nm and less can be achieved. Surface quality of metal micro ablation has been increased significantly and allows the production of tools and parts with r_a-values less than 0.5 µm. However, using very small spot sizes of 10 – 20 µm, these accuracies only can be achieved at medium and low pulse energies in the range of 5 – 10 µJ. Using very low fluences on the one hand or high fluences on the other hand lead to a significant quality decrease, which cannot be allowed for high precision manufacturing. At very low pulse energies and larger processing depths in metals micro cones are formed, which grow in further increasing the ablation depth. At high fluences micro scale holes and dimples are formed in the ablated surfaces, which destroy the original surface quality. In figure 1 two results for picosecond ablation in tool steel with low and high fluence are shown.



(a) (b)

Figure 1 (a) Tool steel surface with cones after ps-ablation with low fluence.
(b) Tool steel surface with holes and dimples after ps-ablation with high fluence

For further increase of ablation speed with retention of the principal high surface quality of ultra short pulse laser machining, a carefully selection of the material has to be carried out. Especially the history and the metallurgy of the material plays an important role for the formation of surface defects, which will be shown in comparison of different materials. Furthermore, ablation strategies for the avoidance of cone and hole formation will be presented using variations of pulse energy and other processing parameters.

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Ultra fast laser machined hydrophobic stainless steel surface for drag reduction in laminar flows

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Hydrophobic surfaces have attracted much attention due to their potential in industrial applications such as microfludics, lab on chip devices and as coatings for the automotive and aerospace industry. The combination of a dual scale roughness with an inherent low-surface-energy coating material is the key factor for the development of an artificial superhydrophobic surface. Ultra short pulse laser (USPL) machining/structuring is a promising technique to obtain the dual scale roughness on a metal surface. Moreover, ultra short laser machining delivers such micro and nano-scale surface structures without or with limited thermal effects.

Flat stainless steel (AISI 304L) plates were laser machined with ultraviolet laser pulses of 6.7ps, with different laserprocessing parameters. The samples produced at the optimum conditions were coated with perfluorinated octyltrichlorosilane (FOTS) to get a superhydrophobic surface. Static contact angle measurements were done to evaluate the degree of hydrophobicity. The laser patterned surface has longitudinal microchannels, which can trap air inside the grooves and provide a shear-free boundary condition at the air-liquid interface upon the metal surface. Drag reduction in flow can be obtained due to the shear free boundary condition at air-liquid menisci[1].The geometry of the patterns was analyzed with optical and scanning electron microscopy. Micro-particle image velocimetry (µPIV) has been employed to measure the effective slip lengths achieved in such patterns.

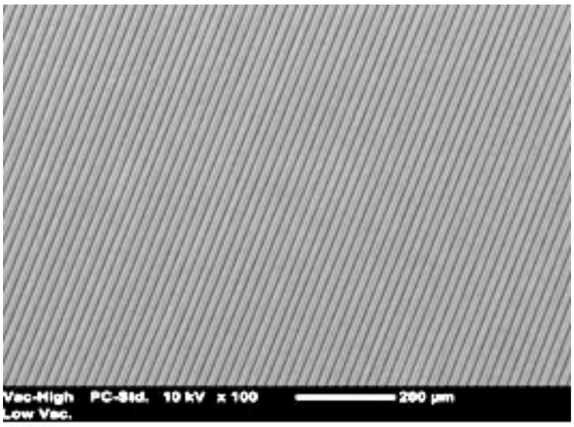

Fig.1 SEM image of Laser patterned longitudinal channels

Reference
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Three-dimensionally Isotropic Resolution of Femtosecond Laser Micromachining Using Spatiotemporally Focused Pulses

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We provide a solution to achieve a three-dimensionally symmetric spherical intensity distribution of the focal spot by spatiotemporally focusing of the femtosecond laser beam [1]. The input laser beam size is controlled by an adjustable circular aperture. A pair of parallel gratings is used to separate the spectral components of the incident pulses [Fig. 1(a)]. The pulse duration can only reach its shortest value at the focal point of the objective lens while being broadened again elsewhere, through which the intensity distribution at the focal volume can be adjusted and the axial fabrication resolution can be greatly improved [2]. We demonstrate both theoretically and experimentally that the cross-sectional aspect ratios of hollow microfluidic channels embedded in fused silica can be controlled by varying the incident femtosecond beam size. In particular, microfluidic channels with isotropically circular cross sections [Figs. 1(b) and (c)] can be created using this method. It is also expected that this technique will allow for fabricating circularly symmetric optical waveguides regardless of the translation direction of the femtosecond laser beam.

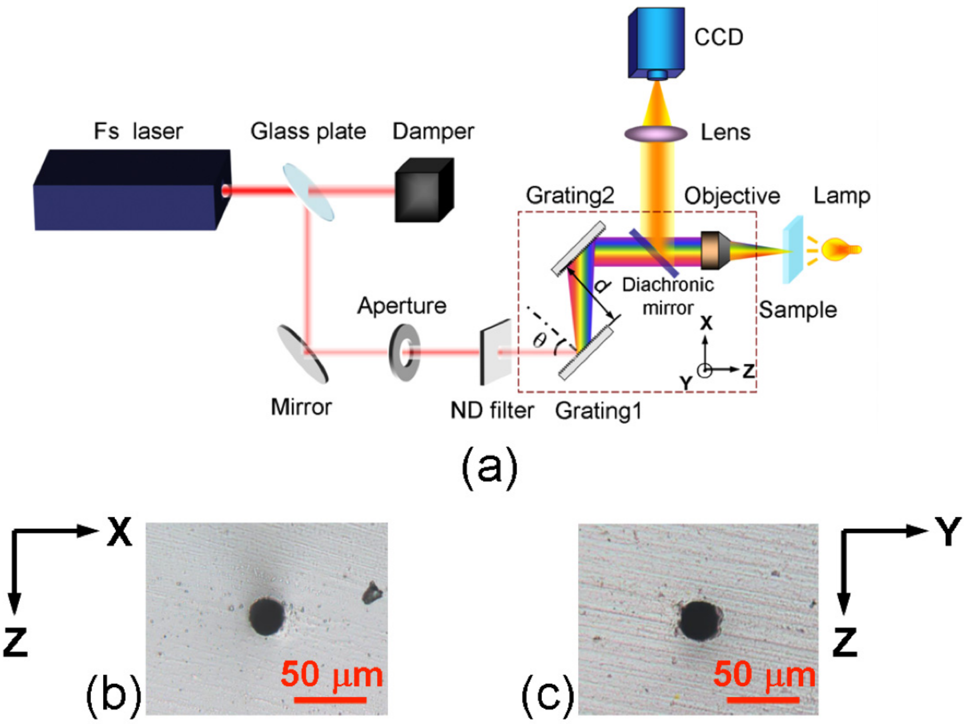

Figure 1 (a) Schematic of the femtosecond laser micromachining setup using temporal focusing scheme. Optical micrographs of cross-section view of microfluidic channels aligned in both (b) XZ and (c) YZ planes show circular shapes.

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Reliable laser micro-welding of Copper

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The reliability of copper (spot) welds is still a problem today concerning the high demands of e.g. spot or contact welding for the electronic or medical industry. There are two aspects characterising this reliability which is the reproducibility of the weld geometry and at the same time the elimination of thermally induced side effects, especially sputtering during the welding.

One problem is the low absorption of the clean polished Cu surface of about 5% at room temperature on the 1 micron emission of the industrial used lasers. This small absorption in combination with the unique thermal properties of Cu lead to the fact, that even a small contamination of the surface lead to drastic variation in weld quality if the laser parameters do not match the the local requirements. Intelligent sensor solutions taking the information from the reflected laser beam and the temperature of the surface before and during welding offer the potential of solving this problem for these lasers.

According to the room temperature absorption spectrum of copper a wavelength in the visible spectral region would improve the reliability due to the strong increase in absorption. Diode lasers at 808 nm or frequency doubled lasers at 532 nm seem to be promising. The need for high intensity on the copper surface narrows the selection at the moment to pulsed frequency doubled lasers at 532nm. The radiation of these frequency doubled laser sources are used in special application modes and show remarkable improvement of quality and reliability in spot welding on copper.

Interferometric in-process measurement of free-form surfaces in laser chemical manufacturing

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In this contribution, we report on a fibre-coupled interferometer for in-process measurements of free-form surfaces. In this context, several experiments were performed in order to investigate the interferometric measurability of rough surfaces at high angles of incidence in both air and inhomogeneous liquids. Here, different materials were tested in streaming and index of refraction fluctuant water. Thus, the critical angles for interferometric measurability of these particular materials were determined. In order to realise a control loop as shown in figure 1, this measurement technique was integrated into a laser chemical manufacturing process, in particular the laser-jet method [1, 2]. By the actual value input signal, a selective and scalable machining process can be realised.

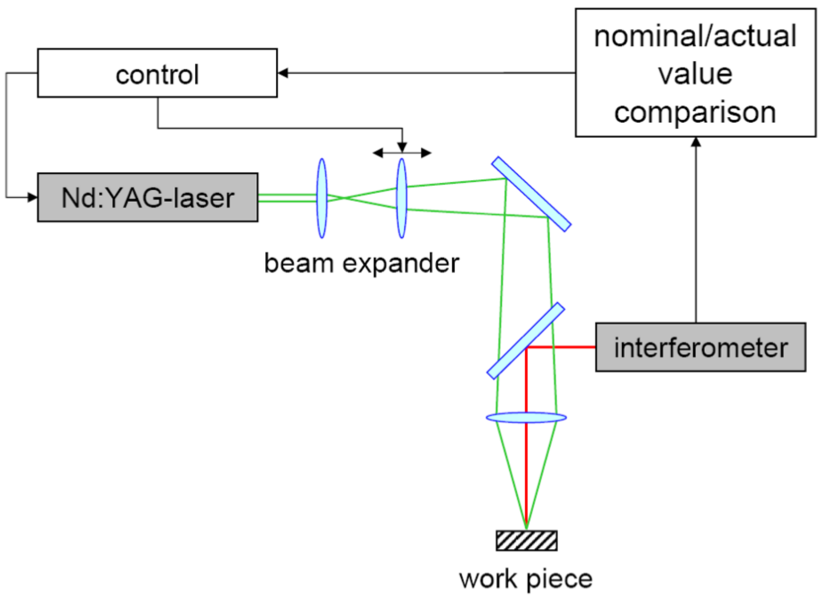

Figure 1 Layout of the control loop based on interferometrically measured actual value input signals

Thus, the performance and measuring accuracy of the fibre-coupled interferometer during the manufacturing process was evaluated on the basis of simple work piece geometries. In this connection, several process parameters such as laser power, laser beam diameter, flow rate of the used etching medium and traverse speed of the work piece were varied in order to determine the influence of those parameters on the measuring accuracy of the fibre-coupled interferometric measurement setup.

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Generation of periodic micro and nano structures by polarization-controlled laser beam interference

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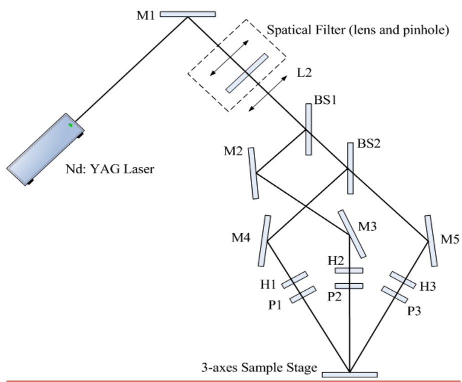
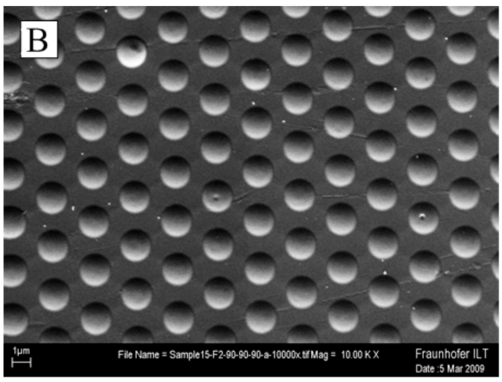
Periodic micro and nano structures are required for a variety of different products in micro optics, semiconductors and products with functional surfaces. Today the common approach is standard lithography with numerous processing steps including masking imaging, resist development and subsequent etching. However, for the structuring of large areas with structures sizes in the range from 500 nm to 2 µm at short processing times, new approaches are necessary to meet the demand of a highly efficient manufacturing line. Laser interference structuring can be an appropriate solution to provide a manufacturing technology which is able to process polymers as well as semiconductors and metals in a single processing step without any subsequent etching. Different methods have been developed to realize the fabrication of two-dimensional micro structures by interference technology. The most common method in multiple-beam interference is the phase-controlled four beams interference. By changing the phase differences of the beam pairs, arrays of micro bumps, micro columns and many other surface textures can be obtained. Based on the superposition of the electrical vectors of the incident waves, the resulting spatial intensity distribution in the overlap area can be controlled by energy ratios, phase differences and the intersecting angles of the incidents waves. One difficulty of phase-controlled interference is that the phases of the beams are very sensitive regarding the position of the components and the environment of the lab. For multiple exposures of dual- or three- beam interference, the interference beams of different exposures need to overlap on the area, which demands an accurate tool to monitor the spatial orientation.



(a)



(b)

Figure 1 (a) Beam geometry for polarization controlled three-beam interference setup,
(b) Micro scale interference pattern structured on the surface of a photoresist

For further increase of geometry flexibility and further stabilisation of the imaging and ablation process, a multi beam interference technology with polarisation control of the interfering beams and furthermore an ultra short pulsed laser has been used. According to the theoretical deduction and simulation of results, different polarization arrangements of the beams were tried out to fabricate different shaped periodic microstructures. Arrays of circular microbumps, circular microcavities, "eyelike" microcavities, and even rectangular columns were obtained.

Production of Microstructures in wide-band-gap materials using pulsed laser ablation at 157 nm wavelength

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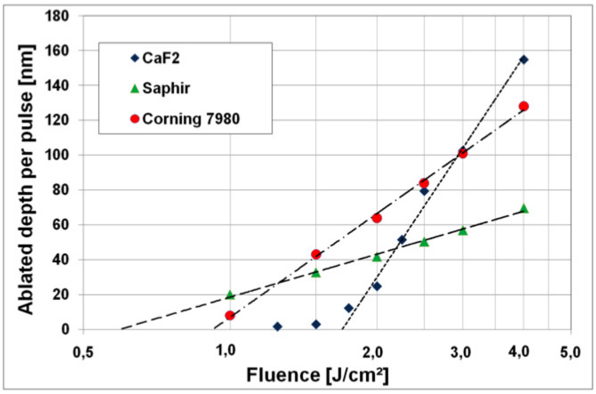
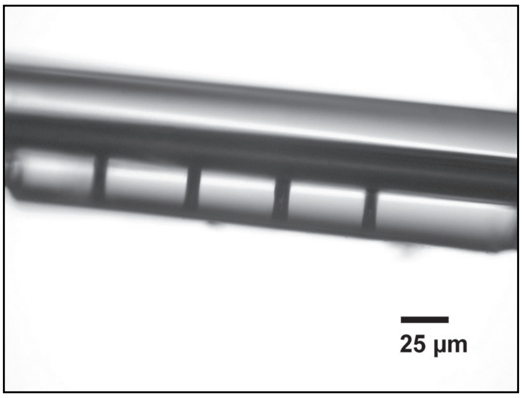
New results on three-dimensional micro-structuring of quartz glass, calcium fluoride, sapphire, magnesium fluoride and PTFE using pulsed laser ablation at 157 nm wavelength will be presented. A largely automated high-precision fluorine laser micromachining station was used for the investigations. The investigations of the ablation behaviour of the various materials in dependence of the laser processing parameters will be presented. It will be shown that, on the basis of the knowledge of the ablation rates and the laser beam parameters, bores of a few µm size and complex 3D microstructures with a variety of geometries can be produced in the surface of the materials. It will be shown that the materials can be micro-structured without cracking if proper parameters are used.



(1)



(2)

Figure. 1 Ablated depth per pulse for fused silica (Corning 7980), calcium fluoride and sapphire as a function of laser fluence.

Figure. 2 Optical micrographs of four bores with 6.6 µm diameter produced in a fused silica fibre. The fibre has a metal core and a total thickness of 80 µm (microstructuring parameters: 3.0 J/cm^2 fluence, 200 Hz repetition rate, 7.5 µm diameter of the projected laser beam with the imaging plane being 10 µm below the sample surface, 10000 pulses in burst mode, no post-treatment).

Optical system for on-line monitoring in selective laser melting technology

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A monitoring system is developed to visualize and to control the process of Selective Laser Melting (SLM) of metallic powder. The system is integrated with industrial PHENIX PM-100 machine. Visualization is carried out using LED illumination and CCD-camera; a home developed pyrometer is applied for monitoring of thermal phenomena in the zone of laser impact. Deviation of temperature from its optimal value is chosen as a criterion for the express method of quality control.

Methods and diagnostic tools for surface temperature monitoring in laser machining were developed some years ago [1-7]. The next step is to develop appropriate monitoring systems and integrate them with laser technological equipment. In the present paper, development of a monitoring system adapted for SLM-process, and basics of real-time process control, are discussed. SLM-systems are intended for melting a wide range of powder materials with greatly different properties, including melting point. Therefore the technological windows (i.e. optimum values of laser power, beam scanning speed, powder layer thickness, etc.) are rather different for different powders. The fabrication of a part with complex form and relatively large size can continue during 10-20 hours without any information about work in progress and possible problems. The absence of on-line monitoring and process quality assurance is one of the main obstacles for wide implementation of SLM technology in modern manufacturing industry. Typically SLM process is carried out in closed environment without optical access for diagnostic equipment.

To control the correct choice of process parameters and to inspect visually process quality, a monitoring system for SLM process was designed, fabricated and integrated with industrial PHENIX PM-100 machine.

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Applications and perspectives of ultrashort pulsed lasers

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Well-known trends in automotive industry are for example miniaturization, higher precision, diversification of materials, variety of variants and smaller lots. Always on scope has to be cost-effectiveness and outstanding quality.

About ten years ago ultrashort pulsed laser material processing showed the potential to satisfy a lot of the named requirements. So BOSCH coordinated the public funded projects PRIMUS (FKZ 13N7707/04) and PROMPTUS (FKZ 13N8576) together with universities and industrial partners to develop the ultrashort pulse laser technology from an academic level to a cost-effective production technology.

First step was to build up knowledge of the fundamental process, in detail the interaction of ultrashort laser pulse and material [1]. This gives the possibility to define the specifications of applicable laser systems, for example pulse duration, pulse energy and repetition rate.

In a second step the laser systems were used to build up knowledge in the application process on defined demonstrator products. Out of this, the laser systems and further system technology is optimised in an iterative way with respect of robust and cost-effective processes.

The last step was the transfer of this new technology in our production plants.

Since 2007 are ultrashort laser pulses used at the BOSCH plant in Bamberg for production of exhaust gas sensors, shown in figure 1 left. They are made of a special ceramic layer system and can measure the exhaust gas properties faster and more precisely. This enables further reduction of emissions by optimised combustion control.

Since 2009 BOSCH ultrashort pulsed lasers are micro structuring the injector of common rail diesel systems. A drainage groove allows a tight system even at increased pressures of up to 2000 bar. Diesel injection systems become even more reliable, powerful and environment-friendly.

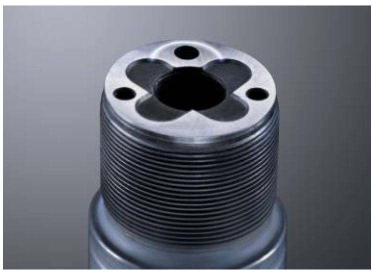

Figure 1 Left: Cross section of a lambda-probe trimmed by ultrashort laser pulses. Right: View on top of a diesel injector body. A drainage groove is structured around the high pressure passage by ultrashort laser pulses.

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Cu Micropatterns Fabricated by Femtosecond Laser Direct Writing Using Cu Nanoparticle Ink

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The copper interconnection is one of the most important technologies in microelectronics. The recent development of the printable & flexible electronic devices requires a new Cu wiring technology by all wet process. The fabrication of Cu micropattern by sintering of Cu nanoparticle is one of the candidates. The combination of the Cu nanoparticle dispersed ink with laser direct writing method provides some advantages [1-3]. The fast sintering process by laser irradiation may be able to reduce the surface oxidation of the Cu nanoparticle and conductivity deterioration. In the case of the conventional heat treatment process using an electric furnace, the oxidation of the Cu nano-particle surface occurs during thermal decomposition of organic group stabilizing the Cu nano-particle and the sintering of Cu nanoparticles in air because of the slow rate of the decomposition and sintering. In this study, we report the fabrication of Cu micropatterns by femtosecond laser direct writing using Cu nanoparticle dispersed ink. The surface oxidation of the Cu nanoparticle during sintering is expected to be decrease due to the short pulse duration of the femtosecond laser. The increase in the thickness of the sintering layer by femtosecond laser irradiation is also expected by nonlinear effects. As Fig.1 shown, the Cu nanoparticles was sintered by 800nm, 80MHz femtosecond laser and a copper line with ~9 μm high and ~30μm width is formed on glass substrate. Figure 2 shows a hollow column can be produced by the same femtosecond laser with the high ~6μm and outer and inner diameter of ~50 and ~15μm.

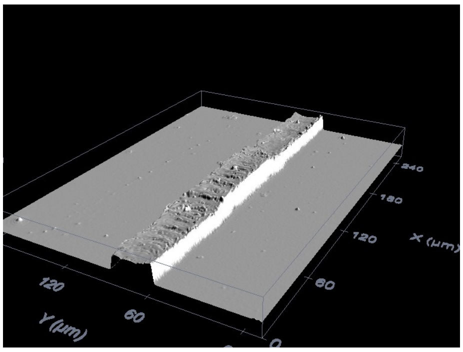

Figure 1 Cu line formed by femtosecond laser sintering. The line width is ~30μm and the high is ~9μm.

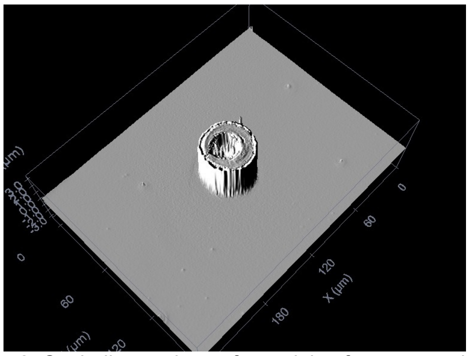

Figure 2 Cu hollow column formed by femtosecond laser sintering. The high is ~6μm and outer and inner diameter are ~50 and ~15μm.

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Laser-induced plasma investigations during material processing

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Laser-induced breakdown spectroscopy (LIBS), a versatile analytical tool used to determine sample compositions, has recently been applied to monitoring and control of laser material processing [1,2]. By observing the induced plasma during laser machining, information about e.g. the amount of ablated material is obtained, and thus an insight of the current processing stage can be estimated.

The aim of this project [3] is to use the already present plasma in laser material processing to improve the quality of the product by means of spectroscopic analysis, based on the fact that plasma characteristics depend on the properties of the ablated surface and laser parameters.

For example, spectrograms are acquired varying the surface-lens distance during machining to identify a specific behaviour of the spectral lines that correlates with the laser focus position. The presence of such a characteristic pattern in the relative intensities, as seen in figure 1, is used to implement a control strategy to guarantee the most efficient material removal rate.

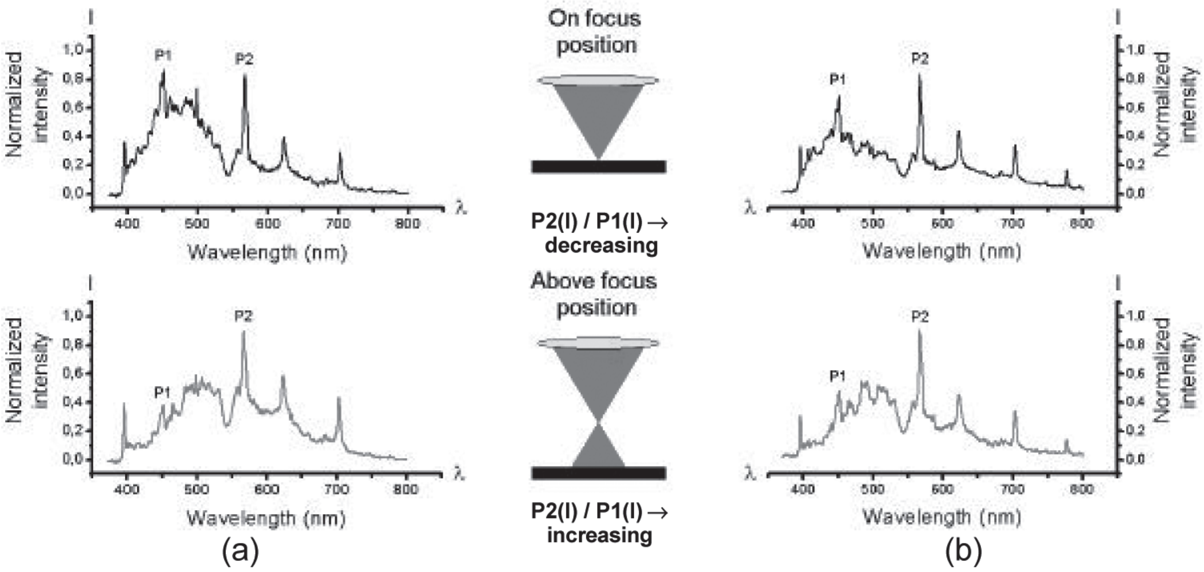

Figure 1: Emission spectra of plasma during laser material processing for different focus positions. P2(I) / P1(I): Peak intensity ratio correlating to the position of laser focus relative to surface of the ceramic. (a) Material: aluminium nitride (AlN). (b) Material: aluminium oxide (Al_2O_3).

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[2] M. Lentjes, K. Dickmann and J. Meijer, Influence of process parameters on the distribution of single shot correlation coefficients obtained by correlating LIB-spectra, Applied Physics A, vol. 88, pp. 661-666, 2007.
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A practical method to determine laser induced refractive index changes in transparent media using a Fourier approach

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Femtosecond laser direct-writing has become a promising tool to create 3D photonic devices in transparent materials. The ability to change the refractive index of glasses has already been applied in various optical components such as waveguides [1] and diffractive optical elements [2]. However, for efficient design of those elements, detailed information about the refractive index modification is essential. Most common techniques to measure refractive index changes are either costly in terms of required facilities or based on assumptions that only provide adequate results for ideal structures. We have developed a new practical method based on an Iterative Fourier Transform Algorithm [3] capable of analyzing the local refractive index change of complex structures (Figure 1) accurately. By combining the dimensions of the modified region with the corresponding phase change extracted from far field intensity measurements, we are able to spatially resolve the amount of refractive index change.

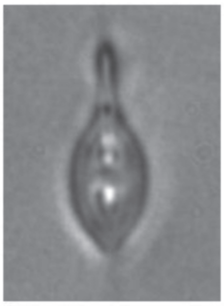

Figure 1 - Microscope cross section image of the fs laser modified region in Borosilicate glass with a power of 340mW at f_{rep} = 1 kHz.

We will present our initial results using this method to analyze basic grating structures written in borosilicate glass. In addition to evaluating the accuracy and the limits of this technique, we demonstrate the influence of the writing power on the femtosecond laser modified region.

[1] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, “Writing waveguides in glass with a femtosecond laser,” Opt. Lett. 21, 1729-1731 (1996)
[2] J. Choi, M. Ramme, T. Anderson, M. C. Richardson, “Femtosecond laser written embedded diffractive optical elements and their applications”, Proceeding SPIE Photonics West 2010, 7589-44
[3] R. W. Gerchberg and W. O. Saxton, „ A practical algorithm for the determination of phase from image and diffraction plane pictures”, Optik (Stuttgart) 35, 237 (1972)

Frequency-doubled High-power Nanosecond Lasers for Materials Processing

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High-power short-pulsed lasers in the green spectral range are becoming a versatile tool for highly productive materials processing in the photovoltaic and electronic industry. We present the development and promising applications of a green ns pulsed high-power laser based on a Q-switched Yb:YAG thin-disk laser.

The advantages of the thin-disk laser concept [1] – high efficiency, excellent beam quality, and low depolarization losses – make this reliable platform well suited for the generation of high power lasers in the infrared as well as the green spectral range. Green pulses with a few hundred nanoseconds of pulse duration can be generated by inserting a fast electro-optic switch inside the laser resonator and by employing intracavity-frequency conversion [2]. We have obtained a maximum output power of 700 W at a wavelength of 515 nm at 100 kHz pulse repetition frequency. An LBO crystal cut for critical phase matching of type I was mounted near one of the end mirrors inside the laser cavity for frequency doubling. An optical efficiency with respect to incident pumping power greater than 35% could be reached. The pulse duration of the laser system can be adjusted between 200 ns and 750 ns. The beam parameter product of 4 mm mrad ($M^2 < 25$) allows for beam delivery via a 100 µm optical fiber.

To the best of our knowledge, the average power significantly exceeds all previously published results for lasers in the visible spectrum and enables a high productivity for the laser applications. Typical applications include drilling, surface structuring, annealing and cutting of hard, brittle material such as silicon and diamond.

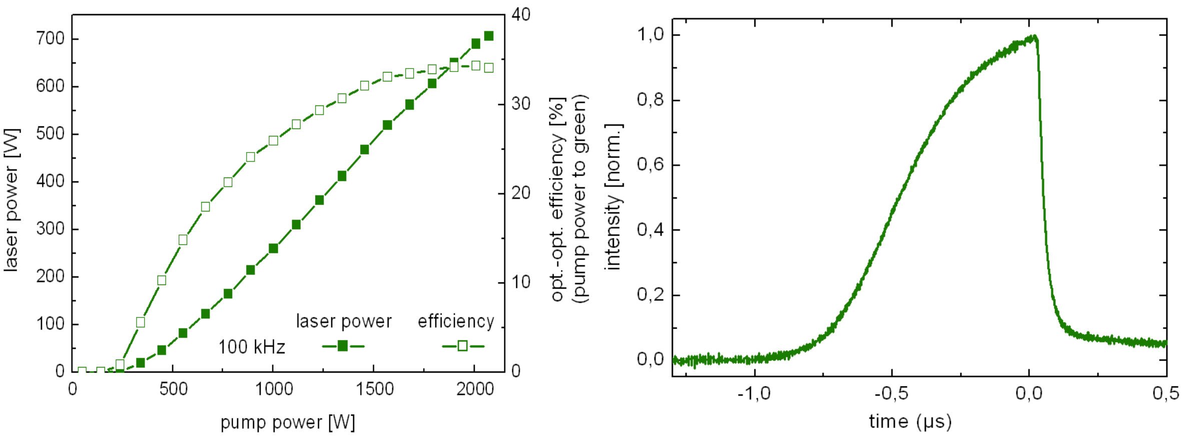

Figure 1 Short-pulsed frequency-doubled disk laser at 100 kHz repetition rate.
Left: Output power and opt.-opt. efficiency. Right: Typical pulse shape with 500 ns pulse duration.

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Surface ablation of dielectrics with sub-10 fs to 300 fs laser pulses: Aspect ratio and crater shape evolution as a function of laser intensity

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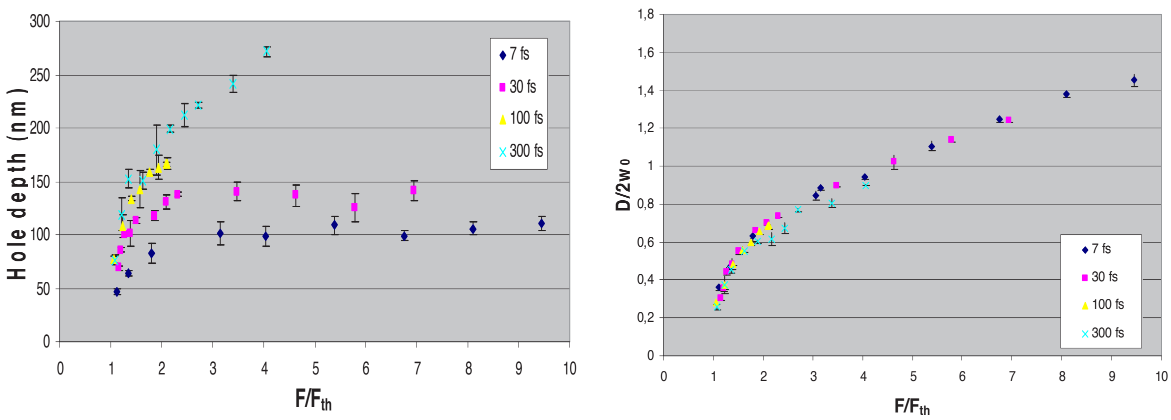
Femtosecond laser pulses provide a variety of possibilities for high precision processing of both metals and dielectric materials [1]. In particular, the advantages of these interactions include the minimization of collateral damages, the reduction of heat-affected zones, a deterministic damage behavior, and the ability to machine sub-diffraction limited target regions. These advantages facilitate the development of numerous applications, such as ultra-precise laser treatment, laser surgery, and industrial micromachining (drilling, writing, etc.).

In this paper, we study the physical characteristics of surface ablation craters in fused silica (Suprasil) created by direct laser drilling with sub-10 fs to 300 fs single laser pulse (800 nm). These investigations aim to provide knowledge and control over important laser processes parameters like damage/ablation threshold fluence [2], crater depth, diameter and shape, and extension of heat-affected zone, as a function of applied laser intensity. In particular, we show that it is possible to access different ranges of crater depths by selecting different pulse durations (see figure 1a) while the crater diameter only depends on the applied fluence (see figure 1b). We also demonstrate that selective crater morphology, e.g. Gaussian-like to top-hat micrometer crater, can be obtained with the same laser system, mainly depending on the applied fluence. These informations are of crucial importance for finalizing any laser-based micromachining processes and for laser-matter technology in general.



(a) (b)

Figure 1a,b. Evolution of depth (a) and normalized crater diameter $D/2w_0$ (b) as a function of normalized fluence and for different pulse durations. F_{th} refers to the ablation threshold fluence and w_0 to the beam waist ($w_0 \cong 4.5\ \mu m$ in all the experiments). The error bars correspond to the standard deviation observed in the AFM measurements (typically on 3 to 5 events per fluence point).

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Laser-matter interaction in fusion welding of glass using ultrashort laser pulses -Formation mechanism and prevention of weld defects-

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We have shown that glass can be welded using laser pulses with duration between several hundred femtoseconds [1] to ten picoseconds [2] without pre- and post-heating, when welding conditions are well selected for glass materials including borosilicate and fused silica. We also found, however, weld defects can be produced, when the welding conditions are not selected appropriately. The paper analyzes the cause of weld defects under different process conditions such as pulse energy, pulse repetition rate, translation speed, NA of focusing lens and focus position with respect to the surface. The analysis is based on thermal conduction analysis to investigate the effect of temperature field on cracking. The stress field in also analyzed numerically. The pictures are also taken using high-speed camera to observe the laser-matter interaction. The effect of mechanical strength of molten zone produced in bulk glass material is also experimentally investigated using three-point bending test, indicating the strength is equal to or even higher than base material, as shown in FIg. 1. The mechanical strength of overlapped weld joint is also made using shear stress test.

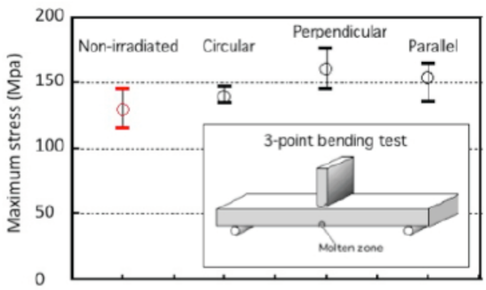

Fig. 1 Mechanical strength of molten zone of borosilicate glass determined by three-point-bending test.

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Robust and flexible picosecond lasers for industrial micromachining

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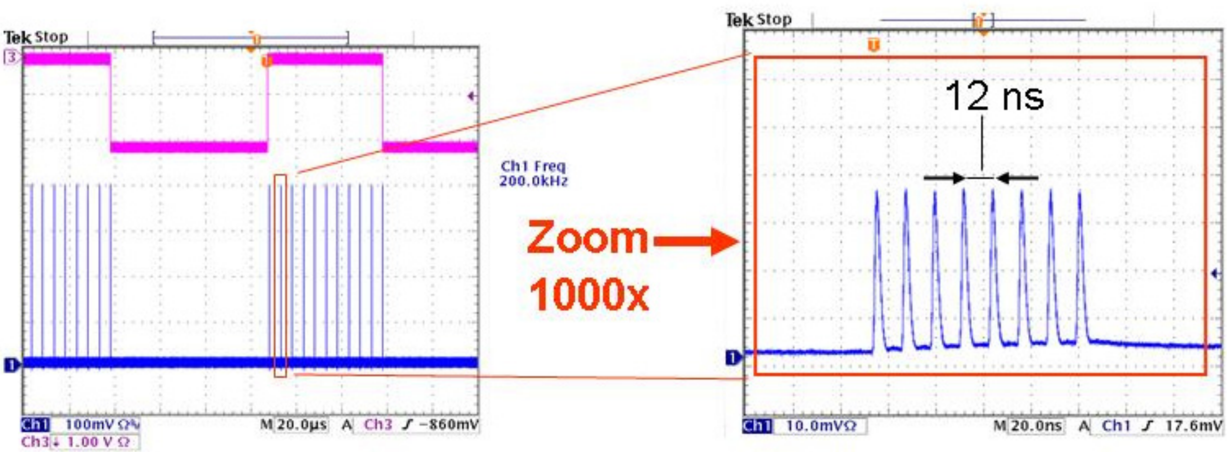
Picosecond pulsed lasers with high pulse energy (>10 µJ) and high average power (>10 W) provide reliable and high-quality microprocessing of many different materials via a process called *cold-ablation*. These laser sources open new process windows that cannot be addressed by typical nanosecond Q-switched lasers in applications like precision hole drilling, micromachining, thin-film scribing and more. Industrial picosecond lasers are rapidly approaching the durability, cost, and turn-key performance of mature Q-switched lasers. However, achieving optimized process performance with picosecond systems requires lasers offering the appropriate flexibility.

The paper reviews recent developments in industrial picosecond laser performance and the features required to achieve optimum performance. Often, the first key choice a user must make is the average optical power of the system, which is driven by the desired process speed. If speed is an issue, high average power is required, but equally important are high-speed scanning, careful process development, and a laser allowing for fast pulse repetition rates.

The typical process development starts with the determination of the minimum pulse energy required for cold ablation. Highest quality is typically achieved when the laser is operated just over the ablation threshold. Therefore, the laser should offer the freedom to adjust the pulse energy. With fixed repetition rate lasers based on regenerative amplification, the only way to obtain the desired pulse energy is to attenuate the beam, which is not ideal from a cost point of view. More efficient is to decrease the pulse energy by increasing the repetition rate, as this allows using the full optical power at any pulse energy. This requires systems with “true” repetition rate flexibility (e.g. 100 kHz to 10 MHz) that is offered only by lasers based on a MOPA architecture.

Another advantage of MOPA lasers is the possibility to replace an individual pulse with bursts of pulses on the nanosecond time scale, which can further improve process performance. This extra flexibility is implemented using a newly developed feature, *FlexBurst*™, allowing for a user-defined energy distribution within the burst, as shown below.



(a) (b)

Figure 1 (a) Fast pulse-on-demand switching. (b) *FlexBurst* pulse control showing a train of closely spaced pulses. Shown is an equal pulse energy burst, however each pulse can have an arbitrary user-set energy within the burst.

Picosecond laser induced colour centres: Stress-free markings and choice of guiding optics

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It is known that ionizing radiation (X-ray, gamma rays, electrons) can induce numerous changes in the physical properties of glasses. The most obvious effect is visible colouration, which is caused by the accumulation of colour centres (defects) in the irradiated volume. The application of such induced colour centres has prompted a renewed interest since they can be generated and bleached reversibly.

In this contribution we present results on laser induced colour centres in different types of glasses using picosecond laser pulses [1]. For example, an unexpectedly low peak power threshold of < 0.2 MW for the laser induced colouring in BK7 glass is observed at a wavelength of 355 nm and a pulse width of 6ps. The transmission spectra in Fig. 1 demonstrate a strong absorption of laser induced colour centres between 330 and 800 nm for BK7. In addition, picosecond laser pulses at a longer wavelength of 532 nm and even 1064 nm induce colour centres in many different glasses, making marking application more feasible, see the examples in Fig. 2.

By applying different focussing optics the influence of changing focal length and energy flux density on the volume colouring effect have been analysed. Transmission changes, non-linear optical effects and possible implications for future optics guiding ultra-short laser pulses are presented.

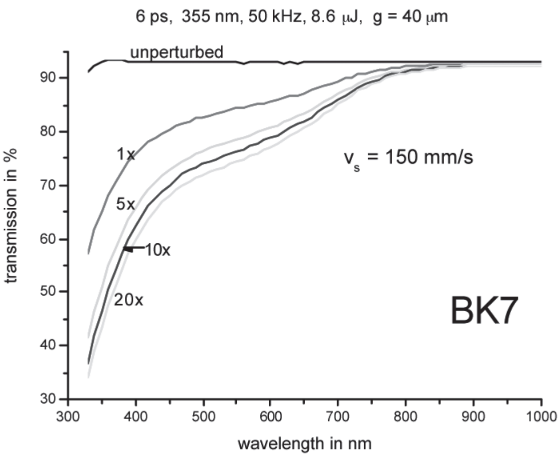

Figure 1: Transmission of white light after colouring of BK7 with 6 ps laser pulses at a wavelength of 355 nm and a different number of cycles.

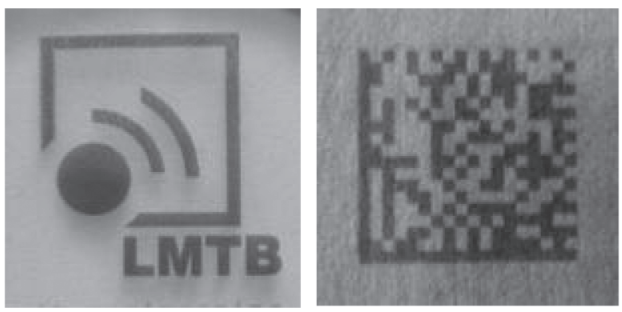

Figure 2: Induced colour centres in BK7 (LMTB Logo, left) and soda lime glass (Data Matrix Code, right).

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Ultrafast Laser Microwelding of Glass Substrates with High Strength by Sparse Scanning Technique

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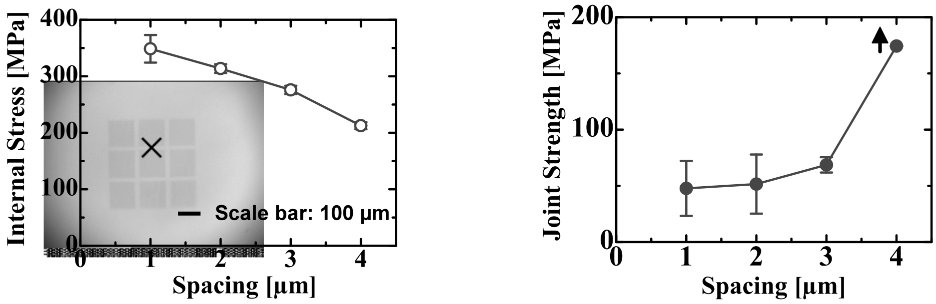
Ultrafast laser microwelding [1-3] using focused femtosecond laser pulses can join transparent glass material [1] as well as dissimilar materials [2-3]. An intriguing application is hermetic sealing with glass while keeping the sample at the room temperature [4]. Although the joint strength is as high as 15 to ~30 MPa, there is a room to further improve it considering the strength of glass (~1 GPa).

Recently we found that a large amount of internal stress accumulates inside a glass substrate after the irradiation of focused femtosecond pulses over a planar region through the raster scanning of the sample [5]. Furthermore, the stress can be significantly reduced when the spacing between the adjacent scans is sparse. In this paper, we demonstrate that such sparse scanning technique effectively enforces the joint strength in ultrafast laser welding through the reduction of internal stress.

Two BK7 substrates with a size of 5 x 5 x 1 mm^3 were stacked, and pressed from the top and the bottom to achieve precise contact. After the pressure is released, femtosecond laser pulses (800 nm, 100 fs, 1 kHz, 5 μJ) were focused by an objective lens (x10, NA0.3) at the interface between the substrates. The sample position was raster-scanned at a velocity of 0.1 mm/s to form 9 welded regions with a size of 100 x 100 μm^2. After the irradiation, the internal stress was investigated by polarized microscopy, and the joint strength was measured by the tensile test. The spacing between the scans was varied from 1 to 4 μm, and three samples were prepared for each condition. As shown in Fig. 1, the internal stress decreases and joint strength increases as the spacing increases. When the spacing is 4 μm, the joint strength is drastically increased to >170 MPa, which is limited by our measurement setup. In this way, the sparse scanning technique is effective for achieving strong joint in ultrafast laser microwelding technique.



(a) (b)

Figure 1 Dependence of (a) internal stress and (b) joint strength on the spacing between the adjacent scans. Inset: optical microscope image of the joint. Cross: the location where the internal stress is evaluated.

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Recent advances in high power ultrafast thin disk laser oscillators

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Ultrafast thin disk laser oscillators achieve the highest average output powers and pulse energies of any laser oscillator technology. The thin disk concept avoids thermal problems occurring in conventional high power rod or slab lasers and enables high power TEM_{00} operation with broadband gain materials [1]. Stable and self-starting passive pulse formation is achieved with semiconductor saturable absorber mirrors (SESAMs, [2]). The key components of ultrafast thin disk lasers such as gain material, SESAM and dispersive cavity mirrors are all used in reflection. This is an advantage for the generation of ultrashort pulses with excellent temporal, spectral and spatial properties, because the pulses are not affected by large nonlinearities in the oscillator. Output powers above 100 watts and pulse energies above 10 µJ are directly obtained without any additional amplification, which makes these lasers interesting for a growing number of industrial and scientific applications such as material processing or driving experiments in high field science. Ultrafast thin disk lasers are based on a power-scalable concept, and substantially higher power levels appear feasible.

Until recently, most thin disk lasers relied on the gain material Yb:YAG. Its good thermo-mechanical properties and well-established manufacturing process make it an excellent choice for high power continuous-wave applications. However, its limited gain bandwidth restricts the pulse duration in mode-locked operation to about 700 fs. Other Yb-doped gain materials exhibit a larger gain bandwidth and support shorter pulse durations. In this presentation, we discuss the latest development of ultrafast thin disk lasers based on other gain materials.

The recently developed sesquioxide materials are particularly promising as they enabled the highest optical-to-optical efficiency (43%) and shortest pulse duration (227 fs) ever achieved with a modelocked thin disk laser. The gain material $Yb{:}Lu_2O_3$ is particularly interesting for power scaling, because it has a better thermal conductivity compared to Yb:YAG and can be efficiently pumped at the zero-phonon line at 975 nm with a low quantum defect. The first mode-locked thin disk laser based on $Yb{:}Lu_2O_3$ achieved a pump power limited average power of 24 W and an optical-to-optical efficiency of 43%, which was higher than for previous ultrafast thin disk lasers [3]. Very recently, we demonstrated successful power scaling of this material to an average power of 141 W, setting a new record for mode-locked laser oscillators. The laser generates 738 fs pulses with an optical-to-optical efficiency of 40.1% in a diffraction limited beam ($M^2 < 1.2$). The laser crystal used for this experiment has a diameter of 5.2 mm, which is not suitable for a further increase of the pump spot diameter. With larger disk diameters and a more powerful pump, an average power towards several hundred watts appears feasible, as the current experiment did not reveal any other limiting factors.

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Laser processing of tungsten powder with femto second laser radiation

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In this paper laser irradiation of dispensed tungsten powder layers with grain sizes smaller than 1 µm was investigated by using high repetition rate femto second laser technologies. Laser processing was performed line by line with repetition rates of 1 MHz and varying processing parameters, such as laser power, processing speed, number of over scans, and pressure. Next to expected material ablation and melting, novel phenomena, such as crystallisation, emerge of ripple structures, extensively agglomeration, and formation of nano wires will be qualitatively discussed by means of SEM photographs. Further a dependence of light pressure, pulse overlap, and irradiated energy per unit section will be demonstrated. As a first application of innovative laser micro sintering technology using highly repetitive femto second laser pulses, highly resolved micro structures will be presented.

Laser Glass frit Bonding for Hermetic Sealing of Glass Substrates and Sensors

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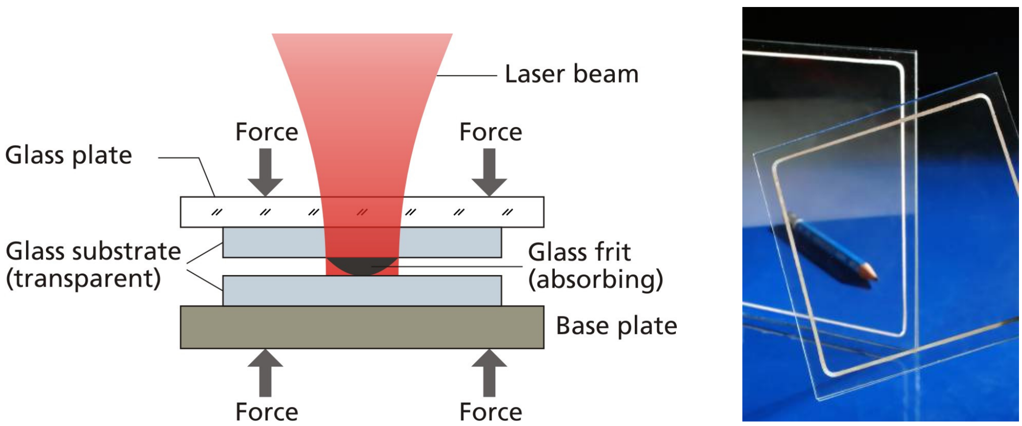
Today glass frits are used in the industrial manufacturing, particularly in the electrical engineering and electronics especially with electric bushings and the hermetic sealing housings. The durability and the mechanical load capacity of such a connection are depending on the mechanical tensions having an effect on the junction. On account of these tension problems most joining processes go through a temperature time profile what signifies a high, nevertheless necessary temperature load for the whole assembly.
For many applications, e.g., to the encapsulation of microsensors or microactuators or the production of assemblies with organic components these necessary process temperatures are too high, so that single components are already damaged by diffusion processes. The necessity of a low temperature joining technology or a joining technology with locally restricted energy bringing into play is indicated therefore. The laser beam soldering by means of glass frit shows a possibility which concentrates the necessary energy spatially restricted in the junction area thus minimises the whole warming of the components. Laser beam soldering using glass solder makes it possible to concentrate the energy needed for making the connection so that it is spatially limited to the joining zone and thus to minimize the total increase in heat of the components being joined. The energy necessary for melting, wetting and connecting the parts being joined is based on the absorption of the laser radiation applied in the glass solder. The local introduction of energy must be adjusted in terms of time and geometry in such a way that the viscosity needed for adequate flowing and wetting is achieved in the glass solder and the evaporation of glass solder constituents is avoided.



(a) (b)

Figure 1 (a) Experimental setup for laser based glass frit bonding Captions in 8 point form. (b) Glass frit bonding of two glass substrate to create a hermetically sealed cavity between the two plates.

Through a high scan speed of the laser beam up to 1000 mm/s and a multiple overlapping of the Scan contour the parts are joined in a "quasi-simultaneous" process where in the junction area steady warming, melting and connecting of the glass frit is reached in. High temperature gradients are avoided with this action. Simultaneous warming up and sinking of the whole contour minimizes thermal tensions. The soldered seams are characterized by a perfect form fit of the parts without pores cracks. Possible applications of this technique include sealing microsensors and microactuators, encapsulating organic lighting devices and producing liquid crystal displays.
The paper gives an insight in the basics of laser glass frit bonding and shows possible applications.

Structural arrangement of titanium microcolumnar surface structures induced by femtosecond laser irradiation

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The surface textures formed in metallic and semiconductor materials by ultra-short pulse laser treatment have been investigated since a few years [1, 2], but a detailed understanding of their formation mechanisms is far from being achieved. In particular, it is difficult to predict the type of surface texture formed and its exact geometry and dimensions, which are of upmost importance to define properties such as wettability and human cells/material interactions. Surface texturing has many potential applications, such as biomedical implants [3], self-cleaning surfaces [4, 5] and enhancement of adhesive joint strength [6, 7]. In a previous work we investigated the topography of these induced textures on Ti and Ti alloy surfaces as a function of the laser processing parameters [8, 9]. The aim of the present work is to study the relationship between the geometry of these surface features and the microstructure of the bulk material. Surface textures consisting of microcolumnar features, as depicted in Figure 1, were produced on commercially pure titanium and Ti-6Al-4V alloy plates by laser surface treatment using a commercial Yb:KYW chirped-pulse-regenerative amplification infrared laser system. The samples were structurally characterized by electron backscatter diffraction (EBSD) analysis of the transverse cross-section of the samples surface in order to relate the crystallographic orientation of the material in the columns with that of the bulk material.

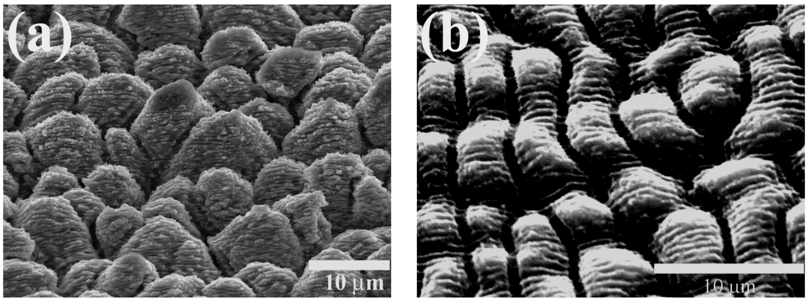

Figure 1 Femtosecond laser induced microcolumnar features produced on titanium (a) and Si (b) surfaces.

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Emission Data and Environmental Costs During Laser Joining of Metals

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Because of the various advantages of laser application for welding of metallic materials, the range of those applications is growing steadily. Typical examples in the automotive industry are the production of the VW Golf V or the automatic gearbox of the Mercedes-Benz A-Class. Furthermore in industry a general trend of increased use of lightweight materials (e.g. Mg, Al, Alloys) is present. A growth segment for pertinent small and medium-sized enterprises (SME, suppliers) in the metal processing are combinations of metal components onto complete metal parts. In this context avoiding and controlling of emissions caused by laser processing of metal/metal composites is an important task. The environmental costs in the laser processing are estimated up to 10% of manufacturing costs. In this public funded project the identification and characterization of specific emission ratios as a function of materials and power depending parameters during laser welding and soldering is carried out.
To characterize emission data, established measurement procedures like isokinetic partial volume flow sampling and weighing of impacted particulate fumes, particle size distribution and energy dispersive X-ray spectroscopy (EDX) are applied. However, concerning laser joining these methods were rarely used in this variety.
The experimental results show that there is a potential health risk caused by laser-generated air contaminants (LGACs). For example, during welding of zinc coated metal sheets appear specific anorganic LGACs like zinc, iron and manganese (Fig.1). Furthermore the particulate matter contained a big amount of nano-sized particles which can cause severe health damage and had to be subjected to a toxicological evaluation. Looking at the mass frequency there is a different distribution (Fig. 2). Comparing both distributions two discriminate maxima occur.

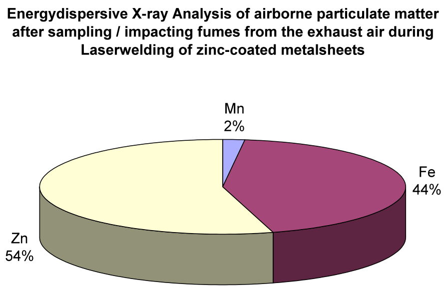

Fig. 1: EDX Analysis of sampled fumes

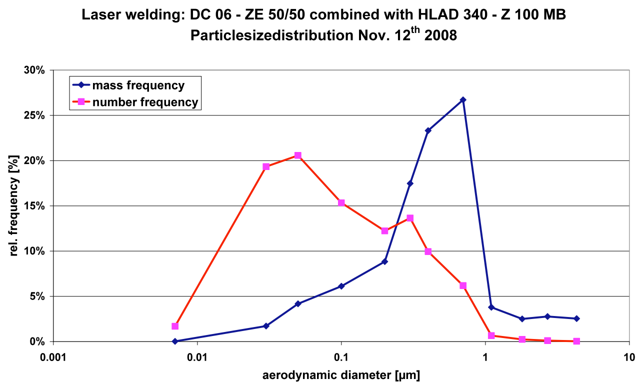

Fig. 2: Particle Size Distribution during Laserwelding

The results will be permanently available without charge at LZH homepage ("Laser Safety" http://www.lzh.de -> Publications -> Database) and link or mirror on the DVS home page (Deutscher Verband für Schweißen und verwandte Verfahren e.V.). This interactive database will be shown as a panel of the input variables (process window) to scale technical necessary actions for environmental protection given by laws and for the selection of protective measures (capturing and exhaust air cleaning systems) and providing information in terms of costs/m (footage of welds), costs/part, costs/production unit etc.

High Power Femtosecond Disk Laser

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Thin disk laser technology [1] has been developed since early 1990s and is now mature for industrial applications. The technology uses a disk-shaped laser material with a thickness of several tenths of mm. This allows efficient heat evacuation and thus high power output. For pulsed lasers and especially for ultra-short pulse lengths the thin disk geometry is particularly suitable since the size of the laser mode on the disk can be nearly freely chosen. So pulse damage can be avoided simply by enlarging of the beam size on the disk enabling very high pulse energies. For ultrashort laser pulses the small amount of the laser material crossed by the laser beam is an additional advantage. Dispersion and non-linear effects in the laser disk are negligibly small.

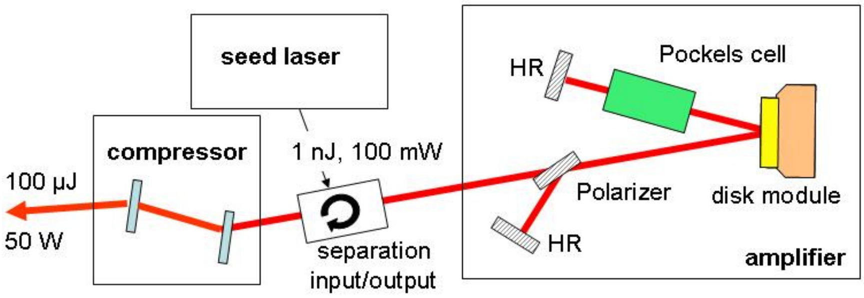

Figure 1 Principal set-up of the femtosecond disk laser

The principal laser set-up is sown in figure 1. Because of the small thickness of the laser disk its gain is relatively low. So a regenerative amplifier realizing 50 to 100 bounces on the laser disk is usually used to amplify the pulses of commercially available seed lasers (typically 1 nJ, 50 MHz) to the 100 µJ level. Except of the seed laser the major components of the set-up are: a disk module, a Pockels cell and a compressor. Disk module utilizes radiation of the laser diode to pump the laser disk and to provide gain in the amplifier. The Pockels cell allows determining the number of round trips in the amplifier and thus the amplification. The compressor compensates dispersion gained during amplification.

With a laboratory set-up an output power up to 100 W with pulse duration of several ps has been already demonstrated. Now a first prototype with a target output power of 50 W has been built. The results will be presented at the conference.

The pulse duration is at the moment limited by the gain bandwidth of the laser material. The mostly used laser material in thin disk laser design is Yb:YAG. In high power operation it can deliver pulse durations as short as 800 fs [2]. Using nonlinear broadening of the pulse spectrum in the Pockels cell even shorter pulse durations can be achieved. Implementing of other laser materials, such as Yb:KLW or Yb:Lu_2O_3 allows for pulse durations smaller than 200 fs without any changes in the laser set-up. Additionally using other seed and/or other operation modes (e.g. cavity dumping) pulses with durations between femtoseconds and microseconds can be produced by one laser system.

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Removal of nano particles on silicon wafer by plasma filament using a femtosecond laser

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The effective removal of nano particles from silicon wafer surface was demonstrated using the self-channeled plasma filament excited by a femtosecond (130 fs) Ti:Sapphire laser (λ_p=790 nm). This process has achieved successfully the removal of 100 nm sized polystyrene latex (PSL) particles from the surface. The photo-induced self-channeled plasma filament in air reached a length of approximately 110-130 mm from the first focal spot with the diameters ranging from 40 to 50 μm at the input intensities more than 1.0×10^{14} W/cm^2. By the scan of wafer using the X-Y-Z stage during self-channeled plasma filament, the removal variation of nano particles on surface was observed *in situ* before and after plasma filament occurred. The cleaning efficiency was strongly dependent on the gap distance between the plasma filament and the surface. The removal efficiency of nano particles reached to 97% with no damage on the surface when the gap is 150 μm.

Long Pulse Fiber Lasers and Applications

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Recent developments in fiber laser technology allow enlarging the pulse parameter range by new laser concept. Beside the increase of average power, repetition rate and a shortening of the pulses, a new laser design enables also an increase of pulse duration for high energy pulses in the ms range. These lasers with pulse energy up to 50 Joule and pulse durations of several ms target the market of cutting, welding and drilling, where today lamp pumped Nd:YAG lasers are present. Combined with the well known advantages of fiber lasers such as efficiency, stability and beam quality these lasers close the gap between the low power, low order mode pulsed or cw lasers and the high power multimode lasers.

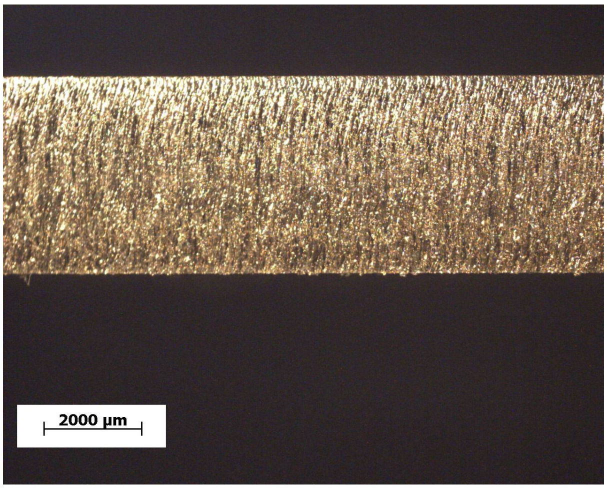

Figure 1 : 4 mm stainless steel cut with 150W average power fiber laser

This paper gives an overview on new pulsed laser applications and shows the potential for these new laser types to cover a wide range from micro to macro applications with only one laser source.

Polarization sensitive devices using ultrafast laser photoinscription of nanoscale periodic arrangements

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Ultrafast laser radiation shows increasing potential in 3D functionalization of optical materials. If at low photon doses isotropic refractive index changes are induced via soft electronic alterations, in more energetic regimes corresponding to thermo-mechanical photoinscription effects, ultrafast laser radiation can generate an intriguing nanoscale spontaneous arrangement, leading to form birefringence and modulated index patterns. This regime was characterized by spectroscopic means, revealing an increased presence of broken bonds and oxygen deficiency centres. Using the birefringence properties and the associated anisotropic light scattering properties characteristic to the ordered nanostructures, polarization sensitive devices were designed and fabricated [1]. The polarization sensitivity allows particular light propagation and confinement properties in three dimensional structures.

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Laser-Bonding in high power electronics

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In the field of high power electronics a trend towards higher thermal loads, rising power density and the need for enhanced dynamic strengths can be seen. These requirements directly influence the joining technologies, which leads to a cumulative replacement of soldering and brazing processes by liquid phase welding applications. Thus it is possible to achieve interconnects based on metal-joints, featuring a high operating temperature and an excellent electric conductivity. In order to realize short process times with a high degree of flexibility and automation, laser based processes are well-adapted to meet these challenges.
In this context, laser-welding of the dissimilar materials copper and aluminum is a matter of particular interest, as copper is characterized by an outstanding conductivity, but also a comparatively high density and an increasing market price. Therefore copper is supposed to be replaced as far as possible by aluminum, which offers a slightly minor conductivity at significant lower density and a cheaper purchase price. However, seen metallurgically, copper and aluminum only feature a limited solubility within each other. As a consequence, the direct metal-joint of these dissimilar materials generally leads to the formation of intermetallic phases in the welding zone coming along with a high brittleness and a reduced load capacity of the connection.
Subject to this complexity, the present article deals with methods and possibilities to increase the mechanical and electrical characteristics of laser-welded copper-aluminum connections. Upon other terms, the influence of a lateral laser-beam displacement towards the aluminum base material and the effects of a pulse modulation within a single laser pulse are discussed. For example, a lateral beam displacement leads to a shifting of the maximum thermal contraction at the end of the laser pulse into the aluminum. Due to the lower yield strength and the higher ductility of pure aluminum in contrast to pure copper, the maximum residual stresses can be reduced by plastic deformation, see figure 1.

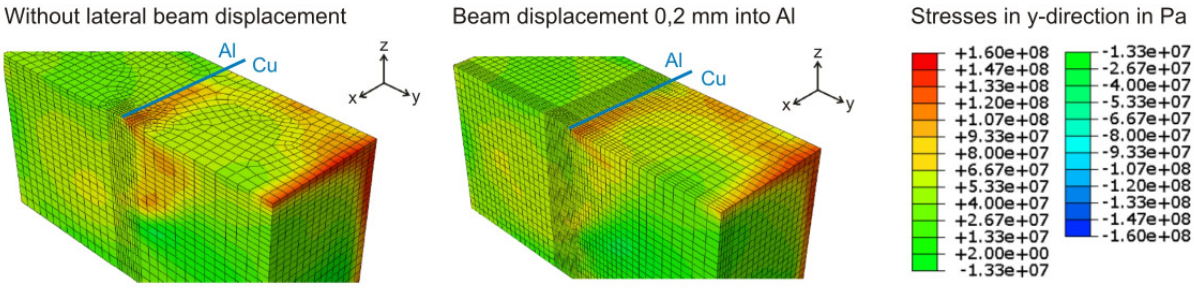

Figure 1 Numerical calculation of the residual stresses in y-direction (orthogonal to the joining gap) without using a lateral beam displacement (left hand side) and a lateral beam displacement of 0.2 mm into the aluminum base material (right hand side).

Furthermore, fittings made from roll-cladded copper-aluminum sheet metal can be used to divide the one dissimilar connection into two similar connections, aluminum-aluminum on the one side and copper-copper on the other side. By doing so, the dissimilar connection is transferred to a standardized process, the roll-cladding, and the formation of brittle phases can be minimized. Thus especially the ductility of copper-aluminum joint can be raised and the contact resistance of the connection reduces.

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Nanoablation using 2D Gold and Dielectric Nanosphere Templates Excited by Femtosecond Laser

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We present the experimental and theoretical results on the nanohole processing using high dielectric particles with small size parameter.

Nanohole processing mediated with the dielectric particle exhibits the smaller features than the diffraction limit. The use of dielectric particles has attracted much attention for industrial applications, because fabrication of the monolayer 2D particle arrangement seems much easier than the metallic ones. Based on Mie scattering theory, the enhanced near-field is determined by the size parameter *x=pD/l*, defined as *p* multiplied by particle diameter D, divided by optical wavelength *l*. The clear nanohole is obtainable with *x~p* but not with the smaller size parameter *x<p*/2 due to the weak enhanced near-field for frequently used particles like polystyrene particle. Therefore, the shorter wavelength is required for downsizing the processed nanoholes, which needs the sophisticated wavelength up-conversion in ultrashort time domain and vacuum UV (*l*<200 nm).

Using dielectric particles having high dielectric constant, the strong enhanced near-field is generated even with small size parameters due to the strong scattering cross-section of the particle. The resonant refractive index of the particle depends on the size parameter, meaning that the used material should be selected as a function of size parameter. In the ablation processing with 2D arrayed particles, the optical field interaction such as inter-particle multiple scattering should be considered and then the optimal spectral condition is different from the single particle case.

The obtained results confirm that the use of high dielectric particles becomes a promising technique for downsizing the produced nanoholes.

This work is supported in part by a Grant-in-Aid for the Global Center of Excellence for High-Level Global Cooperation for Leading-Edge Platform on Access Spaces from the Ministry of Education, Culture, Sport, Science and Technology, Japan.

Controlled Growth of Carbon nanostructures in Laser-assisted Chemical Vapor Deposition

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Single-walled carbon nanotubes (SWNTs) are amongst the most attractive one-dimensional nanostructures to be investigated due to their rich variety of intriguing properties and potential applications [1]. SWNTs have been extensively investigated as one of the most important building blocks for fabricating prototype nano- electronic and optoelectronic devices [2]. Therefore, controllable fabrication and integration of SWNTs are of significant importance in both scientific and applied fields. Currently, chemical vapor deposition (CVD) process is the only economically and technically viable process to integrate SWNTs into devices by yielding selective and aligned SWNT growth directly on various substrates [3]. However, well controlled growth and integration of SWNTs still suffer from several bottlenecks, such as reliability, yield, cost and high processing temperature.

It is well known that ultra-sharp metallic tips can be used as optical antennas in localizing and enhancing optical radiation due to the optical near-field effects [4]. Enhancement of the electric field at the tip results in enhanced eddy currents, which yield local heating enhancement and a significant temperature increase at the tips. In this study, optical near-field effects were applied in a laser-assisted chemical vapor deposition (LCVD) process to achieve self-aligned growth of SWNTs at a relatively low substrate temperature. Figure 1 shows the schematic of optically controlled growth of SWNTs and schematic results of self-aligned SWNTs. The experimental results and numerical simulations using the High Frequency Structure Simulator (HFSS, Ansoft) demonstrated that the laser-induced optical near-field effects could produce nanoscale localized heating at electrode tips, which stimulated the selective growth of SWNTs at the tips. Influence of the laser beam polarization was investigated via numerical simulation using HFSS to optimize conditions for maximal enhancement of the localized electric field and temperature increase. Two obvious advantages are observed for this developed technique: precise position control and low substrate temperature for SWNT growth.

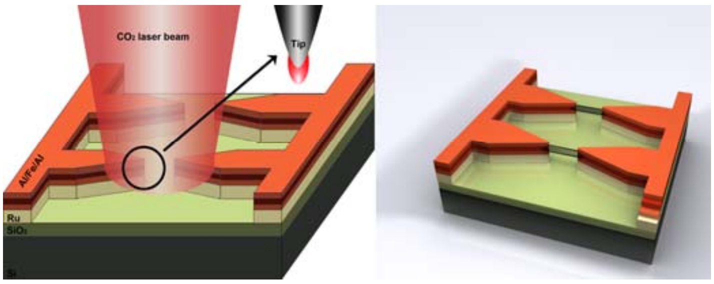

Fig. 1. (a) Schematic of optically controlled growth of SWNTs; and (b) schematic results of self-aligned SWNTs.

In addition to self-aligned growth, LCVD is able to grow carbon nanotubes (CNTs) with selective electronic properties and control directions of multiple CNTs. LCVD has also shown advantages in growing diamond films / crystals and carbon nano-onions.

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Effects of Superposed Continuous Diode Laser on Welding Characteristics for Aluminum Alloy in Pulsed Nd:YAG Laser Welding

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Pulsed Nd:YAG laser and continuous diode laser (λ= 808 nm) were spatially superposed in order to obtain higher absorption of laser beam to aluminum alloy, since the absorption of diode laser (λ= 808 nm) to aluminum alloy is approximately three times higher than that of Nd:YAG laser (λ= 1064 nm) [1, 2]. Therefore, the welding characteristics and effects of superposed continuous diode laser were investigated by using experimental and numerical analysis.
Figure 1 shows center cross sections of weld bead in the scanning direction at the beginning of laser irradiation. When the continuous diode laser was superposed, the welding state became stable. Moreover, the penetration depth was increased by approximately 40% after some laser shots, although the peak power of continuous diode laser was only 2% compared with that of pulsed Nd:YAG laser. However, the penetration depth of the first pulse was shallow. In some applications, the stable penetration depth has been required from the first pulse. Therefore, the pre-heating pulse was irradiated before the first pulse for processing as shown in Figure 1 (c). The absorption of the first pulse was increased by the pre-heating pulse and the deeper penetration depth was obtained.
Figure 2 shows the surface temperature at the center of laser beam before the irradiation of pulsed Nd:YAG laser by the unsteady thermal calculation. In the case of superposition of continuous diode laser, the surface temperature was kept at approximately 200K higher than that without continuous diode laser. Moreover the addition of the pre-heating pulse, could keep the specimen surface at higher temperature from the first pulse of pulsed Nd:YAG laser. Therefore, it was clarified that the penetration depth increased greatly even at the first pulse due to higher absorption of Nd:YAG laser to aluminum alloy by the superposition of continuous diode laser.

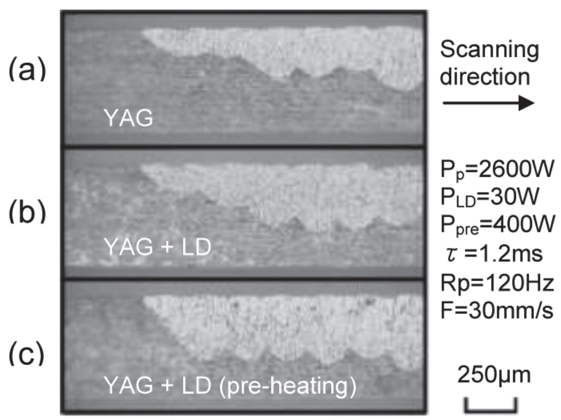

Figure 1 Cross section of weld bead at begining of laser irradiation

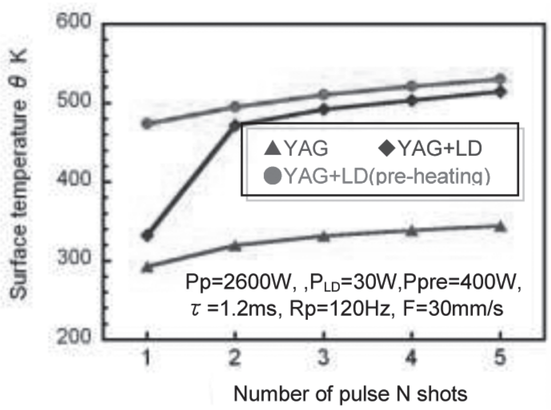

Figure 2 Surface temperature before irradiation of pulsed Nd:YAG laser

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Laser welding with pulsed solid state lasers: strategies and new developments.

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Pulsed Nd:YAG lasers offer a variety of options to broaden the spectrum of laser weld applications especially for challenging materials like refractory materials, aluminium alloys, copper alloys and combinations thereof. Within the last Years an increasing demand to join these materials efficiently is inquired from various industries. The goal is to be able to reduce cost and overall weight, while simultaneously increase the functionality of the final products. These demands lead to challenges regarding the joining technology and the metallurgical aspects to fuse parts together that are, requested for there properties, consist of a wide variety of materials.

Today a whole toolbox of possibilities is available to overcome some of the obstacles that welding engineers are facing today. Within this paper an overview of various methods and strategies is given how such problems can be approached. New findings, e.g. like in Titanium welding as shown in figure 1, are discussed. A modulated pulse can be used to decrease the grain size by up to 50% within the weld nugget and therefore increase the ductility of the weld. This is possible with laser sources that are capable to control the pulse energy very precisely to modulate the heat input into the material and therefore reduce the grain growth.

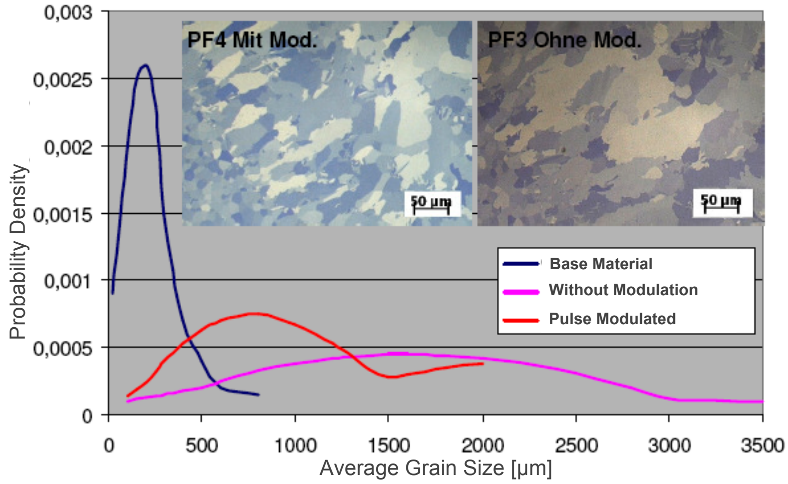

Figure 1 Comparison of grain sizes within the weld nugget of titanium using pulse modulation

The unique characteristics of pulsed solid state lasers like pulse-parameters and pulse-regime in combination with special beam guidance systems or the entry of additional material, e.g. wire feeding, can surely enhance the possibilities and take the welding process up to the next level.

Laser Beam Micro Welding of DCB Substrates

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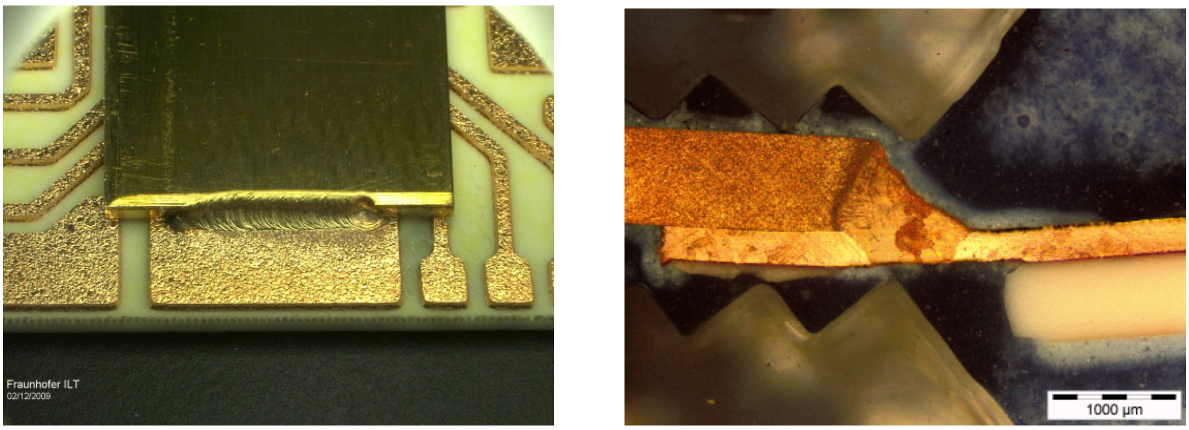
Small seam width and low heat deposition in the component are the outstanding features of laser beam welding as applied to microtechnology. Continuous fiber lasers and pulsed Nd:YAG lasers with high beam quality combined with new process techniques enable highly reproducible joining of metals with weld seam widths below 200 µm. Feed rates up to 1 m/s and high quality weld seams can be achieved with innovative irradiation strategies using a temporal and spatial modulation of the laser beam. With this thermal management of the welding process the total amount of energy deposited in the components can be minimized and the melt pool dynamics can be controlled [1,2].
Copper with its poor absorption characteristics is still a material which is very difficult to weld using laser radiation. However the industrial demands for high thermal and electrical conductivity make it an ideal material for high power electronics.
Recent developments for spatial and temporal modulation in laser beam welding offer new opportunities for the joining of copper.



(a) (b)

Figure 1 (a) Laser welded DCB with contact sheet (b) Cross section of laser welded DCB contact.

The major challenge in welding of DCBs is melting the both copper parts (Cu layer and contact fin) without damaging the underlying ceramic substrate. The combination of linear feed rate and superimposed circular modulation offers the possibility to control the weld depth very precisely and to avoid overheating of the melt pool. The requirements for this approach are high beam quality and high dynamics in beam movement [3].
The paper presents recent developments in spatial and temporal modulation of laser radiation for welding applications in the field of high power electronics on ceramic substrates DCB. The influence of the modulation amplitude and frequency as well the related laser power on weld seam depth and width are discussed. The process limits and further prospects are shown.

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Nanostructuring by infrared fs-laser densification of amorphous dielectrics

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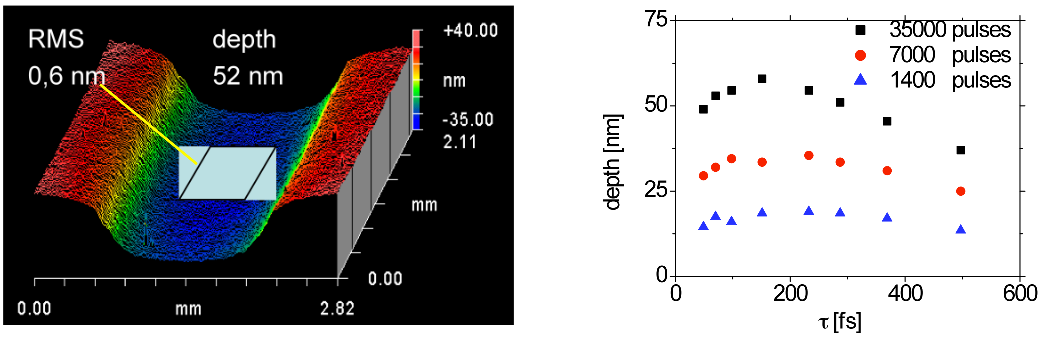
It has been well established experimentally that silica glass can be densified at ambient pressure upon irradiation by photons, electrons, neutrons, and ions [1]. Over the last decade, UV-induced refractive-index change (Δn) profiling in SiO_2-based glasses was widely used for the production of special optical devices for the photonics industry.
We show for the first time that such a densification is possible by infrared femtosecond laser irradiation of different amorphous materials and this method is not restriction to UV transparency of the materials. The densification as observed in irradiation experiments can be attributed to defect generation and subsequent structure relaxation [2].
The modification was performed well below the ablation threshold Fluence F_{th} (0.3-0.9 F_{th}) of the used materials and is easily manipulable by the number of laser pulses with an accuracy of 5%.
In figure 1a is shown as an example of the change of the surface "height" of Zerodur. The densification is observed as a surface level modification.



(a) (b)

Figure 1 a) An example for the surface modification by fs-laser irradiation of Zerodur (Schott), the roughness remains unchanged. b) Modification depth dependence on pulse length, the modification fluence F is 80% of the threshold fluence

In figure 1b is shown the modification strength dependent on the pulse length. The maximal modification is seen around 200 fs. As the number of the generated defects is limited we observe a saturation of the modification strength with increasing pulse number.
We have tested the method also on different crystalline materials but we could not obtain any change at Al_2O_3 and crystalline quartz and only very small changes in CaF_2 and MgO not assessed to the lateral beam profile of the laser pulse.
In conclusion we can say that the infrared fs-laser irradiation below the ablation threshold is a powerful method for nano-scale modification of amorphous materials.

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YAG Laser Spot Welding of PET and Metallic Materials

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A dissimilar material joint have a great interest in industrial applications including automotives, aircrafts, medical, electronic industry and etc. Moreover the combination of plastic and metal in the products would cater advantages in specific engineering application. A few researches have been reported for dissimilar joining between plastics and metals using laser welding method [1, 2]. In this study, direct joining using YAG laser spot welding on the dissimilar materials joint of plastic and different metallic materials have been investigated. The experimental result shows polyethylene terephalate (PET) has been successfully joined to copper (Cu), stainless steel (SUS 304) and aluminium alloy (A5052). Shear tensile test was carried out to evaluate strength of the joint. It was found that failure load increased with the increasing of heat input for all three combinations of the joints as shown Fig.1 (a)-(c). However, the heat input is not only dominant factors for failure load, especially in the PET/SUS304 and PET/A5052 joint. Observations of the cross section of the joints are shown in Fig.2. According to the figure, no significant weld pool was observed in case of PET/Cu joint even at the laser irradiated area. On the other hand, obvious weld pool was observed at the interface in metallic material side for PET/SUS304 and PET/A5052 joints. Differences of the morphology at the interface due to difference of material properties, such as reflectivity and absorptivity of laser beam, thermal conductivity, etc., of metallic materials used may affects on characteristics of strengt (a) ıe joints.

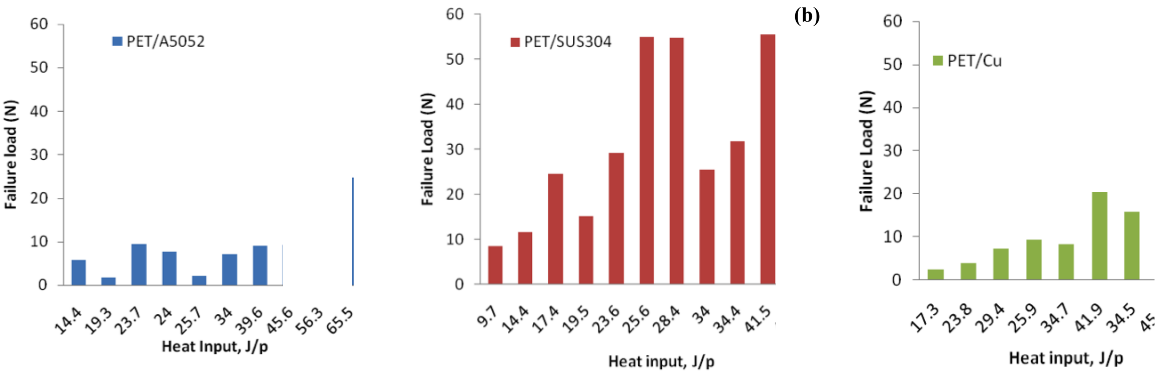

Figure 1Failure load for (a) PET/A5052 joint (b) PET/SUS304 joint (c) PET/Cu joint

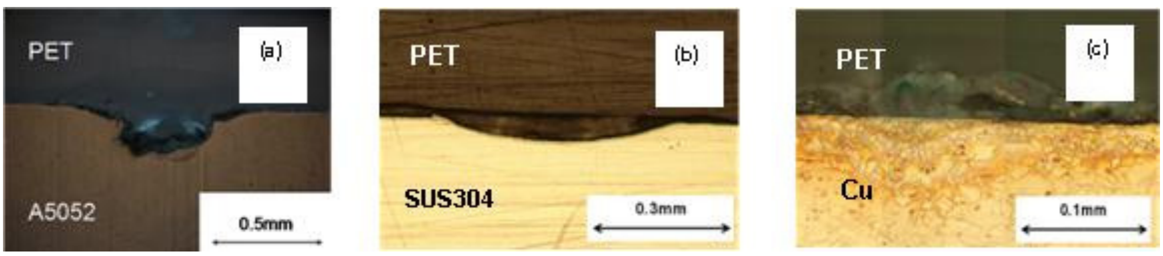

Figure 2 Cross sectional observation at the joint interface for (a) PET/A5052 joint. (b) PET/SUS304 joint. (c) PET/Cu joint.

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Laser micro joining of thin films on flexible substrates for electrical connection

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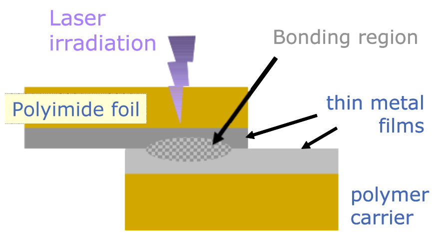
The joining of material is required for electrical or mechanical connection of thin film components for different applications in micro technology, thin film technique and photovoltaic. Classic techniques such as wire bonding and soldering require either specific metal layers such as gold or a sufficient film thickness.
Laser joining techniques offer the opportunity of a fast connection of thin films also on flexible substrates. Currently laser processes for material joining such as welding has been developed mainly for steel and heavy industry as well as for precision engineering. Typical techniques are welding and soldering with and without additional materials. Current studies aim to the development of such bonding processes for micro-, MEMS- and solar cell-applications. However, due to the much lower thickness of the used films and the usage of thermal sensitive substrates, e.g. polymers or semiconductors principally, new approaches have to be developed.

In this presentation a novel technique for connecting two metal thin films or foils of different materials with a thickness down to 1 µm for mechanical and electrical connection is introduced. The connection is achieved without an additional auxiliary material. Dependent on the selected material system the connection is created be a combination of geometrical tooting or thermal intermixing of the metals.
The achieved contact will be investigated and characterize in terms of the electrical and mechanical properties. The findings of the investigations are discussed with thermal calculations to address the understanding of the mechanism and enable further optimizations.



Principal set-up for laser joining of two thin metal films

Fabrication of novel nanostructures on Silicon with femtosecond laser pulses

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In recent years, femtosecond laser directly induced micro/nano structures in many material surfaces. However, most of the research is limited to the linear or circular polarizations. In this study, the fabrication of novel nanostructures on silicon surface using radial or azimuthal polarization femtosecond laser with ~120fs pulse duration, 800 nm wavelength, and 1 kHz repetition rate were presented.

Figure 1 presents a schematic illustration of the experimental setup. As shown, a pinhole with an aperture of 0.25mm is installed in the optical path to improve the beam quality. The linear polarization with Gaussian profile laser beam was passed through an axisymmetric polarization element (SWP-780, Photonic Lattice, Inc.) and the polarization can be changed to radial or azimuthal polarization. The beam profile then changed to donut shape, as shown in Fig. 2. Meanwhile, the transmitted laser beam was passed through a reflective mirror system such that it entered an objective lens (magnification 5x) and was incident in the normal direction on the surface specimen mounted on an X-Y axis stage.

The fabricated silicon surface structures are observed using scanning electron microscopy (SEM). Figures 3-4 presents SEM images of the point irradiated at radial and azimuthal, respectively. Note that the number of irradiated pulses is 200 shots and the laser powers is 440μW and 500μW, respectively. The observation results show that nanogratings with period 600~700nm are formed at low laser fluence region, and microstructures with 2~3μm are formed at high laser fluence region. It can be seen that the orientation of the periodic nanogratings and microstructures is approximately perpendicular and parallel to the polarization direction, respectively.

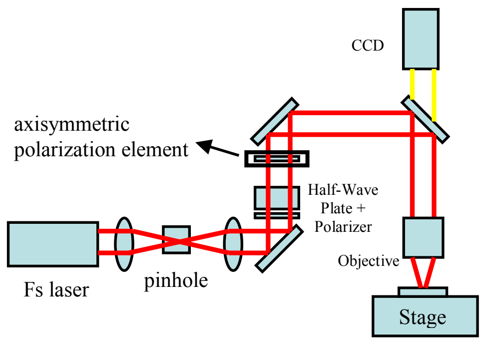


Fig.1 Schematic illustration showing experimental setup

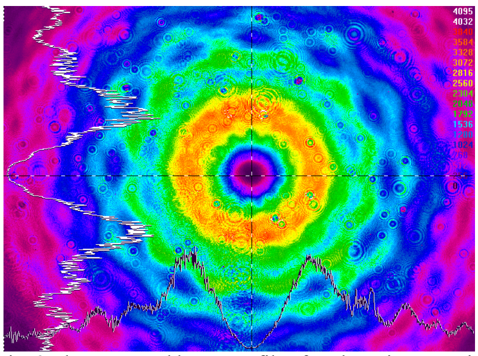
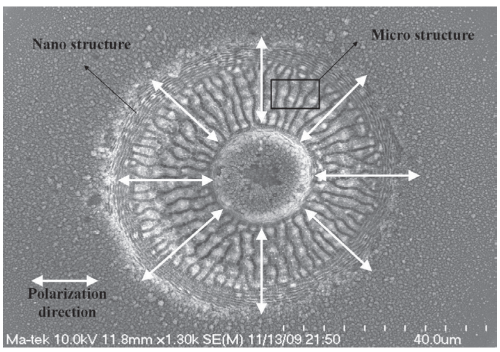
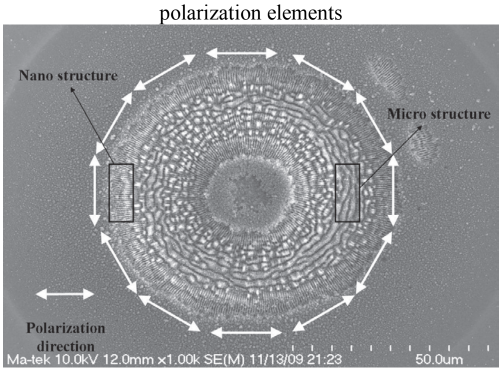


Fig. 2 The measured beam profile after the axisymmetric polarization elements





Silica Based Micro-Cantilevers Fabricated Using Direct UV Writing and Micro-Machining For Chemical and Physical Sensing Applications

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Cantilever-based sensors have received increasing interest over recent years, offering a completely new type of miniaturised transducer with both chemical and physical monitoring capabilities [1]. This paper presents a resonant silica micro-cantilever with direct UV written Bragg gratings intrinsically defined within it, illustrated in Figure 1 (a). To obtain quantitative and qualitative measurements the cantilever is mechanically resonated and the spectral variations in a 'sensor' Bragg grating monitored and cross referenced against a Bragg grating in the bulk. The miniaturised device offers remote, multiplexed sensing capabilities that are conducive to flammable environments.

Device fabrication is uniquely achieved through a combination of surface micro-machining and direct UV writing in a silicon-on-silica platform, using a three stage fabrication process. The first stage uses a precision dicing saw to cut the cantilever's 'outline' into the wafers silica layer, exposing the underlying silicon. This novel technique allows for rapid prototyping, as it does not require photolithograph and etching steps that can be expensive and time consuming, for small device quantities. The second stage of fabrication defined the Bragg grating elements using a direct UV writing technique [2]. In the final stage of fabrication the exposed silicon was wet etched using KOH such to liberate the silica cantilever from the underlying silicon.

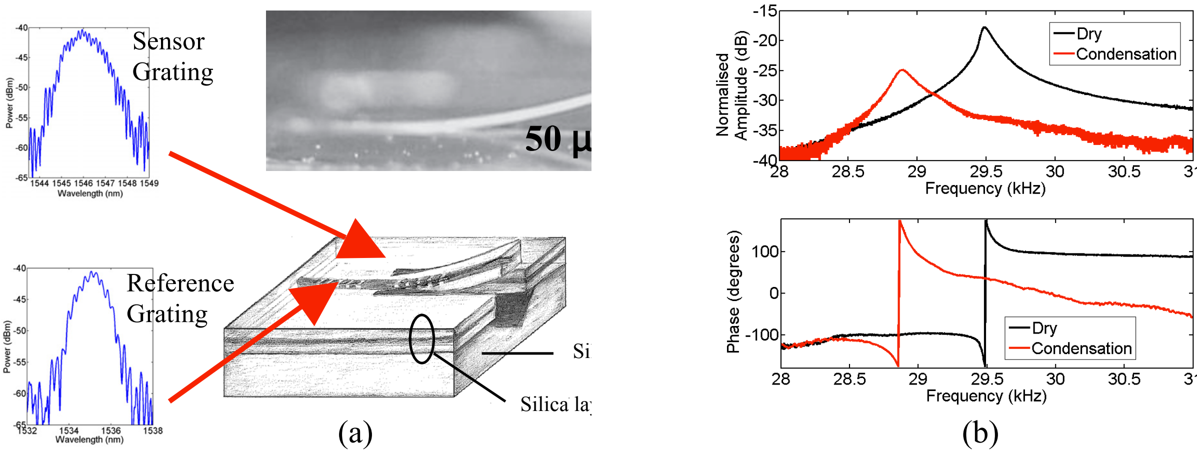

Figure 1 (a) Schematic and photograph of the fabricated silica cantilever. (b) The resonant frequency shift as a result of deliberately induced condensation.

The fabricated cantilever reported has a width of 55 µm a thickness of 50 µm and a length of 4 mm. Figure 1 (b) depicts the shift in mechanical resonance of the fabricated cantilever as a result of deliberately induced water condensation on the surface of the device.

We have demonstrated for the first time a direct UV written Bragg grating chemical and physical sensor, based upon microfabricated cantilevers. We shall report on the microfabrication techniques and the chemical and physical sensing capabilities of the cantilevers, including the multiplexing of cantilever sensing elements upon a single integrated chip.

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Fabrication of 2D periodic nanoholes on GaN surface using wet-chemical-assisted femtosecond laser ablation

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Enhancement of efficiency in blue light-emitting diodes (LED) is significant challenge to realize advanced applications in the future. In typical blue LEDs, Gallium Nitride and its derived materials have refractive indexes much higher than that of air. As a result, the extraction efficiency of blue LEDs is seriously low because of total internal reflection at the device surfaces, although the internal quantum efficiencies of LEDs reach to 90 % or higher. In order to increase the extraction efficiency, integration of two-dimensional (2D) photonic crystal (PhC) structures patterned on the device surface is proposed [1]. One of the widely used existing techniques for fabrication of such structures is an electron-beam lithography followed by plasma dry etching process [2], in spite of its disadvantages for mass production due to high cost and low throughput. By contrast, femtosecond (fs) laser ablation process is an alternative technique in terms of its high-speed, high flexibility, and simple processing. For micro/nanofabrication of GaN, we developed wet-chemical-assisted fs laser ablation in which the second harmonic (λ= 387 nm, 150 fs) of near-infrared femtosecond laser beam was focused using an objective lens on the surface of a single-crystal GaN substrate immersed in 35% hydrochloric (HCl) acid solution [3]. In this method, high-quality and uniform ablation craters can be formed compared with those produced by fs laser ablation in air followed by etching in HCl (two-step processing method). This is due to photochemical or photothermal reaction of HCl solution with ablated materials, resulting in effective removal of debris. In this paper, we have some issues to be resolved, such as density, resolution and periodicity with the aim of practical application. For high densification, we controlled the repetition rate using Pockels cell from 1 kHz to 10 Hz to avoid the scattering from bubbles generated during ablation at neighboring sites. In this case, an incident pulse is transmitted to the substrate surface after the micro-bubble generated by the preceding pulse disappears by self pressurization effect. As a result, the pitch between ablation holes is shortened from 5 μm to 1μm, leading to a 25-fold density growth. Using high NA objective lens, we tried to improve the fabrication resolution of ablation craters further. At present, ablation craters smaller than 200 nm were successfully obtained using an oil immersion objective lens with an NA of 1.4. We have also demonstrate the fabrication of 2D periodic nanoholes by scanning the GaN substrates on piezo XYZ high-precision stage using the second harmonic single fs-laser pulse of 5 nJ, as shown in Fig. 1. Ablated craters, which are as small as 400 nm FWHM with a depth of 50 nm are periodically aligned with a pitch of 1 μm.

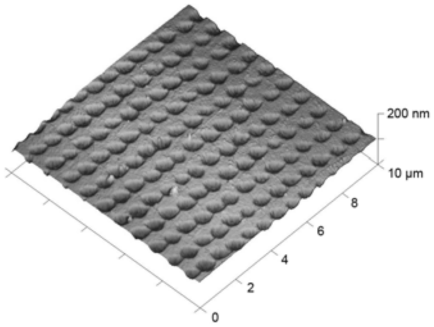

Figure 1 Atomic force microscopy image of the periodic structure fabricated on the surface of GaN substrate.

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Rotational Magnetic Micro-Viscometer for Blood Viscosity Measurements at the Micro Scale

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Here we present a method to measure the viscosity of liquids with sample volumes of the order of microliters, which enables probing of samples that are two or more orders of magnitude smaller than required for commercially available micro-viscometers. Our rotational micro-viscometer is based on a thin rotating disc with the diameter of approximately 50 micrometers, which is made of epoxy photoresist SU-8 doped with ferrous nanoparticles. The disc is fabricated by a multi-step application of laser direct imaging technique which employs an ultraviolet diode laser and a pair of acousto-optic deflectors with control hardware to steer the beam and enable high speed micro-structuring. A magnetic bar is first structured into a doped photoresist layer. The bar is then enclosed into a structured photoresist disc and the device is separated from the substrate surface. When the disc is placed in an external rotating magnetic field, the dopant nanoparticles are subject to a magnetic torque which causes the disc to rotate in the direction of the external magnetic field rotation. The magnitude of the magnetic torque depends on the density and rotation frequency of the external magnetic field, which makes it possible to control the rotation frequency of the disc externally. By balancing the magnetic field torque with that of the viscous liquid surrounding the disc, it is possible to deduce the viscosity of the examined sample. The external magnetic field provides a simple means of transferring energy to the micro scale to power the rotating device, unlike other methods [1, 2] which require more complicated setups such as the use of optical tweezers [3]. Moreover, by enabling quick and precise viscosity measurements on samples with very small volumes, the technique can be successfully used in medicine or biology.

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Characterization of silver nanoparticles prepared by laser ablation in water and DMSO

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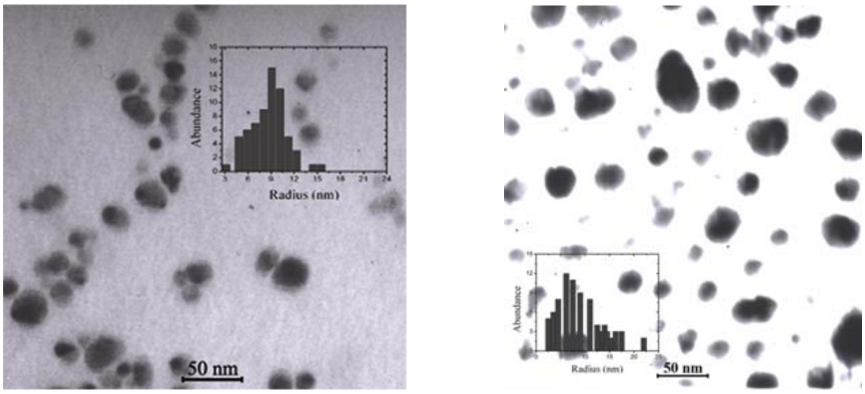
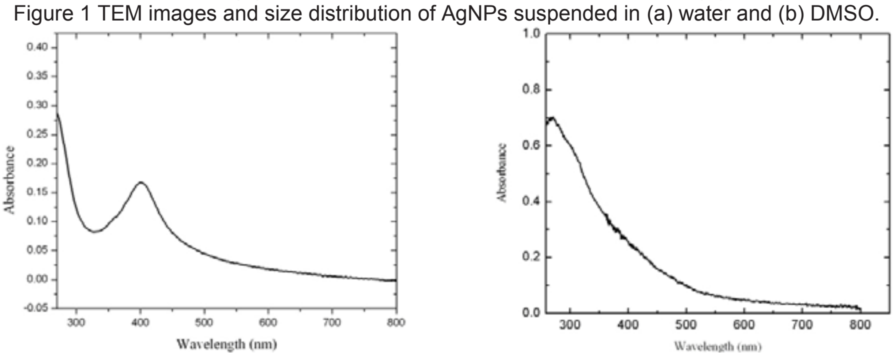
Silver nanoparticles (AgNPs) are widely studied for their properties which find application in many different fields from material to medical science. The control of size, shape, surface functionalization and stability is very important issue in AgNPs synthesis. Synthesis of metal nanoparticles by laser ablation of metallic targets in liquids has open new prospective for the extremely simple synthesis and also for modification of their properties [1, 2].
In the present study, silver nanoparticles are fabricated by laser ablation of a pure silver plate in the water and the DMSO. Laser ablation is conducted by fundamental harmonic of Nd: YAG; i.e.,wavelength: 1064 nm, pulse energy: 20 mJ, pulse duration: 18 ns repetition rate: 1 Hz. Colloids containing silver nanoparticles are studied by transmission electron microscopy (TEM) and shown in figures 1a and 1b. The shape of the silver nanoparticles is sphere and the size distribution are approximately remained the same in both solutions. Figures 2a and 2b show UV-Vis spectrum of AgNPs in the water and the DMSO respectively. One can see that the AgNPs suspended in the water show surface plasmon absorption (SPA) about 400 nm. On the other hand, the AgNP colloids obtain in the DMSO is very stable and does not show any SPA. Property changes of the AgNPs in the DMSO are analyzed using X-ray photoelectron spectroscopy (XPS) and will be reported.



(a) (b)

Figure 1 TEM images and size distribution of AgNPs suspended in (a) water and (b) DMSO.



(a) (b)

Figure 2 Absorption spectrum of AgNPs suspended in (a) water and (b) DMSO

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Microstructured GRIN lens as an external coupler to thin-film waveguides

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Planar optical waveguides consist of a thin film of high refractive index material, usually a metal oxide, on a transparent substrate. Some of the most interesting applications can be found in life science research. For example, the waveguides are used as biosensors which enable a highly efficient and specific excitation of fluorescently labelled molecules on the waveguide surface by the evanescent field of the guided mode. Due to the small thickness of the waveguides with typically 100 - 200 nm, prism coupling or end face coupling are not applicable and grating couplers are usually applied to transfer light into the waveguides. In addition to lithographic methods, direct laser ablation can be used for the fabrication of the grating couplers. The great flexibility of the process allows to tailor the grating couplers to specific applications.

In this work, we present a technique that uses a micro-structured gradient index (GRIN) lens to couple laser light from a single mode optical fiber directly to a planar waveguide (see figure 1). If positioned precisely on the waveguide, the external grating structure on the surface of the lens produces an effective index modulation on the surface of the waveguide and thus provides efficient coupling. The external coupler can be multiply reused. The grating with 500 nm period is fabricated by direct laser ablation with an F_2-laser at 157 nm. The main advantage of this coupling scheme is, that the conventional grating couplers, which induce a major part of the production costs of the waveguide devices, become dispensable. This is especially important in biosensing applications, where the waveguide chips are usually designed for single-use. Experimental results and FEM simulations show that the new technique can provide coupling efficiencies comparable to conventional grating couplers.

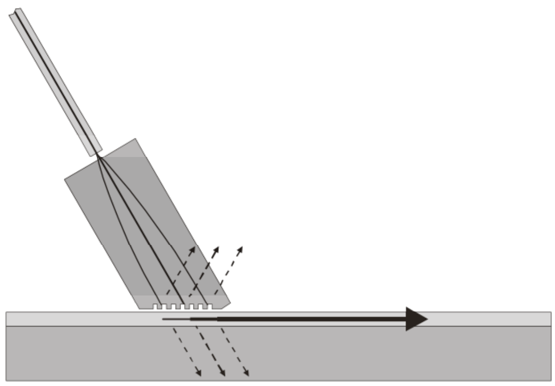

Figure 1: Principle sketch of the waveguide coupling via an external, microstrutured GRIN lens

Size-controlled silicon quantum dots synthesis by gated CO_2 laser pyrolysis

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Controlling the size of quantum dots is a great issue for applications requiring materials with precise adjustable properties brought by nanostructuration [1]. A typical example is the case of Silicon Quantum Dots (Si-QDs) which exhibit strongly size-dependant optical properties for sizes below 10 nm. Various applications are expected in different domains including optical and electronic devices [2], photovoltaic solar cells [3] and markers for biological structures imaging [4].
CO_2 laser-driven pyrolysis is an efficient method to synthesize various high purity nanopowders in a gas phase bottom-up approach. This technique offers a convenient control on the synthesis conditions by adjusting parameters such as laser intensity. Nevertheless, the size control of very small quantum dots remains difficult. We present new developments for precise *in situ* control of the size of Si-QDs in the 3.5-5 nm range by using a gated CO_2 power laser [5]. The original approach consists in controlling in time the energy injected in the process by gating the laser. The laser gate-on duration is adjusted in the 10 to 80 µs range at constant duty cycle and peak power. The gate-off duration is adjusted proportionally to the gate-on duration so that the average laser power is kept constant. *In situ* size characterization is achieved by on-line Time-of Flight Mass Spectrometry (TOF-MS). Si-QDs most probable size as a function of the laser gate-on duration T_{on} is plotted in Fig. 1.

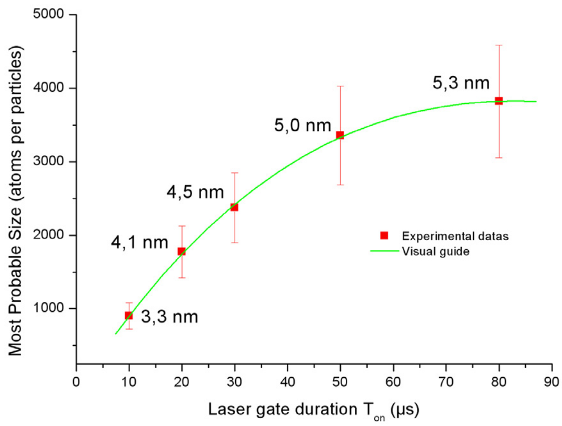

Fig. 1. Si-QDs most probable size as a function of the laser gate-on duration T_{on} for a constant duty cycle $T_{on}/(T_{on} + T_{off}) = 0.2$

The Si-QDs size is monotonically increasing with the laser gate-on duration at a constant laser average power. A simple visual guide suggests that the size can be adjusted precisely between 3.3 and 5.3 nm by adjusting the laser gate-on duration with a constant laser average power.

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Analysis of Regimes for Short Pulse Laser Shock Micro-Forming of Thin Metal Components for MEMS Manufacturing

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Laser shock micro-forming is conceived as a non-thermal laser forming method based on the high intensity laser induced shock waves capability to modify the tensional state of thin targets [1]. The technique has the advantages of laser thermal forming (non-contact, tool-free and high precision), but, additionally, its minimally thermal character allows the preservation and improvement of mechanical material properties by inducing appropriate residual stress fields. In particular, the induction of compressive residual stress fields on the target surface is a desirable feature introducing additional protection of the formed parts against corrosion and fatigue crack propagation.

The use of ns laser pulses provides a suitable parameter matching for the laser forming of an important range of sheet components used in MEMS that, preserving the short interaction time scale required for the predominantly mechanic (shock) induction of deformation residual stresses, allows for the successful processing of components in a medium range of miniaturization but particularly important according to its frequent use in such systems.

Continuing a previous discussion of the problem by the authors [2], in the present paper further analysis is contributed on the physics of laser shock micro-forming and the influence of the different processing parameters on the net bending angle. The experimental setup used for the experiments, sample fabrication and experimental results of influence of number of laser pulses on the net bending angle are also presented.

Results for different geometries relevant for MEMS manufacturing are presented. In figure 1, a sample of the bending achievable by the proposed technique in different micromachined metal specimens is shown.

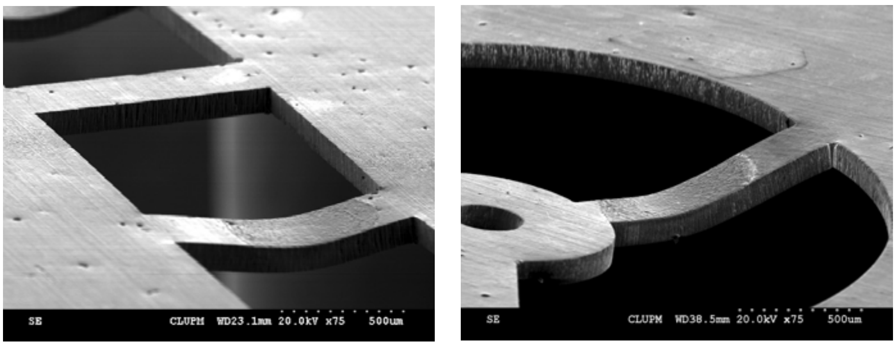

Figure 1: Scanning electron microscope images of laser shock bended AISI 304 specimens in different MEMS geometries

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Tuning Size Distribution of Gold Nanoparticles Generated by Laser Ablation in Water at Different Repetition Rates

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The formation of nanoparticles by pulsed laser ablation in liquids presents many interrelated phenomena, which complicate the study of independent parameters on the resulting colloids. For the sake of profitableness, a productive and controlled fabrication of colloidal nanoparticles is required. The influence on particle size and ablation rate of laser fluence [1], wavelength [2] and liquid medium [3,4], among others, have been investigated for this reason. We present here the effect of repetition rate on ablation efficiency and particle size distribution obtained by ablating a gold target in pure water. In the investigated range (100-5000 Hz) ablation efficiency is constant, and hence a linear increase is obtained for ablation rate. The particle size distribution is strongly affected by the laser pulses repetition rate and the total number of pulses due to radiation absorption happening parallel to the particle generation. Higher fragmentation efficiency (plasmon peak shift per pulse) has been found at pulse delays similar to the characteristic diffusion time trough the focal region (estimated to some milliseconds) (Figure 1). Repetition rate has been shown to be an important parameter affecting the nanoparticle generation in liquids by laser ablation. Productivity as well as particle size might be controlled by a proper choice of the pulse frequency used for ablation.

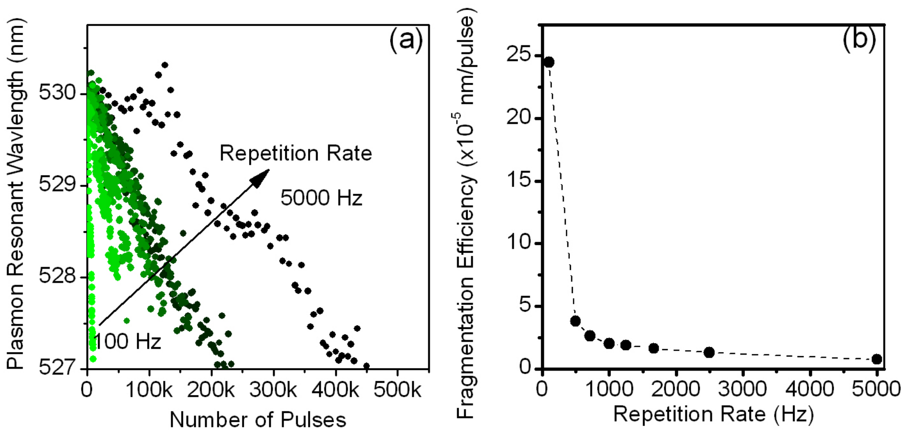

Figure 1 Agglomeration index variation with the number of pulses at different repetition rates [100-5000 Hz] (a) and corresponding fragmentation efficiency of gold nanoparticles in water (b).

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Thin silicon wafers dicing using line-focused nanosecond-pulse 355nm q-switched laser

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The widespread use of thin silicon wafers in the semiconductor industry is driving large and growing interest in laser-based wafer dicing solutions. Especially, as the wafers become thinner, the advantage of laser dicing over saw in terms of both the speed and yield of the process is very apparent and remarkable. For dicing of thin silicon wafers, managing the laser heat input during the dicing process is very important due to increasingly thin wafers and narrow kerf width requirement. In this work, line-focused beam laser-cutting of thin (100 μm and below) silicon is explored using Spectra-Physics® Pulseo® 20-W nanosecond-pulse 355-nm DPSS q-switched laser. Optimal process conditions for cutting various depths in silicon are determined, with particular emphasis on fluence optimization for a narrow-kerf cutting process. By shaping the laser beam into a line focus, the optimal fluence for machining the silicon can be achieved while at the same time utilizing the full output power of the laser source. In addition, by adjusting the length of the laser line focus, the absolute fastest speed for various cutting depths is realized. Compared to a circular beam, a dramatic improvement in process efficiency is observed. Also, the effect of laser pulse width on fastest cutting speed achieved for different cutting depths has been investigated.

Formation of Polycrystalline Ge Micropattern by Laser Direct Writing Method Using Germanium Ink Consisting of Organogermanium Nanocluster

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Recently, solution processing using novel nanomaterials attracts more and more interests toward printable & flexible and large area electronic devices. Although germanium is a fundamental element in electronic devices, there are few reports on a printable process using a germanium ink. In previous studies, we have reported the syntheses and optical and electrical properties of an organogermanium nanocluster (OrGe) which has a germanium nanocluster of a few nanometers and organic groups modifying the nanocluster [1]. The OrGe can be also considered to be a hyper branched organogermanium polymer consisting of Ge-Ge chain. Such an organosoluble germanium nanocluster was prepared from tetrachlorogermane in a solution using Mg, and then the surface was modified by an organic group. The OrGe is a stable Ge source which can be handled even in the air. In this study, we prepared micropatterns of polycrystalline Ge (*pc*-Ge) by a solution process using a germanium ink consisting of the OrGe and an organic solvent. The micropatterning and the crystallization of the OrGe film were achieved by laser direct writing method. In the process, the laser beam was focused through an objective lens and irradiated on the spin-coated OrGe film. Micropatterns of the *pc*-Ge were obtained by scanning the laser beam using PC-controlled xyz stage. By etching using an organic solvent as an eluent, the unirradiated area was easily removed. The laser direct writing method showed a high resolution of a few micrometers. The structural changes of the Ge skeleton were investigated by micro-Raman spectroscopy monitoring the characteristic Raman band around 300 cm^{-1} which is assigned to the TO-phonon band of the Ge skeleton. The linewidth and the peak position of the Raman band are sensitive to the crystallinity. The micropatterns prepared by laser direct writing method using CW Nd:YAG laser (532 nm) under Ar showed a sharp Raman band of *pc*-Ge at 302 cm^{-1} and no band of residual carbon around 1300 cm^{-1} as shown in Figure 1. A microdevice consisting of *pc*-Ge and Ag microelectrodes was fabricated by all wet process based on the laser direct writing method using Ge and Ag nanoparticle-dispersed inks as shown in Figure 2. The formation of the *pc*-Ge was possible even in the air by using laser direct writing method. For the CW laser system, the dependence of the crystallinity on the scanning rate was investigated. The effects of the short duration pulse irradiation and the repetition rate on the crystallinity were also studied by using femtosecond laser systems.

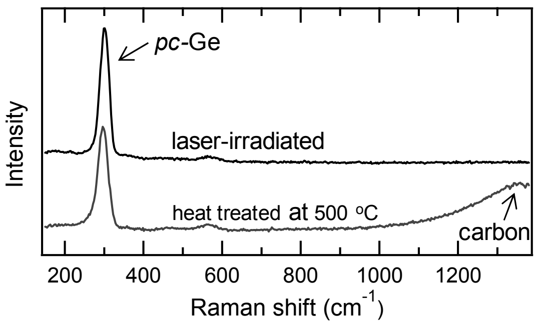

Figure 1 Micro-Raman spectra of micropattern prepared by laser direct writing method using CW Nd:YAG laser (532 nm) under Ar and the OrGe film heat treated at 500 °C in vacuo.

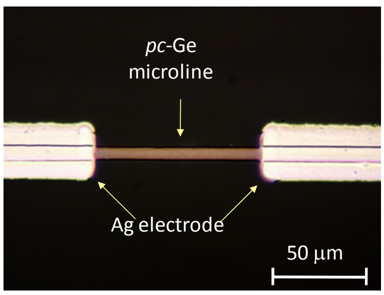

Figure 2 Microdevice consisting of *pc*-Ge and Ag micro-electrodes fabricated by all wet process based on the laser direct writing method.

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Laser Based Vacuum Packaging of Micro-Devices Using Localised Heating

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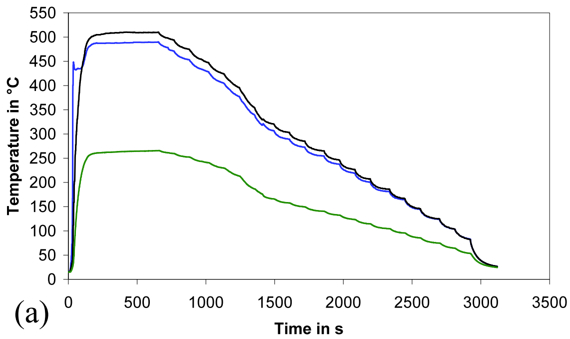
In recent years the interest in micro-devices, including Micro-Electro-Mechanical-Systems (MEMS), from research institutions, firms and the press has risen considerably. However one of the persisting challenges in the fabrication of such devices is the packaging process [1, 2]. A number of different bonding techniques have been developed but in general they require the entire device to be heated to high temperatures. In particular for direct bonding techniques like Si-fusion and anodic bonding, temperatures in excess of 1000°C and strong electric fields (1000-2000 V) are essential for successful packaging. As a consequence the use of temperature-sensitive materials within the package is restricted and problems are generated in multi-stage packaging processes where several heating cycles are carried out in sequence; parts joined in an earlier heating step can disassemble in a later one. Furthermore it is clearly important that the package should not affect the performance of the device or cause any damage. Often hermetic and/or vacuum packaging is required which makes the process application specific and expensive. Therefore it can easily account for up to 50% of the overall device cost and can even reach as much as 90% [3].
Our solution is to combine the benefits of intermediate layer bonding – considerably lower bonding temperatures and absence of electric fields – with the highly localised heating possible with a laser. In addition to localised heating, appropriate heatsinking is required due to the long time-constants of the process (tens of seconds). The device is hence placed in good thermal contact with a heat sink to draw the excess heat away through the base of the device.
In previous studies we have shown that using this process we can achieve full hermetic seals according to MIL-STD-883G for standard electronic packages with a glass frit intermediate layer using our localised laser heating process in an air environment [4]. In this presentation we will describe a further development of this process to vacuum packaging. A laser-based glass frit bonding process is demonstrated which successfully addresses the challenges in vacuum packaging (e.g. choice of materials). In order to optimise the laser bonding parameters temperature monitoring experiments are carried out to match the laser power to the required bonding temperature, and to monitor to the temperature in the centre of the device during the process (see figure 1a). LCC packages have been bonded successfully (see figure 1b) using these optimised parameters, for which the temperature in the centre of the device can be kept at least 200°C lower than in the joining area. All these samples have passed an initial gross leak test demonstrating the feasibility of packaging in a moderate vacuum using localised laser heating.



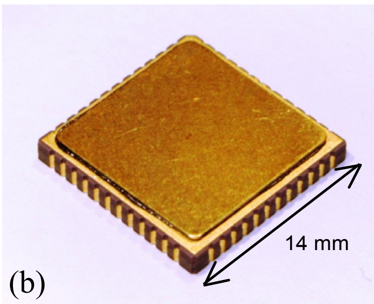


Figure 1 (a) Temperature profile of bonding process; blue and black traces: inside bonding layer; green trace: on substrate in the centre of the device. (b) Laser-bonded LCC Package.

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Femtosecond laser applied to photovoltaic cell processing.

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Two fields of femtosecond laser processing of photovoltaic cells will be presented: i) silicon surface micro/nano structuring and ii) CIS based photovoltaic cell scribing.
The formation of micro spikes and cones on crystalline silicon has been the subject of significant research during the past few years. The objective is to improve the unique optical properties that microstructured Si exhibits, i.e., increased absorptance throughout a wide spectral range, for possible applications in photodetector and solar cells. Significant optical absorption enhancement (more than 50 % in the UV and 35% in the IR) have been obtained, compared to a non-texturized silicon surface. Detailed TEM analyses of the micro-spikes will be presented showing their surprising mono and polycrystalline structures. In order to create an efficient junction for solar cells, we have doped our laser textured surface with a Plasma Immersion Ion Implanter. The Internal Quantum Efficiency has also been increased, especially in the UV. Therefore the electrical performance is also drastically improved: we observed a 50% increase in the photocurrent.

Micromachining of CuInSe2 (CIS)-based photovoltaic devices with short and ultrashort laser pulses was also considered. Ablation thresholds and rates of ZnO, Mo and $CuInSe_2$ thin films have been compared for irradiation with nanosecond laser pulses of ultraviolet and visible radiation and sub-picosecond laser pulses of a Ti:sapphire laser. The cells photo-electrical properties were measured before and after laser machining. Scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analyses were used to characterize the laser-induced ablation channels.

For both studies laser ablation mechanisms and structuring will we discussed as well as material modification and redeposition. Finally the cooperative European project Solasys http://www.solasys.eu dedicated to laser processing of next photovoltaic cell generation will be shortly introduced.

Continuous Fabrication of Colloidal Organic Nanoparticles by Laser Ablation of Microcrystals in Liquid

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Fabrication of colloidal organic nanoparticles is a promising approach to combine molecular properties with tailored nanoparticle characteristics like electronical, optical or solubility properties as a function of particle size. Keto et al. [1] showed that laser ablation of microcrystals (LAM) in an aerosol flow is an efficient and universal applicable method for generating nanoparticles in the gas phase. Asahi et al. [2] adopted the LAM-process for generation of organic nanoparticles in liquid media.

We present a novel approach for continuous fabrication of colloidal organic nanoparticles by laser ablation of microcrystals in aqueous suspension by using a fine liquid jet. The free liquid jet is generated by a nozzle with small diameter and provides a thin liquid filament (d_{fil} < 1 mm) perpendicular to the focused laser beam [3]. This geometry allows tight focusing resulting in high intensities without the danger of damaging an optical element like windows necessary in conventional flow cells or cuvettes and reduces losses of excitation light by avoiding scattering or absorption in front of the focus. To test this scaleable, high-through put method we chose melamine cyanurate as a nearly water-unsoluble microcrystalline model compound. For continuous operation the generated nanoparticles were separated by filtration methods from the cycled microparticle suspension.

The resulting colloidal nanoparticles were analysed by dynamic light scattering, TEM-analysis, UV/VIS-, IR and NMR-spectroscopy. Figure 1 shows TEM-images of the educt (microcrystalline needles in the range of 2-5 µm) and laser irradiated samples which show the formation of nearly spherical nanoparticle in the range of 100-200 nm.

By adding different stabilization agents (neutral and polyelectrolytic polymers like dextrin, dextran, PVP or polyacrylic acid) we were able to stabilize the laser generated nanoparticles *in situ* with tuneable properties like particle size or Zeta-potential.

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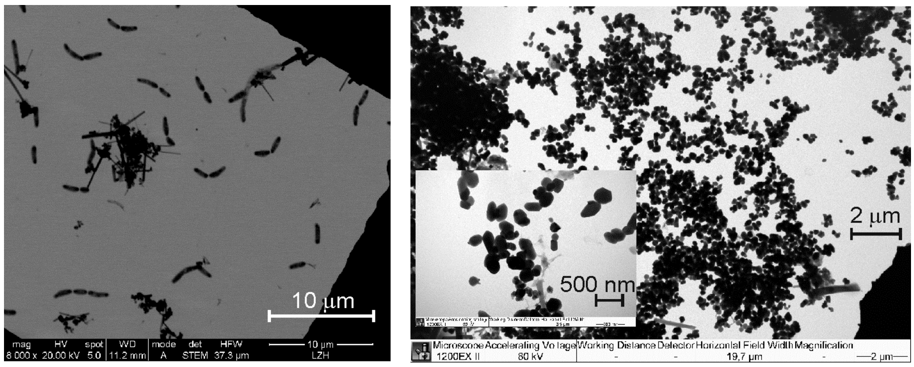

(a) (b)

Figure 1 TEM images: (a) Unirradiated melamine cyanurate. (b) Laser fragmentated melamine cyanurate stabilized with 0.1 wt% dextrin (image by Sachtleben Chemie GmbH)

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Synthesis of nanoparticles in solution using femtosecond laser ablation

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Nanoparticles are known to have many features that make them usable for various applications. Manufacturing of nanoparticles with femtosecond ablation is widely reported in the literature [1-3]. However, there is no description how these generated particles relate to the surface morphology of the ablated surface. We have generated nanoparticles of various metals in the solution using femtosecond laser ablation. Scanning electron microscope images of the ablated surfaces show the spherical particle generation on the surface. These images indicate that the maximal particle size in solution is related to the ablated surface morphology and more specifically to the ripple structure formation. This gives the possibility to control the particle size distribution by manipulating the period of the ripple structure. In the figure 1. is shown scanning electron images of laser induced surface structures formed in solution using focused femtosecond beam on the stainless steel sample.

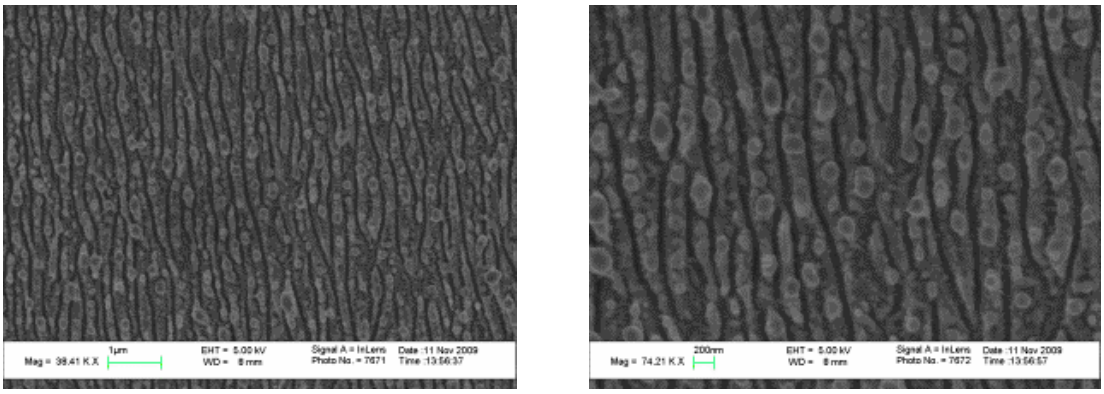

Figure 1. Surface of the stainless steel sample after femtosecond ablation in solution.

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Laser processing for advanced solar cells

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Laser processing is becoming an important production tool in the manufacturing of photovoltaic (PV) solar cells and modules, with huge potential to enable new technology generations in the near future. In this contribution, examples of next generation crystalline silicon and thin-film PV devices that are developed by ECN incorporating laser processes, ranging from macroscopic drilling of holes into silicon to micrometer scale selective ablation of nanometer thin films, will be presented.
Figure 1 shows a so-called metallization-wrap-through solar cell, where 16 laser drilled vias enable the reduction of surface coverage of the solar cell by current collecting silver grids and thus increase the amount of sunlight that can be converted into electricity, see Figure 1. This leads to higher current generation and thus higher conversion efficiency. Additionally, this cell concept allows simpler production of PV modules, and at the same time higher module efficiency. ECN recently achieved a world record module efficiency of 17% with this technology. Even more advanced crystalline silicon solar cells may incorporate laser processes like e.g. drilling of 10000s of holes per wafer in 1-2 seconds, the ablation of nm thin transparent layers, and (local) laser doping.

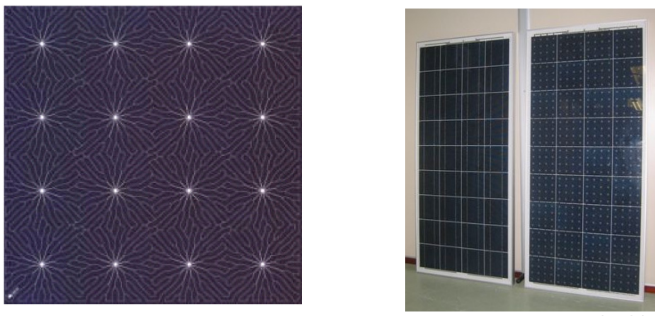

Figure 1. Metallization wrap-through solar cells with 16 laser drilled vias (left), and advanced module concept enabled by this cell technology, side-by-side with conventional crystalline silicon PV module. (Solland Solar Energy Holding BV is the owner of the registered industrial designs Sunweb®)

In the field of thin-film PV, a transition from today's glass based technologies towards devices on foil substrates that can be produced in roll-to-roll fashion, offers a tremendous potential for further cost reduction. Figure 2 illustrates ECN's concept for low-cost high efficiency thin-film silicon PV on steel foil. One special feature in this concept is the advanced monolithic series interconnection scheme, which requires three depth selective scribes (P1, P2, P3).

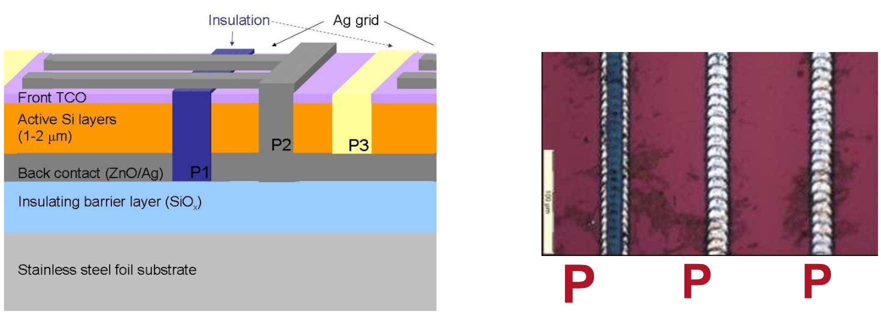

Figure 2. ECN's low-cost high-efficiency thin-film Silicon PV concept requiring three depth selective laser scripes (P1, P2, and P3) and the realization of the three scribes within 250 micrometer width (right image).

Nanojoining of Ag/Au nanoparticles by femtosecond laser irradiation

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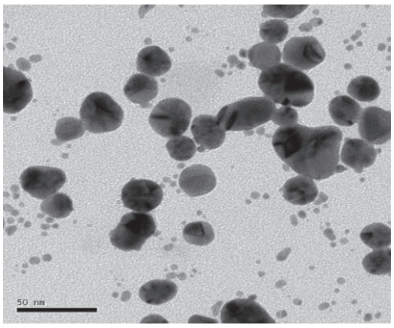
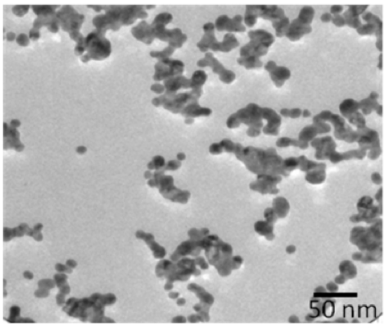
The interaction between femtosecond laser pulses and Ag/Au nanoparticles has been investigated. Three effects are identified at different intensities: photofragmentation at rather high intensity (~10^{14} W/cm^2), nanojoining at low intensity (~10^{10}W/cm^2) and shock wave processing at intermediate intensities. Photofragmentation forms a large number of tiny nanoparticles with an average size of tens of nanometers. After prolonged irradiation a narrow size distribution of nanoparticles is obtained. In the intermediate intensity regime, spherical nanoparticles are changed into a disc shape by interaction with the shock wave. A further increase in laser intensity results in the formation of ring-shaped fragments separated from the core particles. Subsequent splitting of the ring yields more small nanoparticles. Control over irradiation conditions at intensities near 10^{10} W/cm^2 results in nanojoining of most of the nanoparticles. This nanojoining is obtained in both liquid solution and in solid state thin films assembled from nanoparticles.



(a)



(b)

Figure 1 (a) Photofragmentation of Au nanoparticles at a laser intensity of 10^{14}W/cm^2.
(b) Nanojoining of Au nanoparticles at 10^{10} W/cm^2.

Nanojoined Ag nanoparticles are expected to have numerous applications as probes for surface enhanced Raman spectroscopy of DNA molecules.

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Ultraviolet optical near-fields of micro spheres imprinted in phase change films

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The local field enhancement in the vicinity of particles has been identified as a powerful means for nanopatterning applications [1]. We report an experimental method for directly imaging optical near-fields of dielectric micro spheres produced upon illumination with UV light. Placed onto a thin crystalline chalcogenide film, the micro spheres are irradiated by single ns excimer laser pulses at 193 nm wavelength, giving rise to a complex 2D intensity distribution, which is imprinted in the film as amorphous patterns. We have modelled the experiment by rigorously solving Maxwell's equations for a sphere supported on a layered planar substrate, obtaining a close match to the experimental results. The recorded patterns feature multiple types of contrast, including optical [2], electrical [3], and topographic [4]. While the short wavelength used in our case is optimum for imprinting nm-scale features, exploiting the optical contrast for imaging proves problematic because of the limited spatial resolution of optical microscopy. We have exploited therefore other contrast types (topography, electrical conductivity) to allow for high-resolution readout, employing field emission scanning electron microscopy (SEM) and scanning probe microscopy, and report features with sizes of < 200 nm. It is found that heat flow causes the features to fade out only slightly compared to the incident distribution.

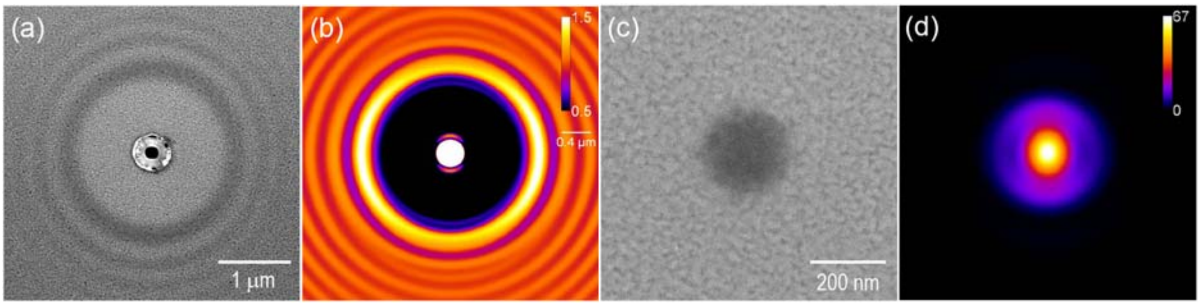

Figure 1 : Amorphous imprints of the optical near-field of 193 nm light interacting with silica spheres (1.61 μm diameter) sitting on thin crystalline $Ge_2Sb_2Te_5$ films. (a) Imprint at high laser intensity recorded by field-emission SEM, showing a central hole and a surrounding amorphous fringe pattern, well reproduced by the (b) calculation when scaling the intensity to display the low intensity wings. (c) Imprint at low laser intensity recorded by field emission SEM, showing a central amorphous spot with a diameter of ≈ 200 nm, somewhat larger than that of the (d) calculated intensity distribution (≈ 100 nm).

Compared to our previous work using infrared femtosecond laser pulses [5], the use of UV ns pulses is identified to be superior in terms of simplicity, downscaling of feature sizes as well as roughness of the imprint. This technique is directly applicable to any type of scattering particle (size, shape and material), thus providing a simple way of imaging its near-field with highest resolution as well as exploiting the near field for high-precision nanopatterning applications.

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Laser based processes in next generation solar cell production, chances and challenges

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World-wide solar cell manufacturers are looking for breakthrough technologies to reduce the cost and enhance the efficiencies of their devices. The main ITRS target is the cost reduction of solar energy below 1 € per Watt. The technology driver, i.e. the cost per watt could be fulfilled by addressing three requirements:

- Decrease the cost of ownership in production
- Decrease the thickness of the cell
- Increase the efficiency

Cost of ownership decrease

The yearly growth rate of PV market exceeds 30% since almost ten years and the world PV solar cell production in 2009 exceeds 7500 MWp [1]. Such significant figures highlight the cost reduction of solar cell by production decrease.

In the same time efforts are done by both PV Manufacturers and Research Institutes for reducing the cost of the solar cell by decreasing the cost of the base material, i.e. the silicon wafers and by increasing the electrical performances of the devices.

Wafer thickness decrease

The wafer thickness development in mass production has shown a constant decrease, from about 300 µm in 2004 to 180µm in 2008 [2] and is expected to be as low as 100 µm in 2020. The material cost savings by reducing wafer thickness is evident but induces technical showstoppers in term of thin substrate integration on the current fabrication technology. It is admitted by the international PV community that 150µm thickness is the limit for the standard technology because of both mechanical integrity and passivation issues. The bowing effect occurring with thin wafers due to the mechanical stress between the back side full sheet screen printed aluminium layer and the silicon prevents any acceptable encapsulation of the cells. Technological breakthrough is thus required for shift toward ultra thin wafer. Especially, the full sheet aluminium layer has to be replaced by a process limiting the stress of the wafer. On the other hand, the absorption depth of long wavelength photons (infra-red) deep in the substrate requires a specific attention in term of back side passivation when substrate thickness decreases. Improved processes based on new dielectric materials have been developed for limiting charge carrier surface recombination. PECVD SiNx [3,4] , Al2O3 [4,6], a-Si [5], SiON and thermal SiO2 [5] layer have proved their efficiency for good surface passivation.

Performances increase

A significant improvement of electrical performances could be reached by complicating the standard industrial solar cell process flow, i.e. KOH texturing, high temperature POCl3 emitter formation, SiNx antireflective coating deposition and front and screen printed back side metallization.

One efficient structure, so called selective emitter, provides an absolute efficiency improvement below +0.5% [8]. A highly doped emitter underneath the contacts provides better ohmic contact while a better blue response and better passivation are achieved by reducing the doping level in the region between the contacts. The fabrication process is currently based either on diffusion barriers opening with etching paste [7,8] or laser ablation [8,9] before high temperature diffusion step, or screen printing doping paste or with emitter etch back procès. The selective emitter structure is little used in industrial silicon solar cell fabrication, except by the Saturn structure of BPsolar and the Pluto structure of Suntech because despite higher efficiency potential, selective emitter requires complex additional steps in the process flow.

All of the other high efficient laboratory or industrial structures are based on complex process requiring specific patterning technology. The PERL structure of UNSW reaches the record efficiency of 24.7% while the IBC rear contact cell of Sunpower reaches 23% and the i-PERC structure of IMEC reaches 22%. This structure combines selective emitter on front side with printed or plated metallization and a localised back surface field on back side on ablated passivation layer with PVD back side metallization. It is well adapted for thin substrate integration but its fabrication remains complex.

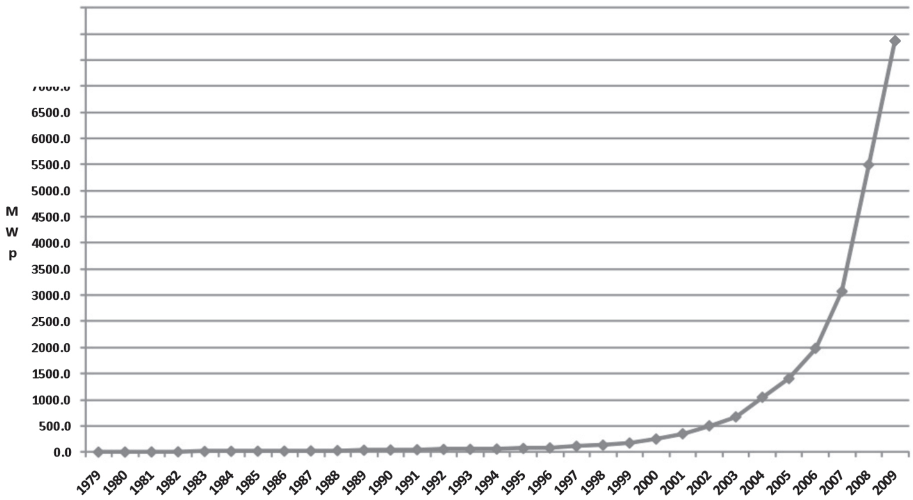

Figure 1 : Industry Growth: 1979 to 2009: 30 year compound annual growth rate of 33% [1]

Laser processes

Many industrial obstacles could be by-passed by using laser for ablation, doping or metallization. The main advantage is the single-step processing through the potential suppression of several additional expensive process steps like second high temperature diffusion, lithography step and various etching steps required during the dielectric opening approach. A strong cost saving could thus be realized by the use of laser for emitter realization. Other advantages are high flexibility, direct writing of structures by moving the laser beam at speed much greater than can be obtained with mechanical tools, no contamination of the material being processed and the extreme focusing that is possible, leading to high resolution feature definition. Furthermore, it has been demonstrated that the laser processing does not require clean-room conditions and could be carried out in ambient air. Finally, the contactless nature of laser treatment makes this technique attractive for processing very thin silicon wafers.
In terms of laser source, parameters have to be selected regarding the targeted application: ablation, doping or metal sintering.
For dielectric ablation on silicon, short wavelength like UV (355nm) or Excimer (308nm) are recommended because light absorption is contained close to the surface, favouring top surface effect and thus low underlying silicon damage. Silicon degradation can be also limited by using short pulse duration like tens of nanosecond or hundreds picosecond regimes to limit thermal-induced heating, melting and debris around ablated regions Engelhart et al. confirmed that, when using picosecond pulses, damage is negligible and the opened areas can be contacted without any damage etching.
For laser doping, thermal effects should be favoured because the irradiated silicon should be melted for letting the doping atoms a chance to be introduced into the crystalline matrix during recrystallisation. The nanosecond thermal regime is thus preferred at a large range of wavelengths, IR to UV and below. On the other hand, the laser induced crystalline damage fatal for electrical performances has to be minimized. The source of dopant atoms could be provided by a residual layer like the phosphorous sheet glass (PSG) remaining after POCl3 high temperature diffusion or by additive doping layer like spin on glass.
The laser sintering requires also a thermal effect since the deposited metal should be melted to contact with the silicon. Scheiderlockneer et al. report firing of PVD aluminium with IR wavelength pulsed laser for back contact of i-PERC structure leading to 22% solar cell efficiency.

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Two dimensional periodic nanostructures with enhanced band-gap emission on ZnO induced by the interference of three femtosecond laser beams

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Surface patterning of two-dimensional (2D) nanostructures has become increasingly important for the applications of nanoelectronics, photonic crystals and super bright light-emitting diodes (LEDs).[1] Due to the high efficiency and low cost, holographic lithography has become an important technology to fabricate 2D nanostructures by adjusting the number of laser beams and their spatial arrangements.[2] Recently, nanoripples with periods much shorter than the laser wavelengths were reported in semiconductors and dielectrics after irradiation of linearly polarized femtosecond laser.[3] These nanoripples were perpendicular to the laser polarization. If laser was circularly polarized, nanoparticles would be induced on the sample surface.

Combining the fabrication of short-periodic nanostructures by femtosecond laser irradiation with HL technology, we made a further investigation of the fabrication of regular and uniform 2D nanostructures on ZnO crystal by increasing the cross angles between any two laser beams. The enhanced band-gap emission of these nanostructures and their applications in nano-LED and high density optical storage were also studied (see figure 1).

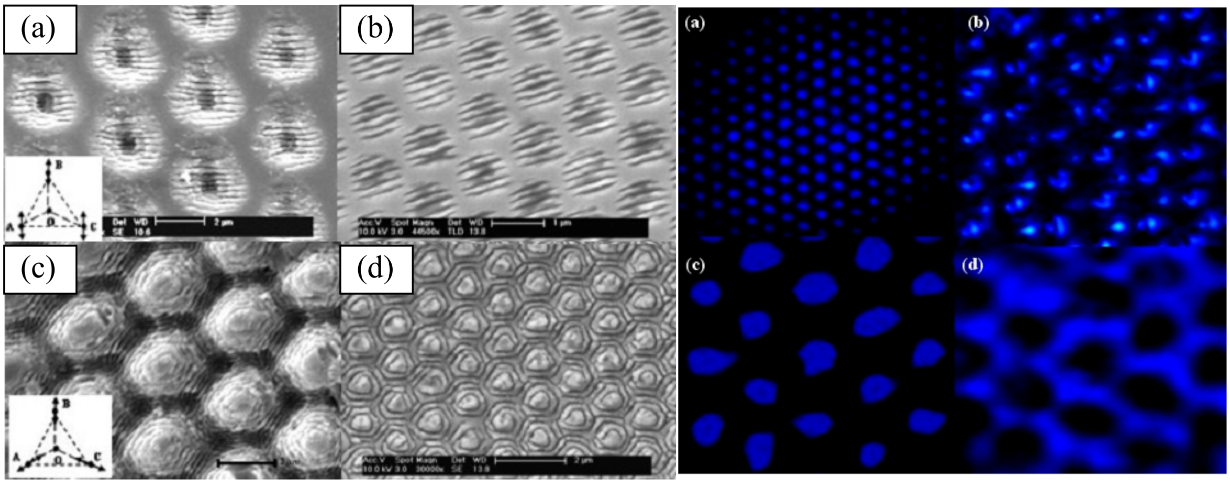

Figure 1. SEM images of the ablation areas induced by the interference of three laser beams. The insets in (a), and (c) show the polarization geometries of the three laser beams, respectively. The left images are photoluminescences microscopes corresponding to the left four images pumped by 800 nm femstosecond laser pulses.

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Thin silicon wafers dicing using line-focused nanosecond-pulse 355nm q-switched laser

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The widespread use of thin silicon wafers in the semiconductor industry is driving large and growing interest in laser-based wafer dicing solutions. Especially, as the wafers become thinner, the advantage of laser dicing over saw in terms of both the speed and yield of the process is very apparent and remarkable. For dicing of thin silicon wafers, managing the laser heat input during the dicing process is very important due to increasingly thin wafers and narrow kerf width requirement. In this work, line-focused beam laser-cutting of thin (100 μm and below) silicon is explored using Spectra-Physics® Pulseo® 20-W nanosecond-pulse 355-nm DPSS q-switched laser. Optimal process conditions for cutting various depths in silicon are determined, with particular emphasis on fluence optimization for a narrow-kerf cutting process. By shaping the laser beam into a line focus, the optimal fluence for machining the silicon can be achieved while at the same time utilizing the full output power of the laser source. In addition, by adjusting the length of the laser line focus, the absolute fastest speed for various cutting depths is realized. Compared to a circular beam, a dramatic improvement in process efficiency is observed. Also, the effect of laser pulse width on fastest cutting speed achieved for different cutting depths has been investigated.

Design of bioconjugated gold nanoparticles by femtosecond-laser ablation

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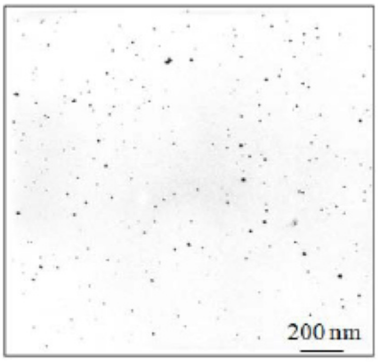
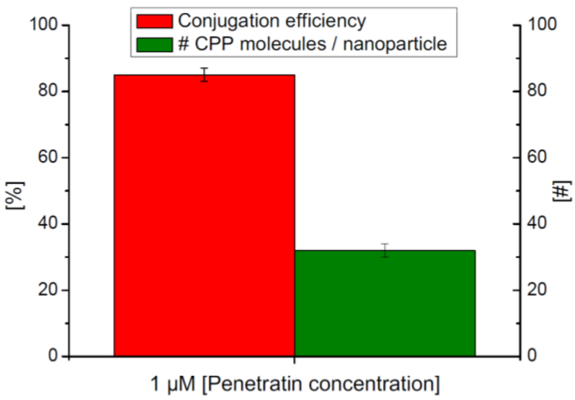
Enhanced by their surface plasmon resonance, gold nanoparticles (AuNP) exhibit photostable light scattering properties under strong light illumination making them particularly useful in cell targeted drug delivery, high resolution bioimaging and medical diagnostics when conjugated with functional entities. In addition gold nanoparticles have been found to induce low cytotoxicity bringing the possibility of using the gold conjugates for biomedical applications.
A popular strategy to improve the delivering efficiency of nanoparticles across cell membranes in a receptor- and energy-independent manner is the functionalisation with cell penetrating peptides (CPP) like the Antennapedia homeodomain derived Penetratin peptide.
The conjugation of AuNP and a CPP was achieved by femtosecond laser ablation in liquid. During this versatile, single step approach ultra-short laser pulses generate pure gold nanoparticles with electron accepting properties from a bulk material. Subsequently *in-situ* surface functionalisation takes place between ablated nanoparticles and the dissolved biomolecules containing electron donor-moities like a thiole or disulfide function. With the biomolecule conjugation the nanoparticle growth is quenched, leading to a narrow size distribution (Figure 1 a). Considering 7 nm of average nanoparticle size, we observed conjugation efficiency of 85 % and estimated 32 coupled CPP molecules per nanoparticle (Figure 1 b) when ablating gold in 1 μM Penetratin solution.



(a)



(b)

Figure 1. (a) Transmission electron microscopy image of Penetratin (1µM)-conjugated gold nanoparticles, generated by laser ablation in liquids. (b) Conjugation efficiency and number of Penetratin molecules per nanoparticle.

In-situ conjugation of gold nanoparticles was also investigated by HIV-derived TAT CPP where an even higher conjugation rate was achieved, probably due to the smaller physical size of the molecule. Furthermore, we revealed that ablating with 100 µJ laser pulses in liquid flow of 450 mL/min significantly enhance nanoparticle production rate by a factor of 5.5 compared to stationary liquid ablation, owing to the prompt removal of nanoparticles from the ablation zone.
In respect to all these promising results we are next going to investigate the biomedical combatibility of the AuNP-CPP conjugates in the cellular system.

Laser processing of thin films for photovoltaic applications

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During the last years, research & development (R&D) activities in the field of photovoltaics have grown enormously. For many new concepts, like thin-film modules, organic solar cells, but also new wafer based cell designs, high conversion efficiencies have been shown. But, for a successful market expansion, efficient and durable products at low costs are necessary. To realize this, laser structuring of thin films is of high importance for all the mentioned types of solar cells. To develop the required low-cost production technology, further R&D in this field is still necessary. For new wafer based cell designs, the structuring of etching masks or dielectric layers without damaging the underlying material has to be done. For thin-film solar cells, structuring is used for monolithical serial connection of cells in a module. Laser ablation is already used for several processes in industry, but challenges according to improved quality, high processing speed, and new material combinations are still enormous.

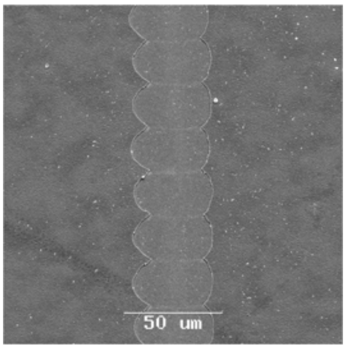

Figure 1: Structuring of silicon-based thin film solar cell for monolithical serial connection of cells in a module

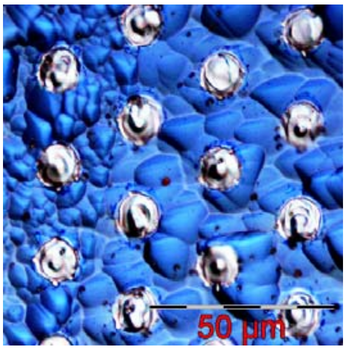

Figure 2: Punctuated SiN_x layer as etching barrier.

This paper discusses the structuring of several thin film materials used for solar cells, e.g. SiNx, SiO2, TCO, and photoactive materials. The focus of the experiments is to obtain an optimal edge quality without damaging either the substrate or the layer below the structured region. Two important laser parameters are wavelength and pulse duration which determine the absorption of the laser radiation in the processed material and the extent of heat influence on the surrounding material. Processing with several wavelengths (e.g. 355 nm, 532 nm, and 1064 nm) and pulse durations in the pico- and nanosecond range are studied. The results obtained with the different laser parameters will be compared according to ablation threshold, debris, and damage due to heat conduction. The quality of laser processing will be demonstrated by scanning electron and optical microscopy and an analysis of electrical characteristics e.g. resistance. Results from the structuring of Transparent Conductive Oxides, organic layers and metal layers are acquired with different laser types. Additionally, comparisons are made regarding the achievable structuring quality for mass production relevant speeds around 1 m/s for thin films and 1-2 seconds processing time for wafer based cells.

Nanostructures on ITO thin film irradiated by different femtosecond laser wavelengths

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The fabrication of crystalline indium tin oxide (c-ITO) microstructures and nanostructures on amorphous ITO (a-ITO) thin film by femtosecond laser-induced crystallization using a fiber laser with a repetition rate of 1 MHz, a pulse duration of ~400 fs, wavelength of 1064 nm and 532 nm were presented. The procedure consists of two steps: (1) irradiation of a-ITO thin film with focused laser beams to form predetermined patterns; (2) removal of unirradiated a-ITO film using an oxalic acid etchant, leading to the formation of the c-ITO pattern.

The fabricated surface structures are observed using scanning electron microscopy (SEM). The morphology of the periodic structures under different experimental conditions such as laser polarization, laser power, and scanning speed were investigated. Figures 1 and 2 show the SEM images of the line patterns with linearly polarized in a direction parallel to the scan direction with laser wavelength 532 nm and 1064 nm, respectively. Figure 3 shows that nanogratings with period ~116nm and ~250nm are formed at laser wavelength 532nm and 1064nm, respectively. The formation of the nanogratings can be attributed to the actions of the second-order harmonic waves within the femtosecond laser beam, i.e. $\lambda/2n$, where λ is the wavelength of the incident laser and n is the refractive index of the irradiated material. In our experiments, the magnitude n of the ITO thin film for 532 nm and 1064 nm laser is approximate 2, the nanograting period is calculated to be 133 nm and 266 nm, which is close to the experimental data shown in Figure 3.

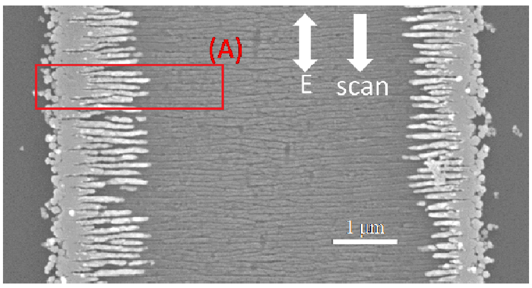

Fig. 1 SEM image of induced structure at laser wavelength 532 nm

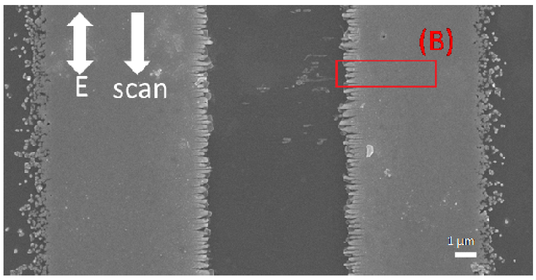

Fig. 2 SEM image of induced structure at laser wavelength 1064 nm

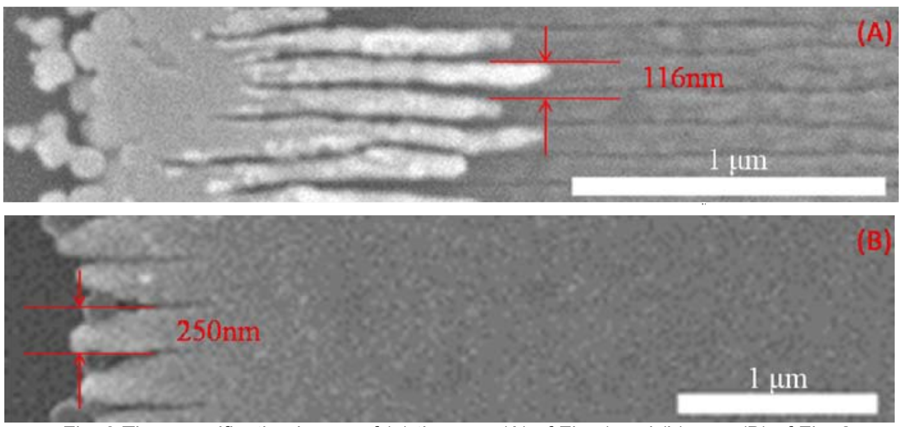

Fig. 3 The magnification image of (a) the area (A) of Fig. 1 and (b) area (B) of Fig. 2

Development and optimization of an industrial laser doping process for crystalline solar cells

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In the rapidly growing field of renewable energies, photovoltaics play an important role, though their share of the current energy production is very small. Lasers have proven to be a useful tool in the race to increase solar cell efficiencies, manufacturing throughputs and process reliability. Establishing lasers as an essential part of the manufacturing chain is the major goal of the European funded SOLASYS project ("Next Generation Solar Cell and Module Laser Processing Systems").
The creation of selective emitters is seen as an important step in improving existing production line cell efficiencies. By adding only one additional processing step, laser doping offers an attractive way of creating selective emitters cells whilst improving efficiency significantly by 0.3-1% absolute.[1] Instead of using an intermediate doping concentration to meet both the demand for good short wavelength current collection and for low contact resistance the doping concentration is increased locally at the positions of the front contacts. This can be achieved by laser doping the contact region before metal deposition. The selection of the proper laser parameters, such as wavelength, pulse length and laser power, allows control of the depth of the doping profile and the amount of laser induced damage. [2]

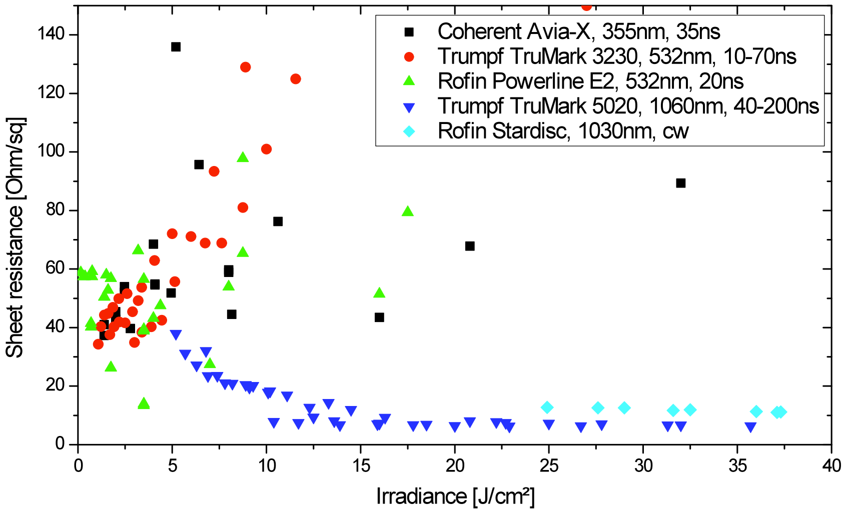

Figure 1 Sheet resistance of Silicon wafers after treatment with different lasers and different parameters. Initial sheet resistances lie between 55 and 100 Ohm/sq. A decrease indicates increased doping, an increase hints at emitter ablation.

In this study several laser sources covering all three main YAG wavelengths (1064, 532 and 355 nm) have been used to increase the doping of standard solar cell emitters. The residual Phosphor glass layer is used as dopant source. The experiments show promising results, with first full cell results forthcoming. The goal of this work is to find a reliable and stable process that can be scaled up toward industrial applicability. The throughput of the laser doping process is one of the main challenges.

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Femtosecond laser irradiation induced modification of gold nanorods inside silicate glass

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Noble metal-doped glass has offered the opportunity to manufacture promising new nonlinear materials, nanodevices and optical elements by manipulation of the nanostructural properties due to their strong surface plasmon resonance (SPR) and enhanced third-order nonlinear optical susceptibilities. [1] Recently, laser-based techniques leading to 3D photo-precipitation and further modifications of the metal clusters have proved to be a very powerful and flexible tool to control the size, shape, density, and spatial distribution of the metal nanoparticles, and thus optimize the linear and nonlinear optical properties of such materials [2-4].

In this paper, we report on the femtosecond laser induced modification of gold nanorods inside Na_2O-CaO-PbO-SiO_2 glass matrix and their strong birefringence, related mechanism about shaping of gold nanorods is also studied. Dependence on glass matrix, together with laser parameters such as laser wavelength, pulse duration or repetition rate are investigated. Figure 1 shows the image in crossed polarizers with rotation the sample 45 degree, where strong birefringence can be observed. Figure 2 shows the absorption spectra of gold rod doped glass before and after femtosecond laser irradiation. Absorption band slight shift with the femtosecond laser irradiation means that the changes of aspect ratio of nanorods, it should result in the second-harmonic generation [4].

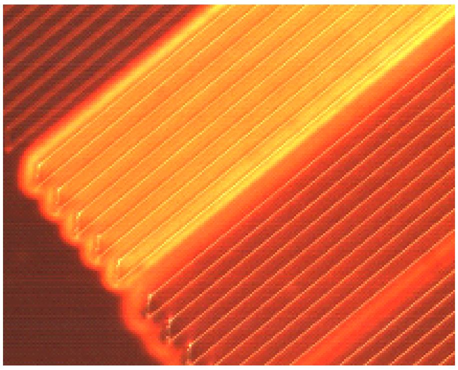

Figure 1 Image in crossed polarizers with rotation the sample 45 degree after 1K HZ femtosecond laser irradiation.

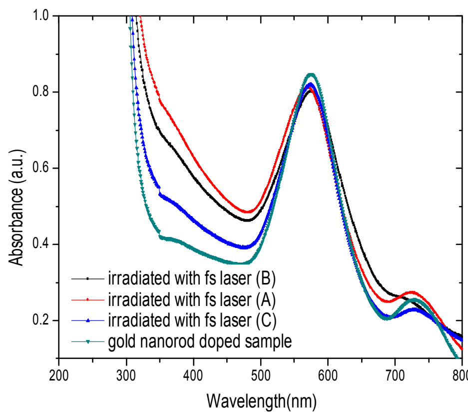

Figure 2 Absorption spectra of gold rod doped glass before and after femtosecond laser irradiation.

Permanent modification of gold nanorods inside silicate glass via irradiation with intense ultra short laser pulses and strong birefringence can be observed, and it is also depend strongly on the laser processing parameters and the characteristics of the irradiated glass. This technique can be applied to different 3D polarization and wavelength selective microdevices such as polarizers, filters, gratings and promising nonlinear optical media for photonic nanodevices .

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AUTHORS INDEX