4th International Symposium on Laser Precision Microfabrication

LPM 2003

Munich

June 21-24, 2003

Conference Chair

Isamu Miyamoto, Osaka University, Japan

Co-Chairs

Andreas Ostendorf,Laser Zentrum Hannover, Germany

Koji Sugioka, RIKEN, Japan

Henry Helvajian; The Aerospace Corporation, USA

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4th International Symposium on
Laser Precision Microfabrication
International Congress Center Munich

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THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING

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Welcome to LPM 2003

The International Symposium on Laser Precision Microfabrication (LPM) focuses on science and technology of advanced laser processing for precision microfabrication. Considering the requests from all over the world, the fourth LPM (LPM 2003) is now held at Munich, Germany, in cooperation with WLT-Wissenschaftliche Gesellschaft Lasertechnik e.V. The last three LPM conferences have won reputation and popularity as one of the most important international meetings in the field of LPM in the world. LPM 2003 is planned as a four day event, and during the conference, you can also enjoy “Laser 2003: World of Photonics” which is one of the largest international trade shows in laser and optics. The aim of LPM 2003 is to provide a forum for discussion of fundamental aspects of laser- material interaction, the state of the art of laser materials processing, and topics for the next generation by the collaboration among fundamental scientists, end users and laser manufactures. I do hope one can find out what technologies are limiting their real applications and future laser technologies to be developed through the papers presented by many world authorities invited to LPM 2003.

Conference Chair
Professor Dr. Eng. Isamu Miyamoto
Osaka University, Japan

Special Thanks to the LPM 2003 Cooperating Organizations

JSPE - The Japan Society for Precision Engineering

JSAP - The Japan Society of Applied Physics

JWS - The Japan Welding Society

Mate 2003

Mate 2003 - Committee of Micro Joining, The Japan Welding Society

LSJ - The Laser Society of Japan

JIEP - Japan Institute of Electronics Packaging

Committees

General Chair:
Isamu Miyamoto *(Osaka University, Japan)*

Co-Chairs:
Andreas Ostendorf *(Laser Zentrum Hannover, Germany)*
Koji Sugioka *(RIKEN, Japan)*
Henry Helvajian *(The Aerospace Corp., USA)*

Program Committee:
David Ashkenasi *(LMTB Berlin, Germany)*
Dieter Bäuerle *(Johannes Kepler University Linz, Austria)*
Boris Chichkov *(Laser Zentrum Hannover, Germany)*
Jan Dubowski *(NRC, Canada)*
Friedrich Dausinger *(University of Stuttgart, Germany)*
Corey Dunsky *(Electro Scientific Industries, USA)*
Gerd Eßer *(Bavarian Laser Zentrum, Germany)*
Arnold Gillner *(Fraunhofer ILT, Germany)*
Malcolm Gower *(Exitech Ltd., UK)*
Peter Herman *(University of Toronto, Canada)*
Ingolf Hertel *(Max-Born Institut Berlin, Germany)*
James Horwitz *(Naval Research Laboratories, USA)*
Hideo Hosono *(Tokyo Institute of Technology, Japan)*
Willem Hoving *(Philips CFT, Netherlands)*
Yoshiro Ito *(Nagaoka University of Technology, Japan)*
Kazuyoshi Itoh *(Osaka University, Japan)*
Takahisa Jitsuno *(Osaka University, Japan)*
Klaus Koerber *(Laser Zentrum Hannover, Germany)*
Vitali Konov *(GPI, Russia)*
C. Lee *(In-Ha University, Korea)*
Y. F. Lu *(University of Nebraska, USA)*
Hiroshi Masuhara *(Osaka University, Japan)*
Johan Meijer *(University of Twente, Netherlands)*
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Michel Meunier *(Ecole Polytechnique Montreal, Canada)*
Hiroaki Misawa *(Tokushima University, Japan)*
Hiroyuki Niino *(AIST, Japan)*
Jyunji Nishii *(AIST-Kansai, Japan)*
Etsuji Ohmura *(Osaka University, Japan)*
Tatsuo Okada *(Kyushu University, Japan)*
Toshihiko Ooie *(AIST-Shikoku, Japan)*
Raj Patel *(IMRA America, USA)*
Alan Petersen *(Spectra Physics, USA)*
Juergen Reif *(University of Cottbus, Germany)*
Uwe Stamm *(XTREME Technologies GmbH, Germany)*
Michael Stuke *(MPI, Germany)*
Vadim Veiko *(St. Petersburg Institute of Fine Mechanics and Optics, Russia)*
Rui Vilar *(University of Lisbon, Portugal)*
Kunihiko Washio *(NEC, Japan)*
XianFan Xu *(Purdue University, USA)*
Takehito Yoshida *(Matsushita Electric Industrial, Japan)*

Organizing Committee:
Zhao-Gu Cheng *(SIOFM, China)*
Friedrich Dausinger *(University of Stuttgart, Germany)*
Gerd Eßer *(Bavarian Laser Zentrum, Germany)*
Burkhard Fechner *(Lambda Physik, Japan)*
Jim Fieret *(Exitech Ltd., UK)*
Kenshi Fukumitsu *(Hamamatsu Photonics, Japan)*
Arnold Gillner *(Fraunhofer ILT, Germany)*
M. H. Hong *(DSI, Singapore)*
Tony Hoult *(Coherent Inc, USA)*
Juergen Ihlemann *(Laser Laboratory Goettingen, Germany)*
Narumi Inoue *(National Defence Academy, Japan)*
Takashi Ishide *(Matsushita Heavy Industry, Japan)*
Shinichi Ishizaka *(Japan Steel Works, Japan)*
Yoshiro Ito *(Nagaoka University of Technology, Japan)*
Takahisa Jitsuno *(Osaka University, Japan)*
Teruyoshi Kadoya *(Trumph, Japan)*
Kazuo Kamada *(Matsushita Electric Works, Japan)*
Hidehiko Karasaki *(Matsushita Industrial Equipment, Japan)*
Kojiro Kobayashi *(Osaka University, Japan)*
Klaus Koerber *(Laser Zentrum Hannover, Germany)*
Christian Kulik *(Laser Zentrum Hannover, Germany)*
William P. Latham *(Air Force Research Laboratories, USA)*
J. M. Lee *(Samsung Electronics, Korea)*
Simon Metev *(University of Bremen-BIAS, Germany)*
Hiroshi Miura *(Shizuoka University, Japan)*
Takashi Miyoshi *(Osaka University, Japan)*
Sumio Nakahara *(Kansai University, Japan)*
Hirokuni Namba *(Sumitomo Electric Industry, Japan)*
Hiroyuki Niino *(AIST, Japan)*
Satoru Nishio *(Tohoku University, Japan)*
Klaus Nowitzki *(OptecNet Deutschland, Germany)*
Etsuji Ohmura *(Osaka University, Japan)*
Toshihiko Ooie *(AIST-Shikoku, Japan)*
Alberto Piqué *(Naval Research Laboratories, USA)*
Juergen Reif *(University of Cottbus, Germany)*
Tomokazu Sano *(Osaka University, Japan)*
Masaaki Tanaka *(Mistubishi Electric, Japan)*
Osamu Wakabayashi *(Gigaphoton, Japan)*
Kunihiko Washio *(NEC, Japan)*
Takehiro Watanabe *(Chiba University, Japan)*

Program Overview

Saturday, 21.06.2003

12:00-14:30	***Room 14C*** **Opening Session: Overview on Laser Precision Microfabrication** **Opening Remarks:** I. Miyamoto; Osaka University, Japan Session Chair: Andreas Ostendorf	
14:30-15:00	*Coffee Break*	
15:00-16:20	*Room 21* **Session 1: Thin-film Processing** Session Chair: Richard Haglund	*Room 22* **Session 2: Fundamentals of fs-laser Processing** Session Chair: Dieter Bäuerle
16:20-16:50	*Coffee Break*	
16:50-17:50	*Room 21* **Session 1** (cont.)**: Thin-film Processing** Session Chair: Richard Haglund	*Room 22* **Session 2** (cont.)**: Fundamentals of fs-laser Processing** Session Chair: Dieter Bäuerle
17:50	*End*	

Sunday, 22.06.2003

08:30-10:00	*Room 21* **Session 3: Machining of Silica and Glass** Session Chairs: Juergen Ihlemann, Koji Sugioka	*Room 22* **Session 5: Precise Structuring** Session Chairs: Alberto Piqué, Gerd Eßer
10:00-10:20	*Coffee Break*	
10:20-12:20	*Room 21* **Session 3** (cont.)**: Machining of Silica and Glass** Session Chairs: Juergen Ihlemann, Koji Sugioka	*Room 22* **Session 5** (cont.)**: Precise Structuring** Session Chairs: Alberto Piqué, Gerd Eßer
12:20-14:20	*Lunch Break*	
12:20-14:20	**Poster Session LPM**	
14:20-16:10	*Room 21* **Session 4: Manufacturing of Microsystems** Session Chairs: Etsuji Ohmura, Howard Baker	*Room 22* **Session 6: Special Session on EUV Technology** Session Chairs: Malcolm Gower, Kai Gäbel
16:10	*Coffee Break*	
16:10-16:40	*Room 21* **Session 4** (cont.)**: Manufacturing of Microsystems** Session Chair: Etsuji Ohmura, Howard Baker.	*Room 22* **Session 6** (cont.)**: Special Session on EUV Technology** Session Chairs: Malcolm Gower, Uwe Stamm
17:50	*End*	
18:30-21:30	*Bavarian Evening at the "Löwenbräukeller" (Bus transfer from Conference)*	

Program Overview

Monday, 23.06.2003

10:15	***Opening of the 16th International Conference on Lasers and Electrooptics*** *Conference room 14 b, ICM International Congress Centre MunichLPM Attendees are cordially invited to attend this meeting.* *10:15-11:00 History and future of solid-state lasers, R. Byer, Stanford University, Ginzton Laboratory, Stanford, CA, USA*	
11:00-12:40	*Room 21* **Session 7, Part I: Micro-Welding and Melting** Session Chair: Arnold Gillner	*Room 22* **Session 9: Precision Marking** Session Chair: Martyn Knowles
12:40-13:40	*Lunch Break*	
13:40-16:00	*Room 21* **Session 8: Applications of fs-laser machining** Session Chair: Henri Helvajian, Andre Egbert	*Room 22* **Session 10: Drilling and Microcutting** Session Chairs: Willem Hoving, David Ashkenasi
16:00-16:30	*Coffee Break*	
16:30-17:50	*Room 21* **Session 7, Part II: Micro-Welding and Melting** Session Chair: Kojiro Kobayashi	*Room 22* **Session 10** (cont.)**: Drilling and Microcutting** Session Chairs: Willem Hoving, David Ashkenasi
17:50	*End*	

Tuesday, 24.06.2003

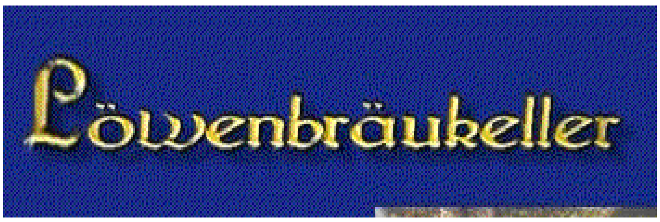
10:00	***Opening Session of LIM 2003, Lasers in Manufacturing*** *Conference room 14c, ICM International Congress Centre Munich.* *LPM Attendees are cordially invited to attend this session.* *10:00 Opening, R. Poprawe, President of the WLT, Germany* *10:05 WLT award ceremony, J. von Schäwen, BMBF, Germany* *10:15-11:00 Laser on demand (keynote), K. Löffler, Volkswagen AG, Wolfburg, Germany*	
11:00-12:50	*Room 21* **Session 11: Laser nano-machining** Session Chair: Isamu Miyamoto	
12:50-13:50	*Lunch Break*	
13:50 –16:10	*Room 21* **Session 12: Manufacturing of Waveguides** Session Chair: Peter Herman	
16:10-16:30	*Coffee Break*	**15:50-17:50** *Room 14C* **Session 14: Post-Deadline Papers** Session Chair: Christian Kulik
16:30-17:50	*Room 21* **Session 13: Dicing Processes** Session Chair: Udo Klotzbach	
17:50-18:00	*Room 21* **Closing remarks:** Andreas Ostendorf, Laser Zentrum Hannover e.V.	
18:00	*End of Conference*	
18:30-22:00	*Dinner Buffet at the "Paulaner am Nockherberg" (Bus transfer from Conference)*	

Invitation: Bavarian Evening (LPM*)

June 22nd, 2003

LPM 2003 is pleased to invite its participants to the following event.

18:30	Bus transfer from West Entrance of ICM (International Congress Center Munich) to "Löwenbräukeller"
19:00	Welcome Typical Bavarian snacks (pretzels, "obatzda" with radish, white sausages; with two free drinks)
21:30	Bus transfer to the hotel



* LPM participants receive their tickets for the evening with the registration materials

Invitation: Dinner Buffet Evening (LIM & LPM*)

June 24th,2003

LIM 2003 & LPM 2003 are pleased to invite
their participants to the following event.

18:30	Bus transfer from West Entrance of ICM (International Congress Center Munich) to "Paulaner am Nockherberg"
19:00	Welcome Dinner buffet (with two free drinks) Dinner speech: Dr. Stefan W. Hell (Direktor of the Max-Planck-Institute for Biophysical Chemistry, Göttingen), Winner of the Berthold Leibinger Innovation Prize 2003 Background music: The band "Duo" will entertain you with rock, pop and jazz
22:00	Bus transfer back to the hotel

* LPM participants receive their tickets for the evening with the registration materials

Oral Presentations

Session Overviews
and
Abstracts

Saturday, 21.06.2003

Room 14C

12:00	**Opening Session: Overview on Laser Precision Microfabrication** Session Chair: Andreas Ostendorf
12:00	**Opening Remarks** I. Miyamoto; Osaka University, Japan
12:30	**Reliable laser micro-spot welding of copper** (invited paper) S. Amorosi; R.P. Salathé; Th. Sidler; Applied Photonics Laboratory, EPFL Lausanne, Switzerland
13:00	**Light-induced single-step nanopattering of surfaces** (invited paper) D. Bäuerle; Johannes Kepler University Linz, Austria
13:30	**Resonant Infrared Deposition of Organic and Biological Molecular Thin Films** (invited paper) R.F. Haglund Jr.; M. R. Papantonakis; K. E. Schriver Vanderbilt University, Nashville, USA; J. S. Horwitz; E. J. Houser; R. A. McGill, US Naval Research Laboratory, Washington, D.C.,USA; D. M. Bubb, Seton Hall University, South Orange, USA
14:00	**Laser Micro-Bending for precise micro-fabrication of magnetic disk-drive components** (invited paper) N. Matsushita; Fujitsu, Japan

Reliable laser micro-spot welding of copper

S. Amorosi, R.P. Salathé, Th. Sidler, *Applied Photonics Laboratory, EPFL, (Switzerland)*

Nd:YAG laser welding of high reflectivity metals is difficult because of the highly non-linear light-material interaction yielding a narrow process window and poor reliability. However, achieving high reliability is mandatory for applying this technique in industrial production lines. The welding control can be improved by real-time monitoring of the process evolution with sensors. Such sensor signals are particularly useful for weld classification and for laser power control in off-line or in closed-loop feedback configurations. The latter possibility is difficult to implement in pulsed lasers and requires a careful sensor choice. Here, we report on laser lap micro-spot welding of thin copper sheets using a pulsed Nd:YAG laser. The welding was performed under atmospheric conditions on pure, 100 µm thick, slightly oxidized and clean copper sheets with pulse durations and energies of less than 6 ms and 8 J, respectively. The process was experimentally analyzed by detecting normal laser reflection, heat emission, and instantaneous laser power with high time resolution. The meaningful signal parameters have then been selected for a closed loop feedback control. The variance of top and bot-tom weld spot diameters could be reduced by more than a factor of 8 in the case of closed loop control.

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Light-induced Single Step Nanopatterning of Surfaces

Dieter Bäuerle, *Angewandte Physik, Johannes Kepler Universität Linz (Austria)*

The talk will give an overview on recent developments in laser-induced submicro- and nano-patterning of material surfaces by means of SNOM-type techniques (scanning near field optical microscope) and by using regular self-organized 2-dimensional lattices of microspheres fabricated from colloidal solutions.

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Resonant Infrared Deposition of Organic and Biological Molecular Thin Films

R. F. Haglund, Jr., *Department of Physics and Astronomy and W. M. Keck Foundation Free-Electron Laser Center, Vanderbilt University (USA)*
and
M. R. Papantonakis, K. E. Schriver, *Department of Physics and Astronomy and W. M. Keck Foundation Free-Electron Laser Center, Vanderbilt University (USA)*.; J. S. Horwitz, E. J. Houser, R. A. McGill, *U. S. Naval Research Laboratory (USA)*; D. M. Bubb, *Physics Department, Seton Hall University (USA)*

Pulsed laser deposition (PLD) using ultraviolet (UV) lasers has been very effective in producing high quality inorganic thin filmsof superconducting oxides, ferrites and ferroelectrics. However, UV-PLD of simple organic or polymeric thin film materials, especially of photochemically labile materials, has had limited success. This is because UV exposure during ablation leads to electronic excitation, which has the potential to initiate photochemical modification in the organic as the excitation relaxes by electron-phonon coupling into vibronic degrees of freedom. We have shown that picosecond, mid-infrared laser irradiation (2 – 10 mm) can be used to ablate and deposit high-quality thin films of a variety of organic materials, in most cases with little or no change in their chemical properties or physical structure. In this resonant infrared pulsed laser deposition (RIR-PLD), an infrared laser is tuned to a vibrational absorption band in the organic material, producing a highly vibrationally excited, gas phase species in the ground electronic state. The organic material can be transferred intact from a solid target to a substrate with high deposition rates, creating, for example, thin films of functionalized polymers that bind reversibly with chemical and biological agents for use in chemical sensors. In this talk, we review the key elements of the vibrational photoexcitation and the relaxation processes that take place in RIR-PLD, and present new results on the transfer of poly(tetrafluoroethylene), bovine serum albumin and nucleic acids. Possible applications to micro- and nanostructured substrates based on lithographic and non-lithographic patterning technologies will be described.

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Laser Micro-Bending for precise micro-fabrication of magnetic disk-drive components

Naohisa Matsushita, *Fujitsu Limited (Japan)*

Laser Micro-Bending technology attracts attention as one of the laser processing technology promising from now on. It has the feature which does not contact and does not have the spring back that fabrication in high accuracy can be performed. In our company, Laser Micro-Bending technology development is tackled about ten years before, and the laser bending fabrication technology of a sheet metal and ceramic material has so far been established. It has utilized as trial production sheet metal processing technology at the beginning of development. But, by re-examination of laser oscillation control etc., it finds out that it is the excellent processing method for manufacture of the high precision mechanism parts for magnetic disk drives. This report explains the technology and machines of the roll and pitch correction of a magnetic head suspension, and flatning or crowning of the air bearing surface of a magnetic head slider by using Laser Micro-Bending technology.

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Saturday, 21.06.2003

Room 21

15:00	**Session 1: Thin-film Processing** Session Chair: Richard Haglund
15:00	**Thin film coating processing using dopant-enhanced laser ablation** K. Dou; T. Metroke; E. Stesikova; E. Knobbe; T. Collins; Oklahoma State University, USA
15:20	**Laser-induced diffusion for glass metallisation** D. Wu; M. Hong; R. Ji; Y. Kaidong; H. Sumei; T.Ch. Chong; Data Storage Institute of Singapore; K. Sugioka; K. Midorikawa; RIKEN, Japan
15:40	**Ultraviolet lasers form ZnO nano-rods synthesized by pulsed-laser ablation** A.B. Hartanto; T. Okada; Y. Nakata; M. Kawakami; Graduate School of ISEE; Kyushu University; X. Ning; Fudan University, Japan
16:00	**Optimized ablation condition to prepare polyperinaphthalene thin films using the third harmonic wavelength of Nd:YAG laser** S. Nishio; Ch. Kanesawa; H. Matsuda; H. Fukumura; Graduate School of Science, Tohoku University, Japan
16:20	Break
16:50	**Fabrication of integrated microelectronic systems by laser direct-write** A. Piqué; C.B. Arnold; R.C.Y. Auyeung; B. Pratap; Naval Research Laboratory, Washington, USA
17:10	**Laser-assisted chemical cleaning of thin oxide films on carbon steel surfaces** D. Kim; H. Lim; POSTECH, Pohang, Korea
17:30	**Fabrication of three-dimensional microstructures by stacking laser-direct-write layers** S. Jeong; S. Han; J.S. Selvan; Kwangju Institute of Science and Technology, South Korea
17:50	End

Thin Film Coating Processing Using Dopant-Enhanced Laser Ablation

Kai Dou, *Department of Physics, Oklahoma State University (USA)*
and
T. Metroke, E. Stesikova, E. Knobbe, T. Collins, *Department of Physics, Oklahoma State University (USA)*

Ormosil thin films are being investigated as corrosion resistant surface treatments for metals. Variation in the ormosil composition produces thin films possessing excellent corrosion resistance characteristics. Due to their chemically inert nature, however, sol-gel derived thin films pose an interesting challenge for removal from metallic substrates, as the coatings are resistant to traditional chemical removal methods. For these reasons, advanced coating removal techniques, such as dopant-assisted laser stripping, are being developed. In the present study, ormosil thin films were prepared from tetraethoxysilane and 3-glycidoxypropyltrimethoxysilane using dip-coating methods onto polished aluminum alloy substrates. UV-absorbers, 0.1-1%, were incorporated into the sol. The dopants chosen in this study were butyl-PBD, polyphenyl 1, and furan 2. Laser ablation with a 308-nm Excimer laser using fluences between 0.2 and 1.0 J/cm^2 was used to remove coatings. Incorporation of UV-absorbers (butyl-PBD, polyphenyl 1, and furan 2) were found to facilitate coating removal using advanced laser stripping techniques. The effectiveness of these dopants to reduce the critical fluence required for coating removal was found to be polyphenyl 1 < furan 2 < butyl-PBD.

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Laser induced diffusion for glass metallisation

Dongjiang Wu, *Data Storage Institute of Singapore (SIngapore)*
and
Minghui Hong, Rong Ji, Y. Kaidong, Huang Sumei, Tow Chong Chong, *Data Storage Institute (Singapore)*; K. Sugioka, K. Midorikawa, *Laser Technology Laboratory, RIKEN-The Institute of Physical and Chemical Research (Japan)*

A method for surface metallization on transparent substrate with laser induced plasma deposition was described. A laser beam goes through the transparent substrate first and then irradiates on a metal target behind. For laser fluence above ablation threshold for the target, the generated plasma flies forward at a high speed to the substrate and induces metal materials deposition on its rear side surface and even doping into the substrate. The diffusion distribution of metallic particles was measured with Time of Flight Secondary Ion Mass Spectrometer (TOF-SIMS). Electrically conducting films are formed on the substrate with laser beam scanning. The near 1Ohm/Square lower resistivity can be formed with precise control of the processing parameters: laser fluence, pulse repetition rate and scanning speed, distance between the substrate and metal target and overlapping of the metal lines. This technology can be used to form electrodes, resistors or electronic circuits on the transparent substrates.

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Ultraviolet Lasers from ZnO Nano-Rods Synthesized by Pulsed-laser Ablation

Agung Budi Hartanto, *Graduate School of ISEE, Kyushu University (Japan)*
and
T. Okada, M. Kawakami, Y. Nakata, *Graduate school of ISEE, Kyushu University (Japan)*; Xu Ning, *Fudan University (Japan)*

Nano-structured zinc oxide (ZnO) films were synthesized by pulsed-laser ablation in a relatively high pressure of oxygen or helium background gas. When the substrate temperature was low (400ºC), the film consists of ball-like structures with diameters less than 1µm and each ball consists of many particles with a size of about 100nm. On the other hand, when it was high (>600ºC), crystalline and well c-axis oriented ZnO nano-rods were grown on sapphire (0001) substrates without any catalyst. These ZnO nano-rods have an average diameter around 200nm and length around 6?m. By the same conditions, ZnO nano-rods were also grown on silica substrates without any catalyst. Characteristic of photoluminescence was observed with an excitation at 355nm by the THG of Nd:YAG lasers at room temperature. Stimulated emission was observed in the as-grown ZnO nano-rods at near UV wavelength of about 390nm. In addition, the ultra-violet Rayleigh scattering method was used to study the behaviors of particles in gas phase. Nano-particles formed by condensation of ablated species and transported on the substrate were observed. It was thought that theformation of nano-particles in the gas phase and their delivery to substrate plays an important role in the nano-rods growth.

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Optimized ablation condition to prepare polyperinaphthalene thin films using the third harmonic wavelength of Nd:YAG laser

Satoru Nishio, *Department of Chemistry, Graduate School of Science, Tohoku University (Japan)*
and
Chihiro Kanesawa, Hiroshi Matsuda, Hiroshi Fukumura, *Department of Chemistry, Graduate School of Science, Tohoku University (Japan)*

Laser ablation of mixture targets of perylenetetracarboxylic dianhydride (PTCDA) with cobalt powder (PTCDA/Co) using the third harmonic wavelength (355 nm) of a Nd:YAG laser enabled us to obtain thin films consisting of better-defined polyperinaphthalene (PPN), one of low dimensional conducting polymer, than those reported before. Drastic decrease in the peak intensity related to anhydride groups of PTCDA was observed with increasing ablation fluence from 0.1 to 0.5 $Jcm^{-2}pulse^{-1}$. The threshold of the fluence for complete removal of the side groups could be reduced to almost half of our previous one using XeCl excimer laser beams. Raman spectra for the films showed a quite sharp peak at 1290 cm^{-1} assigned to C-H in-plane bending mode of perylene skeleton together with peaks at 1560 and 1360 cm^{-1} characteristic of condensed aromatic rings. These results indicate that fragments without anhydride groups and with better-defined perylene skeleton were deposited on the substrates. Increase of the electric conductivity with substrate temperature suggests that the deposition polymerized effectively to form PPN. Further researches for determination of optimized ablation condition to prepare PPN thin films and elucidation of ablation mechanism are now under investigation.

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Fabrication of Integrated Microelectronic Systems by Laser Direct-Write

A. Piqué, C.B. Arnold, R.C.Y. Auyeung, B. Pratap, *Naval Research Laboratory (USA)*

Direct-write techniques have the potential to revolutionize the way microelectronic systems are designed and fabricated. The Naval Research Laboratory has developed a laser-based microfabrication system capable of direct-writing virtually any material in both additive and subtractive form. In additive mode, the system utilizes a laser-forward transfer process for the fabrication of novel structures and devices comprising of metals, ceramics, polymers and composites under ambient conditions on both ceramic and plastic substrates. This process is capable of depositing materials over planar as well as conformal surfaces, which opens the door to the fabrication of novel 3-D structures. In subtractive mode, the system operates as a laser micromachining workstation capable of achieving precise depth and surface roughness control by adjusting the translation distance. This approach is ideally suited for the rapid prototyping of microelectronic systems while allowing the overall design to be easily modified and adapted to any specific application. Examples are provided of various types of miniature microelectronic systems fabricated using this technique. This work was supported in part by the Office of Naval Research.

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Laser-Assisted Chemical Cleaning of Thin Oxide Films on Carbon Steel Surfaces

Dongsik Kim, *POSTECH, Department of Mechanical Engineering (Korea)*
and
Hyunkyu Lim, *POSTECH, Department of Mechanical Engineering (Korea)*

The work introduces a novel laser chemical process for removing thin oxide films on low-carbon steel surfaces by combining laser-induced shock waves and chemical etching technique that is used in the conventional oxide-scale removal process. In the proposed process, a Q-switched Nd:YAG laser (wavelength 1064 nm, FWHM 6 ns) pulse is focused onto the liquid surface and subsequently induces optical breakdown in the acid solution, producing intense pressure waves. The pressure waves act as a non-contact scale breaker and increases the removal rate. It has been demonstrated that the novel process leads to substantial enhancement of the oxide-scale removal, compared with the conventional solvent-based cleaning technique. The removal rate has been measured quantitatively employing an optical microscope, a scanning electron microscope, and energy-dispersive X-ray analysis. Parametric study has been performed to reveal the effect of pressure pulse, laser pulse number, acid concentration, reaction time on the efficiency of scale removal. It is shown that the laser-assisted process can lower the acid concentration, with the cleaning efficiency unchanged or even improved. The results demonstrates a technical feasibility of utilizing the method for industrial applications that required enhanced scale-removal rate or reduced use of toxic chemicals.

****

Fabrication of three dimensional microstructures by stacking laser-direct-write layers

Sungho Jeong, *Kwangju Institute of Science and Technology (South Korea)*
and
Seong-il Han, J. Senthil Selvan, *Kwangju Institute of Science and Technology (South Korea)*

Fabrication of truly three dimensional microstructures by deposition of material is investigated. Laser-induced chemical vapor deposition is applied to fabricate three dimensional microstructures that has cross-sectional profiles other than simple combination of deposited fibers. To fabricate microstructures that does not consist of combined wire-frames, a thin layers of deposit in desired patterns is first written using laser-direct-write technique and on top of this layer a second layer is deposited to provide the third dimension normal to the surface. By depositing many layers, a full three dimensional microstructures can be fabricated. The size and shape of the cross-section can be varied during the multilayer deposition. Optimum deposition conditions for direct writing of initial and subsequent layers with good surface quality and profile uniformity are determined. Using an argon ion laser and ethylene as the light source and reaction gas, respectively, fabrication of truly three-dimensional carbon microstructures with the proposed method is demonstrated.

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Saturday, 21.06.2003

Room 22

15:00	**Session 2: Fundamentals of fs-laser Processing** Session Chair: Dieter Bäuerle
15:00	**Excitation - melting - ablation: Theoretical investigations of key processes during ultrashort-pulsed laser machining** (invited paper) B. Rethfeld; K. Sokolowski-Tinten; D. v.d. Linde; Institut für Laser- und Plasmaphysik, Essen, Germany
15:30	**Novel aspects of materials microprinting applications by ultrafast lasers** (invited paper) C. Fotakis; I. Zergioti; D. Papazoglou; K. Giannakoudaki; Foundation for Research and Technology-Hellas (FORTH), Crete, Greece
16:00	**Microscopic processes in micromachining in dielectrics irradiated by femtosecond laser pulses** T. Jia; Z. Xu; R.X. Li; X.X. Li; D.H. Feng; Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, China
16:20	Break
16:50	**Plasma formation in ultrafast laser irradiated dielectrics** S.W. Winkler; R. Stoian; A. Rosenfeld; M. Hildebrand; I.V. Hertel; Max Born Institute, Berlin, Germany; D. Ashkenasi; Laser und Medizintechnologie GmbH, Berlin, Germany
17:10	**Depth-profiling during micromachining with ultrashort laser pulses: Fundamental studies of ablation rates and applications** J.A. Olesen; K. Vestentoft; P. Balling; Institute of Physics and Astronomy; University of Aarhus, Denmark
17:30	**Material vapor dynamics during ablation with ultrashort pulses** D. Breitling; K.-P. Müller; A. Ruf; P. Berger; F. Dausinger; Institut für Strahlwerkzeuge (IFSW), Universität Stuttgart, Germany
17:50	End

Excitation - melting - ablation: Theoretical investigations of key processes during ultrashort-pulsed laser machining

Bärbel Rethfeld, *Institut für Laser- und Plasmaphysik (Germany)*
and
Klaus Sokolowski-Tinten, Dietrich von der Linde, *Institut für Laser- und Plasmaphysik, Universität Essen (Germany)*

Ultrashort laser pulse interaction with material involves a number of specialities as compared to longer irradiations. Applying femtosecond laser pulses the fundamental physical processes as excitation, melting and ablation are temporally separated, allowing a separate investigation of each of them. The irradiated material passes through highly non-equilibrium states of different kinds on different time scales after irradiation. Thus, the theoretical description of the investigated processes may differ strongly from the classical descriptions valid for equilibrium or steady-state conditions. On femtosecond time scale we investigate the non-equilibrium of the laser-excited electron gas. With help of a detailed microscopic approach we study the applicability of simplified macroscopic descriptions of laser absorption and free-electron excitation. We study different melting processes occuring on different time scales in the picosecond regime. The nature of the melting process depends on laser and material parameters, respectively. Material removal, i.e. ablation, occurs on a pico- to nanosecond time scale, depending on excitation strength. We show theoretical and experimental investigations of the expansion dynamics of the excited material and of the sharp ablation threshold.

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Novel Aspects of Materials Microprinting Applications by Ultrafast Lasers

C. Fotakis, I. Zergioti, D. Papazoglou, K. Giannakoudaki, *Institute of Electronic Structure and Laser (IESL), Foundation for Research and Technology-Hellas (FORTH) (Greece)*

Materials processing by ultrafast lasers offers several unique possibilities for micro/nano scale applications. This is due to the differences of the laser-matter interactions involved, when sub-picosecond pulses are employed. These differences include the reduction of undesirable thermal and photochemical effects, which minimizes the energy diffusion during the processing of sensitive materials (e.g. organic molecular substrates), the ejection of directional and energetic particles, which favours low temperature thin films growth and the possibility for producing phase tailored pulses for control and process optimization. The prospects and limitations of this field will be reviewed in the context of direct microprinting applications of various materials by the Laser Induced Forward Transfer (LIFT) technique [1]. Specific, examples of the direct micro/nanofabrication of patterns of optically active and biological materials will be given and the mechanistic aspects that apply well be discussed [2, 3].

References:

[1] "Laser Induced Forward Transfer (LIFT): An approach to single step Microfabrication", I. Zergioti, G. Koundourakis, N. Vainos, C. Fotakis, review, chapter 16, "Direct Write Technologies for Rapid Prototyping: Applications, Sensors, Electronics and Integrated Power Sources", edited by A. Piqué, D.B. Chrisey, Academic Press, 2002 (ISBN 0-12-174231-8), San Diego, USA.

[2] D.G. Papazoglou, A. Karaiskou, I. Zergioti and C. Fotakis, "Shadowgraphic imaging of the sub-ps laser-induced forward transfer process", Applied Physics Letters, 81, 9 (2002).

[3] A. Karaiskou, I. Zergioti, C. Fotakis, M. Kapsetaki, D. Kafetzopoulos, "Microfabrication of biomaterials by the sub-ps laser-induced forward transfer process", Applied Surface Science, 208-209, 245 (2003).

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Microscopic Processes in Micromachining in Dielectrics Irradiated by Femtosecond Laser Pulses

Tian-qing Jia, *Laboratory for High Intensity Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (China)*
and
Z. Xu, R.X. Li, X.X. Li, D.H. Feng, *Laboratory for High Intensity Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (China)*

The photoionization rates in dielectrics irradiated by femtosecond lasers are calculated by Keldysh Theory. The rates of laser energy absorbed by conduction band electrons (CBE) and the impact ionization rates are studied by using quantum mechanical approach and double-flux model, respectively. The evolution of CBE density is resolved on the basic of avalanche model. The distribution of laser energy density deposited are investigated by treating the sample as a stacks of layers, here CBE diffusion is included. Choosing the damage criterion as the energy density necessary to heat and to decompose the sample, we obtain the dependences of damage threshold on pulse duration and the dependences of ablation depths and volume on pulse energies. The ultrafast processes of phonon emission and CBE-hole recombination are also considered, the dependence of damage threshold on delay time between pump-probe double pulses are represented. Our theoretical model explains well the evolution of Coulomb explosion. Experiments about laser ablation of dielectrics SiO_2, Al_2O_3 and CaF_2 are conducted by using Ti: Sapphire lasers (800 nm, 40 fs, 700 uj). The dependences of damage threshold of 800 nm and 400 nm lasers (double by 0.5 mm KDP) on pulse duration of 45-800 fs are presented. The ablation pits are measured with SEM and AFM, and the dependences of ablation depth and volume on pulse energies are also shown. Our experimental results agree well with our theory.

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Plasma formation in ultrafast laser irradiated dielectrics

Sebastian W. Winkler, *Max Born Institute (Germany)*
and
Razvan Stoian, Arkadi Rosenfeld, Matthias Hildebrand, I.V. Hertel, *Max Born Institute (Germany)*; David Ashkenasi, *Laser und Medizintechnologie GmbH Berlin (Germany)*

Ultrafast lasers offer remarkable capabilities for reduced-scale processing of dielectric materials, taking advantage of the nonlinear and selective interactions, reduced heat effects, and the unique possibility of pulse adaptive manipulation. Concomitantly, new opportunities have been opened in exploring the basic aspects of laser-matter interaction, laser-induced optical damage, and ablation characteristics. These processes include non-linear optical absorption, multiphoton ionization, avalanche breakdown, phonon emission, non-equilibrium phenomena related to overcritical heating. The fast absorption and relaxation properties result in finite amounts of material to be affected and define the range of interactions. The fundamental characteristics of the laser energy coupling to the material together with time-resolved optical observation of the development of the laser-induced free-electron gas and plasma dynamics during the laser exposure will be presented. Based on the specific electronic relaxation times, the material response can be guided by using temporally tailored ultrafast laser pulses, introducing thus the possibility to regulate and manipulate excitation and energy transfer with respect to optimal structuring, and unfolding new perspectives for 'intelligent', feedback-assisted processing of materials.

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Depth-profiling during micromachining with ultrashort laser pulses: Fundamental studies of ablation rates and applications.

Jakob A. Olesen, Kasper Vestentoft, Peter Balling, *Institute of Physics and Astronomy, University of Aarhus (Denmark)*

A method for on-line characterization of ultrashort-pulse laser ablation is demonstrated. The method is used to provide a precise determination of ablation rates for metal surfaces. Examples will also demonstrate that the method is a useful tool for precise control of micromachining. The construction of robust ultrashort-pulse lasers has stimulated intense investigation of industrial and medical applications of short-pulse ablation. In several cases, the special mechanisms governing the interaction of ultrashort light pulses with matter have been demonstrated to provide unique machining possibilities in microprocessing and medical surgery. In this talk, a new method for on-line characterization of the machining process is demonstrated [1]. Time-gated imaging of the backscattered radiation from the ablation region is utilized to obtain the cross-sectional profile of the sample during laser processing. The measurement is performed with the same pulse that undertakes ablation and the method is thus inherently suited for in-situ on-the-fly diagnostics. The depth-profiling method, which ultimately has a spatial resolution of a few micrometers, can obviously be used to control machining in a number of ways. The presentation will demonstrate a few of the possibilities and illustrate that this is a very general technique, which can be used on many different samples, including transparent materials and biological tissue. The depth-profiling technique allows a very convenient determination of laser ablation rates. Recent investigations of a range of metal samples have demonstrated strong variations in the ablation rate versus depth of the ablation region. The talk will show the observations and offer a tentative explanation for the behavior, which includes the effects of laserinduced surface corrugations and associated energy coupling phenomena, foremost the role of surface-plasmon excitation.

[1] R. Lausten and P. Balling, Applied Physics Letters 79, 884 (2001).

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Material vapor dynamics during ablation with ultrashort pulses

Detlef Breitling, *Institut für Strahlwerkzeuge (IFSW), Universität Stuttgart (Germany)*
and
Klaus-Peter Müller, Andreas Ruf, Peter Berger, Friedrich Dausinger, *Institut für Strahlwerkzeuge, Universität Stuttgart (Germany)*

As ultrashort pulsed lasers become available in compact and increasingly reliable systems there is a growing interest in their manufacturing application for high-precision ablation and drilling. Ultrashort laser pulses lead to a number of nonlinear optical phenomena in the vicinity of the laser focus, such as self-phase modulation, self-focusing, and beam filamentation, thus causing laser beam degeneration even for single pulses and without a target. It must be expected that the presence of material vapor plumes during ablation will deteriorate the beam even further, especially when ablated material accumulates over multiple pulses. Indeed, these plasma related effects have been found to exhibit a significant impact on laser processes and might even impose a limit for efficient, high-quality machining at high repetition rates. We have studied ablation plumes generated by fs- and ps-laser pulses using various optical methods for both single pulse ablation as well as for drilling with up to 1 kHz repetition rate. Time-resolved shadow and resonance absorption photographs visualize the plume and vapor expansion behavior in the nanosecond- and microsecond-time domains whereas the detection of Rayleigh-scattered 308 nm-radiation allows to qualify the vapor movement and accumulation up to several milliseconds, i. e. well beyond the typical pulse-to-pulse separation at high repetition rates

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Sunday, 22.06.2003

Room 21

08:30	**Session 3: Machining of Silica and Glass** Session Chairs: Juergen Ihlemann, Koji Sugioka
08:30	**Laser-induced sub-surface modification of the optical properties in transparent materials - NIK-engineering** (invited paper) D. Ashkenasi; G. Müller; Laser- und Medical-Technology GmbH, Berlin, Germany; H.-J. Hoffmann; Technical University, Berlin, Germany
09:00	**Fabrication of 3D microreactor structures embedded in photosensitive glass by femtosecond laser** K. Sugioka; Y. Cheng; K. Midorikawa; RIKEN, Japan; M. Masuda; K. Toyoda; Tokyo University of Science, Japan; M. Kawachi; K. Shihoyama; Hoya Photonics, Japan
09:20	**Three-dimensional microoptical components embedded in Foturan glass by a femtosecond laser** Y. Cheng; K. Sugioka; K. Midorikawa; RIKEN, Japan; M. Masuda; K. Toyoda; Tokyo University of Science, Japan; M. Kawachi; K. Shihoyama; Hoya Photonics, Japan
09:40	**Glass processing using microsecond, nanosecond, and femtosecond pulsed lasers** A. Ozkan-Anderson; L. Migliore; Coherent Laser Application Center, Santa Clara, USA
10:00	Break
10:20	**Fabrication of diffractive phase elements by F2-laser ablation of fused silica** J. Ihlemann; M. Schulz-Ruthenberg; G. Marowsky; Laser-Laboratorium Göttingen; A.H. Nejadmalayeri; J. Li; P.R. Herman; University of Toronto, Canada
10:40	**Laser machining of silica micro-optics for diode laser arrays applications** H.J. Baker; K.M. Nowak; F. Monjardin; D.R. Hall; Heriot-Watt University, Edinburgh, United Kingdom
11:00	**High-quality and high-efficiency micro-structuring of VUV window materials by laser-induced plasma-assisted ablation with a conventional KrF excimer laser source** D. Ashkenasi; H. Jaber; Laser- und Medical-Technology GmbH, Berlin, Germany
11:20	**Site-selective surface-functionalization of fused silica fabricated by LIBWE method** X. Ding; Y. Kawaguchi; H. Niino; National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan
11:40	**UV laser drilling of high aspect ratio microvias in glasses and quartz** Z.L. Li; P.M. Moran; Institute of Materials Research and Engineering, Singapore; Y. Sun; E.J. Swenson; Electro Scientific Industries, Inc., USA; P. M. Moran, Institute of Materials Research & Engineering, USA
12:00	**Titanium-containing glass for laser micromachining** M. Shojiya; H. Koyo; K. Tsunetomo; Kansai Research Center, Nippon Sheet Glass Co., Hyogo, Japan

Laser-induced sub-surface modification of the optical properties in transparent materials - NIK-engineering (TM)

David Ashkenasi, *Laser- und Medizin-Technologie GmbH, (LMTB) (Germany)*
and
Hans-Jürgen Hoffmann, *Institut für Werkstoffwissenschaften und -technologien,Technical University (Germany)*; Gerhard Müller, *Laser- und Medical-Technology GmbH (Germany)*

A new field in laser processing is opened by the method of modifying the optical properties, i.e. the refractive index, absorption- and scattering- coefficient, at minimal mechanical stress inside the material. Focusing ultra short laser pulses inside the transparent media allows to control and modify their optical properties. This is referred to as nik-engineering (TM), relating the technique to changes of the complex refractive index, i.e. (n + ik). Three dimensional patterns of the (n + ik) modifications can be achieved in the subsurface region even on a microscopic scale. New results in nik-engineering (TM) obtained in our application laboratory are presented using different optical materials. The results in laser nik-engineering (TM) of photo-chromic glass using ultra short laser pulses at a wavelength of 800 nm is presented. A model in respect to the relevant processes leading to the observed laser-induced modifications in the optical properties of photo-chromic glass is presented. We discuss the results and the commercial potential of nik-engineering (TM).

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Fabrication of 3-D microreactor structures embedded in photosensitive glass by femtosecond laser

Koji Sugioka, *RIKEN - The Institute of Physical and Chemical Research (Japan)*
and
Ya Cheng, Katsumi Midorikawa, *RIKEN (Japan)*; Masashi Masuda, Koichi Toyoda, *Tokyo University of Science (Japan)*; Masako Kawachi, Kazuhiko Shihoyama, *HOYA PHOTONICS (Japan)*

Microfabrication of true three-dimensional (3-D) structures embedded in a photosensitive glass by femtosecond (fs) laser for microreactor and micro total analysis system (micro-TAS) applications is presented. The processing includes three steps. (1) Scanning exposure of a focused fs laser precipitates Ag atoms in the glass, resulting in formation of 3-D latent images. (2) Modified regions are developed by a post baking process. (3) Then, the modified regions are preferentially etched away by a 10% diluted HF solution. The contrast ratio of etching rate between the modified regions and the unexposed regions is measured to be as high as about 35. It is found that the reaction takes place by a six photons process of fs laser and the critical dose for producing the latent images is determined for precise fabrication of 3-D microstrucrtures. Based on the critical dose, true 3-D microstructures are fabricated inside the glass. This technique is applied for manufacturing microreactor structures which are composed of microcells and embedded microchannels. Free movable microplates are also embedded inside the glass by this technique, which act as microvalves in the microreacter. Finally, mixing of two different solutions in the channels is demonstrated.

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Three-dimensional microoptical components embedded in Foturan glass by a femtosecond laser

Ya Cheng, *RIKEN - The Institute of Physical and Chemical Research (Japan)*
and
Koji Sugioka, Katsumi Midorikawa, *RIKEN-The Institute of Physical and Chemical Research (Japan)*; Masako Kawachi, Kazuhiko Shihoyama, *HOYA Photonics Corporation (Japan)*; Masashi Masuda, Koichi Toyoda, *Tokyo University of Science (Japan)*

To form a compact optical circuit for integrated optics application, it is required to bend the light in a small space. In this presentation we demonstrate this can be accomplished by three dimensional (3-D) micromirrors structured inside Foturan glass by use of a technique established recently for manufacturing micro total analysis systems (micro-TAS). The processing includes mainly three steps: (1) direct writing of latent images in the sample by the tightly focused femtosecond (fs) laser; (2) baking of the sample in a programmable furnace for formation of modified regions; and (3) etching of the sample in a 10% diluted solution of hydrofluoric acid for selective removal of the modified regions. After this procedure, hollow internal structures are formed which act as a mirror. However, the reflected beam was severely divergent because of the high roughness of the etched internal surface, giving a large beam spot on the receiving screen. We find that a post annealing smoothes the surfaces of the fabricated hollow structures, resulting in greatly reduced divergence as well as optical loss. For example, a 45 mirror embedded inside Foturan glass can turn the incident beam 90 at an optical loss only 0.60dB. We also demonstrate fabrication of other microoptical components such as a beam splitter.

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Glass processing using microsecond, nanosecond, and femtosecond pulsed lasers

Arzu Ozkan-Anderson, *Coherent Laser Applications Center (USA)*
and
Lenny Migliore, *Coherent Laser Applications Center (USA)*

The growth of the multimedia and internet communications is driving the demand for more capacity on networks. Optical integrated circuits made of transparent materials are the medium of choice for high-bandwidth applications. Laser micro-fabrication technology has the potential to be a useful tool for the manufacture of these devices. In this paper, we investigated an industrial solution to the manufacture of an active optical component. We present laser processing techniques using microsecond, nanosecond, and femtosecond lasers for surface and sub-surface glass modification. A regeneratively amplified Ti-Sapphire laser operating at a near-IR wavelength with femtosecond pulses and a 300 kHz repetition rate is used to generate 3-D optical waveguides in transparent materials. Surface structures are generated with a diode-pumped solid-state nanosecond pulsed UV laser operating at 266 nm, a Q-switched CO_2 laser operating at 9.25 mm, a CO_2 laser operating at 10.6 mm and the femtosecond pulsed laser operating at 800 nm. The material interactions are examined with respect to the differences in time scale and the appropriateness of each laser type for particular processes.

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Fabrication of diffractive phase elements by F_2-laser ablation of fused silica

Juergen Ihlemann, *Laser-Laboratorium Göttingen (Germany)*
and
Malte Schulz-Ruthenberg, Gerd Marowsky, *Laser-Laboratorium Goettingen (Germany)*; Amir H. Nejadmalayeri, Jianzhao Li, Peter R. Herman, *Department of Electrical and Computer Engineering, University of Toronto (Canada)*

F_2-laser ablation at 157 nm was used for generating sub-micron surface relief structures on fused silica to define binary diffractive phase elements (DPE). A pattern array of 128 x 128 pixels was excised using the F_2 laser in combination with a high resolution processing system comprising of CaF_2 beam-homogenization optics and a high-resolution Schwarzschild reflective objective. A square projection mask provided precise excisions in less than 10 x 10 µm² spots, having sub-µm depths that were controlled by the laser fluence and the number of laser pulses to provide for the required phase delay between ablated and non-ablated pixels. Thus a diffractive phase element (DPE) optimized for first order in the UV spectral range was made. A four-level DPE design computed by the Iterative Fourier Transform Algorithm (IFTA) will be described for generating an arbitrary irradiation pattern without the point symmetry of the binary mask.

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Laser machining of silica micro-optics for diode laser arrays applications.

Howard J. Baker, *Department of Physics, School of Engineering and Physical Sciences, Heriot Watt University (United Kingdom)*
and
Krzyztof M.Nowak, Fernando Monjardin, Denis.R.Hall, *School of Engineering and Physical Sciences, Heriot-Watt University; (United Kingdom)*

Arrays of refractive/reflective elements are essential for the scaling of diode lasers to high average powers, by combining many beams from individual low power emitters. Micro-lenses, deflection mirrors or prism, and other beam correction devices are required. We report laser-cutting of silica using a carbon dioxide laser for rapid-prototyping of these micro-optical elements. An acousto-optic modulator is used to generate the 30 to 40 microsecond laser pulse length which is optimum for clean, controllable ablation of silica, and longer pulses for smoothing to optical quality by re-melting of the surface. Factors influencing the precision of generation of arbitrary refractive surfaces by raster-scan machining and the scatter from the optical surface will be presented and examples shown of micro-optical component performance. For surface feature size greater than 40 microns, the machining process is reproducible and achieves a surface height accuracy of 100 nm. In a recent development, the system has been used to produce corrective phase plates for the fast-axis micro-lenses of diode laser bar arrays. The relative pointing error between bars has been reduced by a factor of 15 and the collimated beam quality of each bar improved.

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High-quality and high-efficiency micro structuring of VUV window materials by laser-induced plasma-assisted ablation with a conventional KrF excimer laser source

David Ashkenasi, *Laser- und Medizin-Technologie GmbH, (LMTB) (Germany)*
and
Houssam Jaber, *Laser- und Medical-Technology GmbH (Germany)*

We report precision micro structuring of fused silica and CaF_2 by laser-induced plasma-assisted ablation with a conventional KrF excimer laser (248 nm). Mask projection of the UV light is realized onto the rear surface of the VUV window material. The plasma generated from a metal target located behind the rear surface of the VUV window effectively assists in the ablation. In the case of fused silica, we obtain high-quality complex micro structures with structure depths even above 500 µm, corresponding to aspect ratios 1:5 and better. The ablation rate in fused silica reaches a level of 1 µm/pulse with this novel method, demonstrating the remarkable high-efficiency. The ablation rates obtained for CaF_2 remain at 50 nm/pulse, however, the ca. 30 µm deep micro structures obtained demonstrate a excellent quality without signs of cracking or stress outside the mask projected area. This technique permits high-quality micro fabrication of bio-medical, electronic and opto-electronic devices based on oxides and fluorides by use of a conventional UV laser.

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Site-selective surface-functionalization of fused silica fabricated by LIBWE method

Ximing Ding, *Photoreaction Control Research Center, National Institute of Advanced Industrial Science and Technology (AIST) (Japan)*
and
Yoshizo Kawaguchi, Hiroyuki Niino, *Photoreaction Control Research Center, National Institute of Advanced Industrial Science and Technology (AIST)*

In this report, we fabricated high quality grid patterns of a functionalized dye layer on the surface of fused silica plates with the method of laser-induced backside wet etching (LIBWE) developed by our group. This method requires a simple optical setup free of high vacuum operation and lower laser fluence and yet provides high etching quality over a large processing area (as large as 2 mm ´ 2 mm) [1]. The surface properties of fused silica plates were modified prior to the LIBWE process by self-assembling of trimethoxysilanes. Self-assembled monolayers (SAMs) provide a valuable approach to fabricate surfaces with a specific chemical functionality, which are extensively utilized in lubrication, corrosion protection, photolithographic or electrical resists, micro-reactors, and microchips in sensing. At the non-irradiated area SAMs survived from the LIBWE process and acted as a template for the dye deposition thereafter. With prudently tuning the terminal groups on the trimethoxysilanes, dye molecules can be selectively deposited on the irradiated areas or non-irradiated area by either chemical bonding or physical and chemical adsorption.

Reference:
1.X. Ding, Y. Kawaguchi, H. Niino, A. Yabe, Appl. Phys. A. 75(2002), 641.

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UV laser drilling of high aspect ratio microvias in glasses and quartz

Zhongli Li, *Institute of Materials Research & Engineering (Singapore)*
and
Yunlong Sun, Edward J. Swenson, *Electro Scientific Industries, Inc (USA)*.; Peter M. Moran, *Institute of Materials Research & Engineering (USA)*

Fused silica and quartz are usually difficult to machine by conventional UV laser ablation, thermal cracking and rough surface finishes limit the lasers' application. Therefore, femtosecond lasers, F_2 157 nm lasers and DRIE processes are used. Often these processes are expensive and slow. We have developed a fast and flexible processing method to achieve high aspect ratio microvias in materials such as fused silica and quartz using a standard UV laser. We were able to fabricate holes in both fused silica and quartz 95 microns deep and less than 9 microns in diameter using an ESI 5200 microvia drilling machine (266nm wavelength and an 1/e2 spot size of 20 microns). No cracking or significant thermal effects were found. This talk will focus on the method we developed to achieve this as well as the scientific phenomena that make it possible.

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Titanium-containing glass for laser micromachining

Masanori Shojiya, *Technical Research Laboratory, Kansai Research Center, Nippon Sheet Glass Co., LTD. (Japan)*
and
Hirotaka Koyo, Keiji Tsunetomo, T*echnical Research Laboratory, Kansai Research Center, Nippon Sheet Glass Co., LTD. (Japan)*

Laser machining of glass is attractive for fabrication of optical devices such as gratings, lenses and hole arrays used for optical fiber alignment. Recently we found that titanium ions in glasses are effective to reduce the ablation threshold in the UV laser irradiation. The glasses containing titanium ions showed one order smaller thresholds compared with other commercial glasses used for optics or windows. The lowest threshold around 200 mJ cm^{-2} was obtained in the case of the Nd:YAG FHG (266 nm) irradiation. The ablation threshold decreases with increasing the titanium concentration in the glass. On the other hand, the ablation rate shows the maximum value at the molar ratio of titanium oxide around 10 – 20mol% in the glass composition. It was also clarified that the machinability depends not only upon the absorption coefficient related with the titanium concentration but also on the bond strength in the glass network: the ablation threshold decreases with decreasing the single-bond strength averaged over all bonds between oxide ions and cations except for alkaline ions. A 4x4 planer micro-hole array (PMH) consist of the titanium containing glasses was successfully fabricated with a KrF excimer laser (248 nm). Because of the good machinability effective to prevent cracking and chipping during the laser machining, the PMH showed good uniformity of hole diameter (average: 129.9 mm) with σ=0.8 mm

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Sunday, 22.06.2003

Room 21

14:20	**Session 4: Manufacturing of Microsystems** Session Chairs: Etsuji Ohmura, Howard Baker
14:20	**Long distance biomodeling based on laser stereolithography** (invited paper) V.Y. Panchenko; Institute on Laser and Information Technologies, Russian Academy of Sciences, Moscow, Russia
14:50	**A novel modification of selective laser sintering for the generation of microparts** H. Exner; P. Regenfuß; L. Hartwig; S. Klötzer; R. Ebert; Laserinstitut Mittelsachsen e.V. / Hochschule Mittweida, Germany
15:10	**Fabrication of a micropower generator turbine in photostructurable glass/cermaic material** H. Helvajian; S. Janson; D. Harps; W. Hansen; The Aerospace Corporation, Los Angeles, USA; A. Huang; C.-M. Ho; University of California Los Angeles, USA; Y.-Ch. Tai; California Institute of Technology, Pasadena, USA
15:30	**Laser profile machining for 3-D micro turbine blade/vanes** M. Heaton; G. Hong; A. Holmes; Imperial College, London, United Kingdom; P. Rumsby; Exitech, Oxford, United Kingdom
15:50	**Laser-assisted forming and cutting of metallic micro-parts** A. Bayer; A. Gillner; Fraunhofer Institut für Lasertechnik, Aachen, Germany
16:10	Break
16:40	**Laser micro processing - facts and trends** (invited paper) M. Schmidt; G. Eßer; Bayerisches Laserzentrum, Erlangen, Germany
17:10	**Sapphire Tools for Laser-assisted Microforming** J.P. Wulfsberg; S.-E. Hilpert; Laboratorium Fertigungstechnik, Universität der Bundeswehr Hamburg, Germany; A. Ostendorf; C. Kulik; T. Temme; K. Samm; Laser Zentrum Hannover, Germany
17:30	**Laser-adjustable actuators for high accuracy positioning of micro components** M. Dirscherl; G. Eßer; Bayerisches Laserzentrum, Erlangen, Germany
17:50	End

Long distance biomodeling based on laser stereolithography

Vladislav Ya. Panchenko, I*nstitute on Laser and Information Technologies, Russian Academy of Sciences (Russia)*

The paper presents the results of introducing the new laser information technology for long distance biomodeling and implants fabrication for Crania-Maxillofacial Surgery and Neutral Surgery purposes. The technology is based on Computer Tomography Data (X-ray or NMR) of patients transferred through INTERNET to Laser Stereolithography center for creation of the real 3-D copies. The results of experiments on “artificial bone”, fabrication by Laser Stereolithography and Supercritical Fluid Technologies will be presented too. The Creation of three-dimensional microstructures by photoinitialed laser polymerization is under discussion too.The paper presents the results of more than 50 surgeries supported by this technology realised in St. Vladimir children's clinic, Moscow Region Sc.-Res. Clinical Institute and Burdenko Inst. of Neuro-Surgery, Russian Ministry of Healthcare.

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A Novel Modification of Selective Laser Sintering for the Generation of Microparts

Horst Exner, *Laserinstitut Mittelsachsen e.V. / Hochschule Mittweida (Germany)*
and
Peter Regenfuß, Lars Hartwig, Sascha Klötzer, Robby Ebert, *Laserinstitut Mittelsachsen e.V. / Hochschule Mittweida (Germany)*

Microparts with a structural resolution of <40µm and aspect ratios of >10 have been generated by selective laser sintering. The technique includes sintering under conditions of vacuum or reduced shield gas pressures. A novel set-up and raking procedure is employed; the material is processed by a 1064nm Q-switched Nd:YAG laser. The procedure allows the work pieces to be generated from micro- or nano-powders of high melting metals like tungsten as well as lower melting metals like aluminium and copper. Contingent on the parameters, the generated bodies are either firmly attached to the substrate or can be dissevered by a non-destructive method. The technique was developed to produce micro tools or micro-components for tools e.g. micro-structured inserts in die-casting molds, micro-structured electrodes for electro erosion or carriers for chip holder grip-bits and micro-handling devices in general.

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Fabrication of a micropower generator turbine in photostructurable glass/ceramic material

Henry Helvajian, *The Aerospace Corporation (USA)*
and
Siegfried Janson, Dan Harps, William Hansen, *The Aerospace Corporation (USA)*; Adam Huang, Chih-Ming Ho, *University of California (USA)*; Yu-Chong Tai, *Caltech (USA)*

Subsystems of a micropower generator have been fabricated in a glass/ceramic material. The processing technique employs a non-ablative 3-D laser exposure technique, whereby the laser irradiance is varied during the patterning step. The actual turbine, the housing and other elements of the micropower generator have been fabricated in a glass/ceramic material called Foturan (Schott Corporation). We will present data on the processing steps used, tests on the spinning glass/ceramic turbine (>60,000 RPM) and the overall concept of the device.

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Laser Profile Machining for 3-D Micro Turbine Blade/Vanes

Mark Heaton, *Imperial College (United Kingdom)*
and
Guodong Hong, Andrew Holmes, *Imperial College (United Kingdom)*; Phil Rumsby, E*xitech (United Kingdom)*

In this paper we disclose an innovative laser fabrication approach for profiling optimally smooth blade flow contours in a rotor/stator micro-turbine transducer system, (1). The laser micro-machining was achieved using a computer-controlled laser beam and elevating stage to step a moving mask across a fixed mask, i.e. dynamic 'mask dragging'. The moving mask image was projected on to the flat 600 micrometer wide surfaces of each blade and closed in steps/pitches of varying aperture with intermittent laser contouring via depth ablation at every step position. Time Vs surface quality was optimised throughout by using 40 constant depth/increasing length pitches for the steps of the shorter inside concave curve, and 90 gradually increasing depth/decreasing pitch steps for the full outside convex curve quadrant. The laser ablation depth was ~ 0.333 micrometers per pulse at 0.5 J/cm^2, with refocusing after each square step to maintain beam efficiency. A final trailing blade edge extremity thickness of ~ 50 micrometers was achieved where the inside concave slope of, 1:4/3 met with the convex. The blade architecture was of polymerised SU-8, a resilient epoxy photo-resist of high 248 nm excimer laser absorbency for responsive ablation.

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Laser assisted forming and cutting of metallic micro parts

Alexander Bayer, *Fraunhofer Institute for Lasertechnology ILT (Germany)*
and
Arnold Gillner; *Fraunhofer Institute for Lasertechnology ILT (Germany)*

Modern metal forming technologies enable the mass-production of miniaturized parts in electronics, medicine and MEMS. The future trend is to manufacture more complex parts at a high level of economic efficiency and precision. A common method to enhance the geometrical complexity of micro parts is the preheating of the work piece. Conventional preheating processes are extremely time consuming, decrease the productivity and heat the complete work piece, which can be disadvantageous in processes like sheet or massive metal forming. By a direct heating of the work piece with laser radiation during the forming process the temperature of local regions of the work piece can be increased quickly and the achievable process limits can be extended. Transparent tool parts like deep drawing dies, extrusion matrix made of sapphire or hollow cutting punches permit the guidance of the laser radiation directly onto the work piece within the closed tool during the process. This means no further preheating step and the avoidance of an extended total process time. The method is applicable in a wide range of forming and shear cutting techniques. Process limits like the moulding degree, draw ratio or cutting aspect ratio can be extended and process forces can be reduced.

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Laser micro processing - facts and trends

Michael Schmidt, *Bayerisches Laserzentrum gGmbH (BLZ) (Germany)*
and
Gerd Eßer, *Bayerisches Laserzentrum gGmbH (Germany)*

Looking at the world market numbers for laser systems, a continuous growth can be identified in the past and is also predicted for the future. Even though applications in the macroscopic range will still claim the biggest market segment for the next years, laser micro technology is going to obtain more and more importance. Actual topics in research and production reflect this trend. Selected highlights out of both sectors showing the potential of miniaturised processes will be discussed. A detailed focus is set on fs-laser processing with experiments on non thermal impact laser adjustment of stainless steel and silicon. As a second topic laser based micro joining methods for electronics will be discussed and thirdly results on micro processing of plastics are presented. Examples from production range from laser marking up to laser processes in health care. A basis for such an advancement in processes are recent developments in building laser sources like fs-lasers, disc and fiber lasers that will be discussed as well in the article.

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Sapphire Tools for Laser-assisted Microforming

J. P. Wulfsberg, S.-E. Hilpert, *Laboratorium Fertigungstechnik, Universität der Bundeswehr Hamburg (Germany)*
and
A. Ostendorf, C. Kulik, T. Temme, K. Samm, *Laser Zentrum Hannover e.V. (Germany)*

From the general trend towards higher functional integration and miniaturisation results an increasing demand for metallic parts of smallest dimensions. Metal forming processes are best suited for these applications in terms of productivity and accuracy. But problems arise from the so called “size effects” related to these small dimensions, e.g. the influence of the microstructure becomes an important aspect to consider. An approach to these problems is the laser-assistance of the microforming process. Laser light is used to increase the temperature of the material during forming reducing the flow stress and increasing the ductility. By controlling the temperature in the workpiece via laser radiation the microstructure can by modified by inducing recrystallization and thus increasing the formability in the required area of the part. This can also be verified by FE simulations of the forming process. To enable the transmittance of laser light into the workpiece, tools of sapphire are used. The machining of these tools has been carried out by laser ablation with wavelengths in the UV range,e.g. with excimer lasers. Experimental investigations have shown that the manufacturing of sapphire tools and their use in laser-assisted microforming processes are valid options for the production of microparts.

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Laser Adjustable Actuators for High-Accuracy Positioning of Micro Components

Manfred Dirscherl, *Bayerisches Laserzentrum gGmbH (BLZ) (Germany)*
and
Gerd Eßer, *Bayerisches Laserzentrum gGmbH (Germany)*

Miniaturization and integration, especially in mass production of electronic and mechatronic equipment is continuously increasing and demands for new solutions concerning production, handling and assembly of devices in ever-decreasing sizes. Especially high-precision adjustment of smallest optical and electronical components is increasingly recognised as one of the key issues facing micromachining technology. As even narrow production tolerances for all individual parts are often not sufficient to match the tightly specified positioning accuracies of the complete assembly, in situ adjustment techniques are required. Together with research partners from industry and science, the BLZ is developing a contact-free, laser-based adjustment method which allows high-accuracy adjustment of components mounted on specifically designed actuators. The underlying mechanisms do not depend on thermal effects but on selective laser ablation of pre-stressed layers of actuator substrate. This way, slightest deformations or modifications of particular mechanical properties can be initiated. The method promises to be more accurate and less time consuming than thermally induced laser bending. The first set of experiments using Excimer, frequency-tripled Nd:YAG and Ti:sapphire femtosecond laser systems has successfully been completed. A reproducible bending angle could be measured, depending on intensity and repetition count of laser irradiation.

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Sunday, 22.06.2003

Room 22

08:30	**Session 5: Precise Structuring** Session Chairs: Alberto Pique, Gerd Eßer
08:30	**Surface microstructuring of transparent materials by laser-induced backside wet etching using excimer laser** (invited paper) H. Niino; X. Ding; R. Kurosaki; A. Narazaki; T. Sato; Y. Kawaguchi; National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan
09:00	**Laser-induced front- and rear-side ablation** S. Beyer; Laser- und Medizin-Technologie GmbH, Berlin, Germany; V. Tornari; Foundation for Research and Technology Hellas (FORTH), Crete, Greece
09:20	**Surface structuring of metals with short and ultrashort laser pulses** M. Weikert; C. Föhl; F. Dausinger; Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Germany; T. Abeln; Maschinenfabrik Gehring, Ostfildern, Germany
09:40	**Nanosecond laser micromachining using an external beam attenuator** J. Bosman; H. Kettelarij; C. d.Kok; Philips Centre for Industrial Technology, Eindhoven, Netherlands
10:00	Break
10:20	**Laser structuring and modification of surfaces for chemical and medical micro-components** E. Bremus-Köbberling; A. Gillner; Fraunhofer Institut für Lasertechnik, Aachen, Germany
10:40	**Two- and three-dimensional periodic structures produced by nano-pulsed laser irradiation in Ag-doped glass** Y. Kaganovskii; I. Antonov; D. Ianetz; M. Rosenbluh; Bar-Ilan University, Ramat-Gan, Israel; A. Lipovskii, St.-Petersburg State Technical University, Russia
11:00	**Principles and applications of laser-induced liquid-phase jet-chemical etching** A. Stephen; S. Metev; Bremer Institut für Angewandte Strahltechnik, Germany
11:20	**Machining of optical microstructures with 157 nm laser radiation** T. Temme; C. Kulik; A. Ostendorf; Laser Zentrum Hannover, Germany
11:40	**Rotational micromachining tool controlled by optical radiation pressure** Y. Hidaka, T. Miyoshi; Y. Takaya; Osaka University, Japan; T. Sasaki; Nippon Institute of Technology, Japan; K. Shirai; Nihon University, Japan
12:00	**A Model for Pulsed Ultraviolet Laser Ablation** N. Mansour; K.J. Ghaleh; Shahid Beheshti University, Tehran, Iran

Surface microstructuring of transparent materialsby laser-induced backside wet etching using excimer laser

H. Niino, *Photoreaction Control Research Center, National Institute of Advanced Industrial Science and Technology (AIST) (Japan)*
and
X. Ding, R. Kurosaki, A. Narazaki, T. Sato, Y. Kawaguchi, *Photoreaction Control Research Center, National Institute of Advanced Industrial Science and Technology (AIST) (Japan)*

Silica glass is an important material in optics and optoelectronics because of its outstanding properties, such as transparence in a wide wavelength range, strong damage resistance for laser irradiation, and high thermal and chemical stability. However, these properties make it difficult to fabricate micron-sized structures on the surface of silica glass. In order to develop simpler processes of micro-fabricating silica glass using a pulsed laser, we have investigated a one-step method to microfabricate a silica glass plate using laser-induced backside wet etching (LIBWE) upon irradiation with a ns-pulsed UV excimer laser. Our idea of LIBWE is based on the deposition of laser energy on the surface of silica glass using ablation of a dye solution. When the dye solution was ablated upon the laser irradiation with a sufficient fluence, the etching of a surface layer was performed on the silica glass. We have succeeded in the micro-fabrication of such transparent materials as silica glass, quartz, calcium fluoride, sapphire and fluorocarbon resin. The advantages of our LIBWE method are as follows, (i) a low laser fluence and constant etch rate, (ii) micro-fabrication without debris and cracks formation, (iii) large area irradiation with an excimer laser beam through a mask projection, (iv) simple pre-/post-treatment on target substrates. This is a one-step process simpler method at ambient pressure, which would be used, for mass production.

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Laser induced front- and rear side ablation

Stefan Beyer, *Laser- und Medizin-Technologie GmbH, (LMTB) (Germany)*
and
Vivi Tornari, *FORTH - IESL Heraklion (Greece)*

Shock wave generation by short pulse laser irradiation is a well known phenomena in laser material processing. In many cases shock wave ablation is the most efficient mechanism in laser surface processing since it enables to deliver a remarkable part of the photon energy directly to an interface that has to be separated. On the other hand there are several quality aspects based on shock wave generation that have to be taken into account. We present a comparative study of front- and rear side ablation with different lasers for several sample- layer combinations: paint on glass, polymer blend on suprasil, Al on polycarbonat and Mo on glass. We discuss a model to explain the different efficiencies that were obtained to differ by one or even two magnitudes. We give an overview of existing investigations and measuring methods and present approaches to make use of the photomechanical mechanisms for the characterisation of material properties of layers. Also we describe the influence of the chosen set up for the accuracy of the ablated geometry and give a short overview of possible far reaching effects.

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Surface structuring of metals with short and ultrashort laser pulses

Michael Weikert, *Institut für Strahlwerkzeuge (IFSW), University of Stuttgart (Germany)*
and
Tobias Abeln, *Maschinenfabrik Gehring GmbH & Co. KG (Germany)*; Christian Föhl, Friedrich Dausinger, *Institut für Strahlwerkzeuge (IFSW), University of Stuttgart (Germany)*

In recent years industry has shown a growing interest in the field of micro-structuring of surfaces on macroscopic workpieces. Several applications to improve the tribological properties of surfaces are known as well as various techniques for printing and embossing. First industrial applications use pulse durations of nanoseconds or longer. However, the quality of the resulting structures is limited due to the formation of melt that has to be removed by additional post-processing. Experimental results have shown that it is possible to avoid melt formation by shortening the pulse duration into the femtosecond regime when low energy density values are used. Detrimental is the fact that process speed with available laser systems is low compared to nanosecond processing. The contribution will show and discuss results in the field of surface structuring of metals with laserpulses in the range from nanoseconds to femtoseconds. The final decision between nanoseconds and femtoseconds has to be made for the concrete application.

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Nano second laser micro maching using an external beam attenuator

Johan Bosman, *Philips Centre for Industrial Technology-CFT (the Netherlands)*
and
Henk Kettelarij, Corné de Kok, *Philips Centre for Industrial Technology-CFT (the Netherlands)*

Philips Centre for Industrial technology in Eindhoven /The Netherlands has developed a laser micro machining process on the basis of a beam attenuator and an industrial nanosecond solid state laser.

The pulse width - pulse energy relationship of a solid state laser generally reduces the accuracy of micro machined features. Our goal is a depth between 1.6 μm and 0.5 μm with an accuracy of 0.1μm. Reaching this depth in a stable laser process would not have been possible without the beam attenuator. Lowering the pulse energy by reducing the inversion level shortly before the laser pulse, decreases the pulse energy but increases the pulse width. This results in a lower intensity and an unstable process. Another solution for this problem would be a dedicated design of a laser resonator with the desired pulse length - pulse energy relation. This solution would be too costly for industrial use, but the same result can be reached by introducing a beam attenuator.

We used an industrial solid state laser system in combination with an external attenuator for a more accurate laser micro machining of Stavax. An accuracy of 0.1μm is achieved by combining the external attenuator with an external power measurement.

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Laser structuring and modification of surfaces for chemical and medical micro components

Elke Bremus-Köbberling, Arnold Gillner, *Fraunhofer Institute for Lasertechnology ILT (Germany)*

In the production of micro devices for chemistry and biotechnology the surface properties become more and more important with respect to surface wetting, fluidic characteristics and biochemical properties for micro reactors, biochemical miniaturized devices for DNA- and proteome analysis and medical micro implants. In all that cases specific surface properties has to be set to conduct fluids and cells. Plasma treatment and co-polymerisation are well used for large area applications but have limited access to small geometries. For this applications laser technologies for surface processing have been developed to manipulate the fluidic surface properties even for channel sizes < 100 µm. The technology is based on excimer-laser treatment of polymer surfaces using laser wavelength < 200 nm with different fluences and cumulated energies. Additionally short pulse Nd:YAG laser processing have been investigated to produce microfluidic channels and devices. Depending on the processing parameters and used polymers either hydrophobic of hydrophilic surfaces can be produced. In ideal cases the wetting angles can be increased from 90 to almost 140 so that the surface acts with the so called lotus effect. This effect has been used as guiding aids for cells on medical micro-implants leading the cells to grow along desired directions. Typical results for cell growing experiments are shown for different polymers.

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Two- and three-dimensional periodic structures produced by nano-pulsed laser irradiation in Ag-doped glass

Yuri Kaganovskii, *Department of Physics, Bar-Ilan University (Israel)*
and
Irena Antonov, David Ianetz, Michael Rosenbluh, *Department of Physics, Bar-Ilan University (Israel)*;
Andrey Lipovskii, *Department of Solid State Physics, St.-Petersburg State Technical University (Russia)*

Direct laser recording of two-dimensional and three-dimensional periodic structures in a glass containing nanocrystalline Ag clusters is demonstrated. The Ag-doped glasses were irradiated by the third harmonic of a Nd:YAG laser (354 nm) with pulse duration of 7 ns and 10 Hz repetition rate, and fluences which varied from 0.2 to 1.2 J/cm^2 . Four intersecting beams of equal intensity were used to create an intensity-modulated pattern at the glass surface and the fifth beam was used to obtain intensity modulation in the bulk. The resultant gratings written in the glass as well as the kinetics of the laser-induced evolution of the Ag clusters were studied by AFM and optical microscopy. Under illumination the nanocrystals move rapidly toward the surface and towards one another, agglomerate and coalesce. The mechanisms and kinetics of light induced mass transfer occurring during recording are analyzed. The kinetics of cluster motion is estimated.

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Principles and Applications of Laser-Induced Liquid-Phase Jet-Chemical Etching

Andreas Stephen, *BIAS - Bremer Institute of Applied Beam Technology (Germany)*
and
Simeon Metev, *BIAS - Bremer Institute of Applied Beam Technology (Germany)*

In this treatment method laser radiation, which is guided from a coaxially expanding liquid jet-stream, locally initiates on a metal surface a thermochemical etching reaction, which leads to selective material removal at high resolution and quality of the treated surface as well as low thermal influence on the workpiece. Electrochemical investigations were performed under focussed laser irradiation using a cw-Nd:YAG laser with a maximum power of 15 W and a simultaneous impact of the liquid jet-stream consisting of phosphoric acid with a maximum flow rate of 20 m/s. The time resolved measurements of the electrical potential difference against an electrochemical reference electrode were correlated with the specific processing parameters and corresponding etch rates to identify processing conditions for temporally stable and enhanced chemical etching reactions. Applications of laser-induced liquid-phase jet-chemical etching in the field of sensor technology, micromechanics and micromolding technology are presented. This includes the microstructuring of thin film systems, cutting of foils of shape memory alloys or the generation of structures with defined shape in bulk material.

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Machining of optical microstructures with 157 nm laser radiation

Thorsten Temme, *Laser Zentrum Hannover e.V. (Germany)*
and
Andreas Ostendorf, Christian Kulik, *Laser Zentrum Hannover e.V. (Germany)*

The precision machining of glass by laser ablation has been expanded with the short wavelength of the 157 nm of the F_2 excimer laser. The high absorption of this wavelength in any optical glass, especially in UV-grade fused silica, offers a new approach to generate high quality surfaces, addressing also micro-optical components. In this paper, the machining of basic diffractive and refractive optical components and the required machining and process technology is presented. Applications that are addressed are cylindrical and rotational symmetrical micro lenses and diffractive optics like phase transmission grating and diffractive optical elements (DOEs). These optical surfaces have been machined into bulk material as well as on fibre end surfaces, to achieve compact (electro) - optical elements with high functionality and packaging density. The short wavelength of 157 nm used in the investigations require either vacuum or high purity inert gas environments. The influence of different ambient conditions is presented.

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Rotational micromachining to uncontrolled by optical radiation pressure

Yasuhiro Hidaka, *Department of Mechanical Engineering and Systems, Osaka University (Japan)*
and
Takashi Miyoshi, Yusuhiro Takaya, *Department of Mechanical Engineering and Systems, Osaka University (Japan)*; Tetsuo Sasaki, *Department of Mechanical Engineering, Nippon Institute of Technology (Japan)*; Kenji Shirai, *Department of Computer Science, College of Engineering, Nihon University (Japan)*

Recently, the miniaturization of industrial products has progressed and the development of new technique for micromachining has been furthered. We have proposed a new approach for micromachining using optical radiation pressure by a single laser beam. The minute force (the order of pN-nN), which is generated by optical radiation pressure, can trap and manipulate a dielectric grain with micrometer size. Furthermore, the grain is rotated by its irregular or asymmetric shape. When we manipulate a trapped and rotated grain in a transverse direction with pressing against work surface, nanometer-sized machining marks can be experimentally generated. Our purpose is to analyze dominant process condition to improve processing efficiency, and to establish micromachining method using a rotating micromachining tool. In this paper, we fabricated a silica particle (5 µm in diameter) into asymmetrically shape using focused ion beam(FIB),and used it as the rotational micromachining tool. An Ar+ laser (wavelength: 488 nm) was used as trapping laser. The experiment of rotating the micromachining tool found that rotation speed of the micromachining tool was proportional to laser power. Furthermore, we manipulated the rotating micromachining tool on a silicon wafer, and measured surface of the silicon wafer using atomic force microscope (AFM).

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A Model for Pulsed Ultraviolet Laser Ablation

Nastaran Mansour, *Department of Physics, Shahid Beheshti University (Iran)*
and
K. Jamshidi Ghaleh, *Department of Physics, Shahid Beheshti University (Iran)*

A theoretical model for laser ablation of polymers is developed. The model includes the description of radiation transport processes for the two-photon stepwise absorption of chromophores. This processes results in a nonlinear loss for the laser fluence, which can be expressed in term of the effective absorption coefficient. The behavior of the effective absorption coefficient as a function of incident fluence, applied wavelengh, linear absorption cross-section, excited state absorption cross-section and plume absorption cross-section will be analyzed. An expression for the etch depth as a function of incident fluence is derived. This model accounts for a wide variety of observations such as fluence thresholds, wavelenght and fluence dependent etch rates. It will be shown that the theretical analysis describes most experimental data with surprising accuracy.

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Sunday, 22.06.2003

Room 22

14:20	**Session 6: Special Session on EUV Technology** Session Chairs: Malcolm Gower, Uwe Stamm
14:20	**Soft X-ray microscopy and EUV lithography: Imaging in the 20-40 nm regime** (invited paper) D. Attwood; Center for X-ray Optics, Lawrence Berkeley National Laboratory, USA, and University of California, Berkeley, USA
14:50	**An Overview on French EUV Lithography Activities: the PREUVE and EXULITE projects** (invited paper) M. Schmidt; Groupe d'Applications des Plasmas, CEA / DSM / DRECAM, France
15:20	**Extreme ultraviolet sources and measurement tools for lithography and system development** (invited paper) U. Stamm; XTREME technologies GmbH, Göttingen, Germany
15:50	**Compact electron-based EUV source** A. Egbert; B. Mader; B. Tkachenko; A. Ostendorf, B. Chichkov; Laser Zentrum Hannover, Germany
16:10	Break
16:40	**EUV light source development in Japan** (invited paper) A. Endo; EUVA, Kanagawa, Japan
17:10	**A high-resolution EUV microstepper tool for resist testing and technology evaluation** (invited paper) M. Gower; Exitech, Oxford, England
17:40	**EUV emission of solid targets** G. Soumagne; T. Abe; H. Someya; A. Endo; EUVA, Kanagawa, Japan; K. Ikeda; K. Nakajima; Graduate University for Advanced Studies, Kanagawa, Japan
18:00	End

Soft X-ray Microscopy and EUV Lithography: Imaging in the 20-40 nm Regime

David Attwood, *Center for X-ray Optics, Lawrence Berkeley National Laboratory (USA) and Electrical Engineering and Computer Sciences, University of California, Berkeley*

Advances in short wavelength optics, covering the range from 1 to 14 nanometers (nm), are providing new results and new opportunities. Zone plate lenses[1] for soft x-ray microscopy[2,3] are now made to high accuracy with demonstrated resolution of 23 nm with proper illumination and stability. These permit important advances in the study of protein specific transport and structure in the life sciences[4], and the study of magnetic materials[5] with elemental sensitivity at the resolution of individual domains. Major corporations[6] are now preparing the path for the fabrication of future computer chips, in the years 2007 and beyond, using multilayer coated reflective optics, which achieve reflectivities of 70% in the 11-14 nm region[7,8]. These coated optics are to be incorporated in EUV print cameras, known as "steppers". Electronic patterns with features in the range of 40-70 nm have been printed. The first alpha tool stepper recently demonstrated all critical technologies[9] needed for EUV lithography. Pre-production beta tools are targeted for delivery by leading suppliers[10] in 2005, with high volume production tools available for manufacturing in 2007. New results in these two areas will be discussed in the context of the synergy of science and technology.

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2. G. Denbeaux, SRI-2000, Berlin.
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4. C. Larabell, private communication. W. Meyer-Ilse et al., J. Microsc. 201, 395 (2001).
5. P. Fischer et al., J. Synchr. Rad. 8, 325 (2001).
6. Members of the EUV Limited Liability Company are Intel, Motorola, AMD, Micron, Infineon, and IBM.
7. T. Barbee et al., Appl. Optics 24, 883 (1985).
8. S. Bajt, private communication (2002)
9. D. Tichenor et al., SPIE 4343, 19(2001).
10. ASML, the Netherlands, at the SPIE Microlithography conference, Santa Clara, CA; March 2001.

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An Overview on French EUV Lithography Activities: the PREUVE and EXULITE projects

Martin Schmidt, *Groupe d'Applications des Plasmas (GAP), CEA Saclay (France)*

This paper will give an overview of the French EUV lithography (EUVL) activities that started in 1999 in the frame of the PREUVE project. Although many different aspects of this technology have been studied, such as mask blanks, multilayer optics and metrology, the paper will focus on EUV sources and the development of the EUVL micro-tool test bench called "banc d'essai pour la lithographie (BEL)". Three different source concepts have been developed in parallel namely two laser-plasma produced (LPP) sources at CEA-DSM and CEA-DAM and a capillary discharge (CD) source at GREMI. For integration on BEL at CEA-LETI, the CD source has finally been chosen for several reasons. In addition, the LPP source developed by CEA-DSM is currently industrialized in the frame of the European MEDEA+ T405 project and in particular by the French EXULITE consortium that is coordinated by Alcatel Vacuum Technology France (AVTF). Thus, in collaboration with Thalès and the CEA-DSM and CEA-DEN, AVTF develops a prototype power source for EUV lithography production tools until 2005. A low cost and modular high power laser system architecture has been chosen and is developed by Thalès and the CEA to pump the laser plasma-produced EUV source.

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Extreme Ultraviolet Sources and Measurement Tools for Lithography and System Development

Uwe Stamm, *XTREME Technologies GmbH (Germany)*

The availability of extreme ultraviolet (EUV) light sources, measurement tools and integrated test systems is of major importance for the development of EUV lithography for use in large volume chip manufacturing starting in 2007. The EUV steppers will require output power from the EUV source of 100 W at 13.5 nm for economic chip production. In addition, the EUV source must achieve minimum specifications for debris emission and source facing condenser optics lifetime, source component lifetime, repetition rate, pulse-energy stability, plasma size and spatial emission stability, and spectral purity as a result of lithography system design constraints. Significant progress has been made in the development of laser produced plasma and gas discharge produced plasma based EUV sources as well as metrology tools to measure EUV radiation characteristics. As of today, the first EUV sources and measurement equipment are available to be used for EUV system, mask, optics and component as well as lithography process development. The paper will cover 5 topics of commercial semiconductor EUV technology:

- High power EUV sources gas discharge EUV sources for lithography tool inspection development. These sources achieve EUV power in excess of 35 W in 2π sr at 13.5 nm.
- Medium power highest brightness laser plasma EUV sources with output power of 1 W in 2π sr at 13.5 nm to be used in inspection and testing.
- Low power highly compact EUV gas discharge sources for metrology with output power of more than 0.1 W in 2π sr at 13.5 nm and other EUV wavelengths.
- Metrology and measurement equipment as energy and power meters for 13.5 nm, high resolution EUV spectrometers in the 5 to 20 nm range, EUV high speed cameras and tools for measuring angular characteristics of EUV radiation.
- EUV optical systems, vacuum beam lines and filter and attenuation tools as well as EUV reflectometer and resist test systems.

Presented will be an update on the experimentally achieved core specifications of the EUV sources as repetition rate, pulse energy stability, brightness, spatial emission stability and spectral distribution and spectral purity. The underlying technologies for thermal management, increase of conversion efficiency as well as reduction of debris will be explained. Examples for characterization of EUV radiation as well as accuracy of the metrology equipment will be given. EUV systems for resist testing and reflectometer measurements will be described.

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Compact electron-based EUV source

Andre Egbert, *Laser Zentrum Hannover e.V. (Germany)*
and
B. Mader, B. Tkachenko, A. Ostendorf, B.N. Chichkov, *Laser Zentrum Hannover e.V. (Germany)*

Extreme ultraviolet (EUV) lithography has been internationally accepted as the successor to optical lithography for large-scale semiconductor chip manufacturing. At present, laser-produced plasmas and discharge-produced plasmas are considered as the only practical EUV sources for the implementation of next generation lithography. However, these sources still have problems related to long-term operation and the generation of debris. Parallel to the development and optimization of high-power EUV sources and optics for next generation lithography, the realization of table-top EUV sources for "at-wavelength" metrology and small-scale lithographic manufacturing is strongly required. These sources have to be calibrated, stable, low-cost, and should provide a simple and long-term operation. We report on our progress in the development of a compact, debris-free, electron-based EUV source. Beryllium and silicon targets are used to generate radiation at 11.4 nm and 13.5 nm, respectively. Conversion efficiencies from electrons into EUV photons will be presented. This source can be absolutely calibrated by controlling the electron current and the accelerating voltage. Characteristics of long-term operation will be reported. Investigations of possibilities towards power scaling up to the range of several milliwatts and first applications will be discussed.

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EUV Light Source Development in Japan

Akira Endo, *Extreme Ultraviolet Lithography System Development Association (EUVA) (Japan)*

A national Japanese EUV lithography light source project started in September 2002 supported by METI (Ministry of Economy, Trade and Industry, Japan). The goal of the four-year project is development of an EUV light source with 10W clean focus point power. Gigaphoton, Ushio, Komatsu, Canon, Nikon and the National Institute of Advanced Industrial Science and Technology (AIST) are carrying out the project in collaboration with several universities by laser and discharge produced plasma. We are developing the first systems in order to investigate LPP and DPP light source characteristics. Our plasma target is based on Xenon recycled with a gas processing system. A Nd:YAG laser system oscillating at 1064nm is used to create the plasma. The laser system is MOPA configuration with maximum repetition rate of 10kHz. We evaluated two laser systems with a few ns and 30ns pulse width (FWHM) regarding EUV conversion efficiency. A discharge EUV source is under development based on a Z-pinch scheme with Xe at a few kHz repetition rate. We evaluated characteristic emission parameters like energy, energy stability using Flying Circus 2 power meter, emission symmetry using a pinhole camera, and spectra using a spectrometer. We will present on our LPP and DPP-system, our diagnostics and the system's current performance in detail.

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A high-resolution EUV Microstepper tool for resist testing & technology evaluation

Malcolm Gower, *Exitech Ltd (United Kingdom)*

By providing the imaging resolution required for producing IC's three to five years ahead of adoption in manufacturing, Microsteppers are now essential tools in the qualification of new photolithography technology nodes. At the sacrifice of image field size, new resist formulations can be developed and tested prior to their use in production. Microsteppers also provide early learning of potential tool and process related technology blockages associated with e.g. new sources, optics, materials, metrologies, reticles, pellicles, defect printing, contamination, cost of ownership, reliability, lifetime, etc. Targeted to print 35nm lines and spaces in resist on 300mm wafers from 6" EUV reflective masks, in this paper we present key features of the Exitech MS-13 Microstepper tool and its modules currently being developed for EUV resist testing & technology evaluation. The illumination source manufactured by Xtreme Technologies is based on gas discharge produced plasma. In 2p sterradians and 2% bandwidth around 13.5nm wavelength the pinch plasma source emits 35W average power at pulse repetition rates of 1kHz and above. Spatial and temporal plasma emission stability of 6% allows control of resist exposure doses to better than 2%. The 0.3NA, x5, 600x200mm field imaging objective uses a two-mirror aspheric design developed by the EUV Limited Liability Corporation (EUV LLC) under a contract from International SEMATECH. A quasi-critical illumination system including a nested Wolter-type collector is used to provide uniform illumination of the reticle that matches the etendue of the imaging objective. The inner and outer coherence factor of the annular illumination of the centrally obscured objective can be varied between 0.36 and 0.55. Both projection and illumination system are manufactured by Carl Zeiss. With a 15nm autofocus repeatability the tool is targeted to expose 10mJ/cm^2 sensitivity photoresists in 0.25sec. Details of the tool design architecture, module layout, UHV chamber, major subsystems including performance specifications will be presented.

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EUV Emission of Solid Targets

Georg Soumagne, *Extreme Ultraviolet Lithography System Development Association (EUVA), Hiratsuka Research & Development Center, (Japan)*
and
Tamotsu Abe, Hiroshi Komori, Hiroshi Someya, Takashi Suganuma, Akira Endo, *EUVA (Japan)*; Kenichi Ikeda, Kazuhisa Nakajima, *Graduate University for Advanced Studies (Japan) and High Energy Accelerator Research Organization Tsukuba (Japan)*

Extreme ultraviolet (EUV) light sources are of particular interest for next generation lithography. And compact high-brightness soft x-ray sources are attractive for other fields, e.g. solid-state. In order to compare possible plasma targets and to compare the dependence of the EUV emission on the laser pulse width we used a EUV energy meter (Scientech Engineering, Flying Circus II), which includes a multilayer mirror and an absolutely calibrated diode (IRD, AXUV-100G). The curved mirror has a maximum reflectivity near normal incidence of 0.69 at 13.5nm (fwhm: 0.5nm) and images the plasma region onto the diode. Zirconium (Zr) filters were used to block the visible plasma emission. The plasma was generated with a Ti:sapphire laser oscillating at 790nm. Measurements were done for laser pulse widths of 120fs and 300ps (fwhm) with maximum laser focus intensities of about 3 1017 W/cm^2 and 2 1014 W/cm^2, respectively. Cu, Sn, Al and W were used as targets. First results show that tin (Sn) is the strongest emitter and that only for tin a dependence on the laser pulse width is observed with stronger emission at shorter laser pulse length. These results and measurements of the spectral emission will be presented and discussed in detail.

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Monday, 23.06.2003

Room 21

11:00	**Session 7, Part I: Micro-Welding and Melting** Session Chair: Arnold Gillner
11:00	**Pseudo-elastic and bio-chemical properties of Ti-Ni shape memory-alloy wires micro-welded by YAG laser** K. Uenishi; M. Takatsugu; F. Kobayashi; Osaka University, Japan
11:20	**Micro-welding of thin foil with diode laser** Y. Funada; Industrial Research Institute of Ishikawa, Japan; M. Ishide; N. Abe; Osaka University, Japan
11:40	**Microjoining of dissimilar materials for life science applications** H.J. Herfurth; R. Witte; S. Heinemann; Fraunhofer Center for Laser Technology (CLT)
12:00	**Focused laser-induced melting of semiconductor: 3D numnerical simulation using an apparent heat capacity formulation** J.-Y. Degorce; M. Meunier; Ecole Polytechnique de Montreal
12:20	**Measuring the tool of laser micro machining -camera - based focal diagnostics in the range of 10 microns** R. Kramer; H. Schwede, PRIMES GmbH, Germany

Pseudo-elastic and bio-chemical properties of Ti-Ni Shape Memory> Alloy Wires Micro Welded by YAG Laser

Keisuke Uenishi, *Osaka University (Japan)*
and
Masaya Takatsugu, Kojiro F. Kobayashi, *Osaka University (Japan)*

Ti-Ni shape memory alloy wires were micro welded by using YAG Laser for the fabrication of biomedical devices. Effect of laser conditions such as laser power or pulse duration were investigated on the weldability, joint microstructure, joint strength and pseudo-elastic properties. Compared to the micro welding of stainless steel, more precise control of laser conditions was required to obtain sound joints of TiNi wires, but optimization of laser conditions enabled the joining with superior strength and shape memory properties. Besides, bio-chemical properties of the obtained joints were estimated by immersion tests in quasi-biological environments to be comparable with base wires, suggesting the applicability of Laser micro welding to the fabrication of medical devices.

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Micro Welding of Thin Foil with Diode Laser

Yoshinori Funada, *Industrial Research Institute of Ishikawa (Japan)*
and
Masahiro Ishide, Nobuyuki Abe, *Joining and Welding Research Institute, Osaka University (Japan)*

Laser processing is expected to be applied to micro welding of thin foils because of its superior heat controllability in comparison with arc or plasma processing. In this report, welding of thin foils was examined with a direct diode laser system. As the result of the examination of welding of thin stainless foils of 100mm in thickness or less, it was recognized that butt and edge welding of the foils were possible with an elliptical laser beam. Especially, in the case of butt welding, the foils of 50mm in thickness could be welded with a narrow bead width of 100mm at a high speed of 0.3m/sec.

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Microjoining of Dissimilar Materials for Life Science Applications

Hans J. Herfurth, *Fraunhofer Center for Laser Technology (CLT) (USA)*
and
Reiner Witte, Stefan Heinemann, *Fraunhofer Center for Laser Technology (USA)*

Implantable microsystems currently under development have the potential to significantly impact the future treatment of disease. Functions of such implants will include localized sensing of temperature and pressure, electrical stimulation of neural tissue and the delivery of drugs. The devices are designed to be long-term implants that are remotely powered and controlled for many applications. The development of new, biocompatible materials and manufacturing processes that ensure long-lasting functionality and reliability are critical challenges. Important factors in the assembly of such systems are the small size of the features, the heat sensitivity of integrated electronics and media, the precision alignment required to hold small tolerances, and the type of materials and material combinations to be hermetically sealed. Laser micromachining has emerged as a compelling solution to address these manufacturing challenges. This paper will describe the latest achievements in microjoining of non-metallic materials. The focus is on glass, metal and polymers that have been joined using CO_2, Nd:YAG and diode lasers. Results in joining similar and dissimilar materials in different joint configurations are presented, as well as requirements for sample preparation and fixturing. The potential for applications in the biomedical sector will be demonstrated.

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Focused laser induced melting of semiconductor: 3-D numerical simulation using an apparent heat capacity formulation

Jean-Yves Degorce, *Laser Processing Laboratory, Department of Engineering Physics, École Polytechnique de Montréal (Canada)*
and
Michel Meunier, *École Polytechnique de Montréal (Canada)*

Focusing a pulsed visible laser on a semiconductor may induce a local melting without ablation if an appropriate energy range is chosen. This microfabrication technique can be used in many processes and in particular in our new laser process for making highly accurate resistance for microelectronics which consist of laser inducing local diffusion of dopants from the drain and source of a gateless field effect transistor into the channel thereby forming an electrical link between two adjacent p-n junction diodes (M. Meunier et al Applied Surface Science, 186, 52-56 (2002). Numerical calculation of the melt region obtained by focusing a laser on a semiconductor is complicated by the phase change which is often difficult to handle when all materials properties are temperature dependant. We have modified what is called the classical Stefan problem describing this phase change by using an apparent heat capacity formulation. c(T) + delta(T-Tm)L where c(T) is the heat capacity and L is the latent heat energy. In this formulation, it is now easy to consider that all material parameters are temperature dependent including the optical absorptivity. Numerically, delta(T-Tm) is approximated by a gaussian function over a small temperature interval. Calculation in 3-D were performed on silicon irradiated by a Nd:YAG laser (532nm, 50ns pulse width) and are satisfactory compared with melt radius and lifetime, obtained from a transient surface reflectivity measurement using an HeNe probe laser. We have also applied these calculations to our process of making laser diffused resistances.

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Measuring the tool of laser micro machining -camera - based focal diagnostics in the range of 10 microns

Reinhard Kramer, *PRIMES GmbH (Germany)*
and
Harald Schwede, *PRIMES GmbH (Germany)*

Micro machining with the laser requires very small spot sizes. With standard diagnostic systems it is difficult to observe the tools of the processing, the focus with dimensions in the range of only 10 micron. A new camera based focal diagnostic system with a high magnification objective is presented. This system enable to measure the power density distribution of spots down to 10 microns. With a special design of the electronically lay-out a dynamic range of more than 100 db can be achieved with a logarithmic CMOS camera based system as well as with a CCD camera. Measurements are presented: Q-switch-, pulse- and video mode.

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Monday, 23.06.2003

Room 21

13:40	**Session 8: Applications of fs-laser machining** Session Chair: Henri Helvajian, Andre Egbert
13:40	**Fabrication of holes and grooves on glass by a femtosecond laser** Y. Itoh; K. Kuroi; K. Hayakawa; Nagaoka University of Technology, Japan
14:00	**Processing HIP-zirconia with ultra-short laser pulses** K. Werelius; P. Weigl; J.-W.-Goethe-University, Frankfurt/Main, Germany; H. Lubatschowski; Laser Zentrum Hannover, Germany
14:20	**High-precision deep drilling of metals with ultrashort pulses** C. Föhl; F. Dausinger; Forschungsgesellschaft für Strahlwerkzeuge, Universität Stuttgart, Germany
14:40	**New methods to control quality and precision of micro-machining with femtosecond lasers** E. Audouard; R. LeHarzic; N. Sanner; N. Huot; C. Donnet; P. Laporte; Laboratoire Traitement du Signal et Instrumentation, Saint-Etienne, France
15:00	**Micromachining of metals and semiconductors using a new femtosecond laser microfabrication system** M. Meunier; A. Kabashin; A. Houle; B. Fisette; École Polytechnique de Montréal, Canada
15:20	**Experimental assessment of machining accuracy obtainable by femtosecond laser surface structuring** T. Höche; T. Petsch; 3D-Micromac, Chemnitz, Germany; D. Ruthe; K. Zimmer; Institut für Oberflächenmodifizierung, Leipzig, Germany; F. Syrowatka; F. Heyroth; Interdisziplinäres Zentrum für Materialwissenschaften, Martin-Luther-Universität Hall-Wittenberg, Germany
15:40	**Transcriptional ablation using femtosecond laser with mask** Y. Nakata; T. Okada; M. Maeda; Grad. School of ISEE, Kyushu University, Japan

Fabrication of holes and grooves on glass by a femtosecond laser

Ito Yoshiro, *Department of Mechanical Engineering, Nagaoka University of Technology (Japan)*
and
Kuroi Kazumori, Hayakawa Kazuhide, *Nagaoka University of Technology, Department of Mechanical Engineering (Japan)*

Holes and grooves of a few tens of micrometers have been fabricated on glass plates by femtoscond laser pulses in air. Shapes and surface morphology of the fabricated structures have been studied in detail by making their replicas. The holes drilled from the front surface have well defined, crack-free edge at entrances, but their exits at rear surface suffer shell-like cracks to some extent. Details of the internal shape of the strictures formed have been studied by making replicas of them. Development of the shape of drilled hole with the increase in irradiated pulse number shows some distinguishable stages. Smaller number of pulses make channel at the center of rather flat bottom. With the increase of pulse number, the channel changed into conical, funnel-like shape as the depth increased. Shape of the groove depends on the scanning speed, i.e., number of irradiated pulses on the same position. The groove show little cracking or breaking with clear edges. Some amount of debris deposited along the groove but these debris were easily removed by smear. Inner surface of the groove has coarser morphology than that of the hole. Depth of the grove was shallower than that of the hole, even though the number of irradiated pulse was estimated to be equal.

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Processing HIP-zirconia with ultra-short laser pulses

Kristian Werelius, *J.W.Goethe-University (Germany)*
and
Paul Weigl, *J.W.Goethe-University (Germany)*; Holger Lubatschowski, *Laser Zentrum Hannover e.V (Germany)*

Creating individual complex three dimensional structures in HIP-zirconia by conventional mechanical machining, e.g. milling, is time consuming and subject to significant loss in bending strength due to microcracking during the milling process. Utilizing ultra-short laser pulses, individual complex three dimensional microstructures can be created very precisely without severe damage to the structure. This advantage is used to process HIP-zirconia in order to create dental restorations. To evaluate efficiency and quality, different laser parameters such as pulse duration, pulse energy and ablation strategies were studied. The maximum ablation rate was found using 400-700 fs.

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High-precision deep drilling of metals with ultrashort pulses

Christian Föhl, *Forschungsgesellschaft für Strahlwerkzeuge mbH (Germany)*
and
Friedrich Dausinger, *Institut für Strahlwerkzeuge, Universität Stuttgart (Germany)*

Up to now the achievable accuracy of laser drilled holes in metals is limited by the relative large amount of molten material when drilling lasers with pulse durations in the range of nanoseconds or longer are used. Shortening the pulse duration down to the femtosecond regime is considered as a recipe to avoid melt formation, in general. Our investigations have shown that this is valid for drilling of thin materials or when very low pulse energies are used. However, for an efficient drilling of deep capillaries higher pulse energies are required and therefore recast can only be avoided by the reduction of the pulse duration and a combination with well-elaborated drilling procedures. Within this contribution several influences of process parameters such as the repetition rate and the pulse duration on drilling efficiency and hole quality will be presented and discussed. Furthermore different processing techniques for increasing the drilling velocity will be shown. A suitable device for that purpose is a trepanning optic which was specially designed for drilling of injection nozzles. It allows various angles of beam incidence to produce holes with a well-defined conicity in combination with the high precision achieved by helical drilling.
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New Methods to Control Quality and Precision of Micro-Machining with Femtosecond Lasers

Eric Audouard, *Laboratoire Traitement du Signal et Intrumentation Université Jean Monnet (France)*
and
R. LeHarzic, N. Sanner, N. Huot, C. Donnet, P. Laporte, *Laboratoire Traitement du Signal et Intrumentation Université Jean Monnet (France)*

Recent quantitative studies on microprocessing and laser-matter interaction using femtosecond lasers will be reported, particularly ablation rates for several materials. It will be shown how the control of the Heat Affected Zone (HAZ) and control beam improvement allow a to enhance actual microprocessing capability of the existing sources. Specific results will be shown in the field of dielectrics for 3-D photowritting in bulk glasses. tribological considerations will be taken into account because of their role in all requirements and applications relating to the control of friction and wear in mechanical components.

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Micromachining of metals and semiconductors using a new femtosecond laser microfabrication system

Michel Meunier, *Laser Processing Laboratory, Department of Engineering Physics, École Polytechnique de Montréal (Canada)*
and
Andrei Kabashin, Alexis Houle, Bruno Fisette, *École Polytechnique de Montréal (Canada)*; Sergey Broude, *Pascal Miller Resonetics Inc. (USA)*

A microfabrication system with the use of a femtosecond laser was designed for 3-D processing of industrially important materials. The system includes 120 fs, 1 kHz laser; beam delivery and focusing system, systems for automated 3-D target motion and real-time imaging of the sample placed in a vacuum chamber. The system made possible the formation of structures (deep holes, channels) with minimal lateral dimensions of about 3-4 micrometers on the surfaces of different metal (aluminum, stainless steel), and semiconductor (Si, Ge) substrates. We established ablation thresholds for materials investigated and clearly identified regimes of slow and fast ablation for silicon and stainless steel. For both materials, at relatively low laser fluences $I < 10$ J/cm^2 the regime of slow ablation takes place, which is characterized by exceptional quality of the ablated surface, but slow ablation rate (< 25 nm/pulse). This regime is well suited for the patterning of markers on surfaces. The fast ablation at $I > 10$ J/cm^2 also provides high quality treatment without heat-affected zone, while the ablation rate can reach 30-100 nm/pulse, which is sufficient to effectively produce e.g., through holes or deep channels. However, we found that fast ablation regime imposes additional requirements on the quality of delivery and focusing of the laser beam because of the presence of parasitic ablation around the main spot on the tail of the radiation intensity distribution. Possibilities of applying the system for the processing of surfaces with complex profiles will also be discussed.

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Experimental Assessment of Machining Accuracy Obtainable by Femtosecond-Laser Surface Structuring

Thomas Höche, Tino Petsch, *3D-Micromac AG (Germany)*
and
David Ruthe, Klaus Zimmer, *Institut für Oberflächenmodifizierung e.V. (Germany)*; Frank Syrowatka, Frank Heyroth, *Interdisziplinäres Zentrum für Materialwissenschaften, Martin-Luther-Universität Halle-Wittenberg (Germany)*

Using laser micro-machining workstations, surfaces can be rapidly and precisely structured on the micrometer level and when sub-picosecond laser are implemented, all kinds of materials including semiconductors, metal and insulators can be machined. Although computer-controlled structuring is straightforward, the assessment of machining accuracy on the sub-micrometer scale is very challenging. Edge steepness, edge smoothness, lateral range of debris deposition, and chemical composition of ejected material are major characteristics of machining accuracy. However, the latter are hard to assess experimentally. The applicability of all direct optical techniques including interference microscopy and laser profilometry for the characterisation of geometrical issues is rather limited since the bottom of laser-generated superficial structures is generally extremely uneven and edges are very steep. Imaging and X-ray spectrometric techniques in the scanning electron microscope are slightly better suited, particularly when combined with tilting of the sample, but also suffers from severe limitations: the topography of the surface (particularly in deep ditches) is hard to obtain. Moreover, the volume excited by the impinging electrons is in the range of µm3 making the chemical analysis of nanometer-sized particle very sophisticated. We have applied a novel experimental approach to resolve the issues defined above: After micro-machining various materials using a 3D-Micromac femtosecond workstation FS-150-1 (comprising a Clark-MXR CPA-2001 Ti:sapphire laser with 120 fs pulse length), highly accurate surface replica were prepared by allowing a acetone treated cellulose acetate sheet to dry on the samples. After detaching this replica, not only the inverse of the surface topography is obtained but — since this method has been originally introduced for cleaning surfaces — all debris not firmly attached to the surface is torn off, too. Those surface replica were studied in an ambient pressure scanning electron microscope allowing of both imaging (without prior deposition a of conducting film) and electron probe microanalysis. The latter is facilitated since there is no longer a substrate of a composition similar to that of the debris particles studied. This feature is particularly important for the investigation of lateral debris distribution after laser machining of multilayered heterostructures.

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Transcriptional ablation using femtosecond laser with mask

Yoshiki Nakata, *Graduate School of ISEE, Kyushu University (Japan)*
and
Tatsuo Okada, Mitsuo Maeda, *Graduate school of ISEE, Kyushu University (Japan)*

Femtosecond laser has been applied to micro-processing of various materials for its fine resolution and non-thermal processing characteristics. In the past experiments, dot, line or periodical structures have been processed. On the other hand, two-dimensional structure has been fabricated only by scanning of laser or sample. In this experiment, masks were firstly applied to micro-processing using femtosecond laser. A femtosecond laser pulse was induced to a mask, and the shape was transferred on a gold film by laser ablation. Micron-sized structures were successfully transferred.

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Monday, 23.06.2003

Room 21

16:30	**Session 7, Part II: Micro-Welding and Melting** Session Chair: Kojiro Kobayashi
16:30	**Precision microwelding of thin metal foil with single mode fiber laser** (invited paper) I. Miyamoto; S.-J. Park; Department of Manufacturing Science, Osaka University, Japan; T. Ooie; Institute for Marine Resource and Environment, AIST, Japan
16:50	**Laser beam micro-welding of dissimilar metals** K. Klages; A. Gillner; A. Olowinsky; Fraunhofer Institute for Laser Technology ILT, Aachen, Germany; F. Wagner; Bremer Institut für Angewandte Strahltechnik BIAS, Bremen, Germany; A. Studt; S. Fronczek; FCI Automotive Deutschland, Nürnberg, Germany; E. Lepin; Wieland Werke, Ulm, Germany
17:10	**Diode laser micro-welding using novel line sources** T. Hoult; Coherent Laser Applications Center
17:30	**Use of pre-pulse in laser spot welding of materials with high optical reflection** I. Mys; M. Geiger; University of Erlangen-Nuremberg, Germany
17:50	End

Precision microwelding of thin metal foil with single mode fiber laser

Isamu Miyamoto, *Department of Manufacturing Science, Graduate School of Engineering, Osaka University (Japan)*
and
Seo-Jeong Park, *Department of Manufacturing Science, Osaka University (Japan)*; Toshihiko Ooie, *Institute for Marine Resource and Environment, AIST (Japan)*

Micro-welding of ultra-thin metal foil with thicknesses down to 10 microns was investigated by using a single mode Yb fiber laser with a maximum output of 40W. A knife-edge probe method indicated that the beam diameter at the focal point was approximately 10 microns. Coupling rate of the laser beam was estimated on the basis of moving line-heat source model and experimental bead width measured at different traveling speeds and laser powers, and was as high as 80-100% at thicknesses larger than 40 microns due to multi-reflections in the keyhole. Influence of the assist gas flow rate on the dimensions of the weld bead was examined, and it was found that the the deflection of laser beam in the laser-induced plume cannot be neglected in welding using such a fine-focused beam due to a steep density gradient in the plume. Full-penetration welding was attained at speeds faster than 20 m/min in thickness of 100 micron. Sound lap welding of thickness of 20 microns to 30 microns was demonstrated even with a gap larger than 10 microns.

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Laser Beam Micro Welding of Dissimilar Metals

K. Klages, A. Gillner, A. Olowinsky, *Fraunhofer Institute for Lasertechnology ILT (Germany)*
and
F. Wagner, *Bremer Institut für angewandte Strahltechnik BIAS (Germany)*; A. Studt, S. Fronczek, *FCI Automotive Deutschland GmbH (Germany)*; E. Lepin, *Wieland Werke (Germany)*

The combination of dissimilar metals like brass and stainless steel is often needed in watch movements due to tribologic aspects. For mass production in automotive applications, a joining technique for alloyed copper with alloyed steel is needed. Laser beam micro welding offers an alternative to conventional joining techniques like press fit or soldering. Depending on the joining geometry, two different welding techniques are investigated: seam and spot welding. High strength and reproducibility are the main objective of joining dissimilar metals. Cracks and spillings are affected by the metallic continuity and should be avoided. Lap- and t-joints can be produced by the SHADOW-Welding technique. The length of the continuous welding seams are up to 15.7 mm at a feed rate of up to 60 m/min with a pulsed laser source. The weld width attained is from 50 to 250 µm and a weld depth from 20 to 150 µm. This low energy joining process with minimised heat input results in low distortion of the parts joined. Pin to plate connections require a spot weld. The pulse forming capability is needed especially for highly reflective metals like copper. The welded joints have a higher strength than the basic material.

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Diode laser micro-welding using novel line sources

Tony Hoult, *Coherent Laser Applications Center (USA)*

The most widely used basic building block for diode laser systems is a single multi-emitter diode laser bar. For certain applications a line of light is preferred to a round beam and hence the use of fiber optic delivery may not be necessary. Straightforward optics can be used to convert the divergent output from this bar into a rectangle of light but the uniformity of the beam within this rectangle is a major problem. When diode bars are stacked vertically, this problem becomes 2 dimensional for anything other than a tightly focused beam. If the beam is used to cover a large surface area by motion normal to the long axis of the beam, fluctuations in intensity associated with the individual emitters and the individual bars can cause lack of processing uniformity. This is especially true when a laser line is used to seal multiple micro-fluidic devices. This work reports the use of a novel laser line source with very low ripple to tackle this problem. Results also show the very high level of process control achieved on various forms of thermoplastics such as hard and soft thermoplastic foams.

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Use of pre-pulse in laser spot welding of materials with high optical reflection

Ihor Mys, *Chair of Manufacturing Technology, University of Erlangen-Nuremberg (Germany)*
and
Manfred Geiger, *Chair of Manufacturing Technology, University of Erlangen-Nuremberg (Germany)*

Laser micro welding has become a standard manufacturing technique, particularly in industry sectors, such as automotive and aerospace electronics or medical devices, where the requirements for strength, miniaturisation and temperature resistance are constantly rising. So far the use of laser micro welding is limited due to the fluctuation of the quality of the welded joints, because the welding results for material with high optical reflection and thermal conductivity, such as copper and copper alloys, depend very strongly on the condition of the material surface. This paper presents investigations on the use of a laser pre-pulse in spot welding of electronic materials with Nd:YAG laser. In order to achieve reproducible joining results two strategies are followed-up. The first one utilises a reflection-based process control for measuring the reflection during the short pre-pulse. The intensity of the reflected light is used to calculate an appropriated welding pulse power which corresponds to the measured relative absorption. Adjustment of laser parameters according to the condition of the surface is done in real time before laser main pulse. A second possibility for the stabilisation of copper welding is the employment of a short and powerful laser pre-pulse before laser main pulse. This pre-pulse affects the workpiece surface and creates more reproducible absorption conditions for the main pulse, independent from the initial situation on material surface.

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Monday, 23.06.2003

Room 22

11:00	**Session 9: Precision Marking** Session Chair: Martyn Knowles
11:00	**Pit formation during laser marking of aluminium thin film in transparent resin** S. Nakahara; Y. Okino; S. Hisada; T. Fukita; Kansai University, Osaka, Japan
11:20	**New excimer laser marking method using MMD** T. Kuntze; M. Panzner; U. Klotzbach; E. Beyer; Fraunhofer Institut für Werkstoff- und Strahltechnik IWS, Dresden, Germany
11:40	**Wire marking with UV Lasers: a comparison** J. Koch; Bremer Institut für Angewandte Strahltechnik BIAS, Bremen, Germany; H. Ostersehlte; Airbus Deutschland, Hamburg, Germany
12:00	**Programmable 2-D laser marking device based on a pulsed UV image coherent amplifier** T. Lamarque; B. Loiseaux; J.-P. Huignard; Thales Research and Technology, France; R. Nicolaus; Technische Universität Darmstadt, Germany; G. Slekys; Altechna, Lithuania; J. Xu; Photonics Research Center, College of Physical Science, Nankai University, Tianjin, China
12:20	**Precise focusing of single mode LD for material processing** T. Jitsuno, Institute of Laser Engineering, Osaka University; K. Tokumura, Nalux Co. Ltd; H. Tamamura, Techtoronics Japan Corporation; K. Kazama, Y.E.DATA Co. Ltd, Japan

Pit formation during laser marking of aluminium thin film in transparent resin

Sumio Nakahara, *Kansai University, Department of mechanical engineering (Japan)*
and
Yoshihiro Okino, Shigeyoshi Hisada, Takeyoshi Fukita, *Kansai University, Department of mechanical engineering (Japan)*

Mark formation like pit by laser writing to aluminum thin-film in an optical storage media with a tri-layer design was studied by scanning electron microscope, scanning force microscope, and optical microscopy. The laser marking response of the aluminum thin-film in a transparency resin of read only memory (ROM) medium like a compact disk for identification is controlled by the interplay of optical and thermal effects. Relatively simple analytical expressions were derived that provided a qualitative and semi-quantitative description of the optical and thermal characteristics of a commercial available compact disk. These were used to explain various phenomena that were observed during recording experiments that were performed on compact disk media and evolve a new understanding of the mark formation process.

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New Excimer Laser Marking Method using MMD

Thomas Kuntze, *Fraunhofer IWS (Germany)*
and
Michael Panzner, Udo Klotzbach, Eckhard Beyer, *Fraunhofer IWS (Germany)*

Higher and higher through-puts in marking industry are todays requirements. Mainly packaging industry or cable marking companies ask for part-by-part varying markings like serial numbers, weight, date or barcodes. That gives a need to develop a flexible, high-speed on-the-fly marking technique. Current laser marking techniques like direct writing using a scanned laser beam or excimer laser fixed mask projection offer proven quality and either flexibility or detailism. Their drawbacks are limited speed (direct writing) and invariability (fixed mask projection). The Fraunhofer IWS developed a marking system using excimer laser mask projection with a micro mirror device (MMD) as computer-controlled "flexible mask";. The idea is to generate complexe markings within one laser pulse so the marking speed is only limited by the laser repetition rate. The IWS used a 308nm excimer laser and a reflective phase-shifting mask from Fh IMS to demonstrate the marking capabilities. It was possible to generate free-programmable, high-contrast markings on common mateials like paper and plastic. Furthermore, it could be shown that the technique is also usable to generate 3-D structures in PI. Result of the studies is the development of a very fast marking technique using MMDs in combination with short wavelength and short pulse lasers. It also has high potential in 3-D laser micromachining.

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Wire marking with UV-lasers: a comparison

Jürgen Koch, *BIAS, Bremen Institute of Applied Beam Technology (Germany)*
and
Hartmut Ostersehlte, *Airbus Deutschland GmbH (Germany)*

UV-laser marking of wires is widely used in aircraft industry. For several years, the XeCl-excimer laser established itself on the market. Today, it has to defend its market share against an ambitious competitor: the frequency-tripled Nd:YAG laser. The question, which system is the better one is still unsolved and remains on a more or less philosophic level. Hence, this article's intension is to bring some light into the darkness from a user's point of view. A short review on literature according wire marking by UV-lasers is given with special respect to the marking mechanism. Further, two exemplary representatives of the different kinds of laser systems are introduced, which are compared concerning their performance. Thus, investigations have been carried out to determine the processing speed and to analyse the production results, like contrast and penetration depth, of the respective processing unit. These results are put into correlation to the modification mechanism and to the particular assemblies and their specific features, showing the advantages of the researched laser systems. Additional information on operation expenses and maintenance cycles will be provided, as well.

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Programmable 2-D laser marking device based on a pulsed UV image coherent amplifier

Thierry Lamarque, *THALES Research and Technology (France)*
and
Ralf Nicolaus, *Institut für Angewandte Physik, Technische Universität Darmstadt (Germany)*; Brigitte Loiseaux, Jean-Pierre Huignard, *THALES Research and Technology (France)*; Gintas Slekys, *Altechna Co. Ltd (Lithuania)*; Jingjun Xu, *Photonics Research Center, College of Physical Science, Nankai University, Tianjin (China)*

We present a novel technique for engraving microscopic 2-D patterns in one step with a UV pulsed laser by means of a versatile programmable approach. The laser beam is divided to an expanded low energy signal beam which is spatially modulated by a LCD modulator and a higher energy pump beam with a plane homogeneous wave front. Both beams are superposed in a highly magnesium doped photorefractive lithium-niobate crystal where an energy transfer towards the weaker signal beam takes place. The spatially modulated and amplified signal beam is then de-magnified and imaged onto the surface where the image has to be engraved. The need for the coherent amplifier rises out of the fact that LCDs are unable to withstand the high energy throughput required for etching. The combination of the amplifier with the amplitude modulator leads to a faster and more flexible solution than laser marking with pixel by pixel raster-scan, or fixed mask projection mode. Such a technique can thus be applied to identify valuable items by imprinting a smart and personalised 2-D code onto its surface.

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Precise focusing of single mode LD for material processing

T. Jitsuno, *Institute of Laser Engineering, Osaka University (Japan)*
and
K. Tokumura, *Nalux Co. Ltd. (Japan)*; H. Tamamura, *Techtoronics Japan Corporation (Japan)*, K. Kazama, *Y.E.DATA Co. Ltd. (Japan)*

A new approach for the direct micro-processing with a single-mode laser diode (LD) is reported. The advantage of single-mode LD for high brightness focusing, the source of aberration in LD light, and the method to improve the brightness are described. The recent experimental results on the laser ablative shaping (LAS) are presented. Possible applications of LD micro-marking system are also described.

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Monday, 23.06.2003

Room 22

13:40	**Session 10: Drilling and Microcutting** Session Chairs: Willem Hoving, David Ashkenasi
13:40	**Comparison of diode-pumped solid state lasers with copper vapour lasers for micro-fabrication** M. Knowles; E. Illy; G. Rutterford; A. Bell; A. Kearsley; Oxford Lasers, United Kingdom
14:00	**Geometrical aspects of laser-drilled high precision holes** R. Giedl; F.X. Wagner; M.J. Wild; Delphi, Deggendorf, Germany; H.-J. Helml; GFH, Deggendorf, Germany
14:20	**Physical aspects of high speed drilling with a long pulse excimer laser** A. Schoonderbeek; C.A. Biesheuvel; R.M. Hofstra; Nederlands Centrum voor Laser Research NCLR, Enschede, Netherlands; K.-J. Boller; J. Meijer; University of Twente, Netherlands
14:40	**Microdrilling, -scribing and -cutting with high-quality and high-power ns-Nd:YAG systems** A. Binder; H. Kern; D. Ashkenasi; N. Müller; Laser- und Medizin-Technologie LMTB, Berlin, Germany; T. Riesbeck; Optisches Institut, Technische Universität Berlin, Germany
15:00	**CO_2 Laser spectroscopy of dielectric laminate materials** K. Gulia; F. Villarreal; C.J. Moorhouse; H.J. Baker; D.R. Hall; Heriot Watt University, Edinburgh, United Kingdom
15:20	**Drilling and cutting ceramics, metals and composites using visible and UV laser beams** I. Sárady; N. Miroshnikova; O. Yalukova; A. Kaplan; Lulea University of Technology, Sweden
15:40	**Advanced laser optics for laser material processing** K. Ebata; K. Fuse; Sumitomo Electric Industries Ltd., Japan
16:00	Break
16:30	**Selection of parameters on cutting mild steel plates taking account of some manufacturing purposes** H. Asano; H. Eguchi; Laser Machinery Division, Amada Co., Kanagawa, Japan; J. Suzuki; H. Kawakami; Mie University, Japan
16:50	**Separating and structuring of brittle material by the use of laser radiation** S. Georgi; Jenoptik Automatisierungstechnik, Jena, Germany
17:10	**High speed laser cutting using a 2kW high power and high quality diode-pumped solid-state Nd:YAG** Y. Takenaka; M. Seguchi; J. Nishimae; Mitsubishi Electric Corporation, Advanced Technlogy R&D Center, Hyogo, Japan
17:30	**Novel approach to control the combustion and detonation by resonance laser radiation** A. Starik; N. Titova; B. Loukhovitski; Central Institute of Aviation Motors, Scientific Research Center Raduga, Moscow, Russia
17:50	End

Comparison of Diode Pumped Solid State Lasers with Copper Vapour Lasers for Micro-fabrication

Martyn Knowles, *Oxford Lasers Ltd. (United Kingdom)*
and
Elizabeth Illy, Graham Rutterford, Andrew Bell, Andrew Kearsley, *Oxford Lasers Ltd (United Kingdom)*

The micro-fabrication capabilities of high repetition rate copper vapour lasers and diode pumped solid state lasers will be compared across a range of uv and visible wavelengths. This study will highlight the relative advantages of each laser system. Consideration will be given to the processing capability, system integration and end-user requirements. The applications considered will include photonics, medical component manufacture and micro-electronics. In particular, comparison of process quality and speed between 355nm (diode pumped solid state) and 511nm (copper vapour) for micro-drilling and cutting of metals will be reported.

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Geometrical aspects of laser-drilled high precision holes

Roswitha Giedl, *DELPHI (Germany)*
and
Franz X. Wagner, Michael J. Wild, *DELPHI (Germany)*; Hans-Joachim Helml, *GFH mbH (Germany)*

Laser drilling has become a valuable tool for the manufacture of high precision micro holes in a variety of materials. Laser drilled holes have applications in the automotive, aerospace, medical and sensor industry. The technology is not only competing with conventional machining like high-speed mechanical drilling and non-traditional manufacturing methods like electro-discharge or ultrasonic machining, it also allows the processing of hard and brittle materials, extends the capablity of the existing processes and enables the production of features for which no or no economic manufacturing alternative exists. Depending on the application, a laser is chosen which suits the requirements. In this paper, the results achieved with different lasers and drilling techniques will be compared to the hole specifications in flow control applications. The geometry of low and high aspect ratio laser drilled holes in metals will be investigated and compared to alternatively manufactured holes.

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Physical aspects of high speed drilling with a long pulse excimer laser

Aart Schoonderbeek, *Nederlands Centrum voor Laser Research (NCLR) B.V (the Netherlands)*
and
Cornelis A. Biesheuvel, Ramon M. Hofstra, *Nederlands Centrum voor Laser Research (NCLR) B.V. (the Netherlands)*; Klaus-J. Boller, Johan Meijer, *University of Twente (the Netherlands)*

UV lasers are highly suitable for high-accuracy processing of various types of material, which is due to an increased absorption by the material and a decreased absorption by the plume. Many of such industrial applications, however, require high throughput and thus lasers with high pulse energy, high repetition rate, and excellent beam quality. NCLR combines these requirements in a unique long pulse excimer laser with an average output power of 1 kW. An example is the drilling of many holes simultaneously in different materials. Understanding of the drilling process is a key issue to optimise the efficiency of the process and to control the quality of the drilled holes. Previous studies with this laser have shown that longer optical pulses remove more material. For a better understanding of the drilling process, the interaction between the laser beam and the removed material is studied. Results of this study are presented in this paper.

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Microdrilling, -scribing and -cutting with high-quality and high-power ns-Nd:YAG systems

Alexander Binder, *Laser- und Medizin-Technologie GmbH, (LMTB) (Germany)*
and
Holger Kern, David Ashkenasi, Norbert Müller, *Laser- und Medizin-Technologie GmbH (Germany)*;
Thomas Riesbeck, *Optisches Institut, Technische Universität Berlin (Germany)*

In laser micro machining reduced machine cycle lengths are desired. At the LMTB-laser-laboratories several Nd:YAG systems have been developed that emit high-power ns-pulses at excellent beam-quality. The maximum average output power varies between 16 W (M^2=1.1) and 40 W (M^2=2.5). Additionally, a master-oscillator power-amplifier (MOPA) laser system was designed that emits 95 W (M^2=2.3) with a max. pulse energy of 500 mJ. On account of the excellent beam quality, frequency conversion was efficiently carried out and resulted in 49 W at 532nm and 4,8 W at 266nm. Aiming at high aspect ratios and putting an emphasis on bore hole quality and geometrical constancy drilling experiments into metals and ceramics were made. A maximum aspect ratio of 1:200 in stainless steel was obtained. Furthermore, micro cutting and scribing has been performed targeting minimized groove width at maximum feedrates. The scribing of silicon wafers with excellent groove depth constancy has been achieved at feedrates reaching the 100 mm/s-range. The outstanding reproducibility of the experiments was made possible by an innovative stabilizing system designed at LMTB keeping the power fluctuations below 1 %. Finally experiments on microwelding with stainless steel were carried out. As an exemplary highlight a 25µm-foil on 200µm-sheet was leakprove welded.

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CO_2 laser spectroscopy of dielectric laminate materials

Francisco Villarreal, *Department of Physics, School of Engineering and Physical Sciences, Heriot Watt University (United Kingdom)*
and
Kiran Gulia, Colin J. Moorhouse, Howard J. Baker, Denis R. Hall, *Heriot Watt University (United Kingdom)*

CO_2 laser is the most commonly used laser to process dielectric laminate materials such as polyimide composites. Here the efficiency and quality of the process depends on high absorption bands on the 9 to 11µm spectral region, to which in theory the CO_2 laser can be tuned for an optimal laser-material interaction. However, in the real world, the complexity of the material makes the absorption spectrum vary rapidly within the composite, as well as during the process itself due to chemical and phase changes. Therefore, an effective absorption spectrum is difficult to measure using conventional spectrographic techniques. Here, we are presenting a new approach to determine the effective absorption spectrum in the region of the CO_2 laser emission. Using a Tuneable- CO_2 -MOPA system in conjunction with an acoustic-optic-modulator to produce up to 40 spectral lines in the region of 9 to 11µm with pulse duration of 5 to 150µs and peak powers of up to 100W, we study the dependency of the ablation threshold versus wavelength, fluence and pulse duration for different laminate composite materials such as kapton, FR4 and aramide. Also characterise the process behaviour for high and low absorption bands.

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Drilling and cutting ceramics, metals and composites using visible and UV laser beams.

Istvan Sárady, *Lulea University of Technology (Sweden)*
and
Natalia Miroshnikova, *Deptartment of Experimental Mechanics, Lulea University of Technology (Sweden)*;
Olga Yalukova, Alexander, *Deptartment of Production Development, Lulea University of Technology (Sweden)*

This paper describes the use of 532 nm green and 266 nm UV light generated via frequency conversion of a continuously diode-pumped and acusto-optically Q-switched Nd:YAG laser, using LBO, BBO and CLBO crystals. The average power decreases due to frequency conversion, but the better focusability and the higher absorptivity of the green and UV light can partly compensate for the losses when used for drilling and cutting. The laser is integrated into a four-axis numerically controlled co-ordinate system with positioning and repetition accuracies of +- 1 µm. By this, manufacturing of miniature features was enabled. The SHG and FHG laser beams were successfully used for drilling and cutting hard to machine ceramics (e.g. cubic boron nitride) as well as metals and fibre reinforced composites. The much higher absorption of Cu, Ag and Au at shorter wavelengths has enabled to drill, cut and mark even these highly reflective metals. The use of an all solid state diode-pumped Nd:YAG laser for deep hole drilling may therefore be a possible alternative to Cu-vapour lasers. A comparison of the heat affected zones at the fundamental, second and fourth harmonic wavelengths were investigated by both optical and scanning electron microscopy.

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Advanced Laser Optics for Laser Material Processing

Keiji Ebata, *Core Technology 1st R&D Department, Itami R&D Laboratories, Sumitomo Electric Industries, LTD (Japan)*
and
Keiji Fuse, Takyuki Hirai, Kenichi Kurisu, Takashi Okada, *Core Technology 1st R&D Department, Itami R&D Laboratories, Sumitomo Electric Industries, LTD (Japan)*

Laser processing is now being used increasingly in the area of electronics, especially for drilling micro holes in printed circuits, laser annealing for Thin Film Transistor process in Liquid Crystal Display. But the intensity distribution of laser beam mainly based on Gaussian is not uniform. Therefore, the demand for uniform intensity distribution is rising rapidly in the field of heat processing. To obtain higher uniformity, attempts must be made to convert non-uniform Gaussian distribution into top-hat-shaped uniform intensity distribution. In this study we propose beam homogenizers with an aspheric lenses or diffractive optical elements (DOE) that can convert non-uniform Gaussian distribution into top-hat-shaped uniform intensity distribution. The circler beam homogenizer consists of two aspheric lenses. The first one converts Gaussian profile to uniform irradiation, and the second one performs phase matching. And we propose some kinds of beam homogenizers such as rectangular and line shape with DOE technology. DOE could have high potential to get higher optical performance because it can moderate optical phase directly with Fourier Optics and micro fabrication. Especially we show a spot array generation homogenizer that can anneal some points simultaneously. This paper provides possibilities of advance laser optics for new laser material processing.

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Selection of Parameters on Cutting Mild Steel Plates Taking Account of Some Manufacturing Purposes

Hiroshi Asano, *Laser Machinery Division, Amada Co.,Ltd (Japan)*
and
Jippei Suzuki, Hiroshi Kawakami, *Mie University (Japan)*; Hiroshi Eguchi, *Amada Co.,Ltd. (Japan)*

Before laser cutting work of plate materials,worker has to determine laser parameters on cutting. When selecting laser parameters on cutting,the worker has to consider some purposes such as security of manufacturing accuracy, reduction of manufacturing time and reduction of manufacturing expenses. These purposes require conflicting laser parametets on cutting sometimes,and the worker has to set parameters considering importance levels of these purposes. Also,importance levels of these purposes vary depending on products,and parameters should be set limitlessly. The final purpose of this research is to develop the system that enables to set laser parameters on cutting rationally and efficiently. Therefore,we picked up such manufacturing purposes as cutting speed,roundness of machined hole,dross height of rear surface,roughness of cut surface,shape and size accuracies,and scorch width and laser parameters on cutting such as mild steel plate thickness, cutting speed,laser pulse frequency and duty. We conducted experimental works according to the following three steps: The first step:We neglected the usual standard laser parameters on cutting and changed laser parameters considerably for the experimental works to clarify the manufacturing limit for cutting. The second step: One manufacturing purpose and one laser parameter on cutting are not universal. We analyzed influences of target parameters in various ways by changing other laser parameters. The third step: Although different scales sre applied to manufacturing accuracy and manufacturing costs of products,we compare importance levels of these manufacturing purposes.

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Separating and Structuring of Brittle Material by the use of Laser Radiation

Silvio Georgi, *JENOPTIK Automatisierungstechnik GmbH (Germany)*

For some years now the field of laser technology has been occupying itself with various processes for the processing of brittle material, e.g. glass, which, however, partly come up against the limits of what is feasible. Following intensive development work success has been achieved in (1) developing ElementaryVolumeAblation (EVA) and (2) the cutting of glass with a laser for industrial use with series-produced equipment. With EVA (1) brittle materials can be separated, structured, drilled and removed or stripped off. For the cutting of flat glass (2), e.g. for the production of car windows and windscreens, contour cuts or panels in the electronic industry, the process of thermally induced cutting by means of CO_2 laser, Nd:YAG laser or diode laser is used. By means of laser technology the disadvantages of the conventional mechanical notching by means of a diamond scriber and the subsequent breaking and/or the use of water jet equipment can be avoided. Micro-cracks are avoided, the edge strength of the material is increased by up to 30% and an improved edge quality can be seen.

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High speed laser cutting using a 2kW high power and high quality diode pumped solid state Nd:YAG laser

Yushi Takenaka, *Mitsubishi Electric Corporation, Advanced Technology R&D Center (Japan)*
and
Masaki Seguchi, Jun-ichi Nishimae, *Mitsubishi Electric Corporation, Advanced Technology R&D Center (Japan)*

In order to increase the cutting speed within an economical range for industrial use, a high power and high quality diode pumped solid state Nd:YAG laser has been developed. This new solid state Nd:YAG laser has a 2kW cw laser output power and high focusing ability of passing through conventional optical fiber with core diameter of less than 0.15mm. The laser beam extracted from output end of step index fiber with 0.15mm core diameter has an M2 value of 21 which is the same as the focusing ability of conventional high power CO_2 lasers for laser cutting. In the case of a metal thickness of 1mm, mild steel can be cut with 24m/min. for oxide fine cutting, and stainless steel with 14m/min. for oxide-free fine cutting at the laser output power of 2kW. On the other hand, the cutting results of conventional 2kW CO_2 lasers are e.g. 16m/min. oxide fine cutting for 1mm-thick mild steel and 9m/min. oxide-free fine cutting for 1mm-thick stainless steel because of difference between the wavelength for Nd:YAG and CO_2 lasers. We believe that the new high power and high quality all solid state lasers are promising for laser materials processing.

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Novel approach to control the combustion and detonation by resonance laser radiation

Alexander Starik, *Central Institute of Aviation Motors, Scientific Research Center "Raduga" (Russia)*
and
Nataliya Titova, Boris Loukhovitski, *Central Institute of Aviation Motors, Scientific Research Center "Raduga" (Russia)*

This paper is devoted to the analysis of the potentialities of the control of combustion and detonation processes by laser induced excitation of vibration and electronic states of reacting molecules. Up to now only three approaches by which laser radiation can effect on the combustion processes have been discussed. There are laser-induced thermal method, laser induced photochemical method, and laser-induced spark ignition method. The novel approach considered in this paper is based on the enhancement of the chain mechanism of combustion due to excitation of electronic or vibrational degrees of freedom of molecules. One of the object of our studies is $CH_4(H_2)/O_2$ mixtures irradiated by laser radiation with wavelength 762 nm that results in excitation of oxygen molecules to the b1 electronic state. Another object is $H_2/O_2/O_3$ mixture which is subjected by CO_2 laser radiation at wavelength 9600 nm. This irradiation leads to excitation of asymmetric mode of O_3 molecules that results in initiation of chain-branching reactions and ignition of the mixture at very low initial temperature (T0=300 K) for small laser fluxe energy inputted to the gas (~1-2 J/cm^2). This approach gives a chance to initiate a detonation in supersonic flow at Mach number M0=3-4, initial temperature 500 K and pressure 1-1000 kPa. Without irradiation the detonation at such extremely small flow parameters could not be occurred.

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Tuesday, 24.06.2003

Room 21

11:00	**Session 11: Laser nano-machining** Session Chair: Isamu Miyamoto
11:00	**Femtosecond Laser Micro-machining and self-organized nano-structures in glass** (invited paper) P.G. Kazansky; Optoelectronics Research Centre, Southampton, U.K., J. Qiu Y. Shimotsuma, K. Hirao, Photon Craft Project, Japan
11:30	**Nano-particle laser removal from silicon wafer** J.-M. Lee; S.H. Cho; T.H. Kim; IMT, Kyunggi-Do, Korea; Y.J. Kang; S.H. Lee; J.G. Park; Hanyang University, Korea
11:50	**Sub-micron sized periodic 3-D surface structures generated by single femtosecond UV laser pulses** J.-H. Klein-Wiele; P. Simon; Laser-Laboratorium Göttingen, Germany
12:10	**Ultrafast laser nanofabrication assistes with near-field scanning optical microscopy** W. Wang; M. Hong; D. Wu; Y.W. Goh; Y. Wu; T.Ch. Chong; Data Storage Institute, Singapore; Y.F. Lu; University of Nebraska, USA
12:30	**Robust, single-frequency, tunable, continous-wave, deep-ultraviolet coherent light source for manipulating silicon atoms** H. Kumagai; K. Midorikawa; RIKEN, Japan; T. Iwane; A. Kunieda, M. Obara; Department of Electronics and Electrical Engineering, Keio University, Japan

Femtosecond laser micro-machining and self-organized nano-structures in glass

P.G. Kazansky, *Optoelectronics Research Centre, University of Southampton (United Kingdom)*
and
J. Qiu, Y. Shimotsuma, K. Hirao, *Photon Craft Project (Japan)*

Progress in high power ultra-short pulse lasers has opened new frontiers in physics and technology of light-matter interactions and laser micro-machining. Recently, new phenomena of light scattering and Cherenkov third-harmonic generation peaking in the plane of polarization during direct writing with femtosecond light pulses in glass have been reported. These observations were unexpected because the scattering of light in the plane of light polarization in isotropic medium such as glass is always weaker compared to the orthogonal plane, since a dipole does not radiate in the direction of its axis. The phenomena were interpreted in terms of angular distribution of photoelectrons and sub-wavelength anisotropic index inhomogenities. Another experiments demonstrated uniaxial birefringence of structures in fused silica written by femtosecond light pulses. The index change for light polarized along the direction of polarization of writing beam was much stronger than for the orthogonal polarization. A further anisotropic property in optical materials after being irradiated by a femtosecond laser is strong reflection from the modified region occurring only along the direction of polarization of the writing laser. This can arise from a self-organized periodic sub-wavelength refractive index modulation. The femtosecond-laser-induced birefringence is therefore likely to be caused by these laterally-oriented small-period grating structures. Birefringence of this nature is well known as 'form' birefringence. This effect is the primary cause of all anisotropic phenomena reported in the experiments on direct writing with ultrashort pulses in optical materials. The mechanism of self-organized nano-gratings formation in transparent materials and recent observation of the smallest embedded structures ever created by light will be discussed. The anisotropic phenomena and related nano-gratings should be useful in many monolithic photonic and micro-optic devices and can be harnessed for information storage where nanoscale periodic structuring is required.

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Nano-particle laser removal from silicon wafer

Jong-Myoung Lee, *IMT Co. Ltd. (Korea)*
and
S. H. Cho, T. H. Kim, *IMT Co. Ltd.*; Y. J. Kang, S. H. Lee, J. G. Park, *Hanyang University (Korea)*

Nano-particles were tried to remove from silicon wafer surface by using laser cleaning technique. As the chip density increases the contamination control on the wafer become tighter. Therefore even several tens of nm particles should be removed from the wafer surface in order to increase a die yield in semiconductor manufacturing. However adhesion force of particle on the surface increases significantly with decrease of the particle size so huge cleaning force should be applied for the removal of the nano-sized particle. In this paper, conventional UV laser cleaning and laser shock cleaning which is a newly developed cleaning methodology were applied and compared. It was found that laser shock cleaning was very effective to remove the nano-sized particles whereas conventional UV laser could not remove the particles.

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Sub-micron sized periodic 3-D surface structures generated by single femtosecond UV laser pulses

J.-H. Klein-Wiele and P. Simon, Laser-Laboratorium Göttingen e.V. (Germany)

Surface treatment of metallic and other materials is presented using subpicosecond laser pulses at 248 nm. Applying diffractive optical masks combined with a reflective imaging system sub-micron features are generated on various sample surfaces. Easy adjustment of only one experimental parameter results in a vast variety of 3-D-like periodic structures generated on the sample surface. The size of the achieved structures is well below 1 micron, in cases even reaching the 100 nm limit. A beam homogenization technique for short pulse lasers is also presented. The method provides excellent beam uniformity of short pulse laser beams regardless of beam shape/size, with only minimal influence on the pulse duration and without changing the beam divergence. The presented method allows the fabrication of well controlled structures with excellent reproducibility. The ultrashort-pulse UV laser system applied for surface texturing comprises a Ti:Sapphire-Excimer hybrid device generating 300 fs pulses at 248 nm with an average power of up to 10 W. The above mentioned optical techniques combined with our laser system operating at 300 Hz allows high precision, versatile 3-D texturing of large surfaces opening up new possibilities in industrial applications.

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Ultrafast laser nanofabrication assisted with near-field scanning optical microscopy

Weijie Wang, *Data Storage Institute, National University of Singapore (SIngapore)*
and
Minghui Hong, Dongjiang Wu, Yeow Whatt Goh, Yihong Wu, Tow Chong Chong, *Data Storage Institute (Singapore)*; Yong Feng Lu, *University of Nebraska (USA)*

We have explored the laser nanoprocessing technique by the integration of the ultrafast laser and near-field scanning microscopy (NSOM). The second harmonic femtosecond laser working in the optical near-field with the assistance of NSOM equipment was applied to expose the photosensitive polymer material. The nanopatterns with feature size smaller than the laser wavelength can be generated, which therefore breaks the optical diffraction limitation. We find that the feature size depends strongly on the gap between the fiber probe tip and the substrate surface, as well as the laser coupling efficiency. The approach offers the advantages of high precision, speed and selectivity in nanopatterning, and is promising to be used in data storage device manufacture for higher density recording.

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Robust, Single-Frequency, Tunable, Continuous-Wave, Deep-Ultraviolet Coherent Light Source for manipulating silicon atoms

Hiroshi Kumagai, *Laser Tech. Lab., RIKEN (Japan)*
and
Katsumi Midorikawa, *Laser Tech. Lab., RIKEN (Japan)*; Tetsuaki Iwane, Akira Kunieda, Minoru Obara, *Department of Electronics and Electrical Engineering, Keio University (Japan)*

The single-frequency light field interacting with the cyclic transition of silicon acting as a two-level atom can hold the key to the realization of manipulation of silicon atoms at will through the laser cooling technique. The required laser wavelength is 252.41 nm in the deep-UV region, which is resonant with the 3p 3P1 - 4s 3P0 cyclic transition of silicon. The laser power should be of the mW level for cooling and specifically, more than ten mW for advanced applications such as atom lithography and atom holography. We developed uniquely a robust, high-power, tunable, cw, single-mode, and deep-UV coherent light source by two-stage highly efficient frequency conversions. In the 1st external cavity, a cw Ti:sapphire laser tuned to 746 nm is frequency-doubled. As the nonlinear crystal, we selected the type I phase-matched LBO. The second harmonic power of 589 mW was obtained with the total conversion efficiency of more than 50%. In the 2nd external cavity, the obtained 373 nm light and 780 nm light provided by another Ti:sapphire laser are doubly resonantly sum-frequency-mixed to generate the 252 nm light with the type I phase-matched BBO. The power of 252 nm radiation of 154 mW was obtained, when the input powers of 1.2 W and 0.63 W at 780 nm and 373 nm, respectively. In the presentation, significant interactions of the 252nm light with silicon atoms will be discussed.

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Tuesday, 24.06.2003

Room 21

13:50	**Session 12: Manufacturing of Waveguides** Session Chair: Peter Herman
13:50	**Laser induced sub-micron changes of the chemical composition of SiO2-based optical fibers** (invited paper) M. Fokine; Acreo, Sweden
14:20	**Laser induced index change and its application to optical devices** (invited paper) I. Riant; Alcatel CIT Corporate Research Center, France
14:50	**Fabrication of volume grating induced in silica glass by femtosecond laser pulses** K. Yamada; W. Watanabe; K. Kintaka; J. Nishii; K. Itoh; Graduate School of Engineering, Osaka University, Japan
15:10	**Ultra short laser pulse modification of wave guides** A. Rosenfeld; Max-Born-Institute, Berlin, Germany; D. Ashkenasi; Laser- und Medizin-Technologie GmbH, Berlin, Germany
15:30	**UV-laser-assisted fabrication of dispersive structures in polymeric integrated-optical components** C. Wochnowski; K. Meteva; S. Metev; Bremer Institute of Applied Beam Technology BIAS, Germany
15:50	**Laser machining of optical fibers** M. Osborne; OpTek Systems, Abingdon, United Kingdom

Laser Induced Sub-micron Changes of the Chemical Composition of SiO_2-based Optical Fibers

Michael Fokine, *Acreo (Sweden)*

A method to create sub-micron changes of the chemical composition of silica based optical fibers will be presented and discussed. The method is used to create thermally stable refractive index structures, Fiber Bragg gratings, which can be used e.g. as sensors operating in extreme environments. The method is based on UV induced chemical reactions of the silica glass with in-diffused molecular hydrogen. A change in the chemical composition is attained after thermal treatment, and the mechanism is attributed to diffusion of hydrogen compounds within the glass.

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Laser-induces index change and its application to optical devices

Isabelle Riant, *Alcatel CIT Corporate Research Center (France)*

Index change induced by UV irradiation has become essential for the photoimprinting of Bragg gratings into optical fibers. Applications are numerous in optical telecommunications, sensing and medical domain. After a brief description of the different types of Bragg gratings as well as the mechanisms involved in the photosensitivity process, the presentation will focus on telecommunication applications, with particular emphasis on filtering, chromatic dispersion compensation, amplifier gain flattening, pump stabilizing, and fiber lasers

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Fabrication of volume grating induced in silica glass by femtosecond laser pulses

Kazuhiro Yamada, *Department of Material and Life Science, Graduate School of Engineering, Osaka University (Japan)*
and
Wataru Watanabe, Kenji Kintaka, Junji Nishii, Kazuyoshi Itoh, *Department of Material and Life Science, Graduate School of Engineering, Osaka University (Japan)*

A self-trapped filament of ultrashort laser pulses can induce a several-hundred-micron-long region of refractive-index change in silica glass. The maximum refractive-index change is ~0.01 and the diameter of refractive-index change is approximately 2 μm. The filament is 10-500 μm long along to pulse propagation axis and its length mainly depends on the numerical aperture of a focusing lens. In this paper, we present the fabrication of volume grating induced in silica glass by a self-trapped filament of ultrashort pulses. When the 150-μm-long filament was translated perpendicular to optical axis by 300 μm, a layer of refractive-index change with the thickness of 2 μm was induced. We stacked the layers with the period of several microns and fabricated volume gratings. We entered a He-Ne laser beam at the wavelength of 632.8nm to the grating with the Bragg angle to measure the diffraction efficiency. The maximum diffraction efficiency was 74.8% with the grating that had the period of 3 μm, and the thickness of 150 μm.

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Ultra short laser pulse modification of wave guides

Arkadi Rosenfeld, *Max-Born-Institute (Germany)*
and
David Ashkenasi, *Laser- und Medizin-Technologie GmbH (Germany)*

The high peak powers of ultra short (ps and sub-ps) pulsed lasers available at relatively low single pulse energies potentially allow for a precise localization of photon energy, either on the surface or inside (transparent) materials. Three dimensional micro structuring of bulk transparent media without any sign of mechanical cracking has shown the potential of ultra short laser processing. In this study, the micro structuring of bulk transparent media was used to modify fused silica and especially the cladding-core interface in normal fused silica wave guides. The idea behind this technique is to enforce a local mismatch for total reflection at the interface at minimal mechanic stress to overcome the barrier for enhanced optical outcoupling. The laser-induced modifications were studied in dependence of pulse width, focal alignment, single pulse energy and pulse overlap. Micro traces with a thickness between 3 and 8 µm were generated with a spacing of 10 µm in the subsurface region using sub-ps and ps laser pulses at a wavelength of 800 nm. The optical leakage enforced by a micro spiral pattern is significant and can be utilized for medical applications or potentially also for telecommunications and fiber laser technology.

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UV-laser-assisted fabrication of dispersive structures in polymeric integrated-optical components

C. Wochnowski, K. Meteva, S. Metev *BIAS - Bremer Institute of Applied Beam Technology (Germany)*

In the field of optical communication and sensor technology dispersive structures play a more and more relevant role. Especially gratings, written in the planar substrate surface or in integrated-optical components like waveguides etc., are of great interest since such type of simple integrated-optical components can serve as a basic device e.g. for a multiplexer, for a grating interferometer or for a bragg-sensor. In this contribution we present a new laser-assisted method for the realisation of such a simple integrated-optical component e.g. a grating with or without a waveguide. Both the waveguiding and the dispersive structures are generated by the same UV-laser assissted technology of the photochemical modification of the optical polymer properties. For the grating fabrication the phase mask method is employed. By variation of the irradiation parameters both a surface relief grating (SRG) as well as a volume grating have been successfully generated with different specific topographical properties. The surface morphology of the surface relief gratings are characterized by various surface analytical methods like SNOM and AFM, while the optical properties of the volume gratings like refractive index distribution are examined by fluorescence and interferometric spectroscopy. In the end some applications of such kind of dispersive integrated-optical components are discussed.

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Laser Machining of Optical Fibers

Mike Osborne, *OpTek Systems (United Kingdom)*

Methods of preparing optical fibers have changed little in many years despite the vastly increased usage in optical communications. We describe a novel method of laser micromachining optical fiber ends. This method produces a surface finish, and hence optical performance, superior to standard cleaving and polishing techniques. Moreover, the laser micromachining route allows an unprecedented range of geometries. These include flat surfaces at almost any angle, curved and aspheric surfaces giving lens performance, asymmetric aspheric surfaces producing cylindrical and biconic lenses. Sub-micron tolerances can be routinely achieved and applied in production applications, with process times measured in seconds rather than the tens of minutes typical of conventional processing methods. As well as producing these features on individual fibers, the laser route is also well suited to replicating this on multiple fibers in the form of ribbons, arrays and even planar circuits. We will also describe how these processes can be combined in-situ to produce previously unachievable results, and with an unprecedented level of automation.

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Tuesday, 24.06.2003

Room 21

16:30	**Session 13: Dicing Processes** Session Chair: Udo Klotzbach
16:30	**High power UV laser machining of silicon** T. Corboline; T. Hoult; Coherent Laser Applications Center, Santa Clara, USA
16:50	**Silicon micromachining using short pulse high repetition rate diode-pumped laser** M. Li; Spectra-Physics, Mountain View, USA
17:10	**High precision laser processing of sensitive materials by Microjet** L. Mayor; F. Wagner; B. Richerzhagen; Synova SA, Ecublens, Switzerland
17:30	**Laser machining of aluminum nitride** L. Migliore; Coherent, Santa Clara, USA

High Power UV Laser Machining of Silicon

Tom Corboline, *Coherent Laser Applications Center (USA)*
and
Tony Hoult, *Coherent Laser Applications Center (USA)*

As the demand for thinner silicon wafers increases, mechanical machining techniques are approaching their practical limits. Recent scaling of output power has enabled uv lasers to be used as a practical economic solution to meet the demands of the microelectronics industry. This paper presents new data on machining thin silicon wafers using high average power 355 nm uv lasers. Cut quality is assessed in a semi-quantitative manner using a combination of surface roughness measurement and metallographic analysis. It is shown that excellent cut quality can be achieved through a process of parameter optimization and by fully utilizing the flexibility of the laser system. Higher average power is also shown to produce higher material removal rates.

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Silicon micromachining using short pulse high repetition rate diode-pumped laser

Mingwei Li, *Spectra-Physics, Inc. (USA)*

Laser micromachining of semiconductor materials such as silicon and sapphire has attracted more and more attention in recent years. High precision laser cutting and drilling processes have been successfully used in semiconductor, photonics, and microelectromechanical system (MEMS) industries for applications including wafer dicing, direct via forming, and three-dimensional structuring. In the current study, a newly developed short pulse (< 13 ns), high repetition rate (up to 300 kHz) diode-pumped solid-state (DPSS) laser is used to machine silicon wafers at different wavelengths (1064, 532, 355, and 266 nm). Various laser cutting, percussion drilling, and trepanning drilling applications are investigated. Experimental results are compared between different wavelengths, different power levels at each wavelength, and different pulse repetition rates. The implications of these laser micromachining processes are then discussed.

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High precision laser processing of sensitive materials by Microjet

Laetitia Mayorエラー! ブックマークが定義されていません。, *Synova SA, (Switzerland)*
and
Frank Wagner, Bernold Richerzhagen, *Synova SA, (Switzerland)*

Material laser cutting is well known and widely used in industrial processes, including micro fabrication. An increasing number of applications require nevertheless a superior machining quality than can be achieved using this method. A possibility to increase the cut quality is to opt for the water-jet guided laser technology. In this technique the laser is conducted to the work piece by total internal reflection in a thin stable water-jet, comparable to the core of an optical fibre. The water jet guided laser technique was developed originally in order to reduce the heat damaged zone near the cut, but in fact many other advantages were observed due to the usage of a water-jet rather than an assist gas stream applied in classical laser cutting. In brief the advantages are three-fold: the absence of divergence due to light guiding, the efficient melt expulsion, and better work piece cooling. In this presentation we will give an overview on industrial applications of the water-jet guided laser technique. These applications range from the cutting of CBN or ferrite cores to the dicing of thin wafers and the manufacturing of stencils, each illustrates the important impact of the water-jet usage.

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Laser Machining of Aluminum Nitride

Leonard Migliore, *Coherent, Inc.(USA)*

Aluminum nitride (AlN) is beginning to replace alumina as a substrate and heat sink for electronic circuits. The thermal conductivity of AlN, about 8 times that of alumina, is the primary reason for its selection in these applications. While beryllium oxide has even higher conductivity, concerns about that material\'s toxicity reduce its appeal. Alumina is easily scribed and cut with carbon dioxide lasers. The high thermal conductivity that makes AlN useful, however, makes it difficult to machine with a laser because the material can absorb considerable incident energy without melting or vaporizing. Process settings that produce good results with alumina are not suitable for AlN. It is therefore necessary to develop a new processing regime for aluminum nitride. We cut 0.63 mm thick aluminum nitride sheet with a carbon dioxide laser using a large matrix of process variables and examined the resulting edges for surface quality, microcracking, aluminum deposition and recast. With this information, we defined the volume in process space where effective processing can be accomplished.

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Tuesday, 24.06.2003

Room 14C

15:50	**Session 14: Post-Deadline Papers** Session Chair: Christian Kulik
15:50	**Laser additive patterning: Options and opportunities for the consumer electronics industry** W. Hoving, Philips Electronics Nederland B.V., Centre for Industrial Technology - CFT, The Netherlands
16:10	**Femtosecond direct-write waveguide fabrication in optical materials** K.A. Richardson; Schott Glass Technologies, Duryea, PA, USA; M.C. Richardson*, A. Zoubir, C. Rivero, C. Lopez; School of Optics/CREOL, University of Central Florida Orlando; USA
16:30	**Theoretical Analysis of Second Harmonic Characteristics Generated by KTiOPO4 Crystal** K. Nomura, E. Ohmura, I. Miyamoto, Graduate School of Engineering, Osaka University, Japan; D. Fujimaki, Faculty of Engineering, Osaka University, Japan; A. Horn, Lehrstuhl für Lasertechnik, RWTH Aachen, Germany
16:50	**Atomic layer etching of Si(111) surface by laser irradiation** K. Mochiji; H. Imai; T. Hasegawa; Himeji Institute of Technology, Hyogo, Japan; H. Ostersehlte; Airbus Deutschland, Hamburg, Germany
17:10	**Theoretical analysis on influence of temporal pulse-shape on second harmonic generation** E. Ohmura; K. Nomura; D. Fujimaki; I. Miyamoto; Graduate School of Engineering, Osaka University, Japan
17:30	**Preparation of channel waveguides with extremely thermally stabilized laser-induced gratings** H. Nishiyama; T. Sano, E. Ohmura; I. Miyamoto, Graduate School of Engineering, Osaka University, Japan; K. Kintaka; J. Nishii, National Institute of Advanced Industrial and Science Technology, Japan

Laser Additive Patterning: Options and Opportunities for the Consumer Electronics Industry

Willem Hoving, *Philips Electronics Nederland B.V., Centre for Industrial Technology - CFT (the Netherlands)*

Laser induced processes are powerful tools for making sequential and local modifications of materials and/or its surface properties. Laser micro-machining and ablation technologies are subtractive technologies commonly used to obtain high-resolution surface modifications whereby material is removed. In some cases these methods can be very unattractive from the product (quality) and production (speed/debris) points of view. A different approach are the laser based additive processes which offer unique opportunities to put down small amounts of material with the desired properties in a flexible way and with a high level of accuracy. In this paper an overview will be given of the options and opportunities of this technology for the micro-electronics and display industry.

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Femtosecond Direct-write Waveguide Fabrication in Optical Materials

M.C. Richardson, *School of Optics/CREOL, University of Central Florida (USA)*
and
A. Zoubir, C. Rivero, C. Lopez, K. A. Richardson, *School of Optics/CREOL, University of Central Florida (USA)*

We report the characterization of waveguiding devices fabricated in optical materials using a femtosecond pulse train from a Ti:Sapphire laser at a 25 MHz repetition rate. Both interferometry and Raman Spectroscopy have been used as diagnostics to evaluate optical and structural changes within the glass matrix. Permanent changes in the optical properties can be induced by tightly focusing near-IR femtosecond pulses in transparent materials. This technique offers the possibility of fabricating 3-D structures. Different devices have already been fabricated in various materials. A high repetition rate high pulse energy Ti:Sapphire laser was specially developed for this application. The extended cavity design produces 20 nJ sub-50 fs pulses at 800 nm at a 25 MHz repetition rate. We present the micro-fabrication of waveguides in chalcogenide and other glassy thin films using femtosecond direct writing. We characterize the waveguide geometry and measure the refractive index differential through interferometric microscopy. Transmission measurement and propagation into the waveguiding structures are also presented. Raman scattering spectroscopy is used to investigate the molecular bond changes upon intense femtosecond irradiation in the near-IR. This approach to waveguide fabrication allows for the rapid production of 3-D microstructures without the need of costly and complex laser amplification systems, and should open a pathway towards the practical use of femtosecond laser micro-fabrication.

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Theoretical Analysis of Second Harmonic Characteristics Generated by KTiOPO4 Crystal

Kazufumi Nomura, *Graduate School of Engineering, Osaka University (Japan)*
and
I. Miyamoto, D.Fujimaki, E. Ohmura, *Faculty of Engineering, Osaka University (Japan)*; A. Horn, *Lehrstuhl fur Lasertechnik (Germany)*)

In the harmonic generation using nonlinear optical crystals, phase-matching technique is indispensable to obtain high conversion efficiency. As the first step of our study, we have investigated crystal temperature variation induced by laser absorption and its influence on conversion efficiency in second harmonic generation (SHG) by solving the coupling problem composed of heat conduction equation and complex wave amplitude equations. Beam profile of second harmonic during repetitive laser irradiation was examined simultaneously. In this study, we focused on the declination of irradiation-angle of laser beam from the optimum, which is equivalent to the declination of cut angle of crystal. The angle declination was considered to our analysis model, and its influence on SHG characteristics were examined supposing $KTiOPO_4$ (KTP) crystal. The main results obtained are as follows: When the angle declination is only 0.1 deg, conversion efficiency is decreased to half of one obtained under perfect phase-matching condition. Significant disorder in transverse mode of output beam of second harmonic is also caused by the angle declination even if temperature is controlled ideally. This essential problem on output-beam profile should be considered in precision microfabrication. It was concluded that it is very difficult to realize perfect phase-matching actually.

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Atomic Layer Etching of Si(111) Surface by Laser Irradiation

Kozo Mochiji, *Department of. Mechanical Engineering, Graduate School of Enginnering, Himeji Institute of Technology (Japan)*
and
Hidenori Imai, Takahide Hasegawa, *Department of. Mechanical Engineering, Graduate School of Enginnering, Himeji Institute of Technology (Japan)*

Atomic-layer etching of bromine (Br)-chemisorbed Si(111)-7x7 surface under laser irradiation was investigated by using scanning tunneling microscopy (STM). An uniformly Br-chemisobed Si(111) surface is prepared by dosing Br2 gas to the clean surface. Br2 molecules are dissociatively chemisorbed onto the dangling bonds of the Si(111)-7x7 surface at room temperature. At the gas dose of 100 L, Si adatoms are almost saturated with Br atoms while the 7x7 structure is retained. By the irradiation of laser pulses (wavelength; 266 nm, fluence; 10-30 mJ/cm^2), brominated adatom-layer is selectively etched and underlying rest-atom layer is clearly imaged. The etching rate is increased with the laser fluence. Thermal etching induced by the laser irradiation at the fluence of 10-30 mJ/cm^2 can be ignored. We propose the multi-hole localization process for the breaking of the back-bonds of the Si adatoms. It was also found that a small number of Si adatoms are desorbed from a clean (not Br-chemisorbed) Si(111)-7x7 surface by the laser irradiation at the same fluences as for the etching of Br-chemisorbed surface. We will discuss the electronic excitation process and the role of Br-chemisorption for the etching.

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Theoretical Analysis on Influence of Temporal Pulse-Shape on Second Harmonic Generation

Etsuji Ohmura, *Graduate School of Engineering, Osaka University (Japan)*
and
Kazufumi Nomura, Daisuke Fujimaki, Isamu Miyamoto, *Graduate School of Engineering, Osaka University (Japan)*

Recently frequency conversion technique using nonlinear optical crystals is becoming more and more important to solid-state laser applications for precision microfabrication. It is well known that the frequency conversion efficiency is very sensitive to temperature of crystal. As slight temperature change causes unstable conversion efficiency, temperature control of crystal must be strict. This undesirable temperature change is caused by laser absorption in the crystal. In the previous study, we have analyzed a problem of second harmonic generation (SHG), coupling the electric field to the temperature field with laser absorption and supposing KH_2PO_4 (KDP) crystal. The analysis results showed that not only normal SHG conversion but also remarkable inverse-conversion of SHG appears in the repetitive laser irradiation especially under high incident power density. These two conversions cause the complicated power density fluctuation spatially and temporally. As a result, significant distortion in transverse mode of output beam of second harmonic is generated. In this study, temporal pulse-shape dependence of SHG was investigated theoretically using the same analysis model, and KDP and KTP ($KTiOPO_4$) were compared. It was concluded that pulse shape affects significantly in the beam profile of second harmonic especially under pulse irradiation with high peak power.

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Preparation of channel waveguides with extremely thermally stabilized laser-induced gratings

Hiroaki Nishiyama, *Department of Manufacturing Science, Graduate School of Engineering, Osaka University (Japan)*
and
Tomokazu Sano, Etsuji Ohmura, Isamu Miyamoto, *Osaka University (Japan)*; Kenji Kintaka, *National Institute of Advanced Industrial and Science Technology (Japan);* Junji Nishii*, National Institute of Advanced Industrial and Science Technology (Japan)*

Waveguide filters with extremely thermally stabilized KrF laser-induced gratings were fabricated. Laser-induced grating devices have been already used as add/drop multiplexers and many other applications in WDM network. It's generally known that the laser-induced refractive index changes are thermally unstable. The thermal decay of the laser-induced index change causes the reduction in diffraction efficiency and the diffraction peak shift. We fabricated the laser-induced gratings formed in the highly photosensitive Ge-B-SiO_2 thin films, and it was discovered that the diffraction efficiency and its thermal stability of the grating increased markedly after the annealing at 600° C. Such thermo-induced gratings couldn't be erased after the repeated heat treatment up to 600° C. We printed the grating in slab waveguide by the irradiation with KrF excimer laser (248 nm, 80mJ/cm^2, 27000shots, 10Hz) followed by the annealing 600° C, and then formed the channel in the region of the grating using the standard photolithography process. The diffraction peak with the depth of 17dB was observed at 1535 nm. The filter characteristics of these waveguides were unchanged upon repeated heating up to 400° C. These thermally stabilized waveguide filters are promising candidate for the highly reliable optical and sensing devices.

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Poster Presentations

Session Overview and Abstracts

Poster Session LPM 2003
Sunday, 22.06.2003, 12:20-14:20

High-Average Power Repetitively Pulsed CO_2 Laser with unique discharge technology
X. Chai, Z. Cheng, H. Gao, *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (China)*

Micro Sculpting Technology Using DPSSL
W. Chang, B. Shin, J. Kim, K. Whang, *Nanoprocess Group, KIMM (Korea)*

A New Device of Alarm and Control of "Dewfall" for Laser Optics
Z. Cheng, R. Li, *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (China)*

A Versatile Device for Selective Laser Sintering of Microparts
H. Exner, R. Ebert, S. Klötzer, P. Regenfuß, L. Hartwig, *Laserinstitut Mittelsachsen e.V. / Hochschule Mittweida (Germany)*; T. Petsch, *3D-Micromac AG (German)y*

Development of heat resistant UV transmission optical fiber
S. Funahashi, M. Sugihara, S. Takai, K. Imamura, *Mitsubishi Cable Industries, Ltd. (Japan)*

CO_2 Laser Annealing of RF Magnetron Sputtered NiTi Thin Films
Q. He, M. Hong, T.Ch. Chong, *Data Storage Institute (Singapore)*; W. Huang, Y.Q. Fu, H.J. Du, CMMS, *Nanyang Technological University (Singapore)*

Comparison of the structural characteristic and surface morphology of ZnO thin films grown on various substrates by pulsed laser deposition
K.J. Hong, K.-C. Lee, C. Lee, *University of Inha (Korea)*

Fabrication of micro-holes in silica glass by femtosecond laser pulses
Y. Iga, W. Watanabe, T. Ishizuka, K. Itoh, *Department of Material and Life Science, Graduate School of Engineering, Osaka University (Japan)*; Y. Li, *VBL, Osaka University (Japan)*; J. Nishii, *National Institute of Advanced Industrial Science and Technolog (Japan)*

Effect of pulse duration on scribing of Ceramics and Si wafer with ultra-short pulsed laser
Y. Iwai, T. Arai, T. Honda, *Fukui University (Japan)*; R. Tanaka, T. Takaoka, *Fukui Industrial Support Center & Matsuura Machinery Corporation (Japan)*

Scribing characteristics of ceramics with Nd:YLF Laser
Y. Iwai, T. Mizuno, T. Arai, T. Honda, *Fukui Universit*y (Japan); R. Tanaka, T. Takaoka, *Fukui Industrial Support Center & Matsuura Machinery Corporation (Japan)*

Recording of gratings in Ag-doped glasses by a femtosecond pulsed laser
Y. Kaganovskii, I. Antonov, D. Ianetz, M. Rosenbluh, *Department of Physics, Bar-Ilan University (Israel)*; J. Ihlemann, S. Mueller, G. Marowsky, *Laser-Laboratorium Gottingen e.V. (Germany)*; A. Lipovskii, *Department of Solid State Physics, St.-Petersburg State Technical University, (Russia)*

Fabrication of microlenses in glasses with Ag-doped diffusion layer
Y. Kaganovskii, I. Antonov, M. Rosenbluh, *Department of Physics, Bar-Ilan University (Israel)*; A. Lipovskii, *Department of Solid State Physics, St.-Petersburg Technical University (Russia)*

Laser Processing at Solid-Liquid Interfaces using Femtosecond Pulse Laser Sources
K. Katayama, H. Yonekubo, T. Sawada, *Graduate School of Frontier Sciences, University of Tokyo (Japan)*

Laser cleaning technology of contact hole for semiconductor manufacturing
D.-J. Kim, H.-J. Kim; J.-K. Ryu; S.-S. Pak, *R&D Center, Hantech Co., Ltd. (Korea)*

Numerical simulation of pulsed laser ablation in air
D. Kim, B. Oh, *POSTECH (Korea)*; W. Chang, B.-S. Shin, *KIMM (Korea)*

New high power picosecond laser for micro-machining
R. Knappe, B. Henrich, T. Herrmann, A. Nebel, *Lumera Laser GmbH (Germany)*

Fabrication of micro-sized metal oxide patterns using laser-induced forward transfer technique
K. Komorita, T. Sano, E. Ohmura, I. Miyamoto, *Osaka University (Japan)*

Laser microfabrication on glass substrates by pocket method
B. Lan, M. Hong, K. Ye, T.Ch. Chong, *Data Storage Institute, (Singapore)*

Optoelectrical and optoacoustic analysis of the laser cleaning process of a photoresist on Si, glass and ITO
K.-C. Lee, C. Lee, *Institute for Electrical Engineering, University of Inha (Korea)*

Ablation in Al_2O_3 induced by femtosecond laser
X. Li, T. Jia, D. H. Feng, Z. Xu, *Laboratory for High Intensity Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Soscience (China)*

Measurement of plasma parameters in femtsecond laser ablation plume using electrostatic probe
M. Murai, T. Sano, E. Ohmura, I. Miyamoto, *Graduate School of Engineering, Osaka University (Japan)*

Direct laser diode welding system with anti-reflection unit
D. Nagayasu, H. Sakatani, K. Ichihashi, J.-B. Wang, K. Fujii, *Matsushita Industrial Equipment Co., Ltd. (Japan)*

Time-resolved measurement of surface displacement in excimer laser ablation of Si
T. Ooie, *National Institute of Advanced Industrial Science and Technology (Japan)*; S. Asada, *Mitsubishi Electric Corporation; I. Miyamoto, Osaka University (Japan)*

Femtosecond pulsed laser induced phase transition in iron
T. SanoH. Mori, E. Ohmura, I. Miyamoto, *Graduate School of Engineering, Osaka University (Japan)*

Study on properties of EUV emission for laser-produced plasmas at ILE, Osaka
K. Shigemori, H. Nishimura, M. Nakai, N. Miyanaga, T. Norimatsu, K. Nagai, H. Nagatomo, V. Zhakhovkii, K. Nishihara, M. Nakatsuka, Y. Izawa, *Institute of Laser Engineering, Osaka University (Japan)*; S. Uchida, Y. Shimada, H. Furukawa, *Institute for Laser Technology, Osaka University (Japan)*

Carbon Nitride Films Synthesized by Pulsed Laser Deposition with Additional Laser Irradiation to Plume
T. Shinozaki, T. Ooie, T. Yano, *National Institute of Advanced Industrial Science and Technology (Japan)*

Laser Etching of Indium Tin Oxide Thin Films by Ultra-short Pulsed laser
R. Tanaka, T. Takaoka, *Fukui Industrial Support Center, Matsuura Machinery Corporation (Japan)*; H. Mizukami, T. Arai, Y. Iwai, *Fukui University (Japan)*

Direct femtosecond laser writing system for sub-micron and micron scale patterning
E. Vanagas, D. Tuzhilin, I. Kudryashov, S. Suruga, *Tokyo Instruments, Inc. (Japan)*; M. Zinkou, A. Sedunov, N. Vasiliev, V. Kononov, *LOTIS TII (Belarus)*

Laser amorphisation of glass–ceramics (LAGS) laws and new possibility to form a number of microoptical components
V.P. Veiko, Q.K. Kieu, P.A. Skiba, *St. Petersburg State Institute of Fine Mechanics & Optics (Russia)*

Sub-wavelength grid patterns on silicon surface by pulsed CO_2 laser irradiation
W. Wang, M. Hong, T.Ch. Chong, *Data Storage Institute (Singapore)*; M. Tan, *National University of Singapore (Singapore)*

Development of Capillary Z-pinch Discharge EUV Light Source
M. Watanabe, T. Kasao, M. Okamoto, I. Song, A. Okino, K. Horioka, E. Hotta, Tokyo Institute of Technology *(Japan)*

Melt Expulsion by a Coaxial Gas Stream for Trepanning with Microsecond Nd:YAG Laser Radiation
J. Willach, A. Horn, E.W. Kreutz, *Lehrstuhl für Lasertechnik, Rheinisch-Westfälische Technische Hochschule Aachen (Germany)*

Fundamental Properties of 3-D Microfabrication Using a Femtosecond Laser
M. Yamanoi, S. Wada, M. Anzai, H. Ohmori, A. Makinouchi, *RIKEN (Institute of Physical and Chemical Research) (Japan)*

Surface modification of silicon and PTFE by laser surface treatment: improvement of wettability
K.D. Yong, L.K. Cheol, L. Cheon, *University of Inha (Korea)*

3-D Micro Channels in Laminated Resins by UV Laser Ablation
Y. Yoshida, *Tokyo University (Japan)*

High-Average Power Repetitively Pulsed CO_2 Laser with unique discharge technology

Xiongliang Chai, Zhaogu Cheng, Haijun Gao, *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (China)*

In the field of high power laser macro processing, the pulsed laser is often more efficient than a CW laser with the same average power level. The reason is that it is easy to damage the surface and create a "keyhole" in deep penetration welding, especially for the high-thermal conductivity and high-reflectivity materials. A unique electrode structure and discharge technique for a new high power CO_2 laser is presented in this paper. The operation of a transverse-flow CO_2 laser with the preionized pulse-train switched technique results in pulsation of laser power, and the average laser power is on the level of 5kW. The laser pulse parameters are duration 1ms; output energy 10 J and peak power 10 kW. The characteristic of preionized pulse-train switched technique is switching the preionization pulses into pulse-trains so as to use a small preionizer power (hundreds of watts) to control the large main-discharge power (tens of kilowatts) in the condition of non-sustained discharge. By this means, the cost of the laser and the complexity of the power supply are greatly reduced.

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Micro Sculpting Technology Using DPSSL

Wonseok Chang, Bosung Shin, Jaegu Kim, Kyunghyun Whang, *Nanoprocess Group of KIMM (Korea)*

Multiple pulse laser ablation of polymer is performed with DPSS (Diode Pumped Solid State) 3rd harmonic $Nd:YVO_4$ laser (355nm) in order to fabricate three-dimensional micro components. Here we considered mechanistic aspects of the interaction between UV laser and polymer to obtain optimum process conditions for maskless photomachining using DPSSL. The photo-physical and photochemical parameters such as laser wavelength and optical characteristics of polymers are investigated by experiments to reduce plume effect, which induce the re-deposited debris on the surface of substrate. In this study, LDST (laser direct sculpting technique) are developed to gain various three-dimensional shape with size less than 500 micrometer. Main process sequences are from rapid prototyping technology such as layer-by-layer machining, CAD/CAM modeling of products, machining path generation and so on. This method can be applied to manufacture the prototype of micro device and the polymer mould for mass production without expensive mask fabrication.

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A New Device of Alarm and Control of "Dewfall" for Laser Optics

Zhaogu Cheng, Rufeng Li, *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (China)*

A water-cooling method is almost used to protect laser optics from heat damage and keep stable operation. When the cooling water temperature is low enough in comparison with the room temperature, "dewfall" on the laser optics surfaces is inevitable even with small relative humidity in the air. Under this condition, it is possible to damage the expensive optics if the high power laser operates. A new alarm and control device of "dewfall" is developed. It is also suitable for the other conditions, which are necessary to alarm and control of "dewfall". The device consists of three parts, a simulator sensor and a circuit including a comparator and an amplifier, and a unit of alarm or control. The key is to keep the simulator sensor and the actual protected optics in the same or similar conditions, including size, material, cooling circumstance and so on, in order to avoid the error emergence due to the circumstance differences. The device features very good sensitivity, which can easy be set according to an actual requirement.

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A Versatile Device for Selective Laser Sintering of Microparts

Horst Exner, Robby Ebert, S. Klötzer, P. Regenfuß, L. Hartwig, *Laserinstitut Mittelsachsen e.V. / Hochschule Mittweida (Germany)*; T. Petsch, *3D-Micromac (Germany)*

A laser sintering unit has been built at the Laser Institut Mittelsachsen e.V. with support by 3D-Micromac A.G.. It is a versatile asset for the generation of microparts by selective laser sintering. The integrated chamber is gas-tight and vacuum-proof. It allows processing under pressures of reaction gases or shielding atmospheres in the range of 10-6 mbar up to 2 bar. A special raking device and regime applies the sinter material in layers with a thickness below 10 µm down 0,8µm. Sinter materials with consistencies from dry powders over paste-like to liquids can be handled. The grain size of the solid body should be below 10 µm. Powders with a size down to 0,1µm could be raked, the minimum for solid bodies within suspensions is even lower. By now the asset is employed for selective laser sintering of metal and ceramic structures as well as for reaction sintering. Prearrangements for the integration of a CVD-process are being made.

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Development of heat resistant UV transmission optical fiber

Satoshi Funahashi, Masahisa Sugihara, Sinji Takai, Kazuo Imamura, *Mitsubishi Cable Industries, Ltd. (Japan)*

As UV applications are extended to various fields, the developments of light sources have also been in progress. UV light is used in cases such as semi-conductor processing, micro-processing electronic parts and medical examination and treatment. There are two ways of apply UV light. One way is the direct transmission of light through air using optical components such as lens and mirrors. The other is through optical fibers, allowing the user more flexibility during application. In either case, damage to the optical components due to UV light, particularly deep ultraviolet radiation(DUV:200-300nm) and deterioration in the optical properties due to vacuumed ultraviolet radiation (VUV:200nm) have been problems. In addition, with transmission using optical fibers, high energy density and use under prolonged transmission length makes UV transmission a cause for transmission decline in the DUV region. We have developed a heat resistant optical silica glass fiber to improve resistance against UV light. Under the deuterium lamp (0.21mW/cm² @250nm), after 1,000 hours of irradiation, the transmission rate was maintained at 70%/3m (initially 100%), indicating the effects of our improvement. With the ArF excimer (193nm) laser irradiation (12mJ/cm²/pulse), the transmission rate was approximately 54%/1m at 1.2×10^7 pulses.

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CO_2 Laser Annealing of RF Magnetron Sputtered NiTi Thin Films

Qiang He, Minghui Hong, Tow Chong Chong, *Data Storage Institute (Singapore)*; Wenmin Huang, Yong Qing Fu, He Jun Du, *CMMS, Nanyang Technological University (Singapore)*

It has been proved that NiTi shape memory alloy thin film is the best one for micro actuators as compared to electrostatic, electromagnetic and piezoelectric thin films. In general, the deposition of NiTi thin film on silicon wafer is carried out at room temperature. The resultant thin film is amorphous without shape memory. Subsequent annealing is required for thin film re-crystallization. It is normally done in an oven. In this paper, we present an alternative annealing approach, by CO_2 laser. After the laser annealing, optical microscope, X-Ray Diffraction (XRD) and Atomic Force Microscope (AFM) are applied to characterize the crystallized NiTi thin film properties. Strong austenite/martensite lattice structure is observed. The relationship between surface roughness of annealed NiTi thin film and temperature is studied using AFM. The results show that the CO_2 laser annealed NiTi thin film posses shape memory character.

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Comparison of the structural characteristic and surface morphology of ZnO thin films grown on various substrates by pulsed laser deposition

Kim Jae Hong, Kyoung-Cheol Lee, Cheon Lee, *Microprocess Lab., Div. of Electrical and Computer Eng., University of Inha (Korea)*

Various substrates were compared for the investigation of the structural characteristic and surface morphology of ZnO thin films have been deposited on (100)p-type siliscon substrates and (0001)sapphire substrates by pulsed laser deposition(PLD) technique using an Nd:YAG laser with a wavelength of 266nm. As grown ZnO thin films were optically pumped to investigate the dependence of laser action and photoluminescence (PL) on the structural characteristic and surface morphology of the films. The experiments were performed for oxygen gas flow rate of 100-900 sccm and substrate temperatures in the range of 200-500. We investigated the structural and morphological properties of ZnO thin films using X-ray diffraction(XRD), scanning electron microscopy(SEM) and atomic force microscopy(AFM).

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Fabrication of micro-holes in silica glass by femtosecond laser pulses

Yasunobu Iga, Wataru Watanabe, Kazuyoshi Itoh, Tomohoko Ishizuka, *Department of Material and Life Science, Graduate School of Engineering, Osaka University (Japan)*;Yan Li, *VBL, Osaka University (Japan)*; Junji Nishii, *National Institute of Advanced Industrial Science and Technology (Japan)*

By laser-micromachining from the rear surface that is in contact with distilled water, we can directly produce 3-dimensional micro-holes in silica glass. The micro-holes have the constant diameters of several microns and the high aspect ratios. In this paper, we present the morphological characteristics of the micro-hole. Femtosecond laser pulses (130-fs, 800 nm, 1-kHz) generated from an amplified Ti:sapphire laser were first focused onto the rear surface of the silica glass with the thickness of 1 mm by a 0.55-numerical aperture microscope objective. After 48 sequential pulses were launched into the sample, we moved the focal spot by a step of 1 micron toward the front surface. We fabricated micro-holes with the diameter of 4-8 microns by repeating the irradiation and the movement. We observed the morphology of the hole and the debris generated by the laser ablation. We also analyzed the capillary phenomenon in the dead-end micro-holes. We found two phases in the rising of the distilled water: the first phase occurred very fast within 0.1s and second phase was slow. This result agrees with the previous result (N. P. Migoun, et. al., Proc. 15th WCNDT, Roma (2000)) that used a glass capillary tube.

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Effect of pulse duration on scribing of Ceramics and Si wafer with ultra-short pulsed laser

Yoshiro Iwai, Tatsuya Arai, Tomomi Honda, *Fukui University (Japan)*; Ryuzo Tanaka, Tsutomu Takaoka, *Fukui Industrial Support Center & Matsuura Machinery Corporation (Japan)*

Nowadays, electronic products used for cellular phones etc. become smaller and lightweighted, and thus the size of the semiconductor boards of the integrated circuits are required to be reduced. In the case of the cutting process of a thin semiconductor wafer into single chips, conventional processing techniques currently used tend to produce defects. Therefore, we aime at the development of a new cutting processing technique, i.e. a method with less mechanical and thermal damages. In this work, we studied the scribing of Al_2O_3 ceramics and of a Si wafer by a nanosecond-laser (Nd:YLF) and a femtosecond-laser (Ti:Sapphire). In the case of ceramics, better processing shape with high aspect ratio, no debris, no heat influence and good processing efficiency were obtained by the femtosecond-laser than the nanosecond-laser. Additionally, the pulse duration of the femtosecond-laser was changed between 30-500 fs at fixed processing conditions. In the case of different pulse durations in the femtosecond-range, the shape of the groove bottom and side varied. The processing efficiency improved with increasing pulse duration in the range of 30-500 fs, which was a finding contrary to expected results. The scribing of the Si wafer shows a similar tendency to that of the Al_2O_3 ceramics. We therefore conclude that the processing shape and the processing efficiency can be improved depending on the pulse duration.

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Scribing characteristics of ceramics with Nd:YLF Laser

Yoshiro Iwai, Takayuki Mizuno, Tatsuya Arai, Tomomi Honda, *Fukui University (Japan)*; Ryuzo Tanaka, Tsutomu Takaoka, *Fukui Industrial Support Center & Matsuura Machinery Corporation (Japan)*

The laser scribing process is a perspective technique to produce grooves on brittle materials. In this study, we investigated the microscribing of Al_2O_3 ceramics with a diode-pumped Nd:YLF laser. Firstly, we compared the evaluation techniques of scribing characteristics, i.e. the measurements and evaluation of groove width, groove depth and debris height with a stylus profilemeter, a laser microscope and a scanning electron microscope (SEM). According to this, the laser microscopic analysis proved to be more reliable than the stylus profilemeter, but the SEM observation is desirable to measure the cross-section of narrow grooves produced by high irradiation. Secondly, the effect of the focal position of the laser was investigated in a fundamental mode and the second, third and fourth harmonics and then the effect of the wavelength on the processing characteristics was studied. In addition, the effects of the feed rate and the number of laser scans with the third harmonic (349 nm) were investigated. As a result, we found that the fourth harmonic is the most efficient and that the grooves become sharp and finally remain unchanged with increasing numbers of scans. We conclude that an optimum processing condition exists for the scribing of ceramics.

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Fabrication of microlenses in glasses with Ag-doped diffusion layer

Yuri Kaganovskii, Irena Antonov, Michael Rosenbluh, *Department of Physics, Bar-Ilan University (Israel)*; Andrey Lipovskii, *Department of Solid State Physics, St.-Petersburg Technical University (Russia)*

Small transparent in visible microlenses are fabricated on the surface of glass with embedded silver nanoclusters in a subsurface diffusion layer. The samples were irradiated by an Ar ion laser with a wavelength of 488 nm, the beam power varied from 30 to 60 mW. The beam was focused onto the polished glass surface through a 50X-microscope objective lens. The light intensity transmitted through the lens was monitored during exposure. The microlens shapes were analyzed using atomic force microscopy (AFM). By variation of the laser power and position of the focal spot we could vary both the lens diameter (in the range 2 - 10 microns) and the curvature for a given lens diameter. The transmission of the lenses (no AR coating) increased to ~85% compared to 40% for the initial glass. The temperature distribution around the focal spot is calculated taking into account the temperature dependence of heat conductivity, shape of the beam, and the depth of the diffusion layer. A mechanism of the increase of the lens transparancy during fabrication is proposed.

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Recording of gratings in Ag-doped glasses by a femtosecond pulsed laser

Yuri Kaganovskii, Irena Antonov, David Ianetz, Michael Rosenbluh, *Department of Physics, Bar-Ilan University (Israel)*; Jürgen Ihlemann,Sabine Mueller, Gerd Marowsky, Laser-Laboratorium Göttingen e. V. (Germany); Andrey Lipovskii, *Department of Solid State Physics, St.-Petersburg State Technical University (Russia)*

Glass embedded with 20 nm radius Ag nanoclusters has been used to record interference patterns written by two intersecting 500 fs pulsed laser beams. During laser irradiation (496 nm) the Ag-clusters move to the irradiated surface and coalesce forming lines consisting of particles with the average radius of 20 -25 nm, depending on the number of pulses. A mechanism for the motion is proposed, which is based on optical heating of metal clusters and their subsequent motion in the temperature gradients appearing due to overlapping of temperature distributions around adjacent clusters. The temperature distributions around clusters as a function of cooling time, cluster radius, and optical fluence, are calculated. Estimates of the kinetics of cluster growth are in a good agreement with experimental observations.

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Laser Processing at Solid-Liquid Interfaces using Femtosecond Pulse Laser Sources

Kenji Katayama, Hideaki Yonekubo, Tsuguo Sawada, *Graduate School of Frontier Sciences, The University of Tokyo (Japan)*

Recently much attention has been paid to laser processing using femtosecond light sources because of superior features to conventional techniques: primarily a clearer processed edge due to less thermal effect and minimum processing size smaller than the optical diffraction limit using nonlinear absorption. In this study, laser processing by femtosecond pulse sources was applied to solid-liquid interfaces. For a water / silicon interface, AFM measurements revealed several features on the processed silicon surface. First, many ring patterns surrounded by sinusoidal patterns were found within the irradiated spot. Secondly, the processed depth can be reduced by coexisting anions in water. Thirdly, there were less residual aggregates or debris. Particularly causes for the first feature, namely ring patterns were considered, based on the solidication processes of melted silicon and bubble dynamics generated at solid-liquid interfaces. The mechanism was considered as follows. Initially the surface layer is melted by nonthermal or thermal processes within several picoseconds. Next, bubbles are generated by heat transfer from silicon to water. Such bubbles oscillate with a period about several ten nanoseconds, and the oscillation emits an acoustic wave around the bubble, which leaves residual stress on the melted silicon surface.

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Numerical simulation of pulsed laser ablation in air

Dongsik Kim, Bukuk Oh, *POSTECH (Korea)*; Wonseok Chang, Bo-Sung Shin, *KIMM (Korea)*

Pulsed laser ablation is important in a variety of engineering applications involving precise removal of materials such as laser micromachining and laser treatment of bio-materials. Particularly, detailed numerical simulation of the laser ablation process in air, taking the interaction between ablation plume and air into account, is required for many practical applications. In this paper, high-power pulsed laser ablation under atmospheric pressure is studied with emphasis on the vaporization model, i.e. recondensation ratio over the Knudsen layer, and the dynamics of the ablation plume. Thermal ablation of a metal by a nanosecond laser pulse is first analyzed by the proposed numerical scheme and then discussions are also made on numerical modeling of the ablation phenomena induced by sub-picosecond laser pulses. In the numerical calculation, the temperature, pressure, density, and vaporization flux on a solid substrate are first obtained by a heat-transfer computation code based on the enthalpy method, and then the plume dynamics is calculated considering the effect of mass diffusion into the ambient air and plasma shielding. To verify the computation results, experiments for measuring the propagation of a laser induced shock wave are conducted as well.

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Laser cleaning technology of contact hole for semiconductor manufacturing

Dae-Jin Kim, Hyun-Jung Kim, Je-Kil Ryu, Sung-Sik Pak, *R&D Center, Hantech Co., Ltd. (Korea)*

The laser cleaning of the photoresist (PR) layer has been investigated as a function of laser energy density. The cleaning of the PR layer on silicon wafer was performed by a line beam of a KrF excimer laser in a cleanroom environment and then the applied energy density was 100-300 mJ/cm^2. The experimental results showed that the ablation rates of the PR are increased with increasing of laser energy density without silicon wafer damage. It is also shown that the PR and metallic polymer in the contact hole after reactive ion etching (RIE) can be removed completely by the laser cleaning technology.

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New high power picosecond laser for micro-machining

Ralf Knappe, Bernhard Henrich, Thomas Herrmann, Achim Nebel, *Lumera Laser GmbH (Germany)*

Ultra-short laser pulses enable micro-machining with outstanding quality. The benefits of this technique have been demonstrated with femtosecond pulses, generated by Ti:Sapphire-regenerative laser amplifiers. Such Ti:sapphire lasers are complex devices with limited average power and pulse repetition-frequency (PRF). The key issues for fast material-processing, however, are high PRF and high average power. Furthermore, excellent results can be achieved with pulse durations of a few picoseconds. We report on a high power regenerative amplifier, based on Nd:YVO4. The system generates pulses with a duration of 13 ps at PRFs up to 100 kHz. At 15 kHz, a pulse energy of 520 µJ with an average output power of 7.8 W is achieved. At higher PRFs, the output power increases to 12.7 W at 50 kHz and 14 W at 100 kHz. This corresponds to pulse energies of 250 µJ and 140 µJ, respectively. Due to the ps pulse duration, the laser source is a compact setup without elements for pulse streching and compressing. The good beam quality, in combination with high power and high repetition rate qualifies this laser system as a valuable tool for micro-machining. In particular, metallic materials like steel can be processed with a high speed of operation.

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Fabrication of micro-sized metal oxide patterns using laser-induced forward transfer technique

Kousuke Komorita, Tomokazu Sano, Etuji Ohmura, Isamu Miyamoto, *Osaka University (Japan)*

Micro-sized patterns were fabricated by transferring metal thin films using fs and ns pulsed laser-induced forward transfer (LIFT) technique. Surface chemical composition (the oxygen composition ratio) of the fabricated patterns was measured by XPS. The influence of laser irradiation conditions (pulse width, laser fluence and the thin film/substrate distance) on the oxygen composition ratio was investigated.LIFT technique utilizes pulsed lasers to remove a metal thin film from a transparent substrate and deposited it onto an acceptor substrate. Two types of lasers (Ti:Sapphire laser (l=800nm, t=130fs) and KrF eximer laser (l=248nm, t=30ns)) and Sn thin film were used for this study. Sn thin film was prepared on quartz substrate using e-beam deposition method with several hundreds of nanometer thickness. XPS analysis of the deposited patterns fabricated under various conditions revealed the oxygen composition ratio depended on pulse width of laser, laser fluece and the thin film/substrate distance. The theoretical discussion of the oxygen composition ratio considered thermodynamic process and the comparison between XPS results and this discussion will be addressed in this talk.

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Laser microfabrication on glass substrates by pocket method

Bin Lan, Minghui Hong, Kaidong Ye, Tow Chong Chong, *Data Storage Institute (Singapore)*

Glass is an important engineering material used in several applications because of its excellent mechanical properties, chemical stability and transparent nature. Glass structure fabrication is the first step for its applications. Pulse laser-ablation can be a conventional tool for precise structure fabrication. However, micro-cracks, which affect the reliability and quality of structure, may develop during processing on glass. We present in this paper the results of the work carried out to explore the possibilities to dice the glass chips and make microstructures. A low energy AVIA laser (355 nm, 30ns) was used to perform at different combinations of processing parameters, which include laser-scanning speed, pulse energy and repetition rate. Pocket processing method, which scans the laser beam along parallel overlapped paths instead of scanning at the structure edge, was studied. Shape and depth of the cutting kerfs were examined by optical microscopy and scanning electron microscopy (SEM). Results obtained show that by using pocket processing method, the micro-crack at the edge can be reduced significantly, and the limitation of the ablated depth can be solved by changing the focus during processing. It demonstrates that the low energy AVIA laser is a feasible tool for precise fabrication of glass. Optimized processing parameters are obtained to achieve the microstructures on the substrates.

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Optoelectrical and optoacoustic analysis of the laser cleaning process of a photoresist on Si, glass and ITO

Kyoung-Choel Lee, Cheon Lee, *Electrical Engineering, University of Inha (Korea)*

By irradiating Ar+ (λ=514nm, CW) and Nd:YAG (λ=266 and 532nm, pulse) laser beam, we investigated the cleaning process of a photoresist(AZRFP230K) on Si, glass and ITO. Using Ar+ laser, the photoresist doped on Si with thickness of 1.5 μm;was completely removed beneath the laser power of 1.6 MW/mm^2; without substrate damage. In case of a fourth harmonic Nd:YAG laser beam, the cleaning threshold of the laser beam density was 25 J/cm^2 and the damage of substrate was appeared over 40 J/cm^2. In addition, we studied the laser cleaning process as an optodynamic process where an optoacoustic wave is produced in the vicinity of the beam-irradiated surface. With measuring optoacoustic waves the progress of the cleaning process could be observed simultaneously.

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Ablation in Al_2O_3 induced by femtosecond laser

Xiaoxi Li, Tianqing Jia, Donghai Feng, Zhizhan Xu, *Laboratory for High Intensity Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Socience (China)*

Femtosecond lasers are promising tools for microfabrication with high surface quality and reliability. One interesting problem of transparent dielectries is their damage threshold and ablation laws irradiated by femotosecond laser. Experiment about laser ablation of Al_2O_3 are carried with Ti:sapphire lasers(800nm,40fs,700μj). By means of nonlinear crystal, the single-shot damage threshold of Al_2O_3 have been measured on various pulse duration (from 50fs to 800fs). Meanwhile the ablation craters induced by different pulse energies are observed by SEM and AFM. Through doubling frequency with KDP crystal we have got a series experiment results on 400nm. In this paper the dependence of damage threshold of alumina with 800nm and 400nm on pulse duration are presented. The experiment results show that it obviously deviate the scaling rule for pulse duration less than 1ps. According to the avalanche model we calculated the evolution of conduction band electrons density and the theoretical result is well agreed with our experiment results. At the same time the area, the depth and the volume of ablation craters as a function of pulse energies are presented, and the corresponding explanation are given.

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Measurement of plasma parameters in femtsecond laser ablation plume using electrostatic probe

Makoto Murai, Tomokazu Sano, Etsuji Ohmura, Isamu Miyamoto, *Graduate School of Engineering, Osaka University (Japan)*

The planar Langmuir probe was used to measure the properties of plasma induced by Ti:Sapphire femtsecond laser (800nm, 100fs, 10Hz) ablation of copper in high vacuum. When typical conditions at distance 4~8cm from the target, ion and electron density was the order of 10^{10} ~ 10^{11} cm^{-3} and electron temperature was decreased immediately.Ion time-of-flight signals showed that ion energy distributions was shifted to high energies as laser fluence became larger, but these saturated at several J/cm^2.

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Direct laser diode welding system with anti-reflection unit

Doukei Nagayasu, Hiroyuki Sakatani, Koki Ichihashi, Jing-bo Wang, Koji Fujii, *Matsushita Industrial Equipment Co., Ltd. (Japan)*

A laser processing is come into wide use in many fields. It is obvious that a smaller laser system will be preferred for micro-fabrication. A direct laser diode (LD) processing system is smaller than conventional lasers, such as Nd: YAG or CO_2. However, because of its compactness, a direct LD system, especially LD itself, is expected to be more durable than other lasers under high power region. We developed a prototype LD system to improve the durability. This paper reports the specification of the system, up to 1.5kW direct LD laser system, as well as the results of bead on plate welding. The system equipped an anti-reflection unit and realized low contaminated environment for LD to protect it. The system traveled 3m/min and its bead width was 1.2mm for 1.5mm Al (A5052) under the spot size 2.7 x 0.6 mm FWHM. Now the system is under the long-term durability evaluation that welds a high reflective material. After the test, it may indicate the major factors of durability.

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Time-resolved measurement of surface displacement in excimer laser ablation of Si

Toshihiko Ooie, *National Institute of Advanced Industrial Science and Technology (Japan)*; Shinsuke Asada, *Mitsubishi Electric Corporation (Japan);* Isamu Miyamoto*, Osaka University (Japan)*

This paper describes the removal mechanism of a single-crystal silicon in laser drilling by KrF excimer laser. A time-resolved interferometry was used to measure the displacement of the silicone surface during and after laser irradiation at the laser fluence in a range of 4-11J/cm^2. The 2nd harmonic output of Q-switched Nd:YAG laser, the pulse duration of which was 10ns, was used for the light source of the interferometer. The surface displacement increased with increasing excimer laser fluences. On the other hand, the formation of droplets caused to decrease the surface displacement.

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Study on properties of EUV emission for laser-produced plasmas at ILE, Osaka

Keisuke Shigemori, Hiroaki Nishimura, Mitsuo Nakai, Noriaki Miyanaga, Takayoshi Norimatsu, Keiji Nagai, Hideo Nagatomo, Vasilli Zhakhovkii, Katsunobu Nishihara, Masahiro Nakatsuka, Yasukazu Izawa, *Institute of Laser Engineering, Osaka University (Japan)*; Shigaki Uchida, Yoshinori Shimada, Hiroyuki Furukawa, *Institute for Laser Technology, Osaka University (Japan)*

A new research project on EUV source development has just been started in the Institute of Laser Engineering, Osaka University. The main task of this project is to found a scientific basis for generating efficient, high-quality, high power EUV plasma source for LSI industry. The Institute of Laser Engineering, Osaka University has been funded since 1976 mainly for the research of inertial confinement fusion using powerful lasers. In addition, ILE is contributing to the maturity of advanced laser science and technology including efficient, repetitive high power LD-pumped solid state laser, hot-dense-plasma creation, absolute measurement of soft x-ray radiation from laser-plasma, fabrication of various types of targets, and high-grade radiation-hydro code simulations. All these knowledge and technologies will be devoted to the efficient source generation in the 13-14 nm band. A set of experimental data isto be provided to develop a detailed atomic model included in the computer code through the experiments using the GEKKO-XII high powerlaser and smaller but high-repetitive lasers. Optimum conditions for efficient EUV generation will be investigated by changing properties of lasers and targets. In the presentation, researches on EUV radiation from High-Z plasma at ILE will be overviewed, and a plan of ILE EUV project will be discussed.

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Carbon Nitride Films Synthesized by Pulsed Laser Deposition with Additional Laser Irradiation to Plume

Tatsuya Shinozaki, Toshihiko Ooie, Tetsuo Yano, *National Institute of Advanced Industrial Science and Technology (Japan)*

Carbon nitride films were synthesized by a pulsed laser deposition (PLD) technique. A highly oriented pyrolytic graphite target was ablated in nitrogen atmosphere at a pressure of 0.1 Torr. A single-crystal silicon wafer was used for the substrate. The additional laser irradiated the ablation plume at a distance of 1 mm from the target surface 30 ns after the ablation. The ablation and additional lasers were a fourth harmonic and a fundamental of a Q-switched Nd:YAG laser, respectively. The carbon nitride films were analyzed by x-ray photoelectron spectroscopy. The contents of the sp3 C-N bonding increased by the additional laser irradiation. The nitrogen contents also increased. With increasing the ablation laser fluence, the increment of sp3 C-N content and nitrogen content with additional laser irradiation decreased. In order to investigate them, the optical emission from the plume was observed. By additional laser irradiation, the optical emission intensities of C, C+, C2+, C3+, CN, N, N+, N2 and N2+ increased.

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Laser Etching of Indium Tin Oxide Thin Films by Ultra-short Pulsed laser

Ryuzo Tanaka, Tsutomu Takaoka, Hiroyuki Mizukami, Tatsuya Arai, Yoshiro Iwai,*Fukui Industrial Support Center, Matsuura Machinery Corporation (Japan)*

We have investigated laser etching that removed ITO (Indium Tin Oxide) thin films directly and selectively by laser beam in dry process. At first, in order to examine the dependence of laser wavelengths at ablation, the first, second, third and fourth harmonic of nanosecond pulsed Nd:YLF laser were employed respectively. As a result, comparatively good etching was performed by the UV wavelength. In the line patterning of ITO, however, the melted ITO rolled up to the edge of groove. Moreover, a few micro cracks occurred in the molten domain. In this research, therefore, we carried out laser etching by ultra-short pulsed laser (wavelength: l=800 nm, pulse width: 30 fs) to solve these heat influence problems. The line patterning of ITO (film thickness: 330 nm) deposited on glass substrate was performed by control of laser fluence at fixed laser power and feed rate. In conclusion, we achieved good laser etching that the roll-up height and the micro cracks were reduced and there were little debris near the groove, even processing in the atmosphere. Additionally, the removal of ITO was more efficiency as compared with nanosecond laser so that effects of plasma shielding were lower at ablation.

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Femtosecond pulsed laser induced phase transition in iron

Tomokazu Sano, Hiroaki Mori, Etsuji Ohmura, Isamu Miyamoto, *Graduate School of Engineering, Osaka University (Japan)*

Femtosecond pulsed laser induced phase transition in iron was investigated in this study. Existence of new phase of iron under high pressure and high temperature (beta phase) and its crystalline structure have been discussed in this decade. Mirror polished surface of single crystalline iron was irradiated by femtosecond pulsed laser (wavelength: 800 nm, pulse width: 120 fs, fluence: 2.5 J/cm^2, intensity: 1.6x10^{13} W/cm^2, number of pulses: 2000 pulses) in argon atmosphere. Electron beam irradiated the mirror polished vertical section by using colloidal silica under the bottom of the laser irradiated region, and the electron backscatter diffraction pattern was analyzed to determine the crystalline structure. Epsilon phase of hcp structure was detected within 2 micrometer depth from the bottom. Gamma phase of fcc structure was not detected. This result shows the femtosecond pulsed laser shock induced phase transition. It is suggested that this experimental method has a potential to investigate the existence and, if existed, crystalline structure of high pressure and high temperature phase of iron (beta phase).

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Direct femtosecond laser writing system for sub-micron and micron scale patterning

Egidijus Vanagas, Dmitry Tuzhilin, Igor Kudryashov, Shoji Suruga, *Tokyo Instruments, Inc. (Japan)*; Michail Zinkou, Alexander Sedunov, Nikolai Vasiliev, Vladimir Kononov, *LOTIS TII (Belarus)*

Commercial femtosecond micromachining system (FMS) has been developed that capable to process the material in sub-micron (< 200nm) and micron scale. Core of the system are: optical unit, controller unit and software. The other parts: fs-laser system; focusing unit; stage unit can be varied (exchangeable). Two different fs-laser systems already are compatible with core of FMS: Mira/RegA (Coherent) and Hurricane (Spectra-Physics). FMS controller unit allows to control every single fs-pulse delivery on the target. Three possible types of focusing unit are available: microscope type unit, long focal distance lens unit, and axicon lens based unit. Standard stage unit options are: three-axis piezostage, and two-axis air bearing stage combined with Z-axis piezostage. Repeatability for all dimensions is within ±5nm. Also, step motor stages are available. The system allows 3-D scan with confocal laser-microscope (resolution: dr=200nm, dz=540nm) build in optical unit. Software controls all basic functions of the system performance and writing any pattern (including 3-D) on or into specimen. The results obtained by direct fs-laser writing method will be presented and discussed: bits in the range of 100-200 nm sizes, 6 TB/cm^3 density optical storage matrix, waveguides fabrication inside transparent materials, high aspect ratio (1:125) patterning of dielectric materials with Bessel beam.

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Laser amorphisation of glass–ceramics (LAGS) lawsand new possibility to form a number of microoptical components

V.P.Veiko, Quoc Khanh Kieu, P.A.Skiba, *St. Petersburg State Institute of Fine Mechanics & Optics, (Russia)*

The study of an amorphization of glass–ceramics under laser irradiation has been carried out. Processes of phase–structure transformations of glass–ceramics materials are investigated. Amorphisation of glass–ceramics leads to the change of a ratio between amorphous and crystalline phases in microvolumes of a substance. It permits to control an optical properties of glass–ceramics and to receive an optically transparent channels in surface layer of an optically opaque specimen. Spherical mini– and microoptical components are formed by an amorphisation through the whole of substance melting and quick cooling down. Possibility to form different mini– and microoptical components has been investigated by scanning of laser beam, by additional materials co–treatment, by supplementary means as a plasma jet and so on. Prospects of local modification of glass–ceramics structure to produce a number of different photonics component are discussed.

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Sub-wavelength grid patterns on silicon surface by pulsed CO_2 laser irradiation

Weijie Wang, Minghui Hong, Tow Chong Chong, *Data Storage Institute (Singapore)*; Meifong Tan, *National University of Singapore (Singapore)*

Our previous paper reported on pulsed CO_2 laser-induced periodic microstructures on silicon substrates which are coated with a thin material layer at the bottom to promote optical absorption. Our further study shows that two sets of parallel fringes generated at right angles can overlap and produce crossed grid patterns when the laser pulse width just crosses the threshold required for fringe formation. The fringe period is of sub-wavelength scale and the crossed grid pattern is of grid size 2 microns by 2 microns. The fringes are considered to be due to the laser induced periodic surface structure (LIPSS) effect. The crossed grid patterns are only possible when thermal bumps due to the thermal capillary wave effect are minimized, and they become re-writable at higher pulse widths.

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Development of Capillary Z-pinch Discharge EUV Light Source

Masato Watanabe, Tetsu Kasao, Mitsuo Okamoto, Inho Song, Akitoshi Okino, Kazuhiko Horioka, Eiki Hotta, *Tokyo Institute of Technology (Japan)*

Capillary z-pinch discharge produced plasma (DPP) EUV light source has been investigated as a potential source for the EUV lithography. Compared with the laser produced plasma light sources, DPP light sources have following advantages. The DPP can be made compact and it leads to the smaller production costs. Since electric energy can be directly converted into plasma energy, high plug-in conversion efficiency can be expected. However, the DPP has problem of debris generation, which is due to the melting and evaporation of electrodes and capillary caused by the excess input of heat into their surfaces. In order to overcome these difficulties, the device was produced in consideration of following issues. (1) Restriction of the electric energy input to minimum for getting moderate EUV output by increasing conversion efficiency, (2) Plasma confinement by magnetic field away from a capillary wall, (3) Minimization of current density on electrode surface, (4) Stabilization of magnetically confined plasma column, (5) Stabilization of plasma position. Moreover, large EUV collection angle is desirable. In presentation, several fundamental experimental results will be shown.

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Melt Expulsion by a Coaxial Gas Stream for Trepanning with Microsecond Nd:YAG Laser Radiation

Jens Willach, Alexander Horn, Ernst Wolfgang Kreutz, *Lehrstuhl fuer Lasertechnik, Rheinisch-Westfaelische Technische Hochschule Aachen (Germany)*

Trepanning of 200µm holes in 2-5mm thick CMSX-4 turbine material is done by a lamp pumped Nd:YAG slab laser with pulse durations of 100-500µs. A simulation tool for the expansion of the melt front is compared with cross-sections of trepanning kerfs assuming that the melt is removed instantaneously while in the experiment the melt is expelled by a coaxial gas stream. Congestion of the gas stream at the entrance of the kerf and witholding forces in the kerf disable an efficient melt expulsion. A simulation tool for gas stream expansion has been developed in order to improve the melt expulsion in a 60µm wide and 2-5mm deep trepanning kerf. In a flexible design tool different types of nozzles and geometries of material and kerfs can be arranged. The area of gas expansion is automatically meshed for the finite element calculation (FVM Chimera technique, free boundaries) solving Euler equations at the nodes of the mesh. The simulation tool includes a tool for visualisation of the gas expansion (gas density, velocity and pressure) at equidistant time steps. Gas pressures at the lower exit of the trepanning kerf are presented for different geometries and arrangements of nozzles, initial gas pressures and kerf geometries. Calculated parameters for efficient gas flow and melt expulsion at the lower exit of the kerf are examined in experiments.

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Fundamental Properties of 3-D Microfabrication Using a Femtosecond Laser

Mikio Yamanoi, Satoshi Wada, Masahiro Anzai, Hitoshi Ohmori, Akitake Makinouchi, *The Institute of Physical and Chemical Research, RIKEN (Japan)*

Novel processing tools are desired in the IT industry and electric industry for more diversification and miniaturization of products. Femstosecond laser is known as a potential tool in degree of accuracy from micro to submicro fabrication of metal and transparent materials, through many drilling and cutting researches, due to high peak power and ultra short pulse duration, which develop nonlinear phenomena including multiphoton absorption, inverse bremsstrahlung and laser focusing. We consider a novel-processing tool for forming solid matter to be accomplished by applying rapid prototyping method with CAD/CAM controlled system. In this study, accomplishment and practical application of the system is our goal. This system needs superposition of grooving processing. In this report, fundamental properties of additivity of grooving processing on copper and stainless grinded are estimated with a mechanical shutter and convexo-plane lens (f=50mm). As a result, the linear additivity of shape and depth of grooving on both copper and stainless within low level pulse energy are obatained. If the relation is used, the system has a chance to be a practical application tool. It is demanded to store data of processing condition and laser condition to several materials.

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Surface modification of silicon and PTFE by laser surface treatment: improvement of wettability

Kim Dong Yong, Kyoung-Cheol Lee, Cheon Lee, *University of Inha (Korea)*

Laser surface treatment was used to modify the surface of Silicon and PTFE(polytetrafluoroethylene). This method in order to improve its wettability and adhesion characteristics. Using an 4th harmonic Nd:YAG pulse laser (266 nm, pw), we determinded the wettability and the adhesion characteristics of silicon and PTFE surfaces developed by the laser irradiation. Particularly, surface treatment of PTFE was only effective when the irradiated interface was in contact with the triethylamine photoreagent. We investigated that laser surface treatment of materials by the surface energy modification. By using the sessile drop technique with distilled water, we determined that the wettability of silicon and PTFE after the irradiation showed a decrease in the contact angle and a change in the surface chemical composition. In case of the laser-treated materials surface, laser direct writing of copper lines was achieved through pyrolytic decomposition of copper formate films by using a focused argon ion laser beam(514nm, cw) on silicon and PTFE substrates. The deposited patterns and the surface chemical compositions were measured by using energy dispersive X-ray , scanning electron microscopy, X-ray photoelectron spectroscopy, and surface profiler to examine crass section of the deposited copper lines.

****

3-D Micro Channels in Laminated Resins by UV Laser Ablation

Yoshikazu Yoshida, *Tokyo University (Japan)*

This paper describes the fabrication of micro-channels in resin for micro-fluidic devices such as the μ-TAS (Micro Total Analysis System) by a UV laser ablation. Numbers of heat-hardening resin-films are piled up a soda glass. A laser fabricates a part of the channel at the each film every lamination, and then 3-D confluence channels are fabricated. Channels are fabricated by a fourth harmonic pulse of a Q-switched Nd:YAG laser (Quantel Brilliant, 266nm, fwhm 4.3ns). The channels 20-45μm in depths and 30-150μm in width are fabricated. Deionized water is injected into the channels with a microinjection pump (ULTRA-PLUS II, Micro-Tech Scientific, Inc.). This flow rate is 5μL/min. There is no damage to the channel, inlet, and outlet.

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