Laser Parallel Nanopatterning of Lines and Curves by Micro-particle Lens Arrays

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Laser surface nanopattering using near-field enhancement by particle-lens arrays is studied. Experimental and theoretical investigations are made in order to clarify the properties of the nanopatterns produced. The obtained results show that this nanofabrication technique is a flexible method for precise surface nanopatterning. A close-packed monolayer of SiO_2 spheres (r= 500 nm) is directly formed onto the substrate surface by its self-assembling, and a 248nm wavelength KrF excimer laser is used to irradiate the samples. A theoretical treatment of the results obtained is made by FDTD (finite difference time domain) simulation and calculations of the near field scattering cross section based on Mie's theory. The effect of the laser fluences and incident angles is studied. By using lower laser fluence than the ablation threshold of the bulk material, arrays of features can be easily produced. For the first time, it was demonstrated that very flexible patterns like straight lines and curves can be generated on the substrates over a large surface area.

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1. Introduction

Within the last two decades, micron patterning of material surfaces by laser-induced ablation, etching, deposition, and surface modification has been extensively investigated[1]. Normally, laser patterning was performed by laser light directly focused onto the substrate, employing a projection mask, or by the interference of laser beams. Recently, near-field optics (NFO) and nano-optics has attracted great attentions in this area. NFO deals with optical phenomena where evanescence wave becomes significant when the sizes of the scattering objects are of the order of the wavelength or smaller [2]. So far, several near-field patterning techniques exist: scanning near-field optical microscope (SNOM)[3-5] and laser-assisted AFM/STM-tip patterning [6-8]. Their main disadvantages are the expensive and sophisticated setup and the low throughput that can be achieved in a fabrication process.

Different from SNOM or STM, the contacting particle-lens array (CPLA) patterning technique has a very simple setup. It is achieved by means of two-dimensional lattices of micro-spheres that are formed by self-assembly. Such lattices have been used as micro-lens arrays to focus the light. A higher energy localization can be found on the substrate just below the particle[9-11]. The CPLA technique induced direct surface patterning of millions of features simultaneously by a single laser pulse. Feature size well below the diffraction limit can be achieved with the CPLA technique on the substrate surface [12].

2. Experimental procedures

The CPLA technique has a limitation of being a single step processing technique. After laser ablation, most of the particles are removed due to thermal deformation force and/or ablative force exceeding the particle-substrate adhesion force [13]. The disappearance of the particle lens makes it impossible to fabricate complex pattern arrays other than dents/cones arrays. To keep particles on surface for repeatable patterning, a non-contacting technique was introduced [14, 15]. The micro-particles were self-assembled on a quartz supporter which was then positioned just above the substrate surface. However, it is very difficult to control the near-field distance for nanopatterning.

In this letter, we developed a very simple and efficient technique to fabricate patterns like lines, curves or other user defined structures based on CPLA. By using the angled laser beam scanning (ALBS) technique, it is possible to do multiple steps processes. The particles were formed on substrate surface, and then angled beams scanned through the particle-lens. Because the ablation did not occur at the contacting point, the particles would remain on the substrate, which would produce very flexible patterns over a large area surface.

A KrF excimer laser (GSI-Lumonic IPEX848) was used as the light source (wavelength λ =248 nm, pulse duration τ =15 ns and repetition rate from 1 to 10 Hz, non-polarized). The sample was a 20 nm semi-conductive $Sb_{70}Te_{30}$ thin film (refractive index n=1.80+2.07i) coated on a polycarbonate substrate (n=1.57+0.12i). The conductive thin film has a very low damage threshold (the melting point 616 °C). A close-packed monolayer of SiO2 spheres (r_{sp} = 500 nm) was directly formed onto the thin film surface over an area (5mm x 5mm) by its self-assembling. The spheres are a commercially available suspension from Duke Scientific Cooperation.

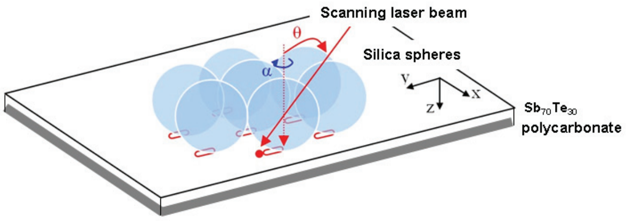

Fig. 1 Schematic diagram of the experimental configuration for laser parallel patterning of lines on substrate surface

Laser beams were tilted in the ***yz*** plane with angle ***θ***, as shown in Figure 1. The light intensity peaks on the substrate were away from the contacting point with a distance ***d***, which was given by the geometrical optics:

$$d \cong r_{sp} \,.\, \tan(\theta) \qquad (1)$$

The ablative forces do not react with the spheres. Therefore, most of them could be kept on surface after processing. As a result, multi-step processing can be applied. The normal incident beam was set to be the final step of the process to avoid removing the particles during the scanning.

The samples were then characterized by a Field Emission Gun Scanning Electron Microscopy (FEG-SEM; Philips XL32) and Atomic Force Microscopy (AFM; Vecco CP2).

3. Results

The optical near-fields around the particle were calculated by a rigorous particle on surface (POS) model based on Mie's theory. The electromagnetic modes, including the evanescent modes were made by FDTD (finite difference time domain) simulation, shown in Figure 2. The details of the theoretical formulation were described in Wang's paper [16].

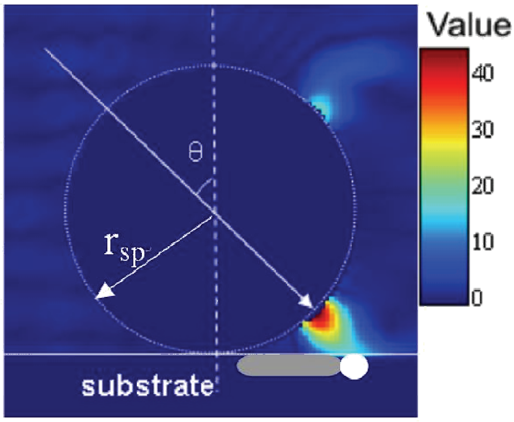

Fig. 2 Calculated Poynting intensity distribution Sz for λ = 248nm radiation under a SiO2 sphere (n = 1.51) of radius rsp=500 nm on a $Sb_{70}Te_{30}$ substrate (n = 1.80, κ = 2.07). The field enhancement in the center is about 40.

It could be seen that the Poynting field was not confined in the contacting point, but in some region between particle and substrate along the incident path. The field maxima were located just outside the particle surface and the intensity drops quickly against the decay length l_{decay} along the incident path, where

$$l_{decay} \approx r_{sp} \,.\, \left[1/\cos(\theta) - 1\right] \qquad (2)$$

The peaks of the enhancement decay quickly with increasing angles as well. The tendency can be thought of as the result of the increasing decay length l_{decay} for large angles. To slow the decay rate, we applied a normalized enhancement factor I_{NEF},

$$I_{NEF} = S_Z / \cos(\theta) \qquad (3)$$

where S_z is the Poynting intensity distribution.

In order to produce a straight line with a uniform lateral dimension by the angled scanning beam, the Poynting intensity enhancement S_z was set to an optimized value. Then the substrate was ablated by a calculated fluence F_{Input} ,

$$F_{Input} \geq F_{thres} / I_{NEF} \qquad (4)$$

where F_{thres} is the damage threshold.

To form a continuous line, multi-step processing is necessary. A single laser pulse was used for every tilt angle and the scanning angle θ was controlled within the range (-45°, 45°). The normal incident beam was set to be the final step of the process to avoid removing the particles during the scanning process. Figure 3 shows the SEM and AFM images of line-shape patterns fabricated by the proposed technique.

It is important to note the proposed technique is not limited to producing just straight lines. Its flexibility can be exploited by designing an appropriate laser scanning path. For example, one can scan the beam with a fixed angle ***θ*** but rotate the substrate through an angle ***α*** (in Fig 1) in ***xy*** plane. This produced arrays of curved structures, shown in Figure 4. A user-define-shaped pattern can also be easily fabricated by varying the both angles.

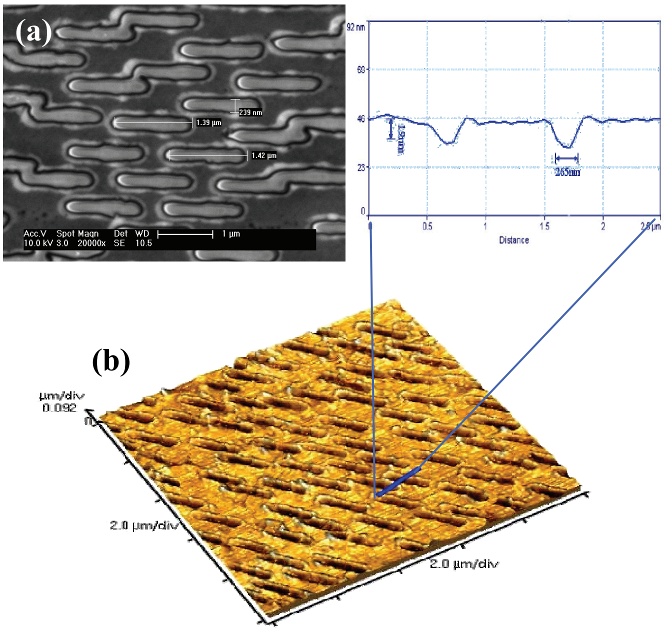

Fig. 3 SEM image (a) and AFM profile (b) of ordered arrays of lines fabricated by the angled laser beam scanning technique. The average line length, width and depth are 1200, 260 and 20 nm, respectively.

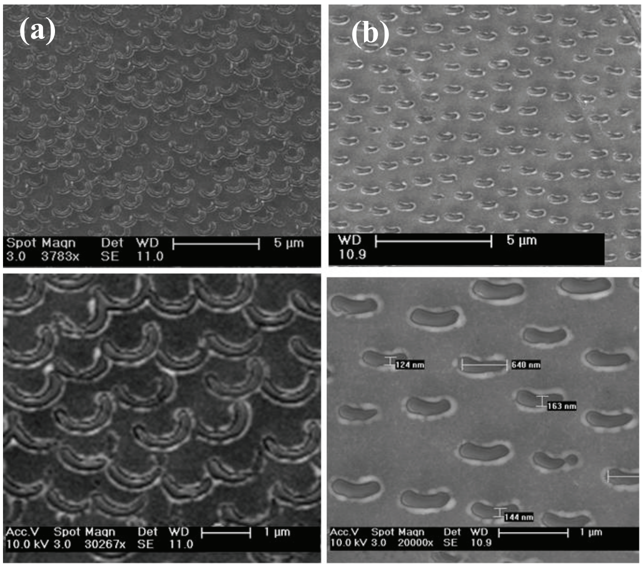

Fig. 4 SEM images of curve-shaped patterns produced by changing angle α with a fixed θ=45° (a) and varying angles α and θ simultaneously (b).

4. Conclusions

We have developed an efficient laser technique to produce straight lines and curves on solid surfaces by scanning an angled laser beam through a self-assembled microparticle lens arrays. As final notes:

1. Each particle works as a near-field focusing lens and the focusing position can be precisely controlled by turning the incident angles.
2. About 10^6 features can be produced in an area of 5mm x 5mm by tens of laser exposures in a very short time.
3. The developed technique is simple, low cost and efficient which holds great potential for industrial applications.

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References

[1] Bäuerle, D., *Laser Processing and Chemistry*. 3rd ed. 2000, Berlin: Springer.

[2] Girard, C. and A. Dereux, *Near-field optics theories.* Rep. Prog. Phys., 1996. **59**: p. 657-699.

[3] Betzig, E. and J.K. Trautman, *Near-Field Optics - Microscopy, Spectroscopy, and Surface Modification Beyond the Diffraction Limit.* Science, 1992. **257**(5067): p. 189-195.

[4] Riehn, R., et al., *Near-field optical lithography of a conjugated polymer.* Appl. Phys. Lett., 2003. **82**(4): p. 526-528.

[5] Wysocki, G., J. Heitz, and D. Bauerle, *Near-field optical nanopatterning of crystalline silicon.* Applied Physics Letters, 2004. **84**(12): p. 2025-2027.

[6] Boneberg, J., et al., *The mechanism of nanostructuring upon nanosecond laser irradiation of a STM tip.* Appl. Phys. A, 1998. **67**(4): p. 381 - 384.

[7] Dickmann, K., J. Jersch, and F. Demming, *Focusing of laser radiation in the near-field of a tip (FOLANT) for applications in nanostructuring.* Surface and Interface Analysis, 1997. **25**(7-8): p. 500-504.

[8] Jersch, J. and K. Dickmann, *Nanostructure fabrication using laser field enhancement in the near field of a scanning tunneling microscope tip.* Applied Physics Letters, 1996. **68**(6): p. 868-870.

[9] Arias-Gonzlez, J.R. and M. Nieto-Vesperinas, *Near-field distributions of resonant modes in small dielectric objects on flat surfaces.* Opt. Lett., 2000. **25**(11): p. 782-784.

[10] Huang, S.M., et al., *Nanostructures fabricated on metal surfaces assisted by laser with optical near-field effects.* Appl. Phys. A, 2003. **77**(2): p. 293-295.

[11] Berry, M.V., *Optical vortices evolving from helicoidal integer and fractional phase steps.* J. Opt. A: Pure Appl. Opt., 2004. **6**: p. 259-268.

[12] M.H. Hong, S.M.H., B.S. Luk'yanchuk, T.C. Chong, *Laser assisted surface nanopatterning.* Sensors and Actuators A, 2003. **108**: p. 69-74.

[13] Luk'yanchuk, B.S., Y.W. Zheng, and Y.F. Lu, Proc. SPIE, 2001. **4423**: p. 115.

[14] Denk, R., K. Piglmayer, and D. Bauerle, *Laser-induced nanopatterning of PET using a-SiO2 microspheres.* Applied Physics a-Materials Science & Processing, 2002. **74**(6): p. 825-826.

[15] M. H. Hong, Z.B.W., B. S. Lukyanchuk, L. S. Tan, and T. C. Chong, *From Transparent Particle Light Enhancement to Laser Nanoimprinting.* Journal of Laser Micro/Nanoengineering, 2006. **1**(1): p. 61.

[16] Wang, Z.B., et al., *Angle effect in laser nanopatterning with particle-mask.* J. Appl. Phys., 2004. **96**: p. 6845-6850.

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