Preparatory School to the Winter College on Optics and the Winter College on Optics: Advances in Nano-Optics and Plasmonics

6 - 17 February, 2012

Introduction to optical fabrication I

O. Martinez
Universidad de Buenos Aires
Buenos Aires
Argentina
Introduction to optical fabrication. I

Oscar E. Martínez
Introduction

Lithography applications
- Integrated Circuits
- MEMs
- Sensors
- Photonic Crystals
- Diffraction gratings

Techniques

Systems
Introduction

- Optical lithography: Ways to break the diffraction barrier
  - $\downarrow \lambda$ (projection, interferencial, ablation)
  - Non linear (multiphoton, near field)

- SPAG – Surface Percolation and Growth
- Protein patterning

- Nano Printing Nano Particles
Visible Light

Quantum Devices

Transistor Gates

Colloidal Particles

Polymers

MEMS Devices

Atoms

Proteins

Bacteria

Liquid Drops

Molecules

Cells

0.1 1 10 100 10^3 10^4 10^5 10^6 nm

Optical Lithography

E-Beam Lithography

Masked Deposition

Scanning Probe Techniques

Molding and Embossing

Contact Printing

Edge Lithography
State of the art in semiconductor industry

193nm

\[ \Delta r = \frac{\lambda}{2 \times NA} = \frac{193 \text{ nm}}{2 \times 1.35} = 71 \text{ nm} \]
Trends and requirements

Dynamic random access memory (DRAM).
Interferomeric lithography at SXR wavelengths

*Source: 46.9 nm discharge pumped table top laser*

*Compact tool*

*Printing different motifs on PMMA and HSQ*

M. C. Marconi, P. Wachulak, M. Capeluto, D. Patel, C. S. Menoni, J. J. Rocca,

NSF Engineering Research Center for Extreme Ultraviolet Science and Technology

and

Department of Electrical and Computer Engineering, Colorado State University

Fort Collins, CO 80523, USA
Capillary discharge laser – 46.9 nm

- High fluence: mW average power
- High monochromaticity
- High spatial coherence

- Rep rate 4 Hz
- High energy per pulse [0.8 mJ]
- High monochromaticity
- Average power [3 mW]


Table top nano-patterning tool
Table top Nanopatterning

Double exposure set up with a Lloyd’s mirror

Two successive exposures allows printing arrays of nanometer size features
Table top Nanopatterning PMMA: large areas

Period 140nm, pillars FWHM ~70nm
Scan size 10x10μm²

Period 95nm, lines FWHM ~47nm
Scan size 7x7μm²
Patterning areas in excess 500 x 500 μm²

10 x 10 μm²

Low dose generates small holes
Table top Nanopatterning PMMA: oval nanodots

Different rotation angles allows printing different motifs

Elongated dots
Table top Nanopatterning PMMA: High dose

Dose: 32 mJ cm$^{-2}$
Printing area: coherence limitations

**Spatial coherence:**

Requirement: \( D \leq 2R_c \)

\[
\frac{R_b}{\cos(\Theta)} = x
\]

**Temporal coherence:**

Requirement: \( b - a \leq l_c \)

\[
\frac{l_c}{2\sin(\Theta)} = x
\]

Radius of coherence: \( R_c \approx 0.5 \text{mm} \)

Coherence length:

\[
\frac{\lambda}{\Delta} \approx \frac{4\pi}{\Theta}
\]
Other applications: Full field zone plate microscope at $\lambda=46.9$ nm can image the surface of semiconductor chips.

**TRANSMISSION MODE**
20 sec exposure EUV image of 70 nm half period dense lines - $\Delta r =70$ nm
Spatial resolution <70 nm

**REFLECTION MODE**
20 sec exposure EUV images of the surface of a semiconductor chip - $\Delta r=200$ nm
Spatial resolution: 150 nm
Holographic lithography

Experimental setup

Computer generated binary hologram fabricated by e-beam lithography

AFM micrographs of the patterns printed in PMMA
Experimental set up

EUV laser

Talbot /Holographic mask
Talbot coherent imaging lithography

EUV laser

Talbot mask

Direct printing of arbitrary patterns
Arbitrary patterns over large area with a spatial resolution of ~ 100 nm in exposures ~ 1 minute
Robust method: “non-contact, defect-free optical nano-imprint”

\[
\Delta_n = \frac{\lambda}{2} \sqrt{1 + \left(\frac{2np^2}{\lambda W}\right)^2}
\]

\[
DOF = \frac{\lambda}{NA^2} = \lambda \left[ 1 + \left(\frac{2Np^2}{\lambda W}\right)^2 \right]
\]
Defect Tolerant Generalized Talbot Nanopatterning
De-magnified Talbot Imaging: Formalism

\[ p' = p \left[ \frac{Z}{f - s} \right] \]

\[ d = 1 - \frac{2np^2}{np^2 + 2\lambda (f - s)} \]
Experiment

EUV Laser
Results
Single shot EUV holograms

Experimental set up
Single shot EUV holograms

First results

Test object: TEM grid 12.5 m period, 5 m bar width and 7.5 m square holes.

First EUV Fourier hologram of the TEM mesh and reconstructed images.
Single shot EUV holograms
**Nano-patterning**

- Short wavelength
- Coherence

  - Interferometric lithography
  - Holographic lithography
  - Talbot lithography

  Non-contact, defect-free optical replication of masks

**Holography**

- Wavelength (48 nm) resolution
- Depth information
- Time-resolved images (1 ns)

  - Imaging technique capable to achieve sub 100 nm resolution
  - No need for special optics
  - No need for sample preparation
WRITING WITH VUV O R-X

PROS:
Not necessary to break the diffraction barrier

CONS:
COMPLEX LIGHT SOURCES
COMPLEX OR UNEXISTING OPTICAL COMPONENTS
NO TRANSPARENT MATERIALS
WRITING WITH STRANGE PENCILS

PROS: HIGH RESOLUTION (MOLECULAR)

CONS:
SLOW
2D

APT FOR MASKS AND PROTOTYPES
WRITTING IN 3D

- MULTIPHOTON POLIMERIZATION
- OTHER NONLINEARITIES
- OUR APPROACH TO THE PROBLEM
Figure 1 Microfabrication and nanofabrication at subdiffraction-limit resolution. A titanium sapphire laser operating in mode-lock at 76 MHz and 780 nm with a 150-femtosecond pulse width was used as an exposure source. The laser was focused by an objective lens of high numerical aperture (~1.4). a–c, Bull sculpture produced by raster scanning; the process took 180 min. d–f, The surface of the bull was defined by two-photon absorption (TPA; that is, surface-profile scanning) and was then solidified internally by illumination under a mercury lamp, reducing the TPA-scanning time to 13 min. g, Achievement of subdiffraction-limit resolution, where A, B and C respectively denote the laser-pulse energy below, at and above the TPA-polymerization threshold (dashed line). The yellow line represents the range of single-photon absorption. TPA-P, TPA probability. h, Scanning electron micrograph of voxels formed at different exposure times and laser-pulse energies. i, Dependence of lateral spatial resolution on exposure time. The laser-pulse energy was 137 pJ. The same data are presented using both logarithmic (triangles; bottom axis) and linear (circles; top axis) coordinates, to show the logarithmic dependence and threshold behaviour of TPA photopolymerization. Scale bars, 2 μm.
Figure 2 Functional micro-oscillator system, in which not only the spring but also the cubic anchor and the bead were produced using our two-photon absorption system. The oscillator was kept in ethanol so that the buoyancy would balance gravity and eliminate bead–substrate friction. a, b, The spring in its original (a) and extended (b) states. Scale bars, 2 μm. c, Restoring curve of the damping oscillation; inset, diagram showing driving of the oscillator by using laser trapping.
Femtosecond laser-induced two-photon polymerization of inorganic–organic hybrid materials for applications in photonics

J. Serbin, A. Egbert, A. Ostendorf, and B. N. Chichkov
Laser Zentrum Hannover e.V., Hollerithallee 8, D-30419 Hannover, Germany

R. Houbertz, G. Domann, J. Schulz, C. Cronauer, L. Fröhlich, and M. Popall
Fraunhofer-Institut für Silicatforschung, Neunerplatz 2, D-97082 Würzburg, Germany

Fig. 1. Predicted and measured data for (left) the diameter and (right) the length of the polymerized volume as a function of the average laser power (for constant irradiation time $t = 40 \text{ ms}$) and as a function of the irradiation time (for constant laser power $P = 30 \text{ mW}$).

Fig. 2. SEM micrometer-scale image of Venus fabricated by 2PP. Only the shell was irradiated by femtosecond laser pulses; the inside region was cured with a UV lamp after the liquid resin was washed away.
A 3D photonic quasicrystal with a five-fold rotational symmetry. The structure was written into the photoresist SU-8. Image: Dr. Alexandra Ledermann (KIT).

http://www.nanoscribe.de/?id=439&page=0

A 3D photonic crystal known under the acronym SP2 - standing for slanted pore structure. Originally proposed for anisotropic etching techniques or GLAD "2" stands for the number of separate drilling/etching/GLAD-processes. With our technique these structure can directly be written into a photosensitive material in one step. Later on these structures can be replicated or inverted e.g. in silicon with our techniques.
Eiffeltower with a scale of 1:3 000 000 written into Nanoscribe resin IP-40.

http://www.nanoscribe.de/data/Module/galerie/451/picture/eiffelturm_IP-40%20lr.jpg
The commercially available photoresist SU-8 (MicroChem) consists of an octafunctional epoxy resin (EPON SU-8), a photoinitiator (mixed triarylsulphonium/hexafluoroantimonate salt in propylene carbonate solvent), both dissolved in gamma-butyrolactone (GBL). On irradiation by near-ultraviolet light (350–400 nm), the photoinitiator generates an acid with a spatial concentration that is an image of the irradiation dose.

To write PC structures into these films, we use a regeneratively amplified Ti:sapphire laser system (Spectra Physics Hurricane) with a pulse duration of 120 fs. The repetition rate can be computer controlled from 1 kHz to single shot mode.

Figure 1 Three-dimensional photonic crystals fabricated by DLW. a, Layer-by-layer structure with 40 layers and a massive wall that prevents bending and reduces distortions due to polymer shrinkage during polymerization, completely fabricated by DLW. b, Side and c, top view of a different broken sample with 12 layers, illustrating the sample quality obtained with the DLW process.
Three-dimensional fabrication of optically active microstructures containing an electroluminescent polymer

C. R. Mendonça,1,2,a D. S. Correa,1,2 F. Marlow,3 T. Voss,2,4 P. Tayalia,2 and E. Mazur2

FIG. 1. (Color online) (a) Scanning electron microscopy of a pyramid microstructure containing MEH-PPV. Fluorescence microscopy images of a pyramid (top view) with laser excitation at 532 nm (b) off and (c) on. Emission spectrum of the microstructure (black line) and of a film of the same composition (red line).

FIG. 2. (Color online) Fluorescent confocal microscopy images of planes separated by 16 μm in a pyramidal microstructure (squared base of 120 × 120 μm²).
High-resolution 200 nm nanoreliefs, which possess a controllable height change ($h$, up to film thickness) and transmittance or reflectance, have been successfully fabricated in 12-nm-thick Sn films by using 532 nm pulsed laser direct writing. Different from current micro/nanofabrication techniques, the height change of the nanoreliefs is generated by a laser-induced-thickening process. The majority of the height change comes from a balling and coarsening effect rather than oxidation of grains. Because both optical density and $h$ of the nanoreliefs are almost linear to laser power, the optical images can highly resemble the topographic images. This technique is useful for fabricating complicated nanorelief structures and fine images.

Fig. 1. (Color online) (a),(b) Optical images in Sn film created by the LDW technique; (c) and (d) are back-lit and front-lit images, where (d) is reverse processed.

Fig. 4. (Color online) Mechanism of height change in the nanoreliefs. (a) Proposed model: (1) as-deposited Sn film with flat grains, (2) balling and coarsening of Sn grains induced by LDW, and (3) after cooling down. (b) SAED results verify the formation of Sn/a-SnO$_x$ core/shell structure. (c) TEM image showing evolution of Sn/a-SnO$_x$ core/shell structures: (1)–(4) are the film morphologies corresponding to different laser powers from low to high.
multiphoton absorption of pulsed 800-nanometer (nm) light is used to initiate crosslinking in a polymer photoresist and one-photon absorption of continuous-wave 800-nm light is used simultaneously to deactivate the photopolymerization.
initiating species are generated by single-photon absorption at one wavelength while inhibiting species are generated by single-photon absorption at a second, independent wavelength.
Confining Light to Deep Subwavelength Dimensions to Enable Optical Nanopatterning

Trisha L. Andrew, Hsin-Yu Tsai, Rajesh Menon

Lines with an average width of 36 nanometers (nm), about one-tenth the illuminating wavelength \( \lambda_1 = 325 \) nm, made by applying a film of thermally stable photochromic molecules above the photoresist. Simultaneous irradiation of a second wavelength, \( \lambda_2 = 633 \) nm, renders the film opaque to the writing beam except at nodal sites, which let through a spatially constrained segment of incident \( \lambda_1 \) light, allowing subdiffractional patterning.
TIME FOR A BREAK