The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA

2328-7

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
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Introduction to optical fabrication. I

Oscar E. Martínez

Dpto de Física | FCEN | UBA


Mexico
Cuba
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Guyana
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Colombia
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Bolivia
MG
MS
ES
Paraguay
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Chile
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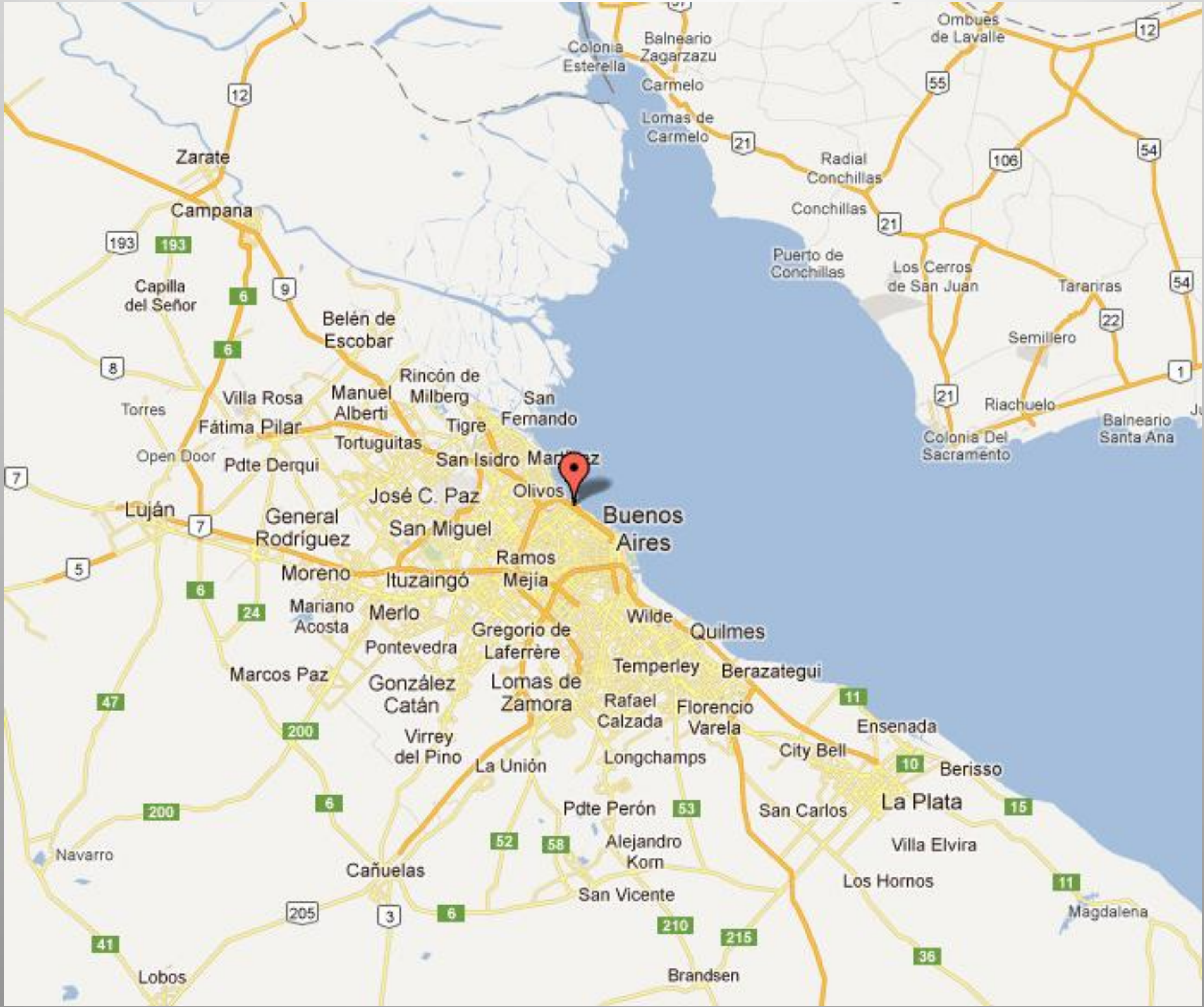
RS
Argentina
South Atlantic Ocean
Sahara
Mauritania
Mali
Burkina Faso
Guinea
Ghana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Balneario Zagarzazu
Carmelo
Lomas de Carmelo
Ombues de Lavalle
Radial Conchillas
Conchillas
Puerto de Conchillas
Los Cerros de San Juan
Tarariras
Semillero
Riachuelo
Colonia Del Sacramento
Balneario Santa Ana
Zarate
Campana
Capilla del Señor
Belén de Escobar
Rincón de Milberg
Manuel Alberti
Villa Rosa
Torres
Fátima
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Tigre
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Tortuguitas
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Moreno
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Mariano Acosta
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Wilde
Quilmes
Gregorio de Laferrère
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Marcos Paz
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San Carlos
Villa Elvira
Navarro
Alejandro Korn
Cañuelas
San Vicente
Los Hornos
Magdalena
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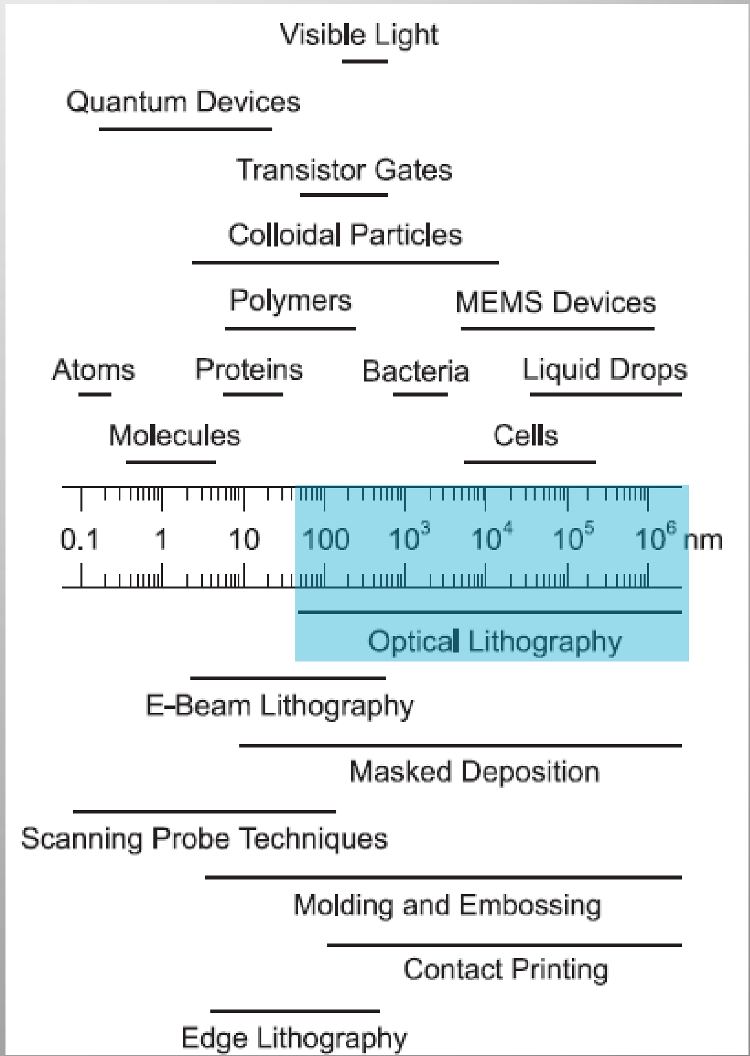
Brandsen

Introduction

Lithography applications

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

Systems



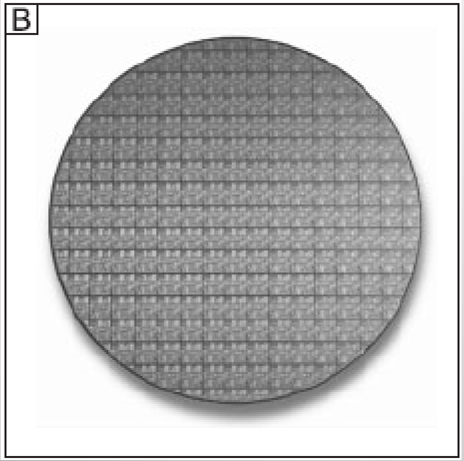
Techniques

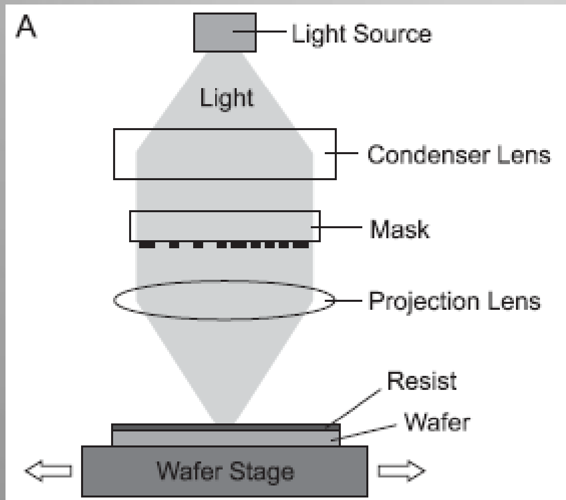
Introduction

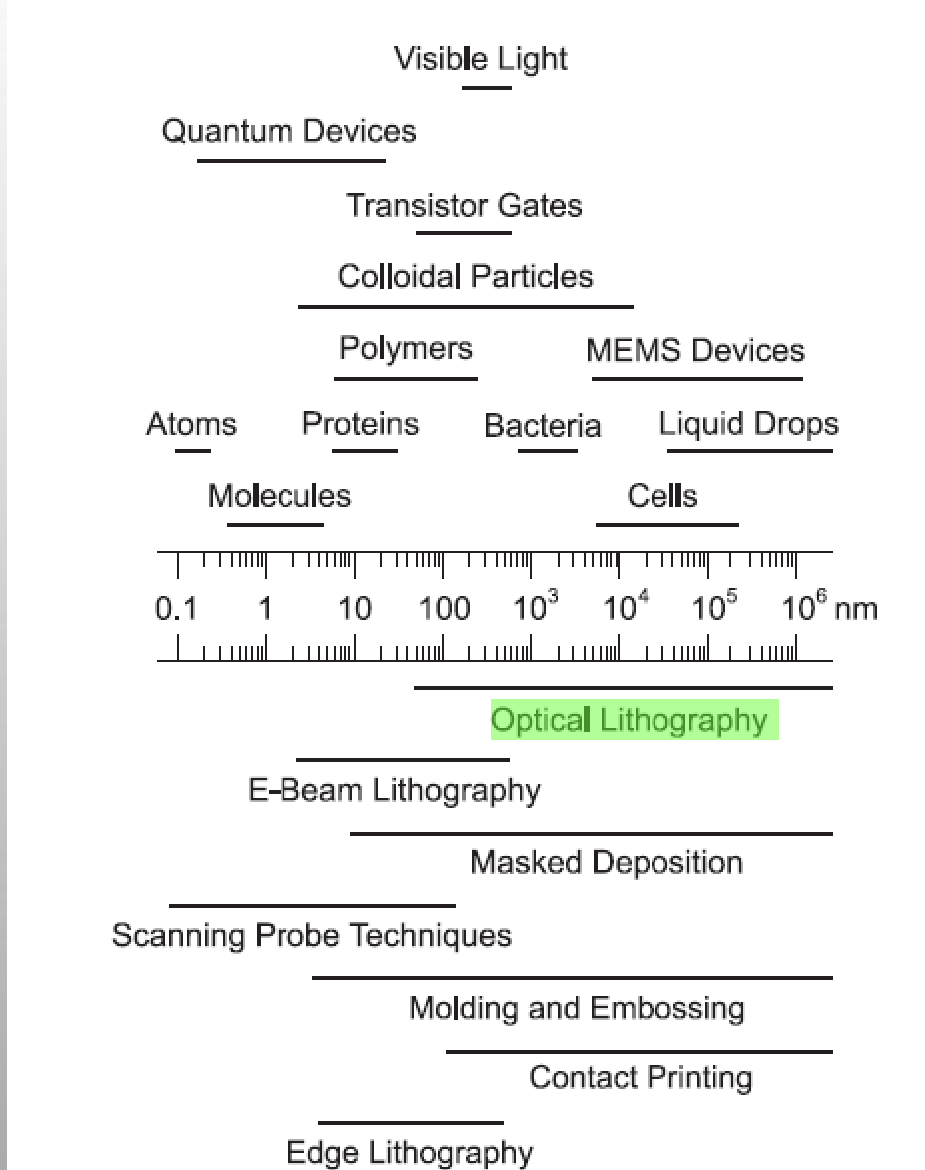
- Optical lithography: Ways to break the diffraction barrier
  - ↓ λ (projection, interferencial, ablation)
  - Non linear (multiphoton, near field)

- SPAG – Surface Percolation and Growth
- Protein patterning

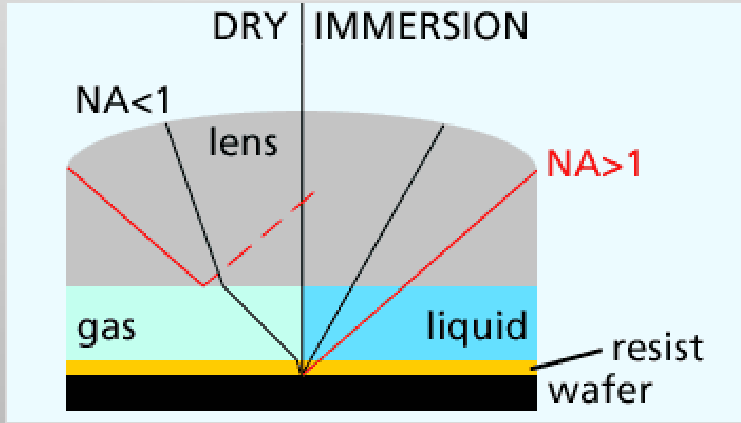
- Nano Printing Nano Particles


B


A
Light Source
Light
Condenser Lens
Mask
Projection Lens
Resist
Wafer
Wafer Stage

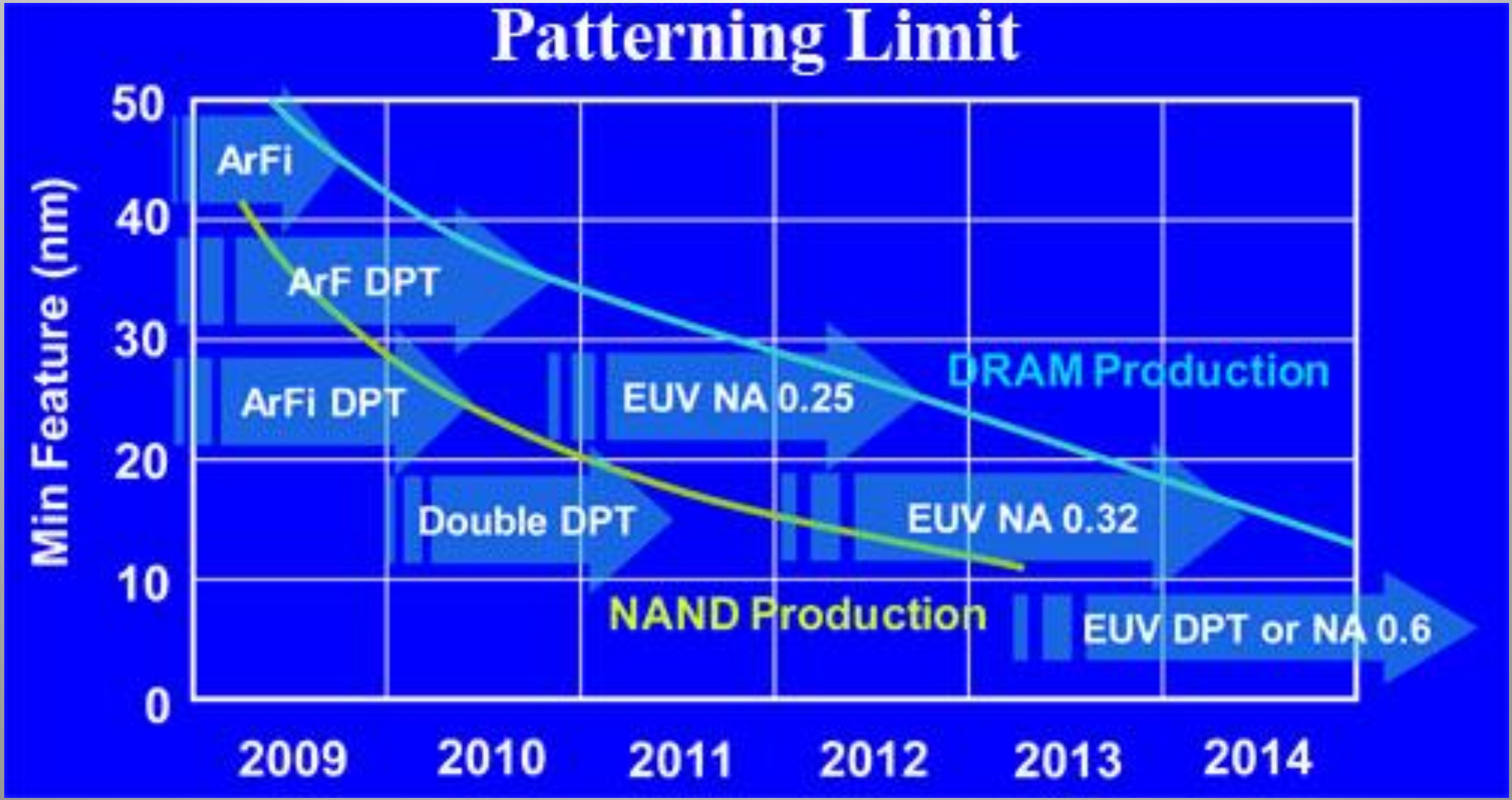

Visible Light
Quantum Devices
Transistor Gates
Colloidal Particles
Polymers
MEMS Devices
Atoms
Proteins
Bacteria
Liquid Drops
Molecules
Cells
0.1 1 10 100 10^3 10^4 10^5 10^6 nm
Optical Lithography
E-Beam Lithography
Masked Deposition
Scanning Probe Techniques
Molding and Embossing
Contact Printing
Edge Lithography

State of the art in semicon industry 193nm



$\Delta r = \lambda / 2 * NA = 193\ nm / 2 * 1.35 = 71 nm$

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,

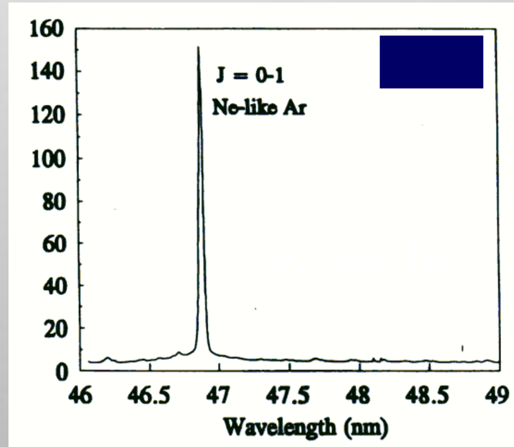
NSF Engineering Research Center for Extreme Ultraviolet Science and Technology
and
Department of Electrical and Computer Engineering, Colorado State University
Fort Collins, CO 80523, USA

Capillary discharge laser – 46.9 nm

• High fluence: mW average power

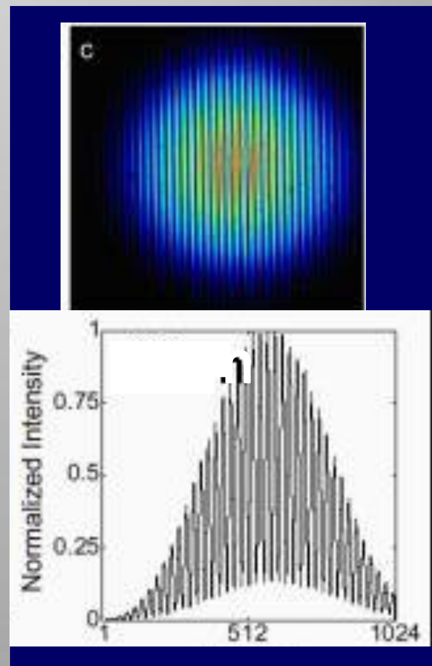
•Rep rate 4 Hz
•High energy per pulse [0.8 mJ]
•High monochromaticity
•Average power [3 mW]

• High monochromaticity



J.J. Rocca, el al. Phys. Rev. Lett. **73**, 2192 (1994).

• High spatial coherence



Y. Liu, et al. Phys. Rev. A, **63**, 033802 (2001).

Table top nano-patterning tool

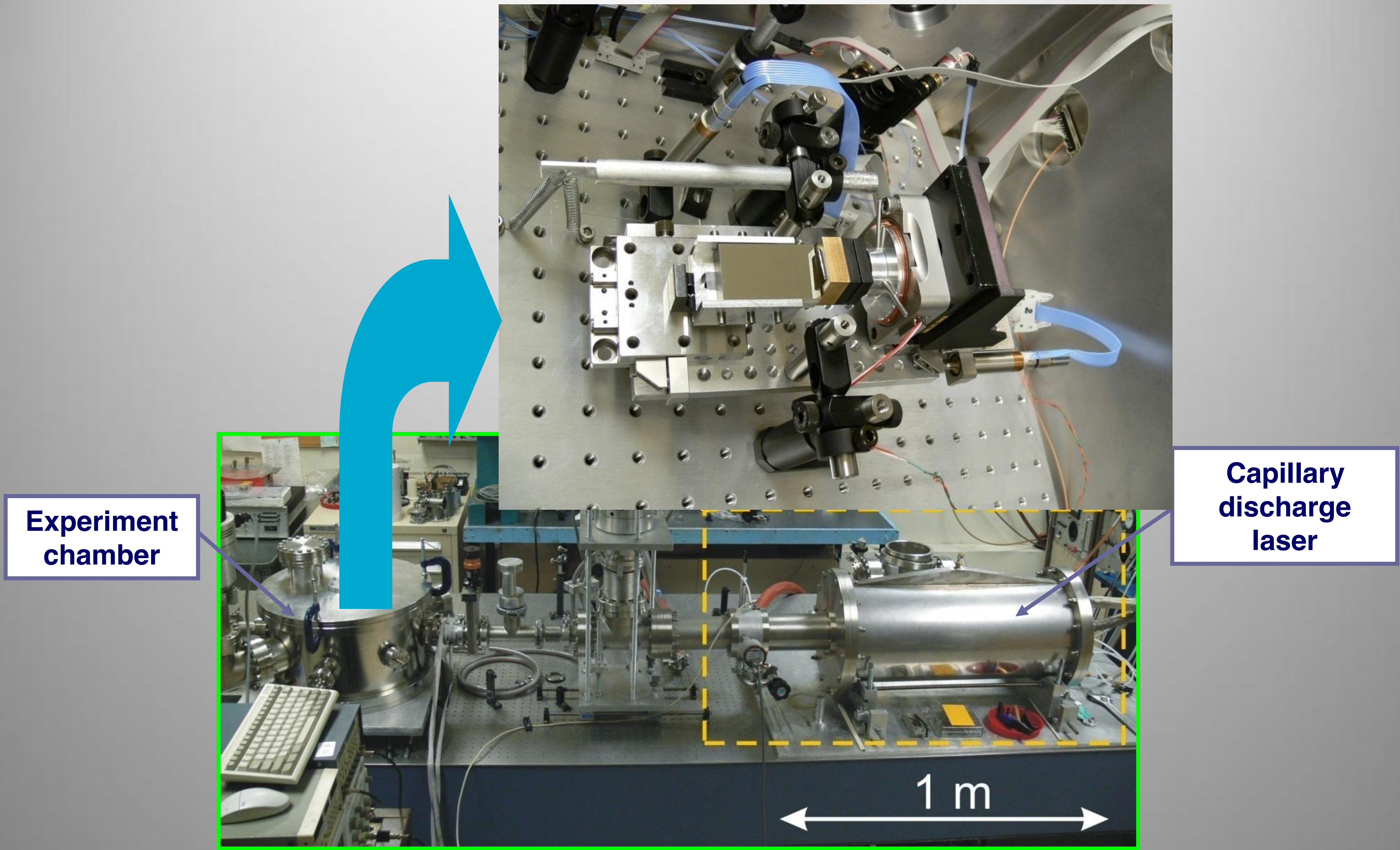
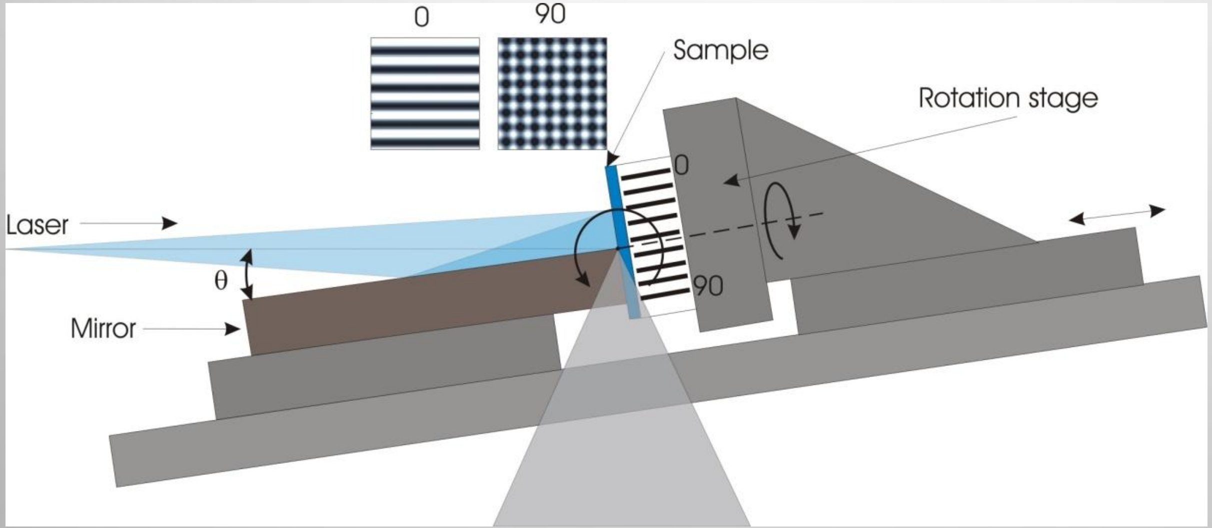
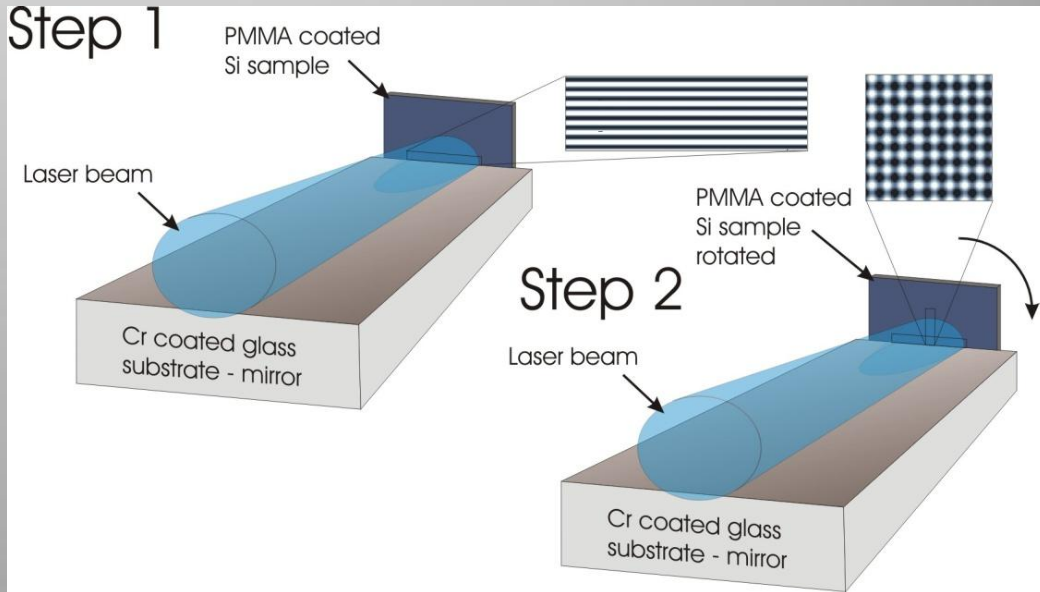


Table top Nanopatterning

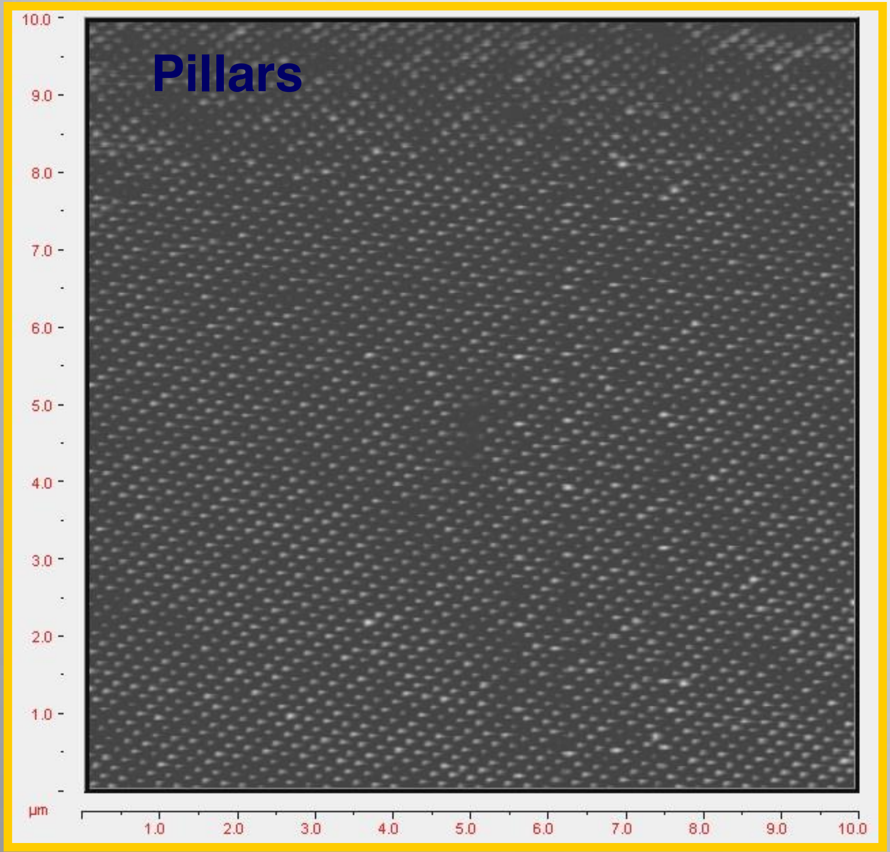


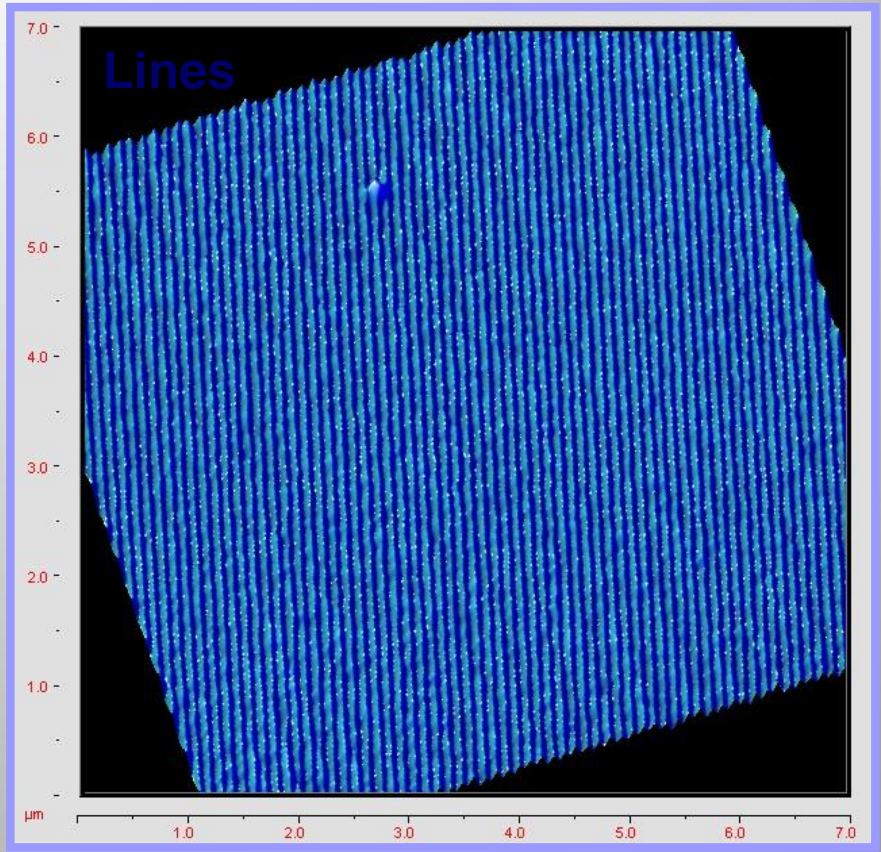
Double exposure set up with a Lloyd's mirror



Two successive exposures allows printing arrays of nanometer size features

Table top Nanopatterning PMMA: large areas



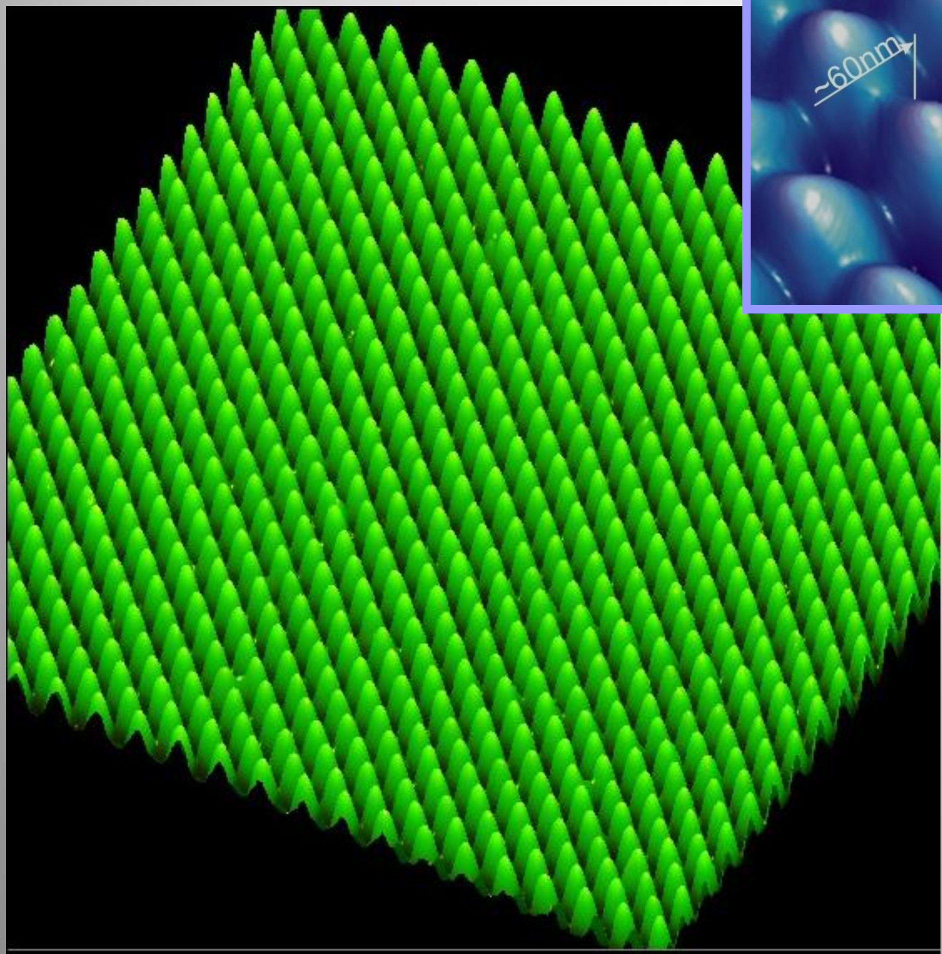


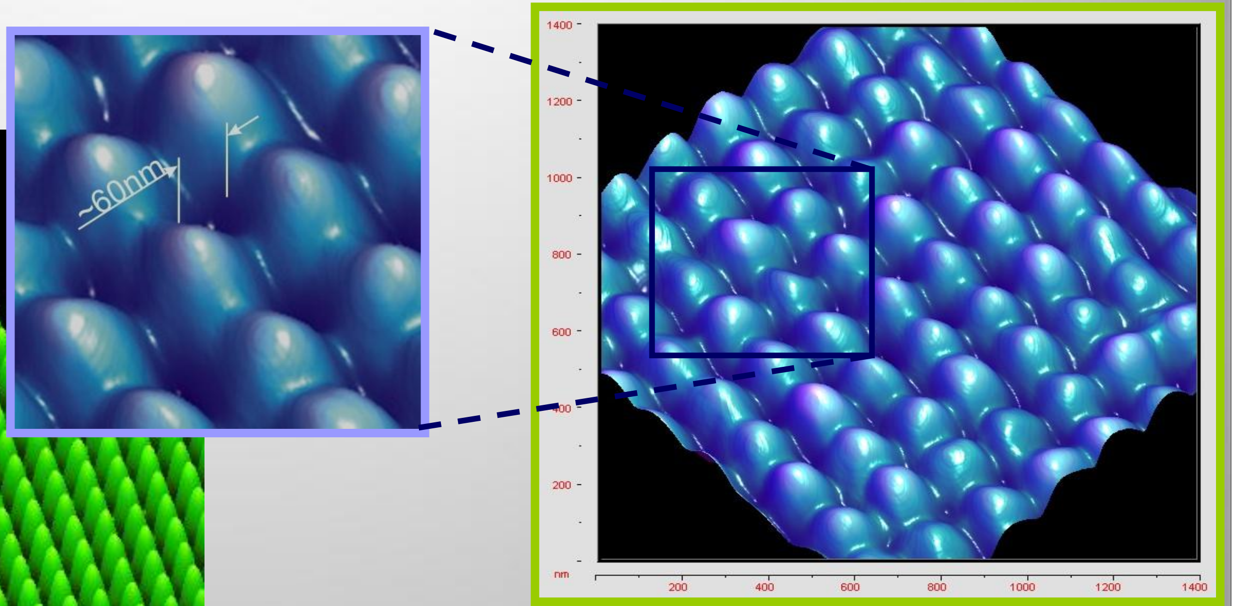
*Period **140nm**,*
*pillars FWHM **~70nm***
Scan size 10x10µm²

*Period **95nm**,*
*lines FWHM **~47nm***
Scan size 7x7µm²

Patterning areas in excess 500 x 500 μm^2

10 x 10 μm^2

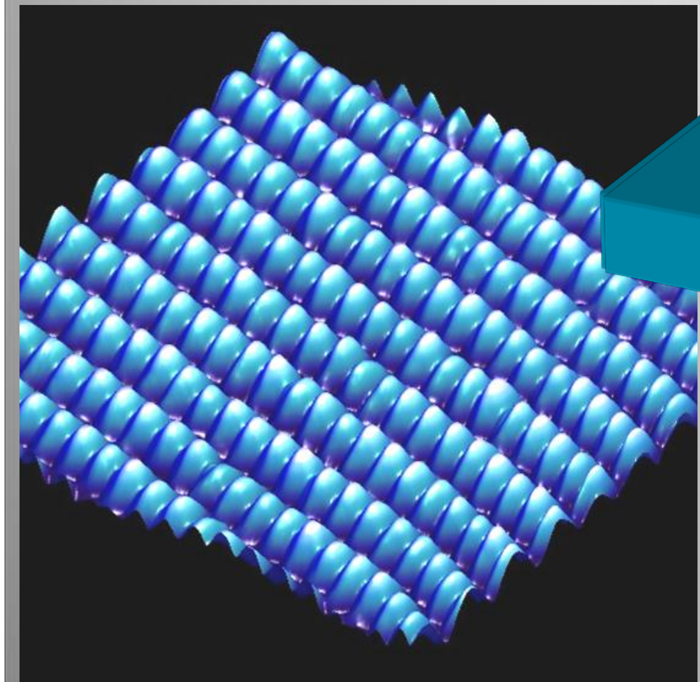


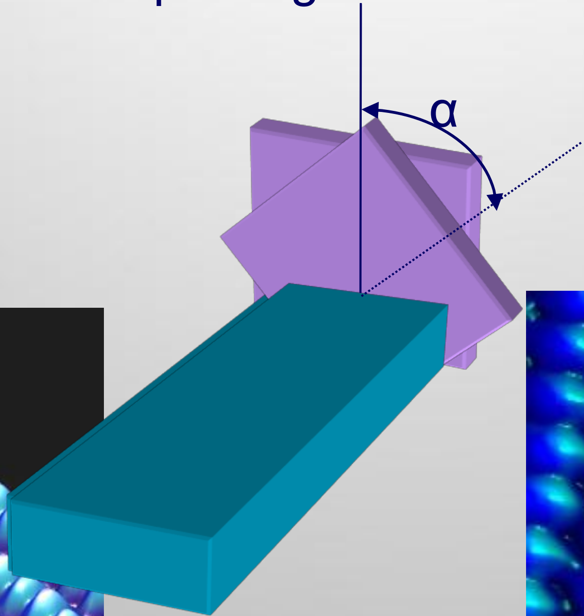


Low dose generates small holes

Table top Nanopatterning PMMA: oval nanodots

Different rotation angles allows printing different motifs





Elongated dots

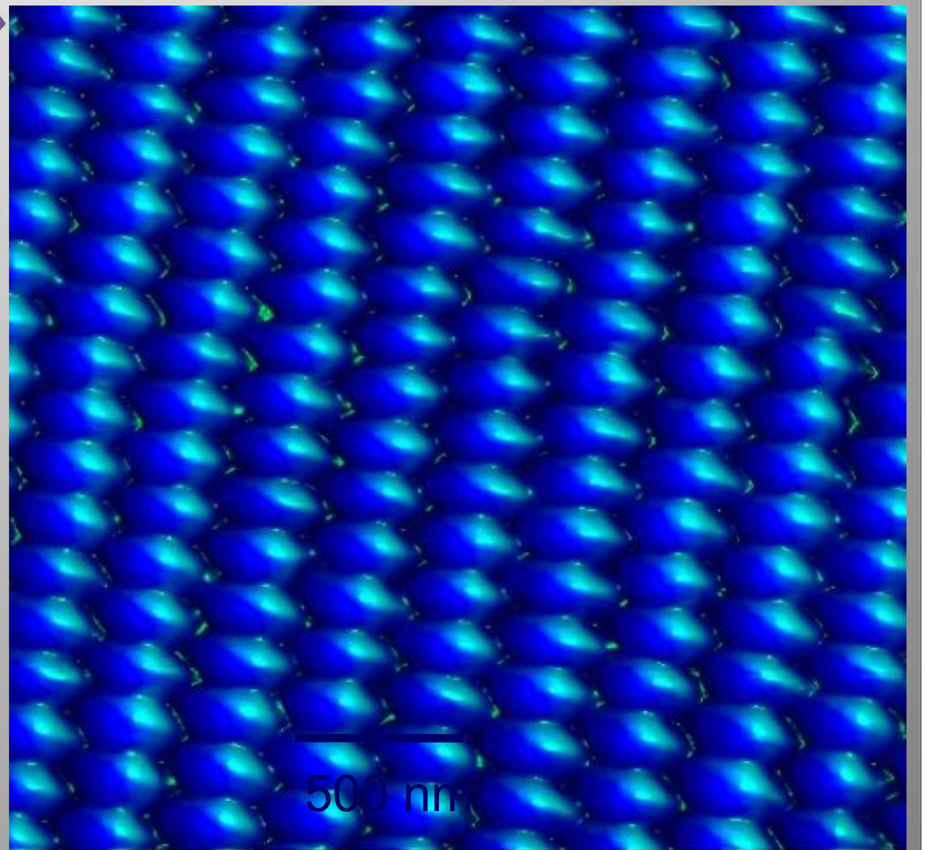
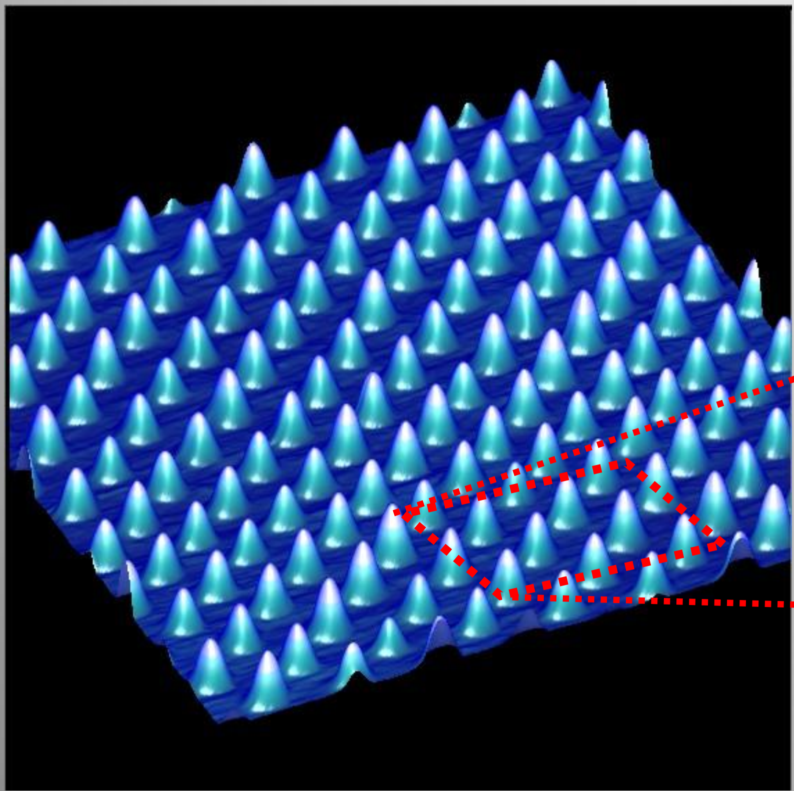
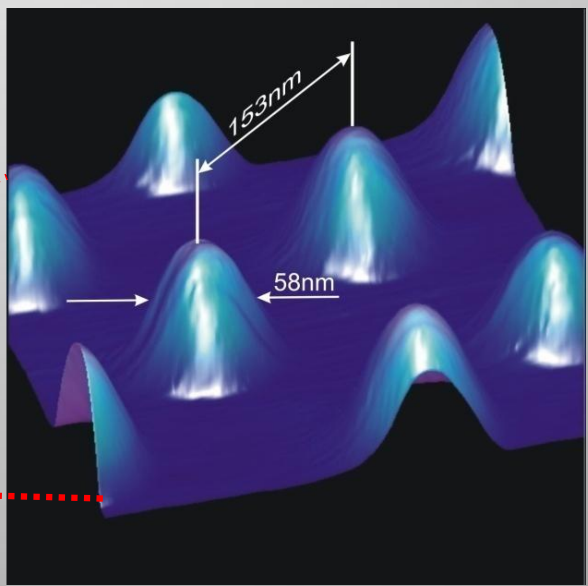


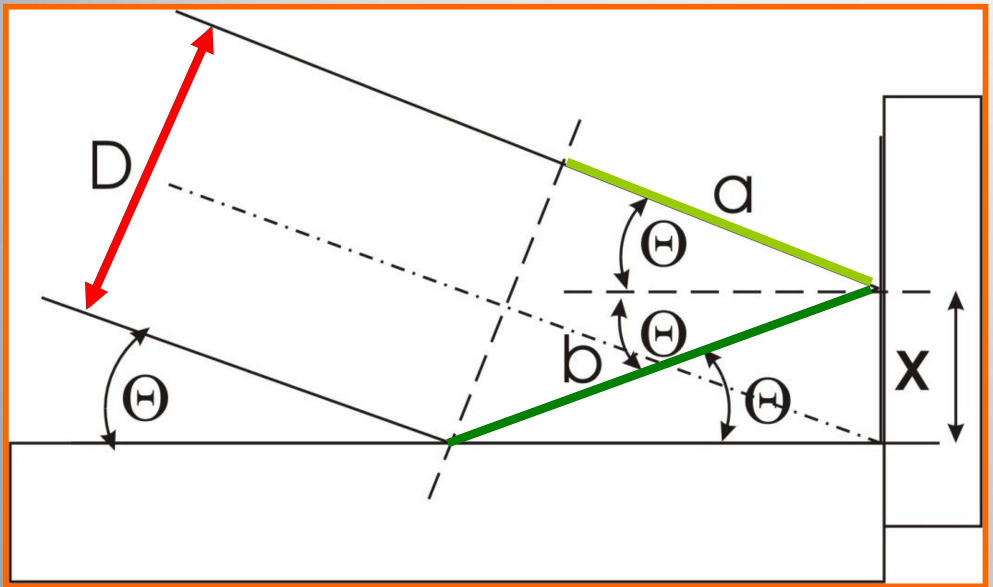
Table top Nanopatterning PMMA: High dose

Dose: 32 mJ cm^{-2}





Printing area: coherence limitations



- Spatial coherence:

Requirement: $D \le 2R_c$

$$x = \frac{R_c}{\cos(\Theta)}$$

- Temporal coherence:

Requirement: $b - a \le l_c$

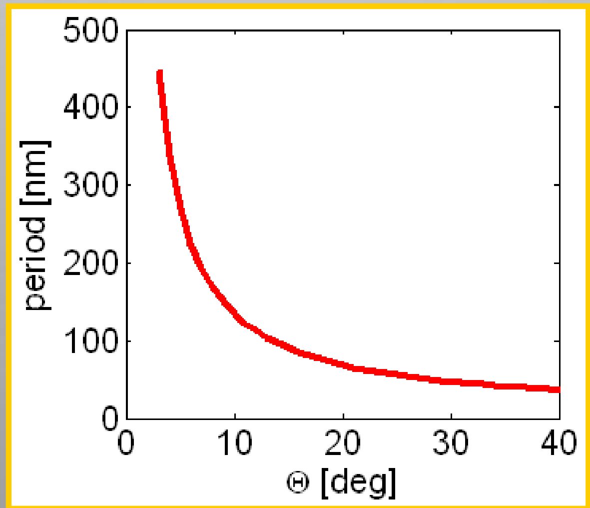
$$x = \frac{l_c}{2\sin(\Theta)}$$

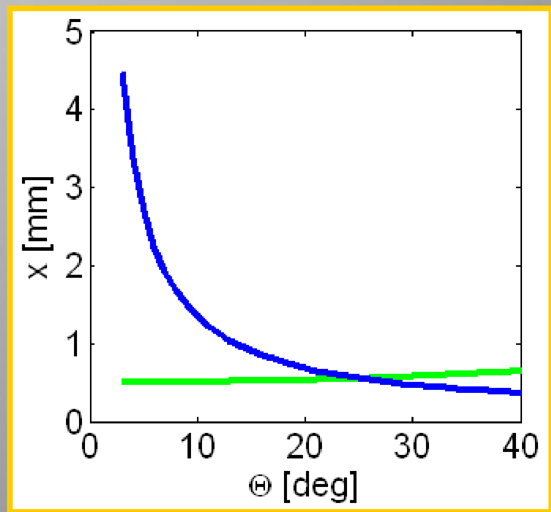
Radius of coherence:

$R_c \sim 0.5\,mm$

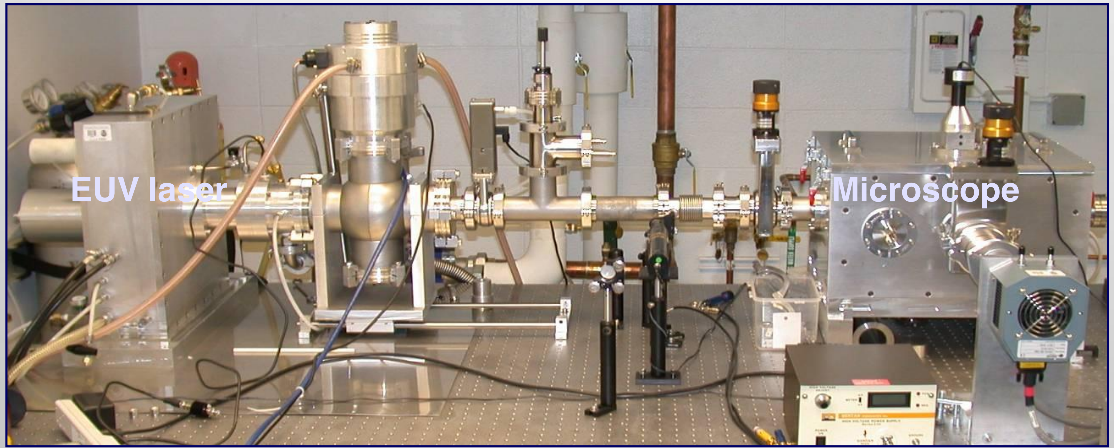
Coherence length:

$$l_c = \frac{\lambda^2}{\Delta\lambda} \approx 47\mu m$$





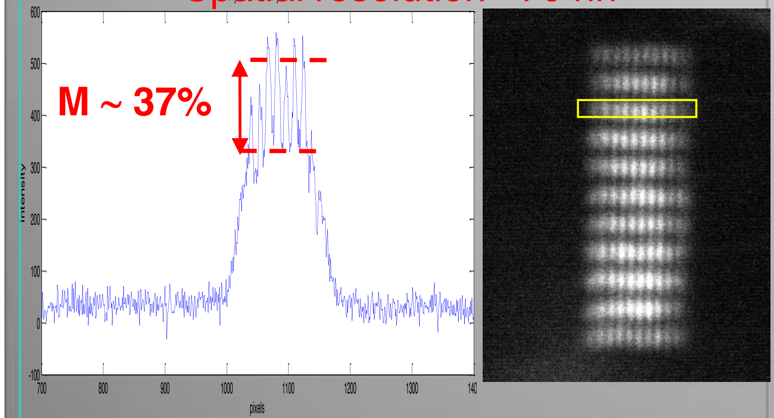
Other applications: Full field zone plate microscope at λ=46.9 nm can image the surface of semiconductor chips.



TRANSMISSION MODE

20 sec exposure EUV image of 70 nm half period dense lines - Δr =70 nm

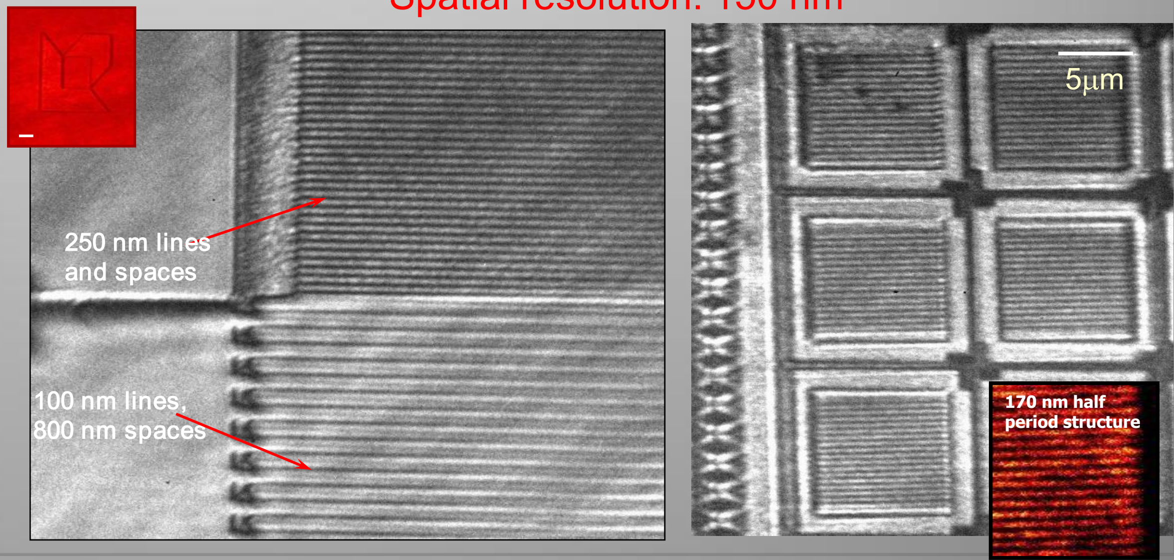
Spatial resolution <70 nn



REFLECTION MODE

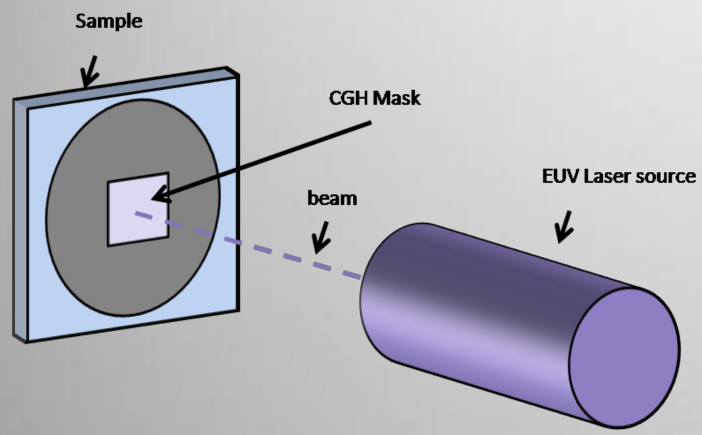
20 sec exposure EUV images of the surface of a semiconductor chip - Δr=200 nm

Spatial resolution: 150 nm

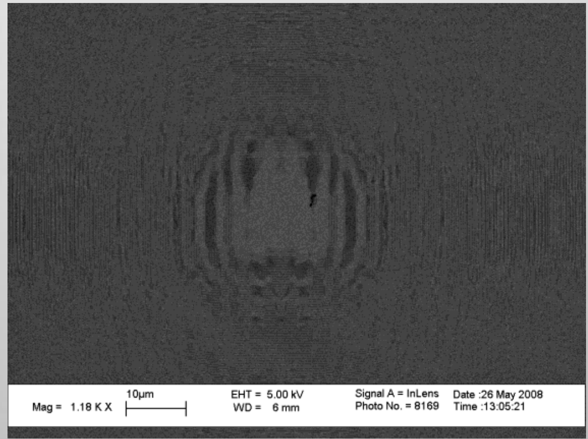


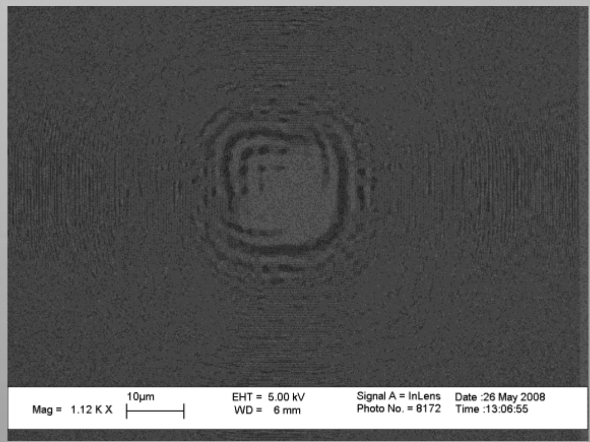
Holographic lithography

Experimental setup

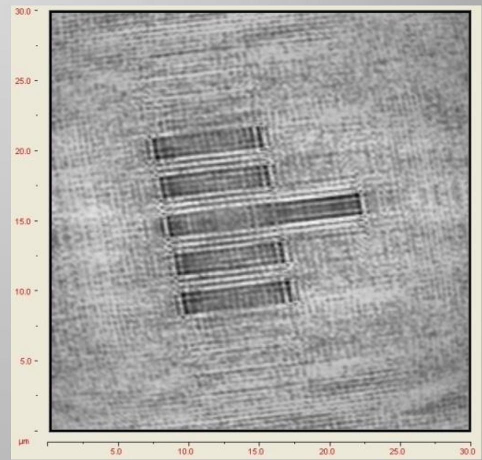


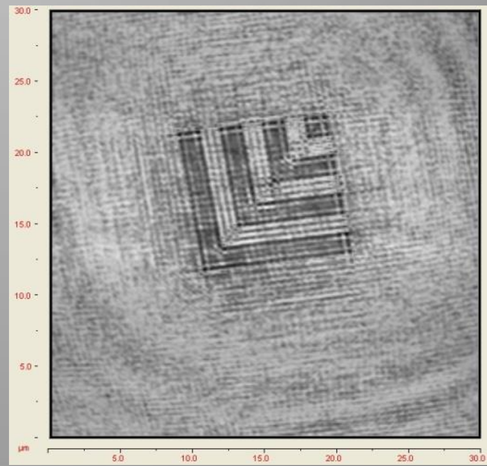
Computer generated binary hologram fabricated by e-beam lithography



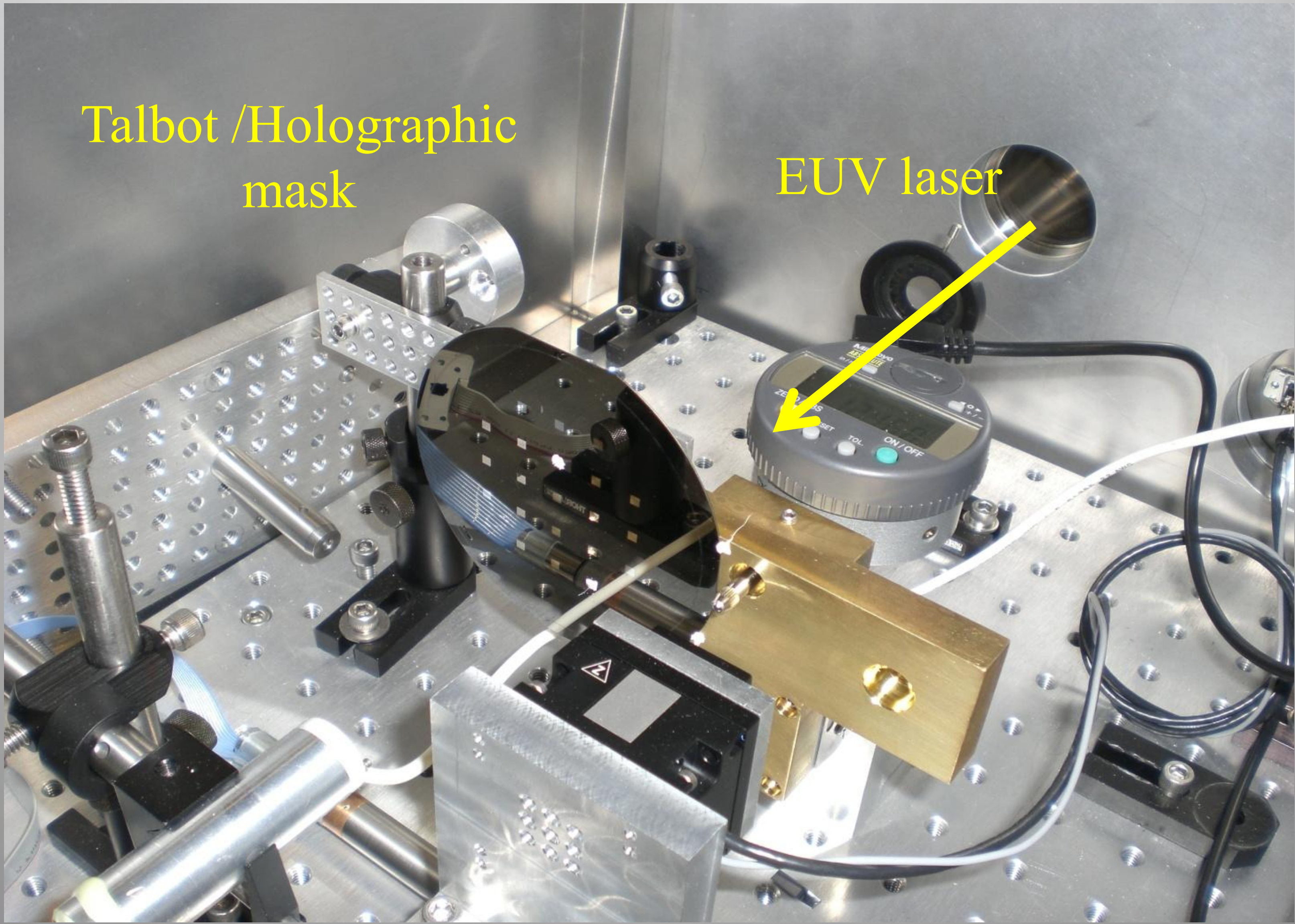


AFM micrographs of the patterns printed in PMMA

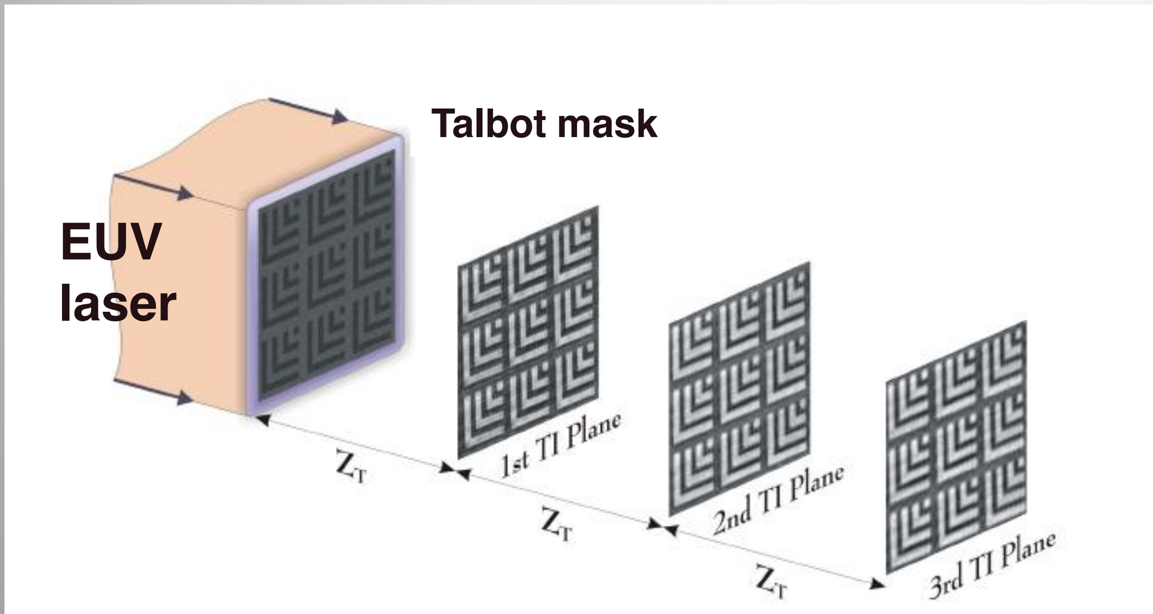


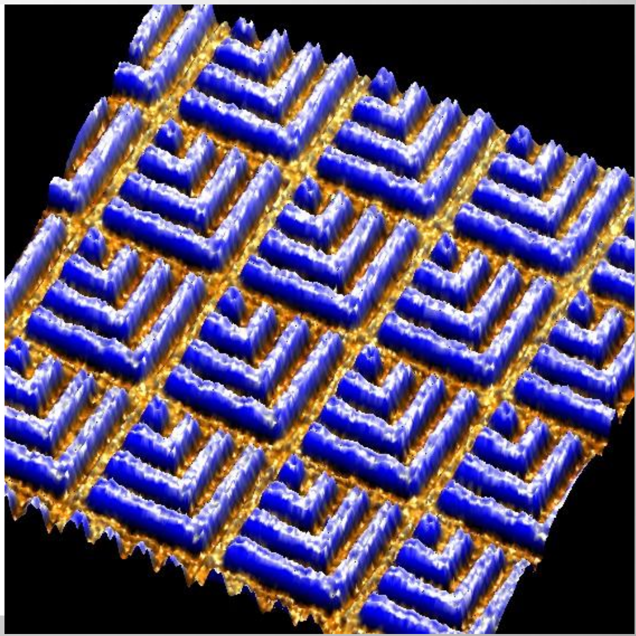


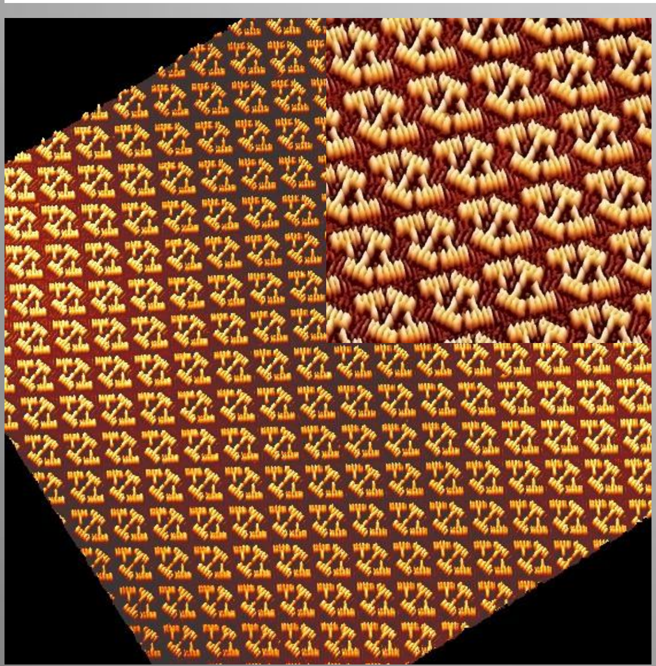
Experimental set up



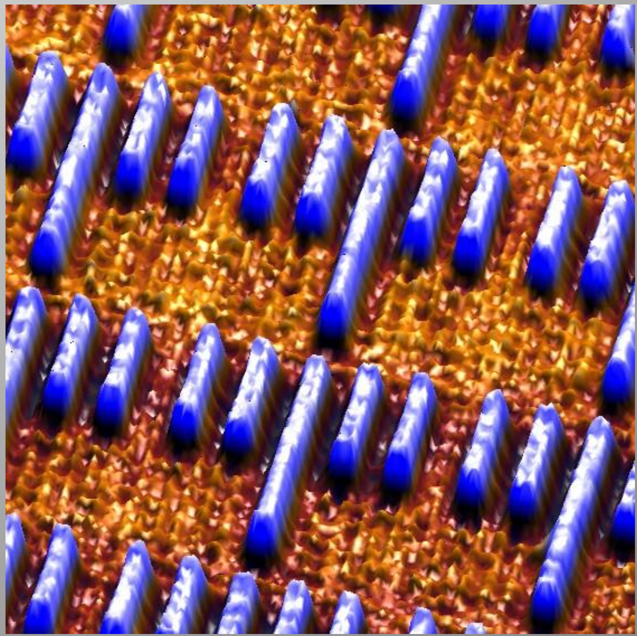
Talbot coherent imaging lithography







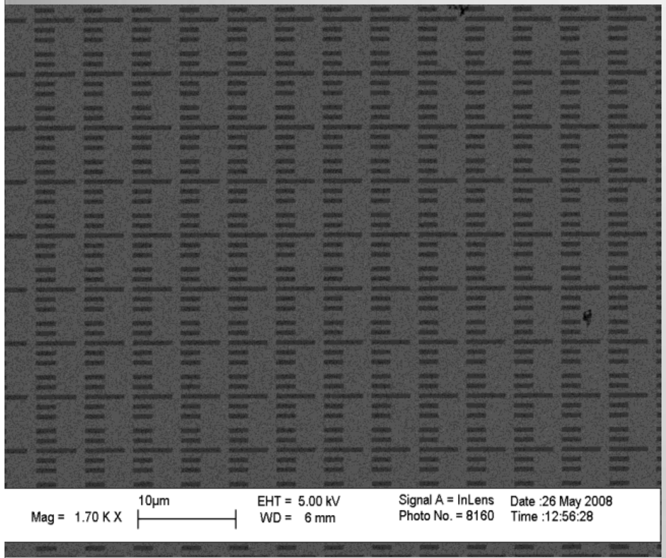
Direct printing of arbitrary patterns

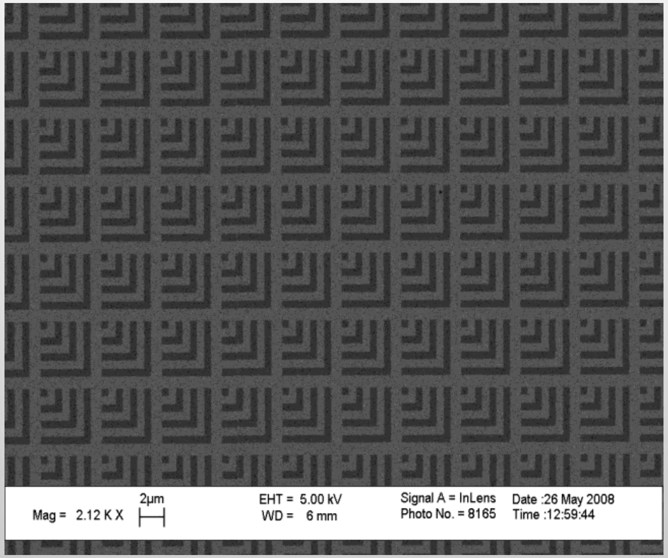


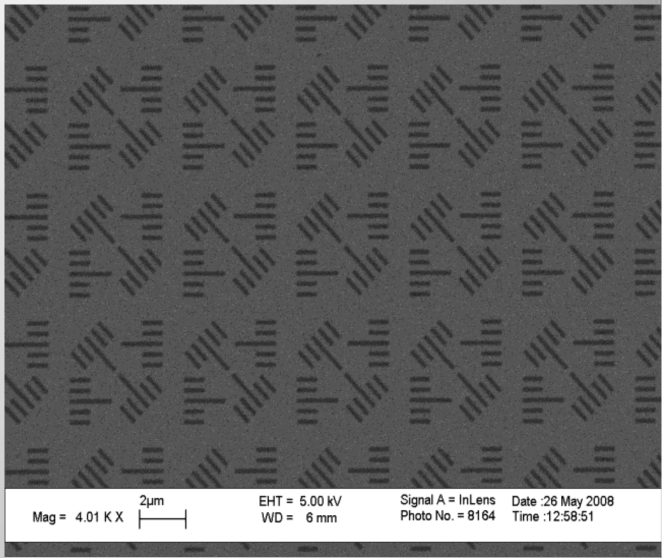
EUV

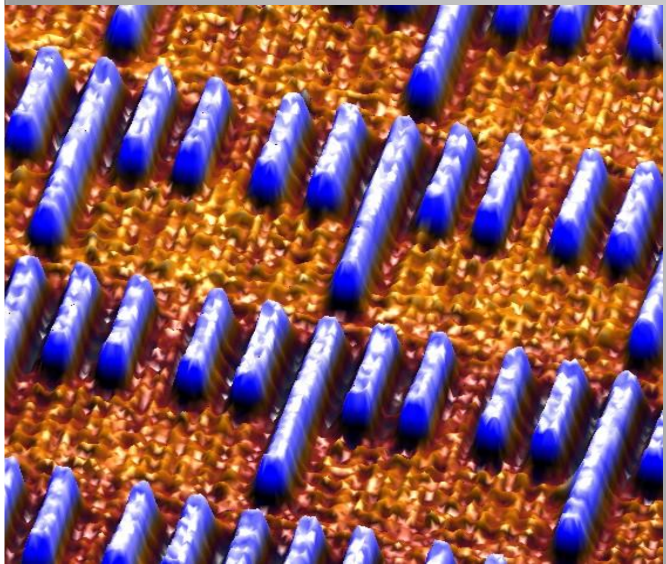
An NSF Engineering Research Center

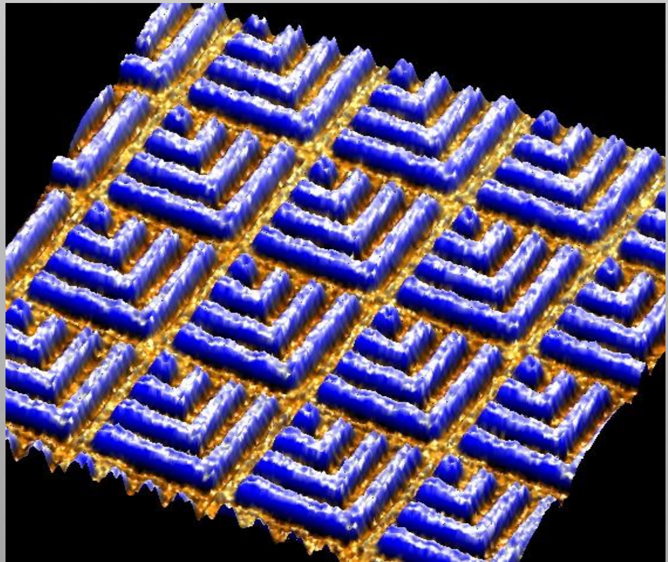
Arbitrary patterns over large areas with a spatial resolution of ~ 100 nm in exposures ~ 1 minute

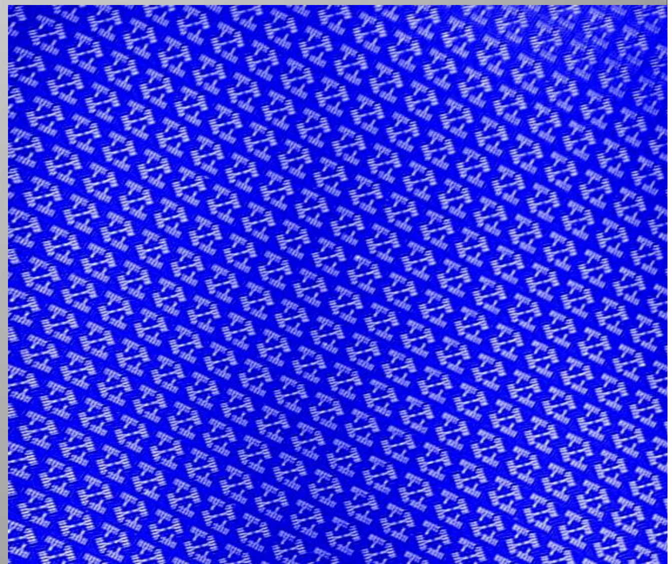


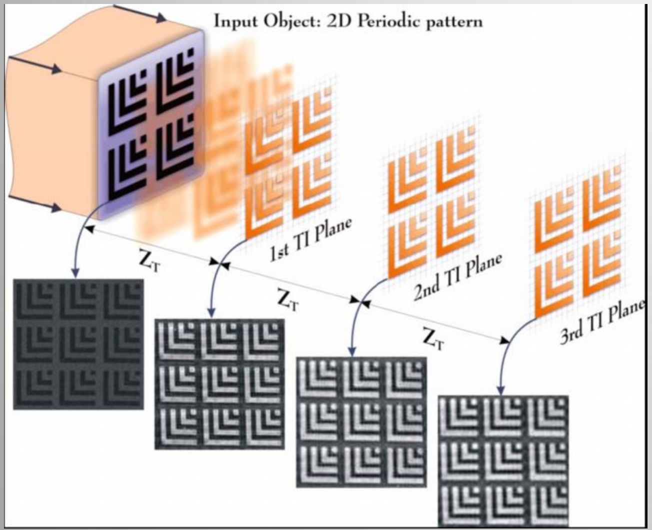








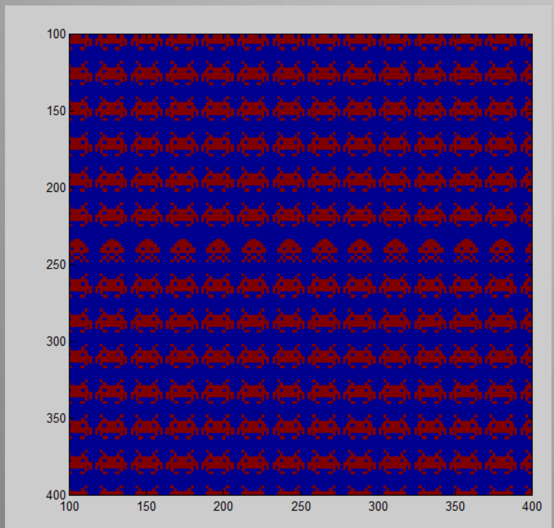


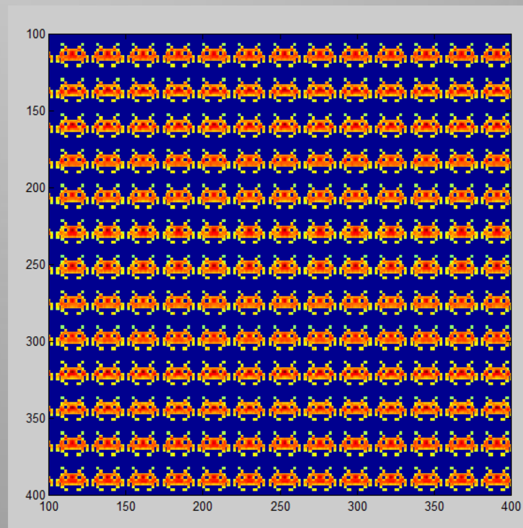


$$\Delta_n = \frac{\lambda}{2}\sqrt{1+\left(\frac{2np^2}{\lambda W}\right)^2}$$

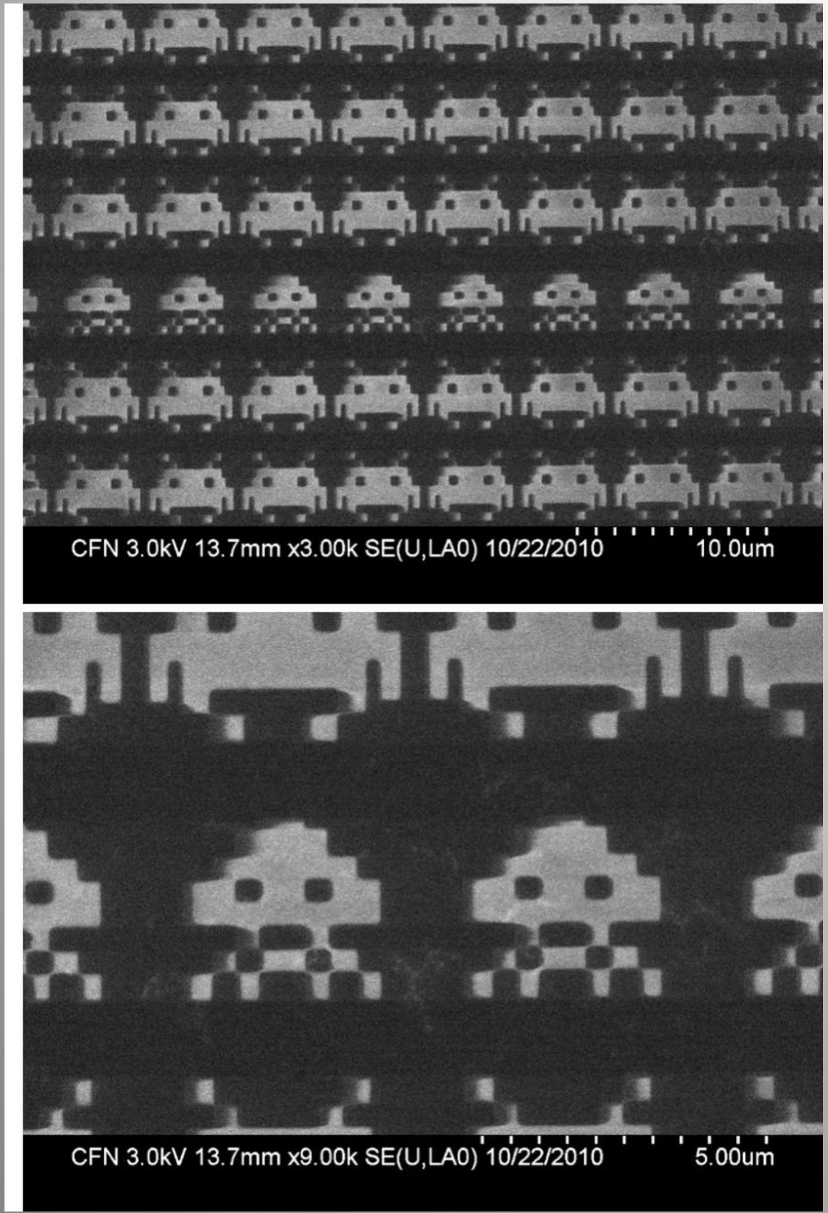
$$DOF = \frac{\lambda}{NA^2} = \lambda\left[1+\left(\frac{2Np^2}{\lambda W}\right)^2\right]$$

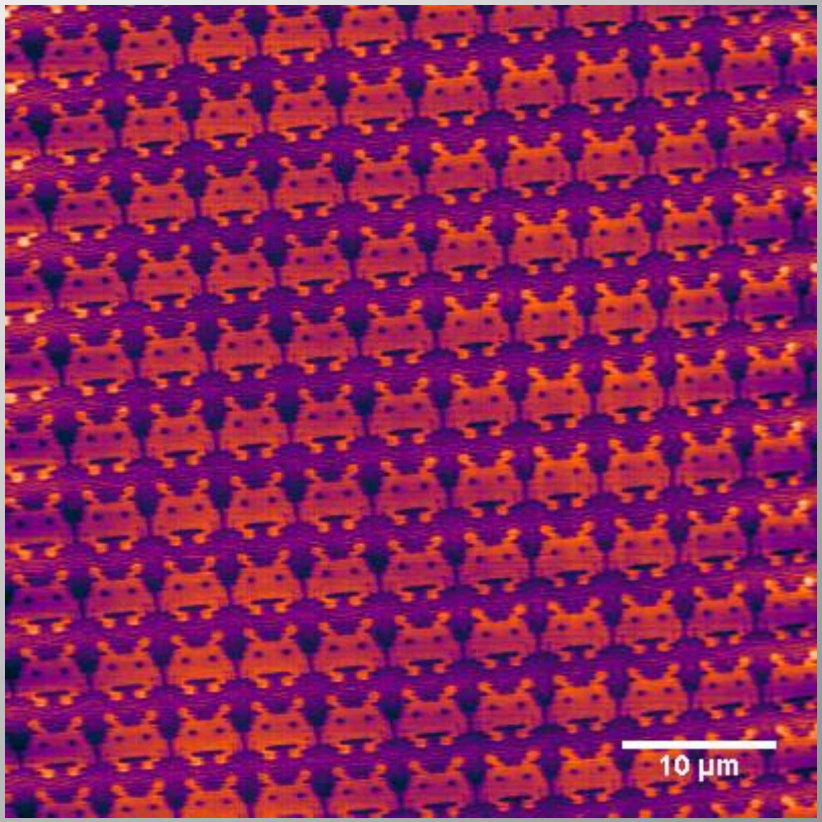
Robust method: “non-contact , defect-free optical nano-imprint”



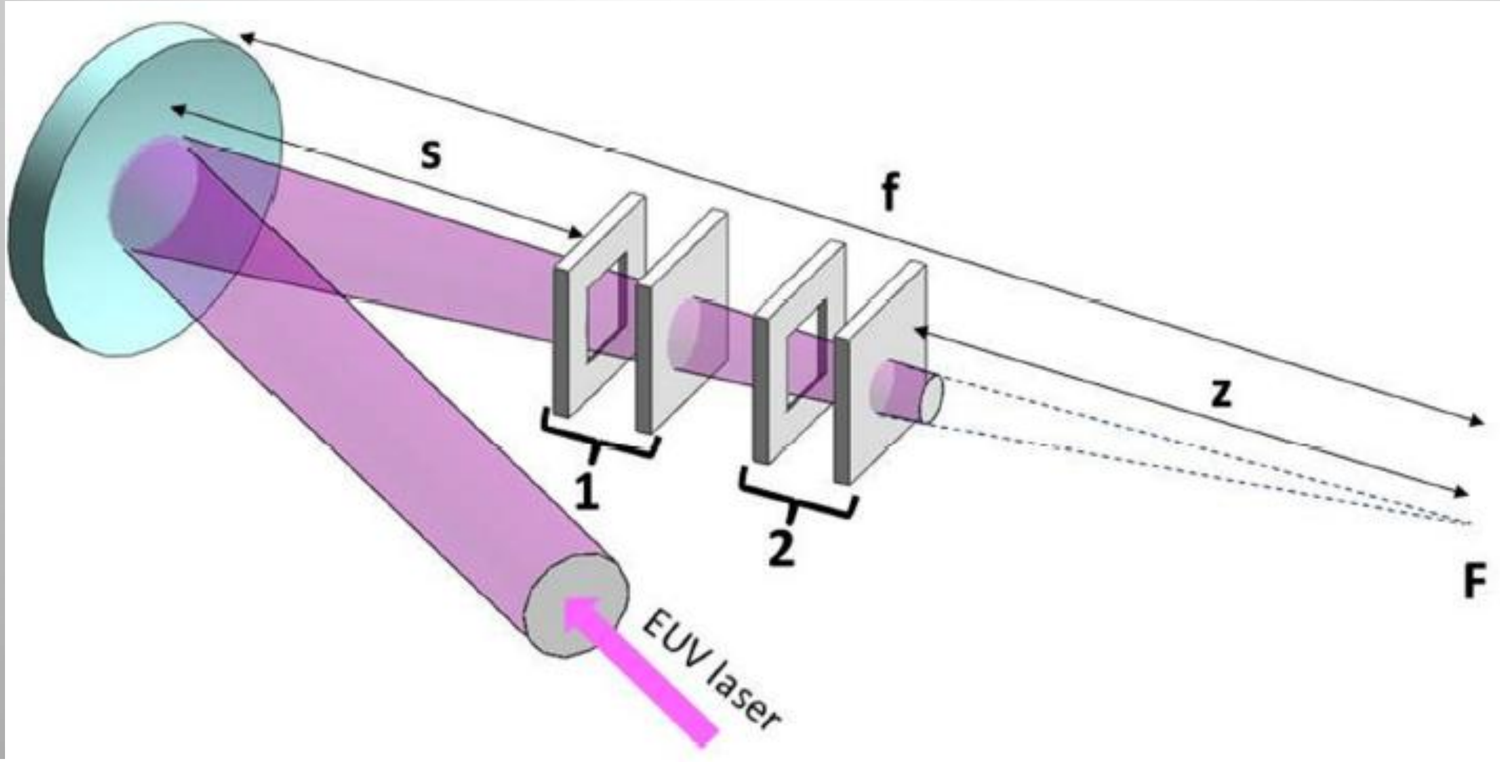


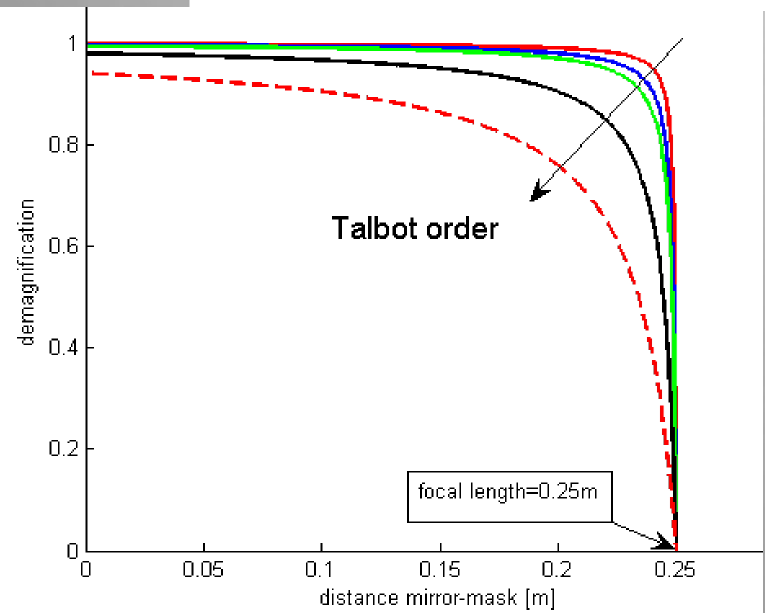
Defect Tolerant Generalized Talbot Nanopatterning





De-magnified Talbot Imaging: Formalism

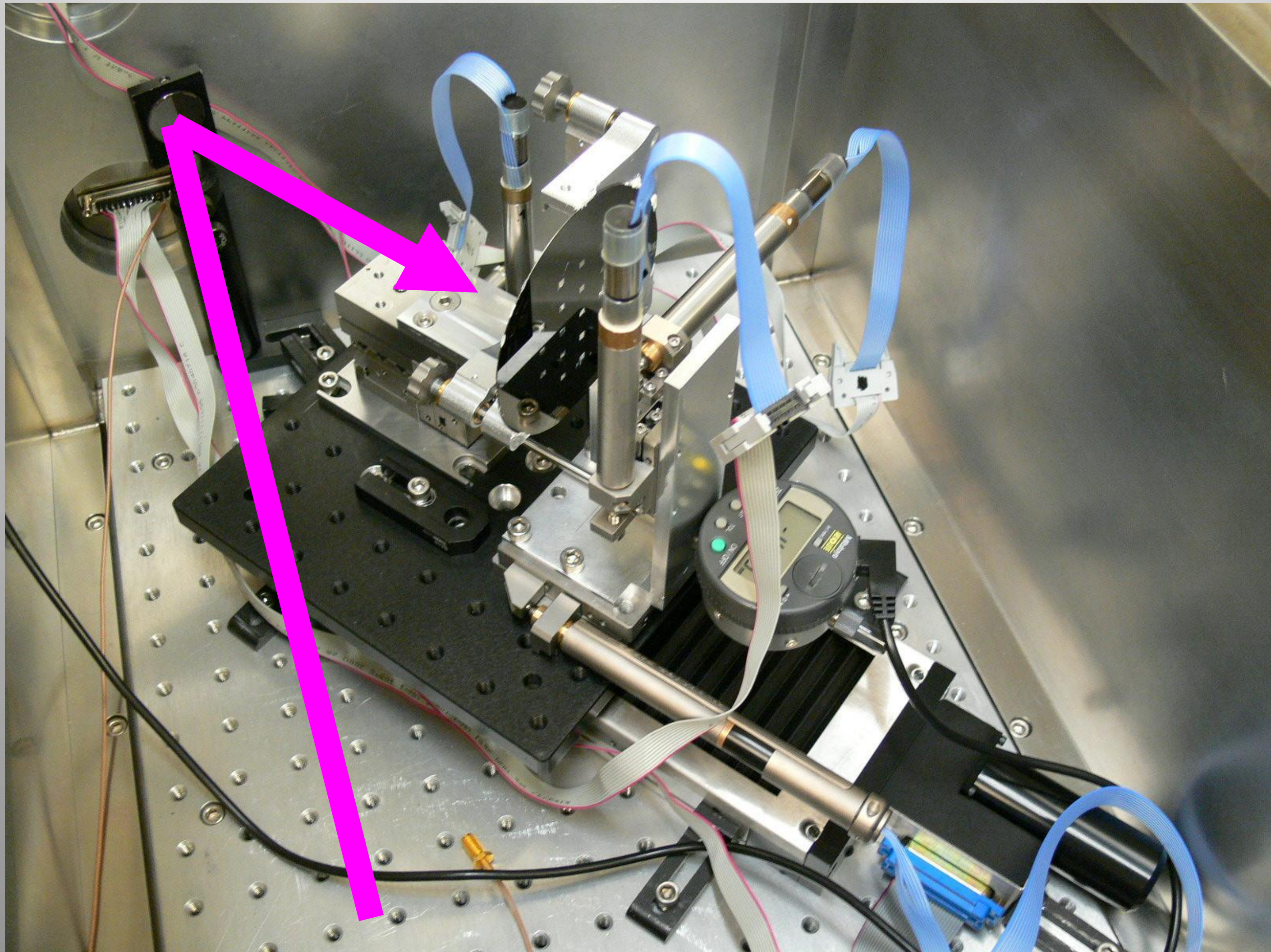




$$p' = p\left[\frac{z}{(f-s)}\right]$$

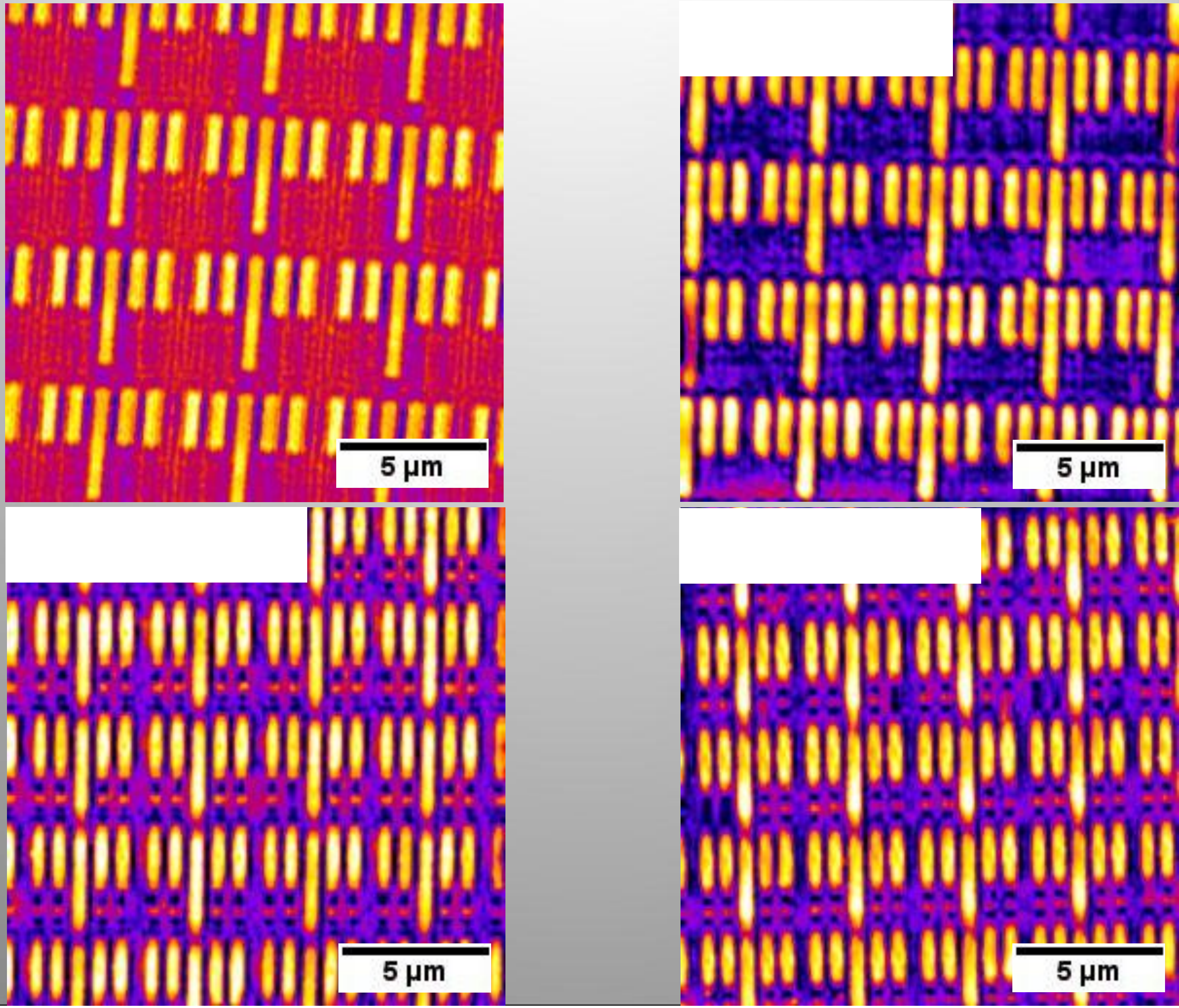
$$d = 1 - \frac{2np^2}{np^2 + 2\lambda(f-s)}$$

Experiment



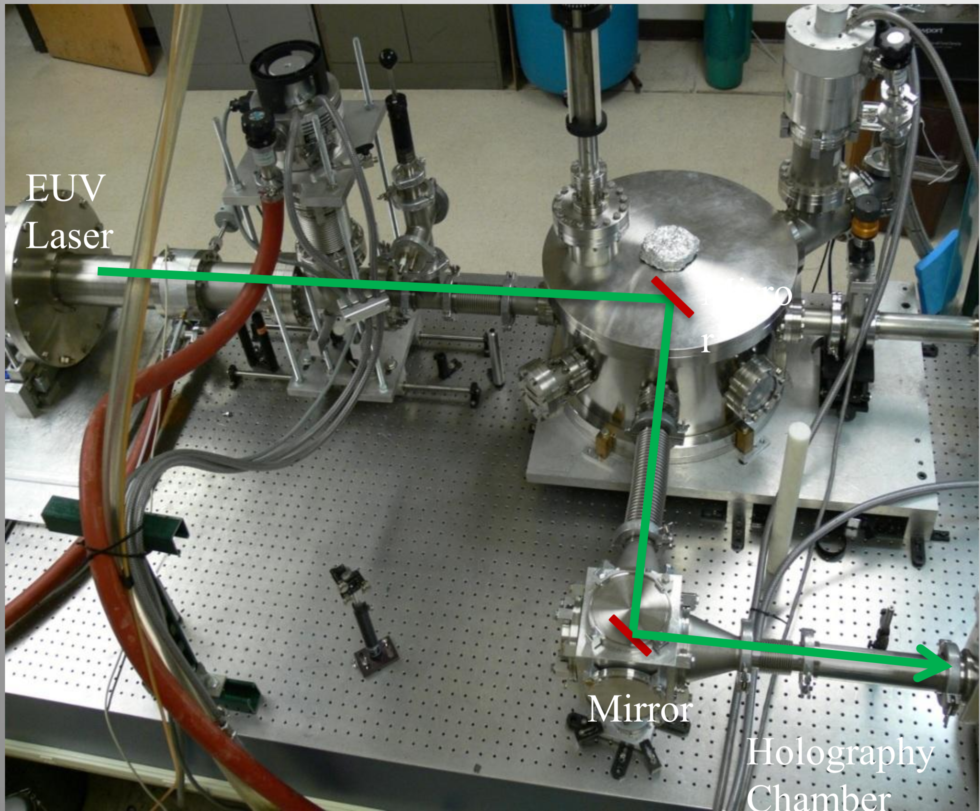
EUV Laser

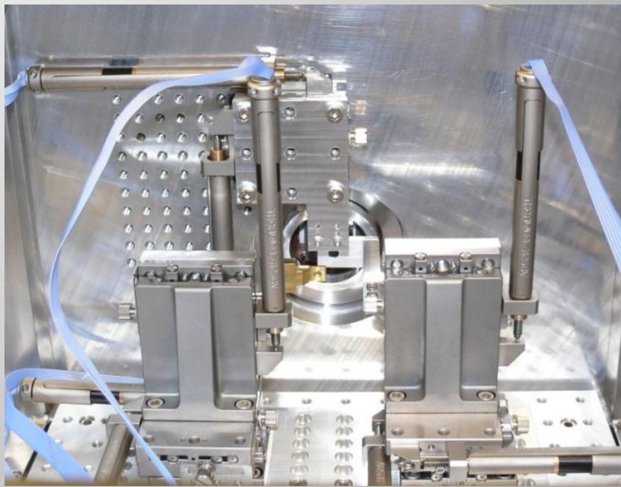
Results

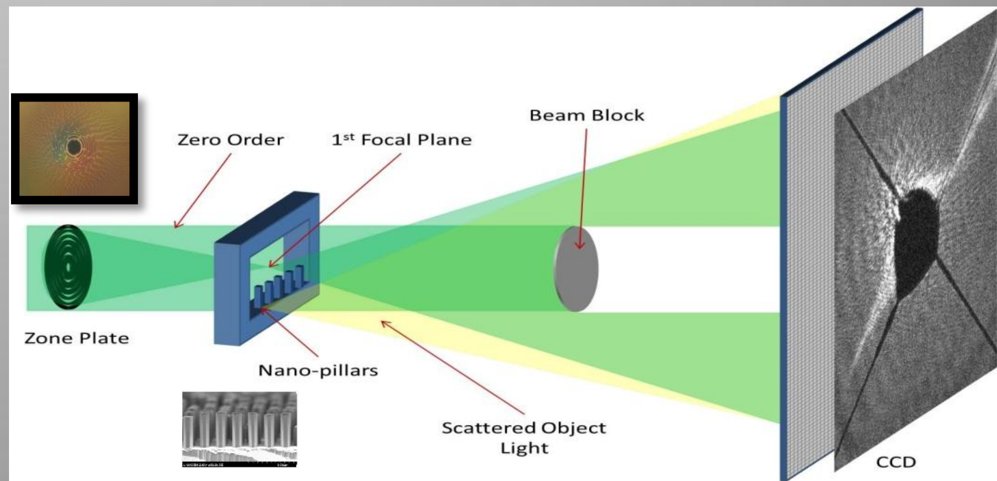


Single shot EUV holograms

Experimental set up

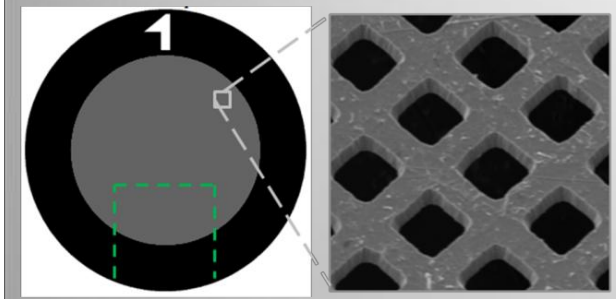




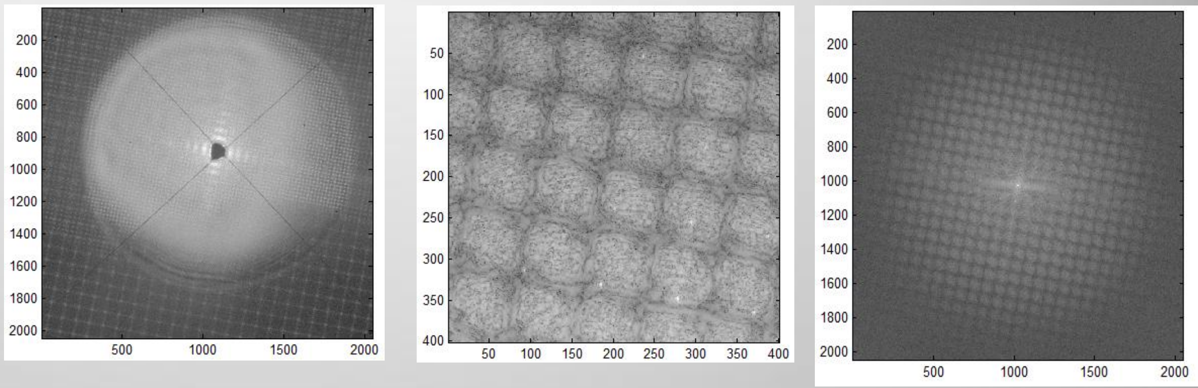


Single shot EUV holograms

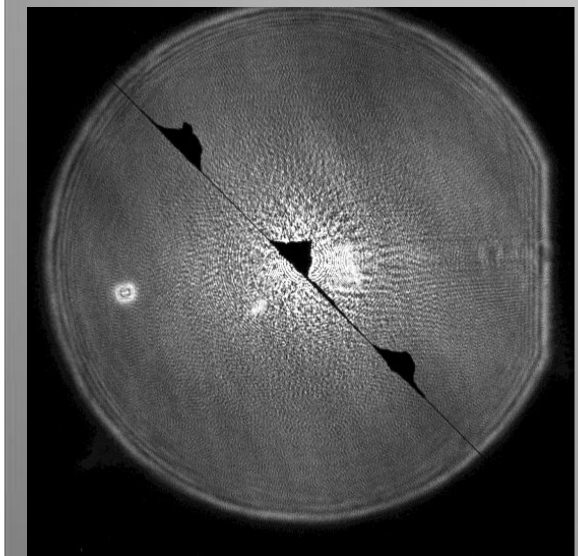
First results

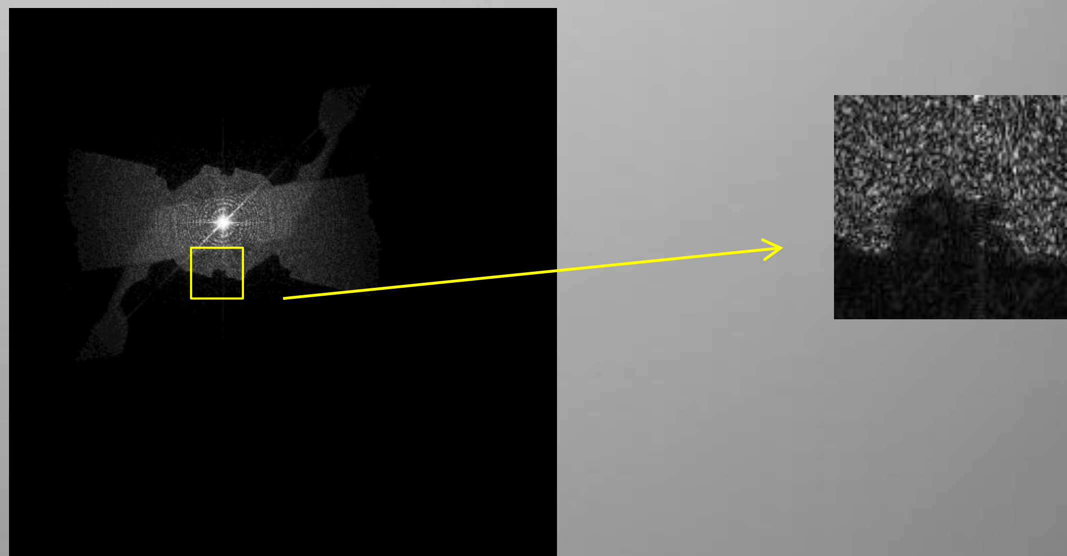


Test object: TEM grid 12.5 m period, 5 m bar width and 7.5 m square holes.

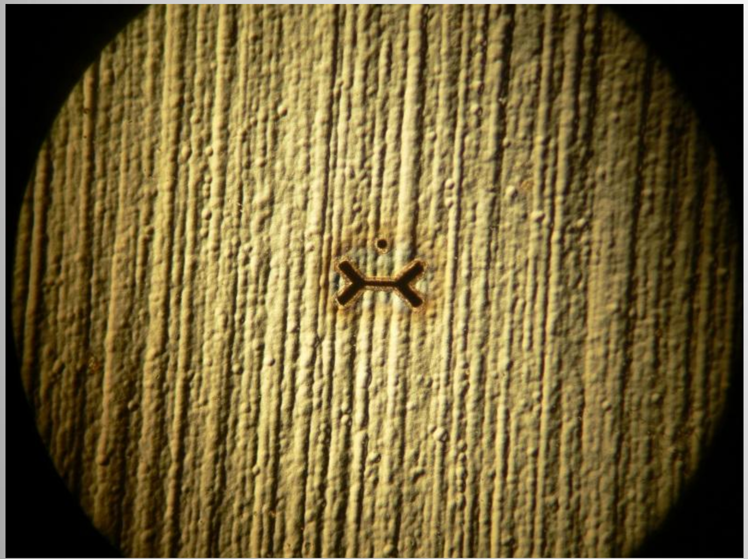


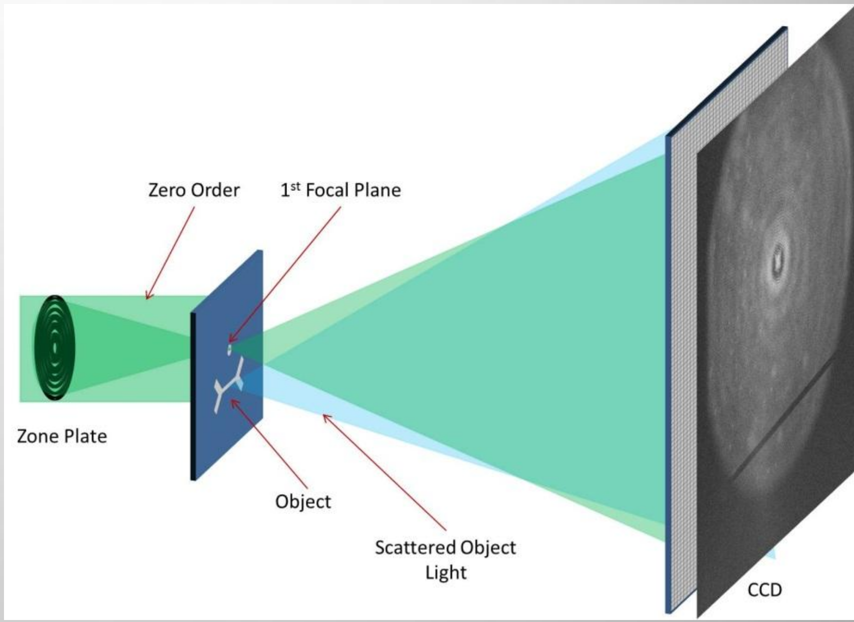
First EUV Fourier hologram of the TEM mesh and reconstructed images

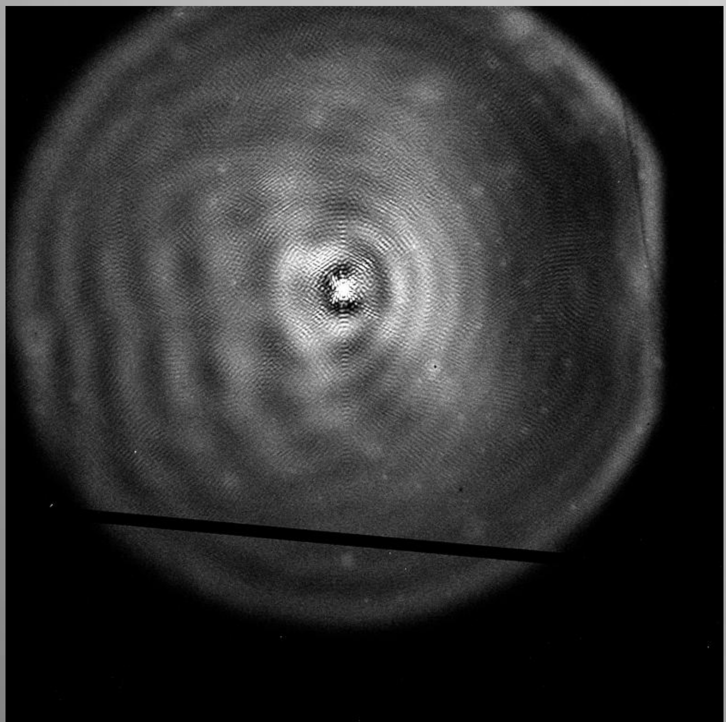


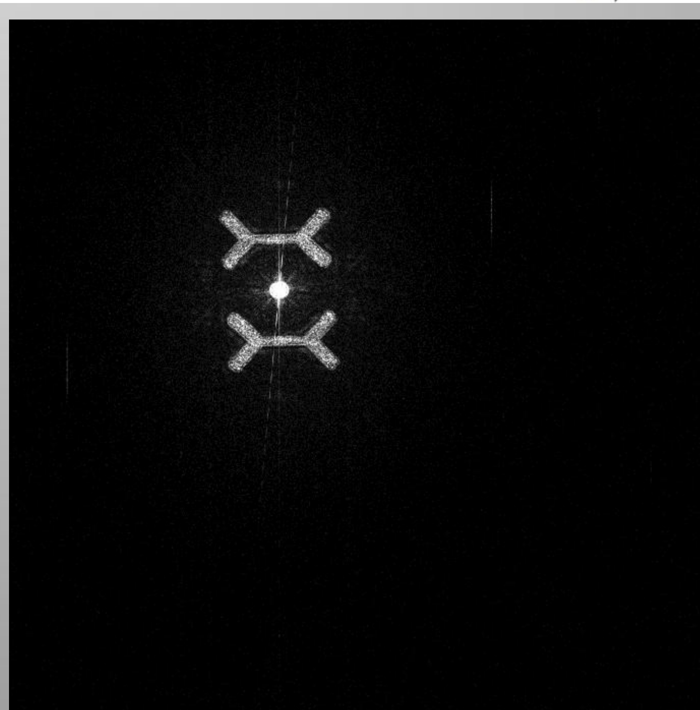


Single shot EUV holograms



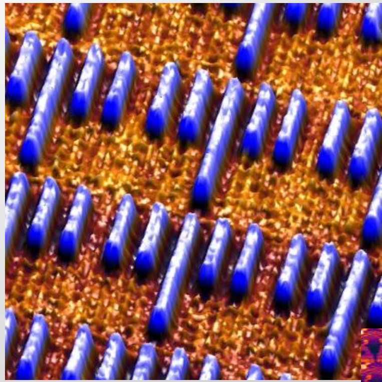


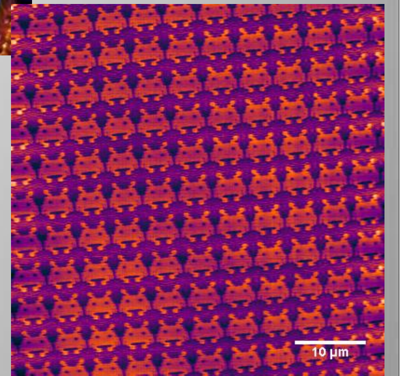




Summary

Nano-patterning

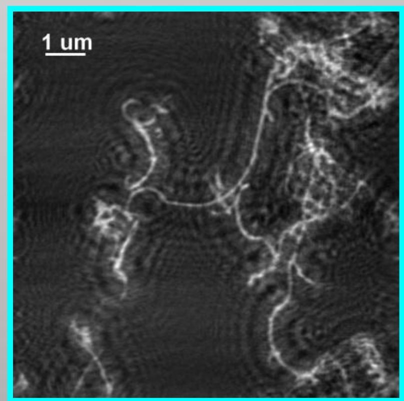




Short wavelength
Coherence → Interferometric lithography
Holographic lithography
Talbot lithography

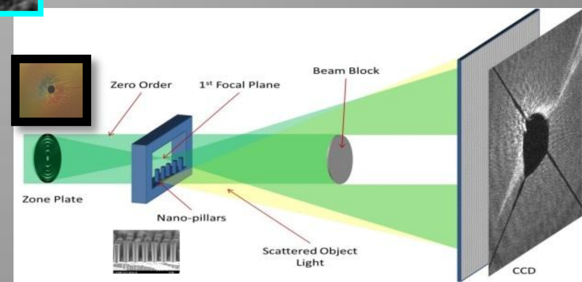
Non-contact, defect-free optical replication of masks

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



Thank you

Erik Anderson - Lawrence Berkeley National Lab
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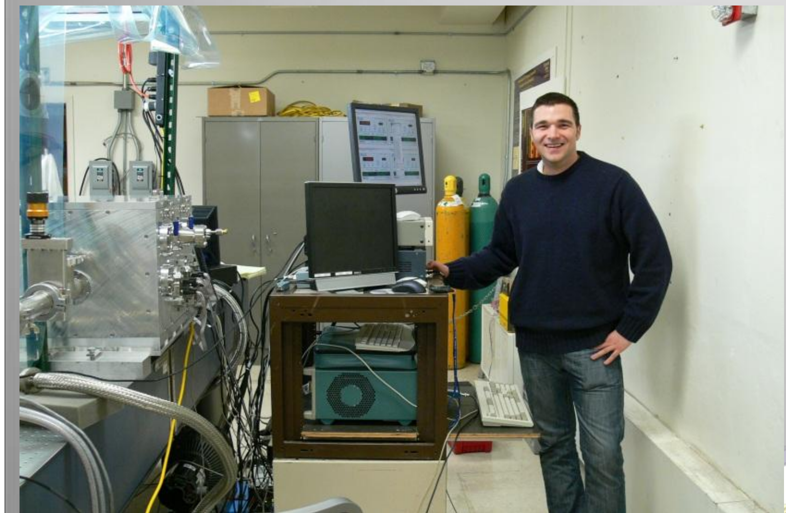
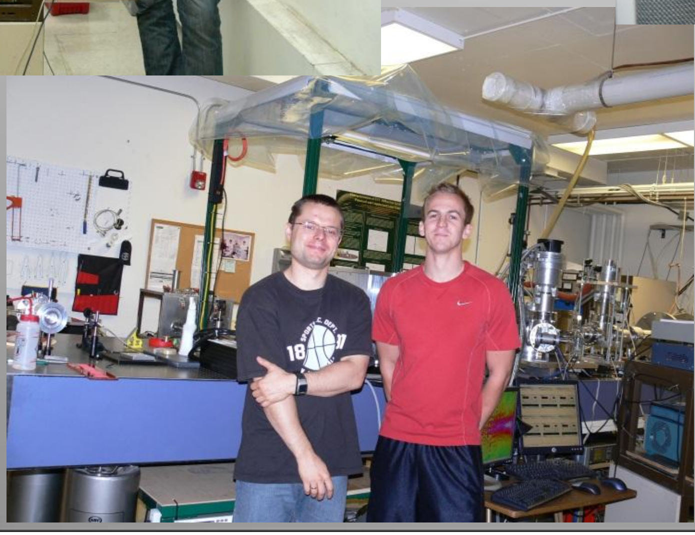
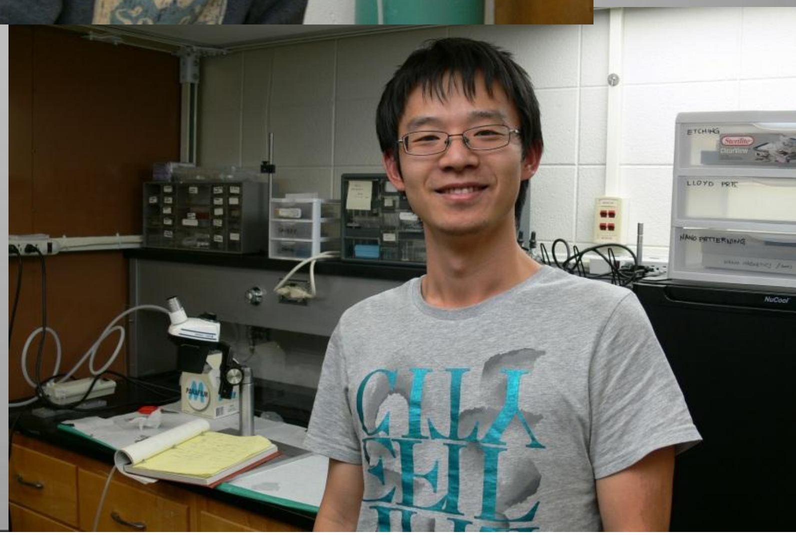
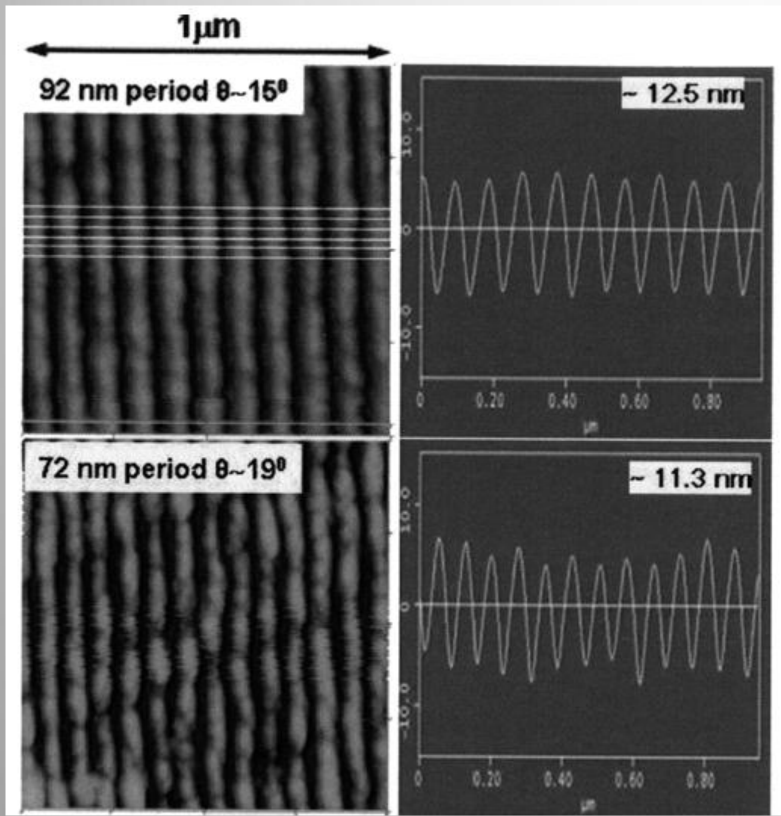
Dave Attwood - Lawrence Berkeley National Lab
Franco Cerrina- Boston University
Artak Isoyan: University of Wisconsin (Madison)
Aaron Stein: Brookhaven National Lab
Carmen Menoni - Colorado State University
Jorge Rocca - Colorado State University



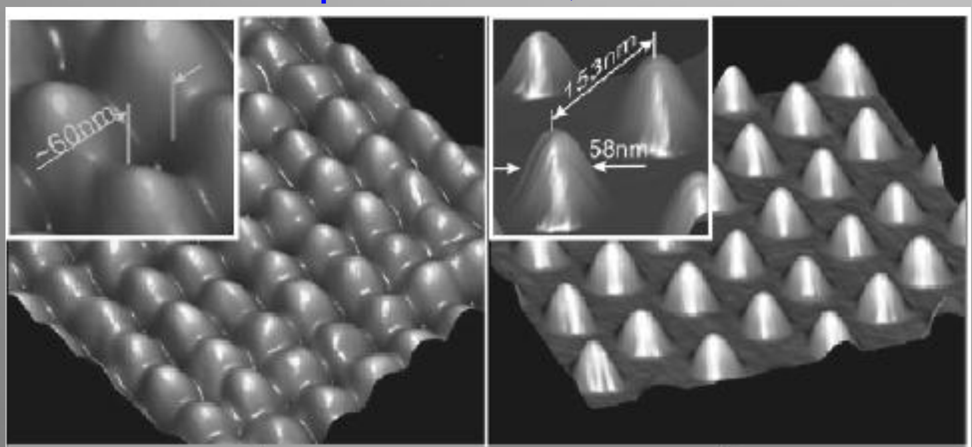




Capeluto et al, 2006



Capeluto et al, 2008



WRITING WITH VUV O R-X

PROS:
Not necessary to break the diffraction barrier

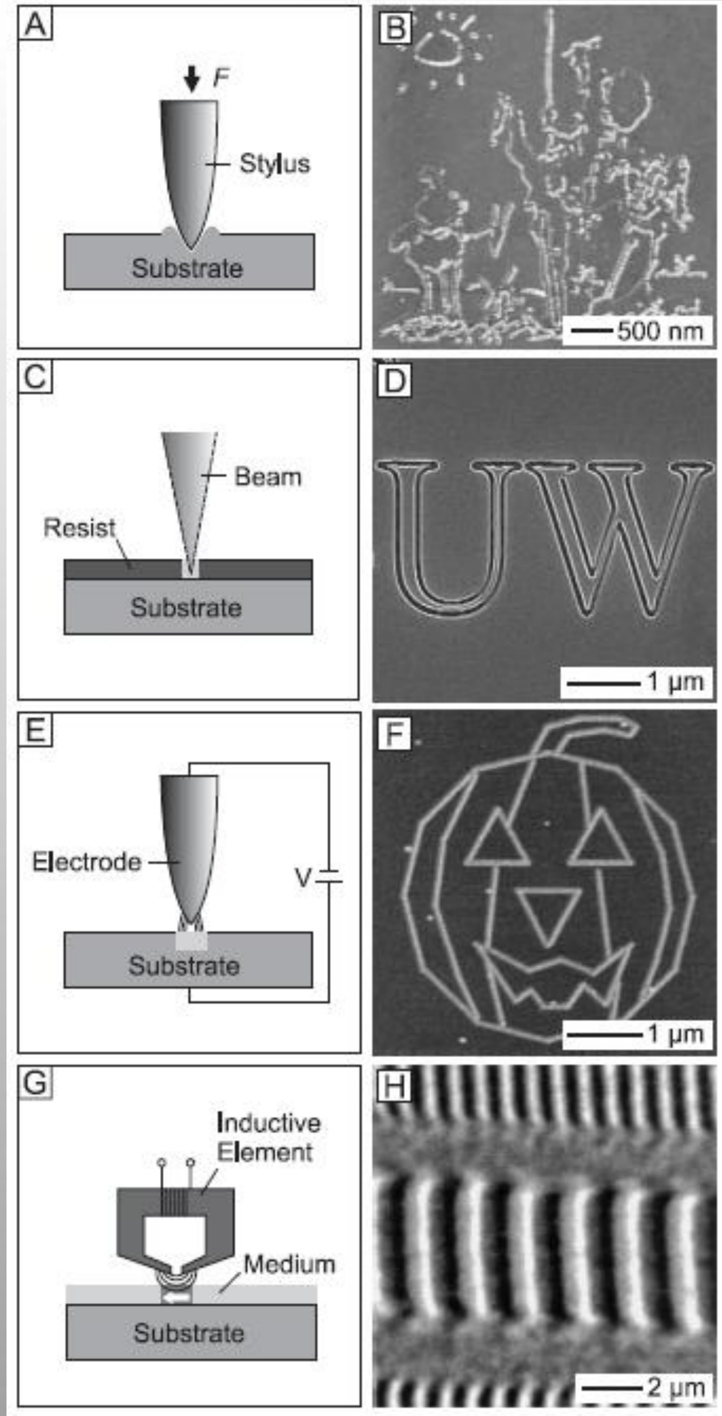
CONS:
COMPLEX LIGHT SOURCES
COMPLEX OR UNEXISTING OPTICAL COMPONENTS
NO TRANSPARENT MATERIALS

WRITING WITH STRANGE PENCILS

PROS: HIGH RESOLUTION (MOLECULAR)

CONS:
SLOW
2D

APT FOR MASKS AND PROTOTYPES



WRITTING IN 3D

- MULTIPHOTON POLIMERIZATION
- OTHER NONLINEARITIES
- OUR APROACH TO THE PROBLEM

NATURE | VOL 412 | 16 AUGUST 2001 |
Satoshi Kawata, Hong-Bo Sun,
Tomokazu Tanaka, Kenji Takada

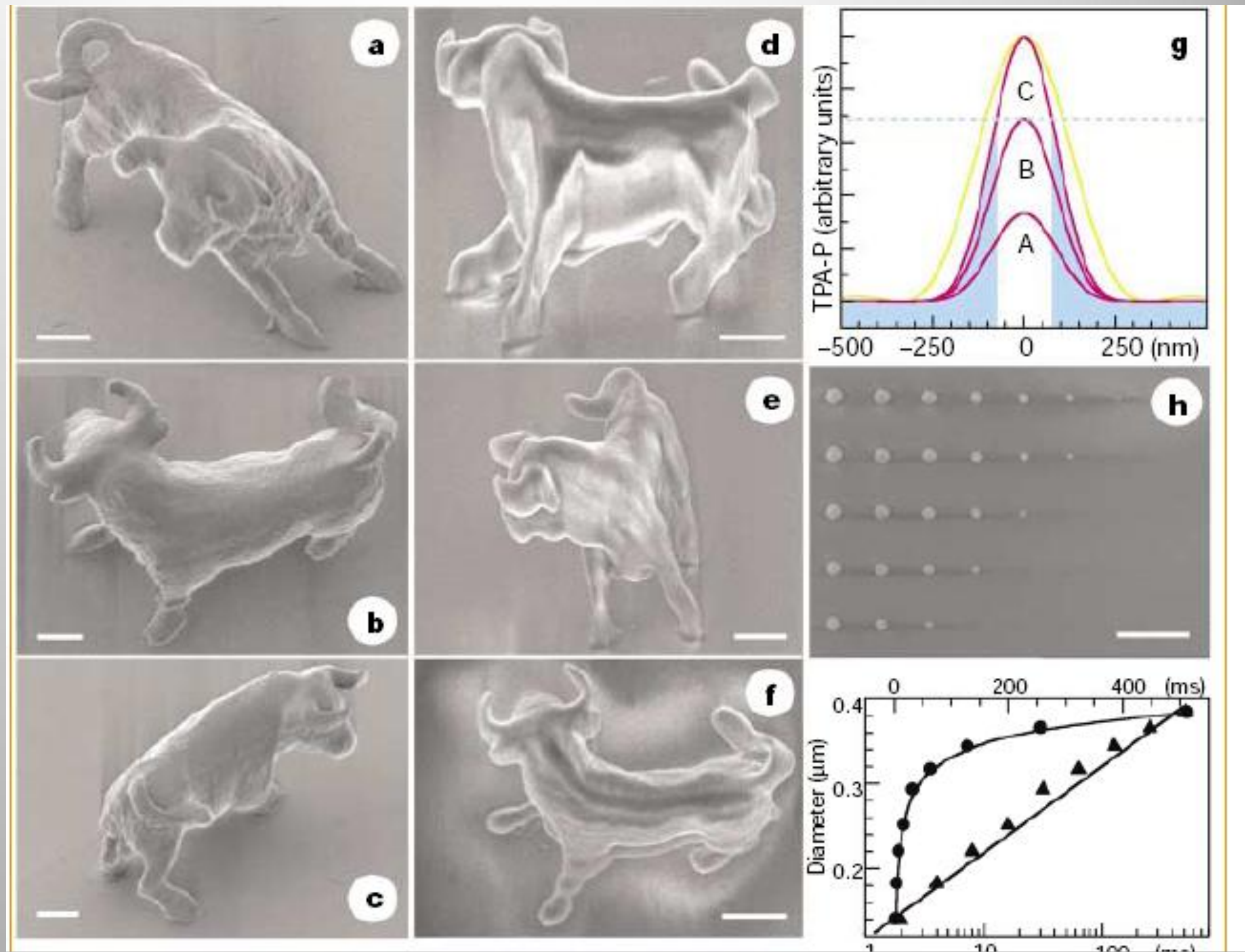


Figure 1 Microfabrication and nanofabrication at subdiffraction-limit resolution. A titanium sapphire laser operating in mode-lock at 76 MHz and 780 nm with a 150-femtosecond pulse width was used as an exposure source. The laser was focused by an objective lens of high numerical aperture (~1.4). **a–c, 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 m.

NATURE | VOL 412 | 16 AUGUST 2001 |
Satoshi Kawata, Hong-Bo Sun,
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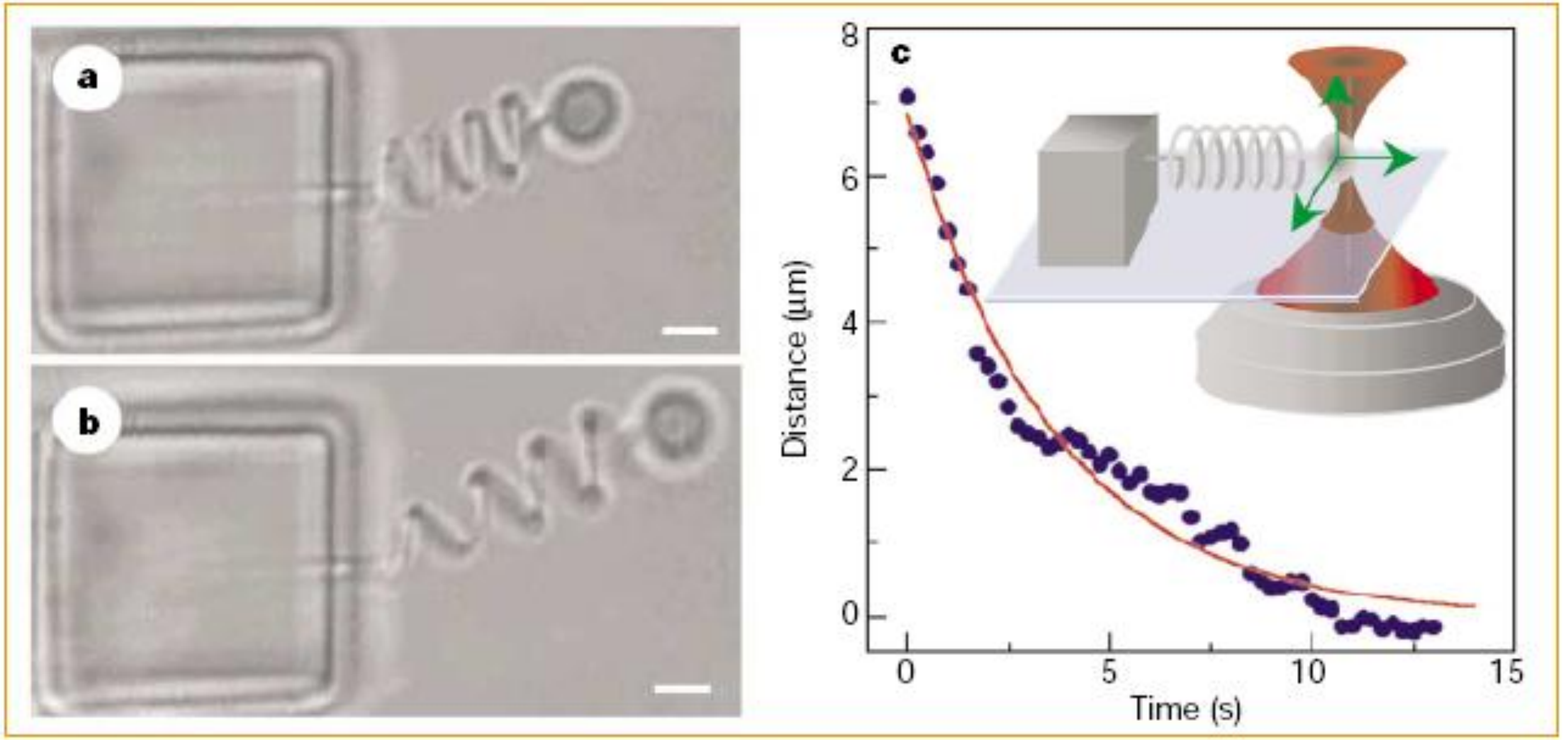

Figure 2 Functional micro-oscillator system, in which not only the spring but also the cubic anchor and the bead were produced using our two-photon absorption system. The oscillator was kept in ethanol so that the buoyancy would balance gravity and eliminate bead–substrate friction. **a, b,** The spring 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.

March 1, 2003 / Vol. 28, No. 5 / OPTICS LETTERS **301**

Femtosecond laser-induced two-photon polymerization of inorganic–organic hybrid materials for applications in photonics

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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

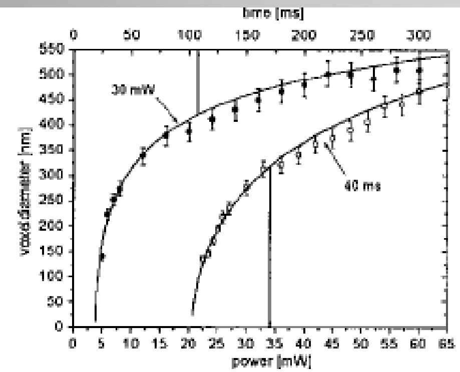


Fig. 1. Predicted and measured data for (left) the diameter and (right) the length of the polymerized volume as a function of the average laser power (for constant irradiation time $t = 40$ ms) and as a function of the irradiation time (for constant laser power $P = 30$ mW).

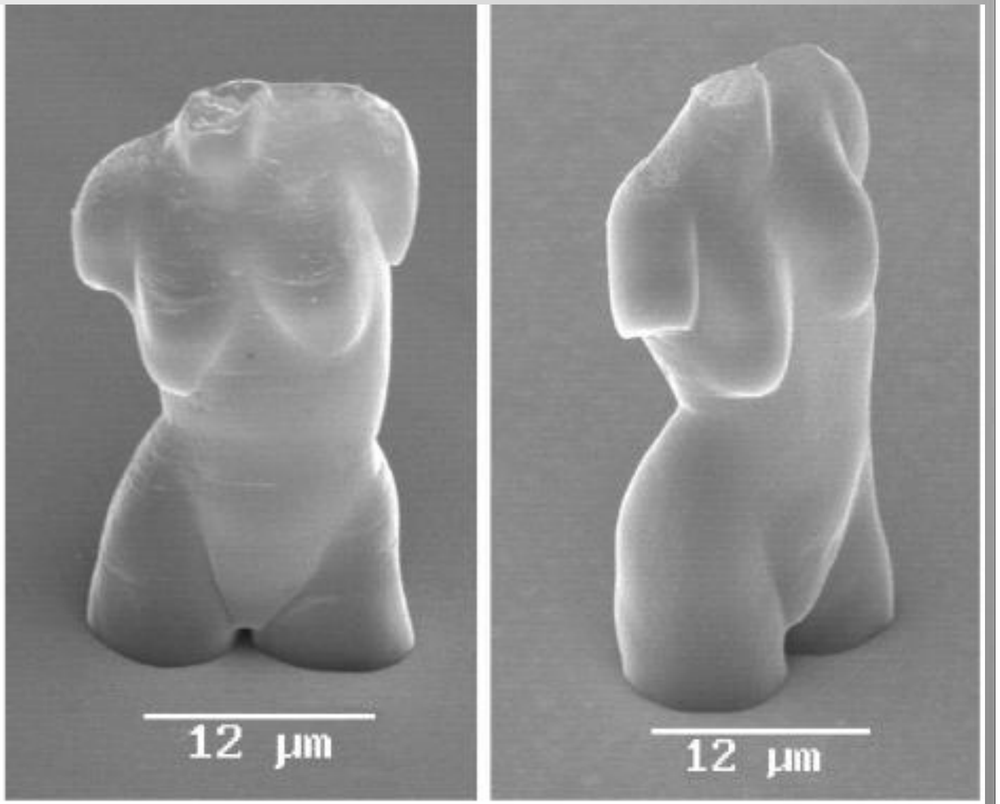
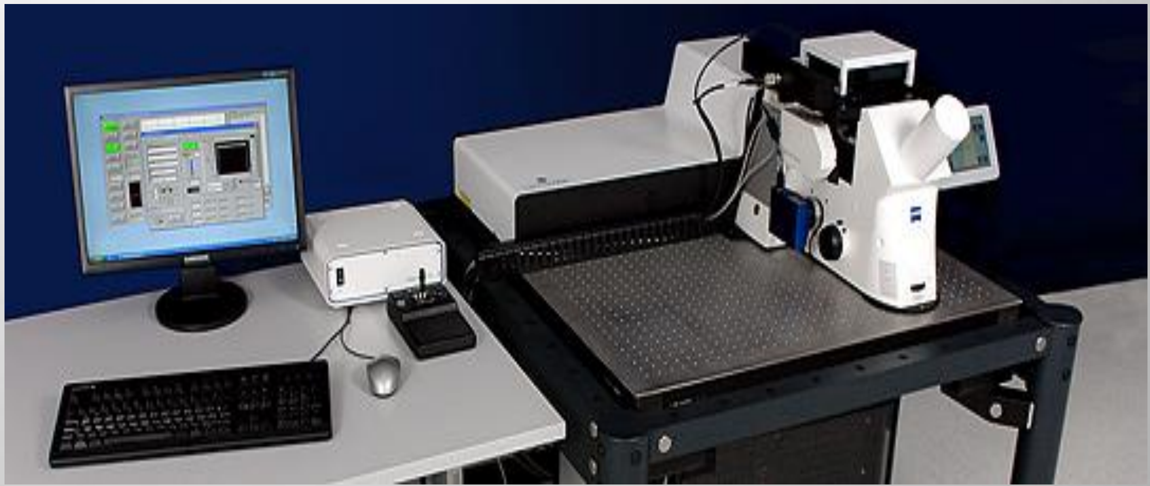
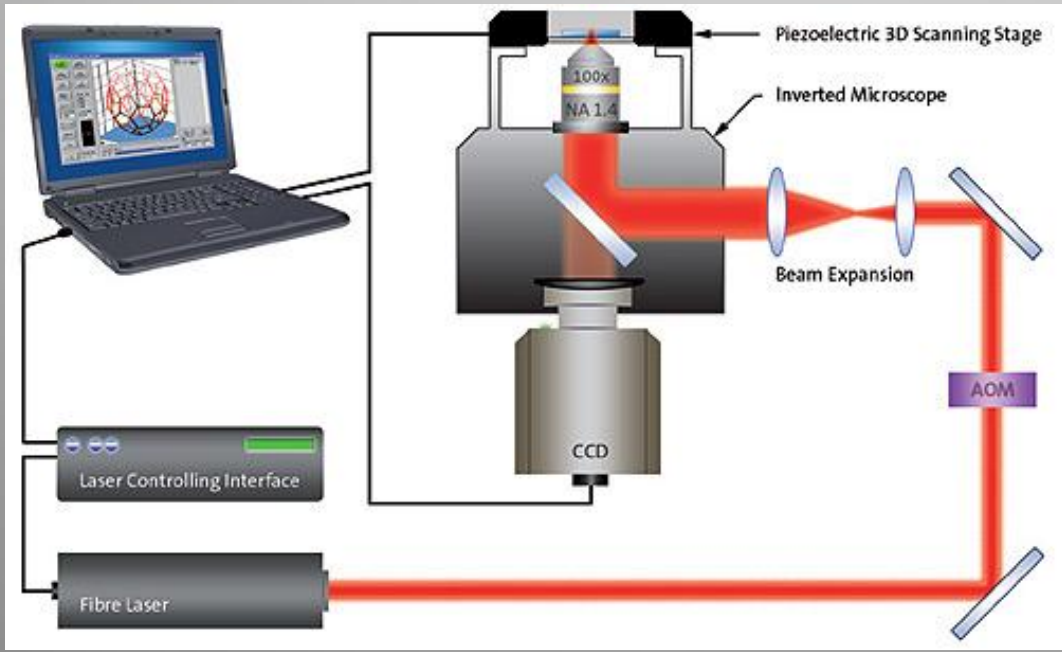


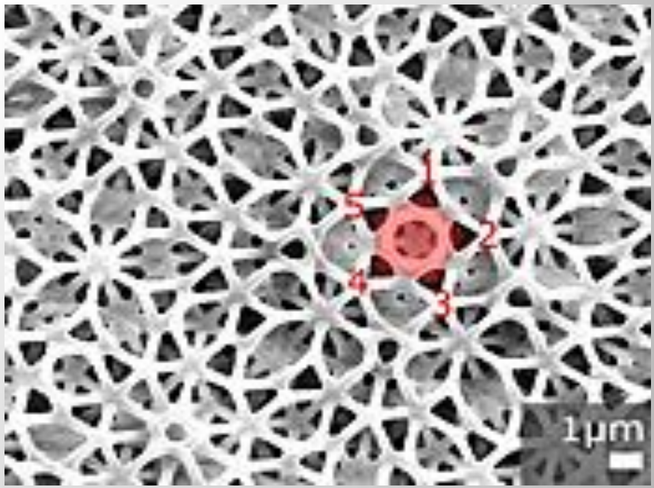
Fig. 2. SEM micrometer-scale image of Venus fabricate by 2PP. Only the shell was irradiated by femtosecon laser pulses; the inside region was cured with a UV lam after the liquid resin was washed away.

http://www.nanoscribe.de/en/technology/direct-laser-writing

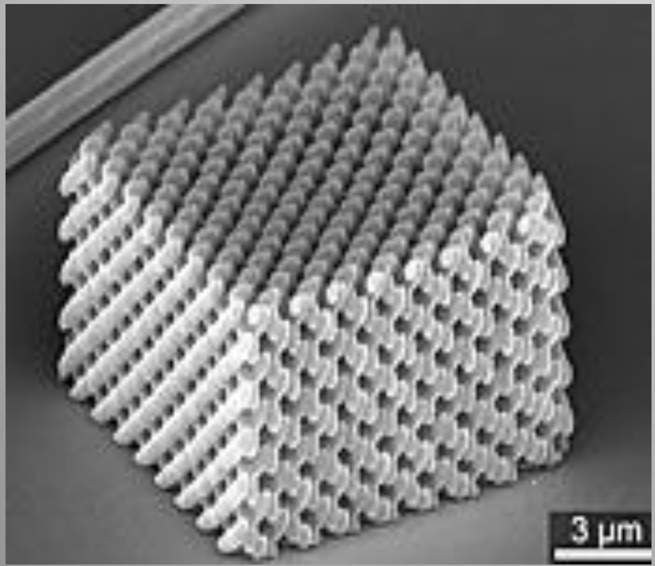




http://www.nanoscribe.de/?id=439&page=0

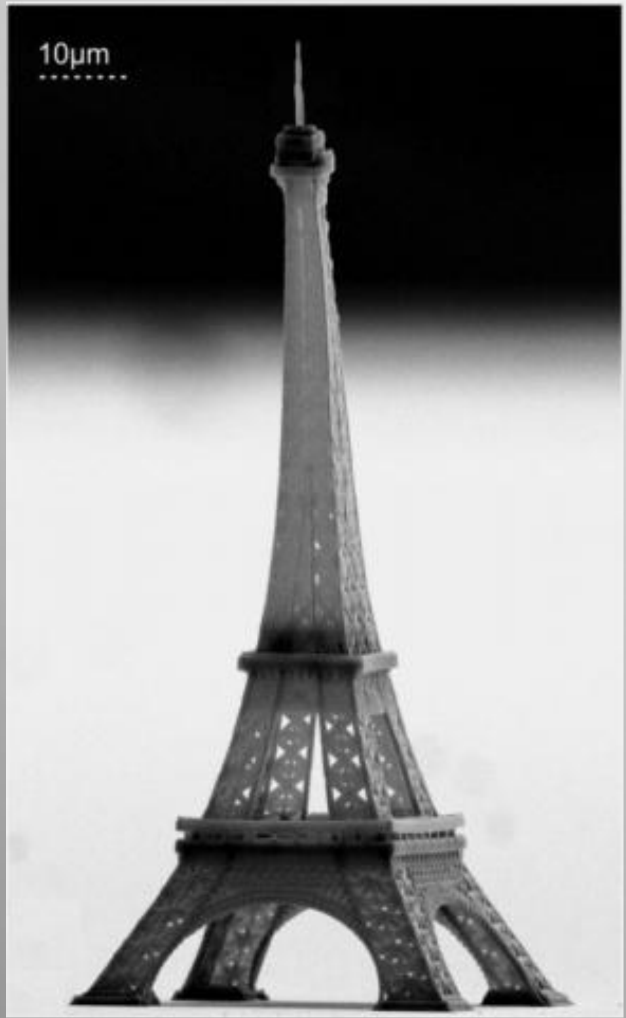


A 3D photonic quasicrystal with a five-fold rotational symmetry. The structure was written into the photoresist SU-8. Image: Dr. Alexandra Ledermann (KIT).



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.

http://www.nanoscribe.de/data/Module/galerie/451/picture/eiffelturm_IP-40%20lr.jpg



Eiffeltower with a scale of 1:3 000 000 written into Nanoscribe resin IP-40.

Direct laser writing of three-dimensional photonic-crystal templates for telecommunications
MARKUS DEUBEL1, GEORG VON FREYMANN1, MARTIN WEGENER2, SURESH PEREIRA3, KURT BUSCH3,4 AND COSTAS M. SOUKOULIS5
nature materials **I VOL 3 I JULY 2004 I** www.nature.com/naturematerials **p444**

- 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.

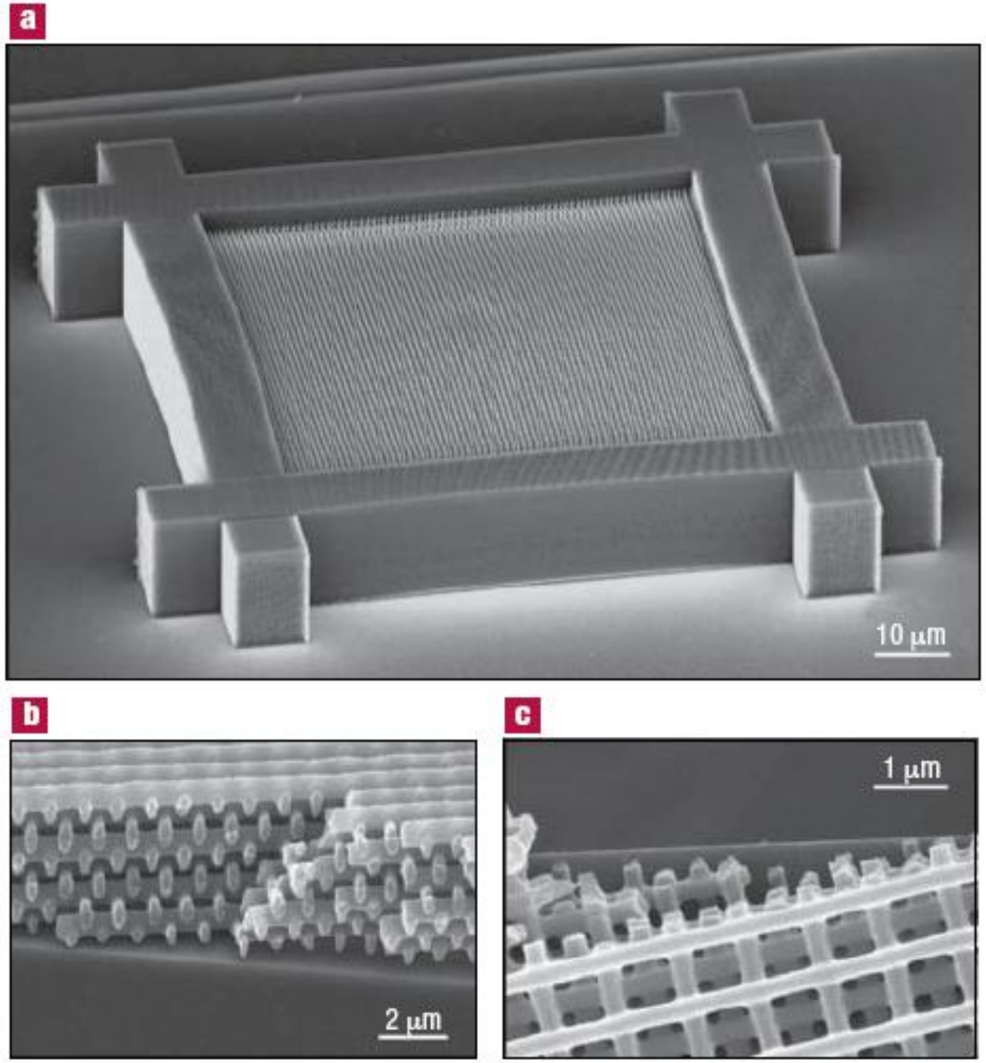


Figure 1 Three-dimensional photonic crystals fabricated by DLW. a, Layer-by-layer structure with 40 layers and a massive wall that prevents bending and reduces distortions due to polymer shrinkage during polymerization, completely fabricated by DLW. **b**, Side and **c**, top view of a different broken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

APPLIED PHYSICS LETTERS **95, 113309 2009**

Three-dimensional fabrication of optically active microstructures containing an electroluminescent polymer

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

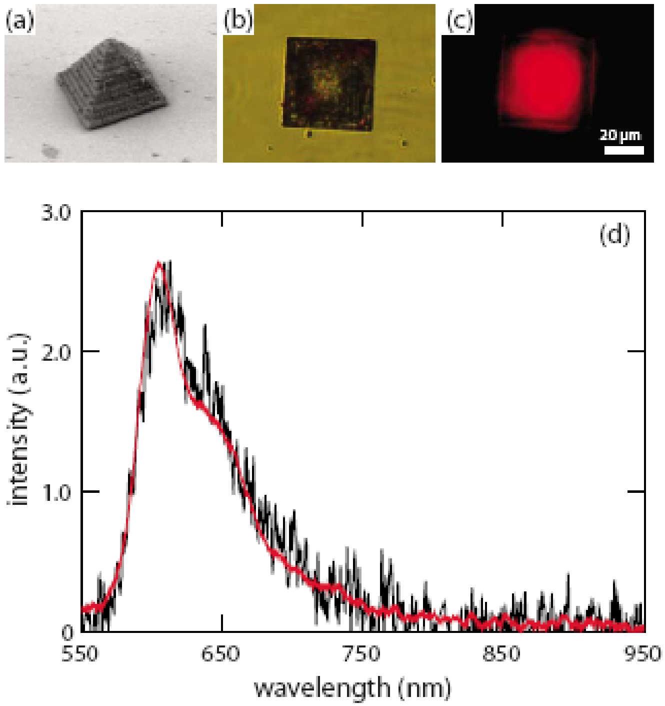


FIG. 1. (Color online) (a) Scanning electron microscopy of a py microstructure containing MEH-PPV. Fluorescence microscopy imag pyramid (top view) with laser excitation at 532 nm (b) off and (c) Emission spectrum of the microstructure (black line) and of a film same composition (red line).

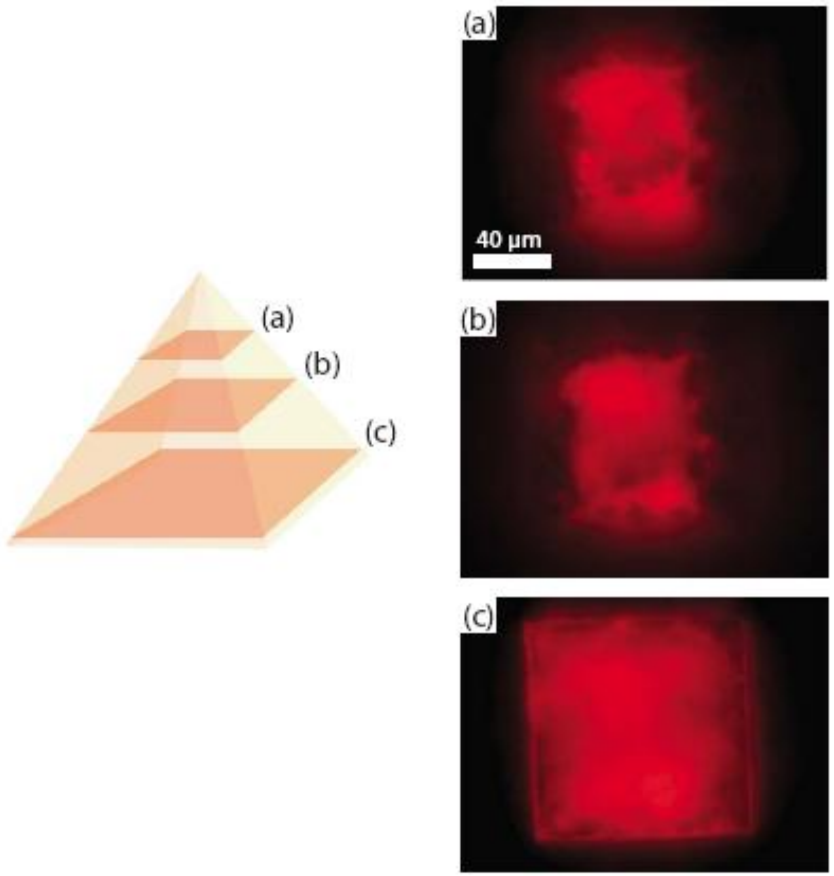


FIG. 2. (Color online) Fluorescent confocal microscopy images of planes separated by 16 μm in a pyramidal microstructure (squared base of 120 $\times 120$ μm^2).

2820 OPTICS LETTERS / Vol. 34, No. 18 / September 15, 2009

Laser direct writing of nanoreliefs in Sn nanofilms **Chuan Fei Guo,1,2 Zhuwei Zhang,1,2 Sihai Cao,1,2 and Qian Liu1,***

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.

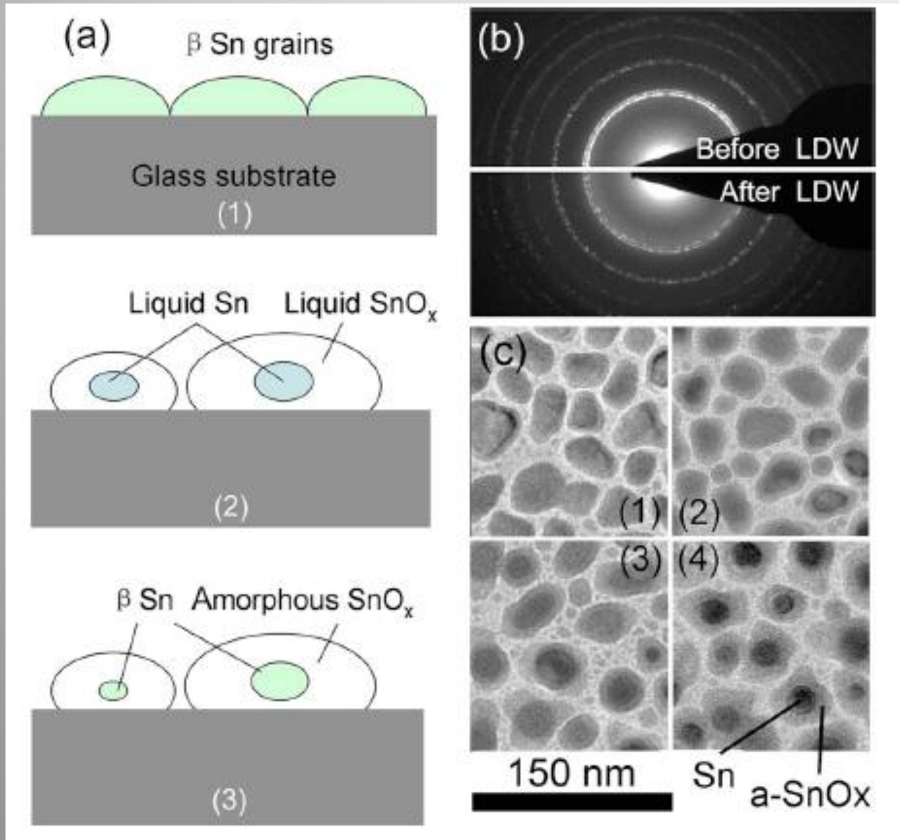


Fig. 4. (Color online) Mechanism of height change in the nanoreliefs. (a) Proposed model: (1) as-deposited Sn film with flat grains, (2) balling and coarsening of Sn grains induced by LDW, and (3) after cooling down. (b) SAED results verify the formation of Sn/a-SnO_x core/shell structure. (c) TEM image 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.

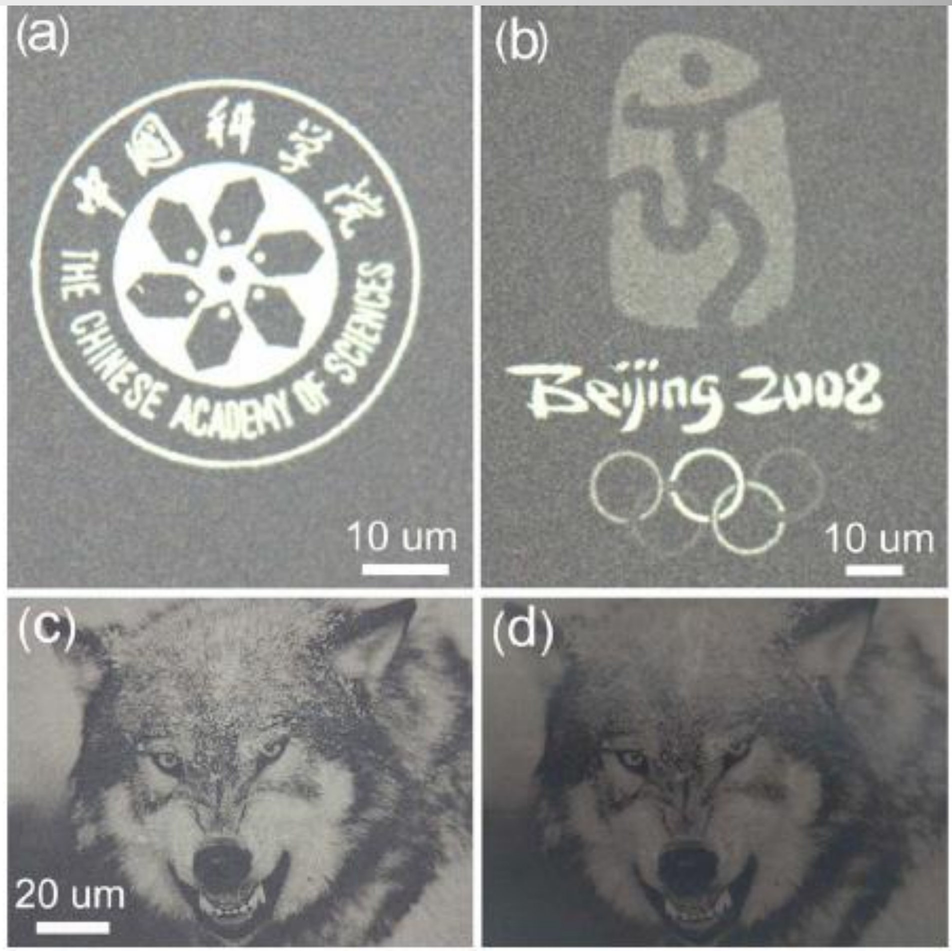
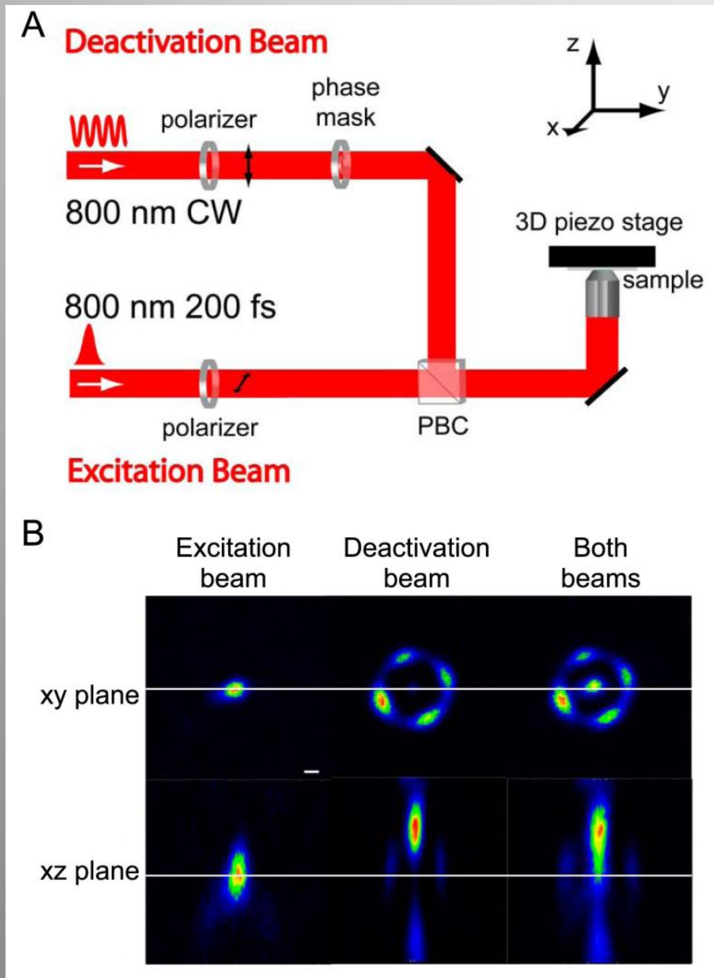
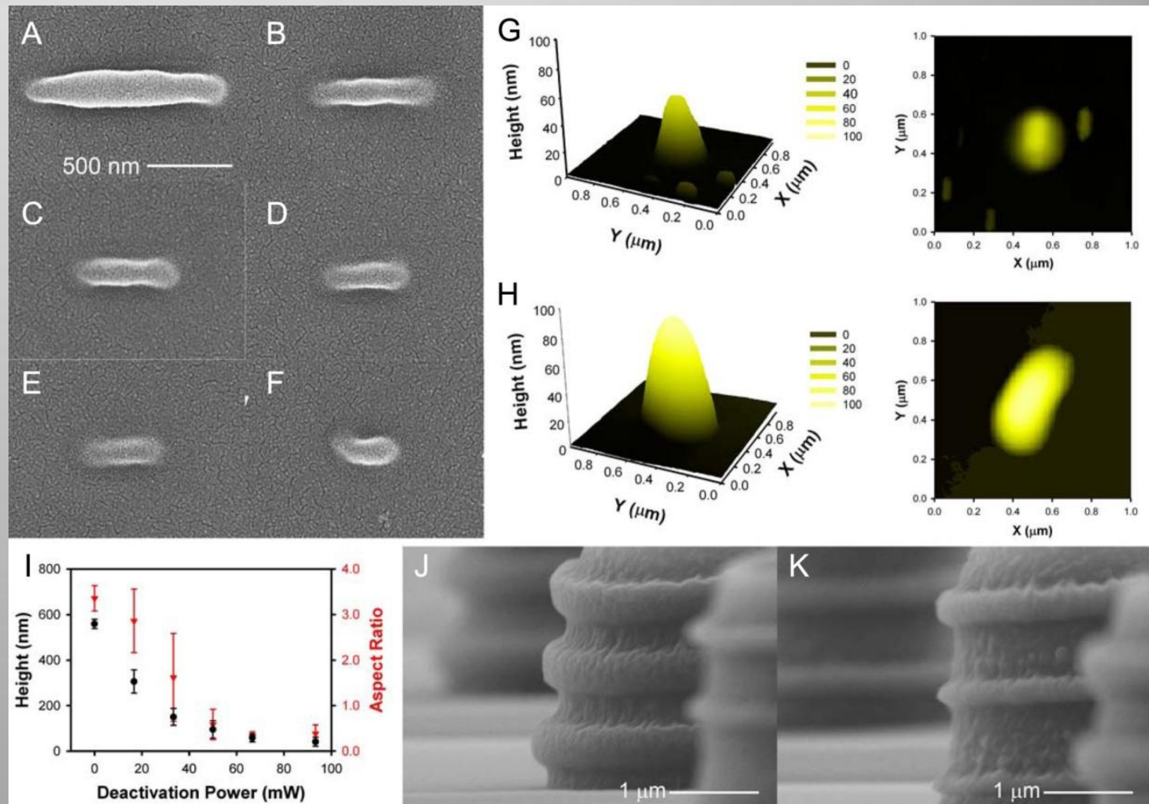


Fig. 1. (Color online) (a),(b) Optical images in Sn film created by the LDW technique; (c) and (d) are back-lit and front-lit images, where (d) is reverse processed.

Achieving λ/20 Resolution by One-Color Initiation and Deactivation of Polymerization
Linjie Li,1 Rafael R. Gattass,1 Erez Gershgoren,1 Hana Hwang,2 John T. Fourkas
www.sciencexpress.org /9 April 2009/ Page 1 / 10.1126/science.1168996

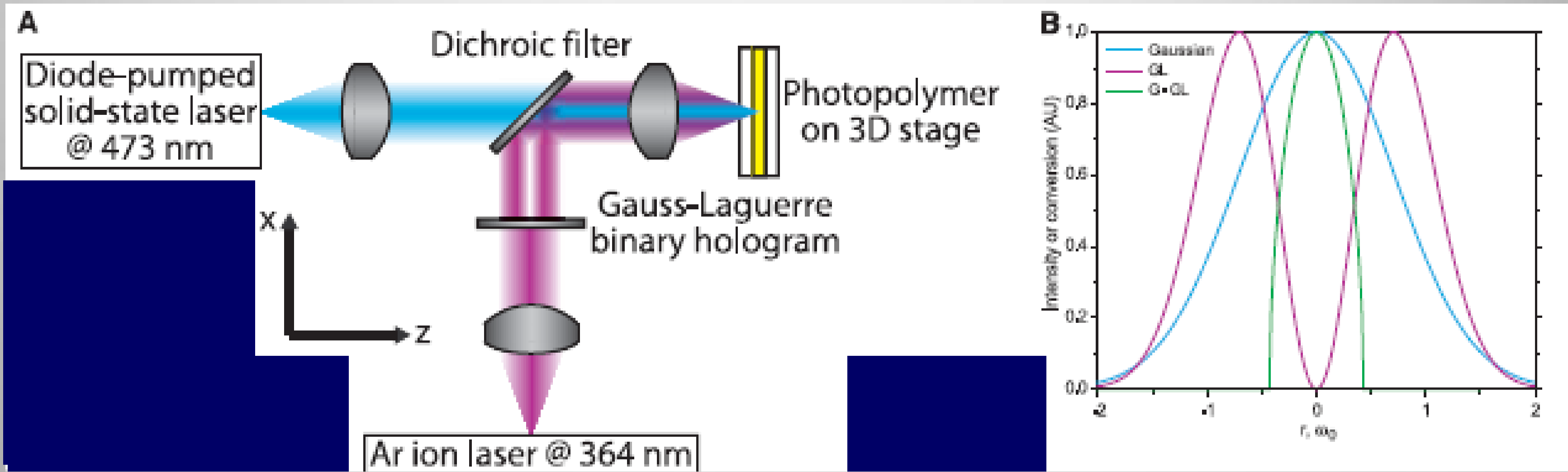
multiphoton absorption of pulsed 800-nanometer (nm) light is used to initiate crosslinking in a polymer photoresist and one-photon absorption of continuous-wave 800-nm light is used simultaneously to deactivate the photopolymerization.





Two-Color Single-Photon Photoinitiation and Photoinhibition for Subdiffraction Photolithography
Timothy F. Scott,1* Benjamin A. Kowalski,2 Amy C. Sullivan,2† Christopher N. Bowman,1 Robert R. McLeod
SCIENCE VOL 324 15 MAY 2009 917

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



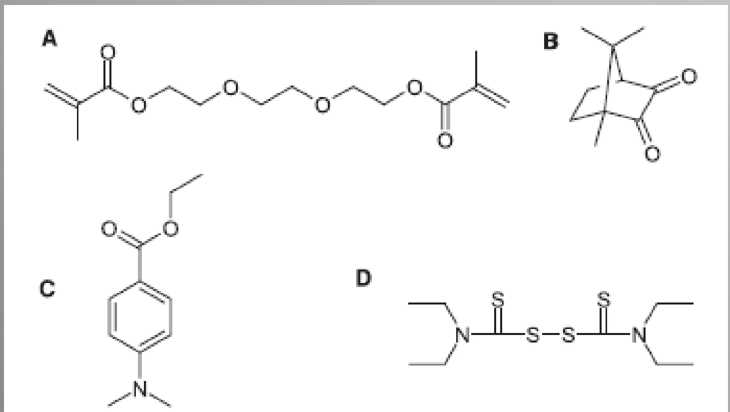
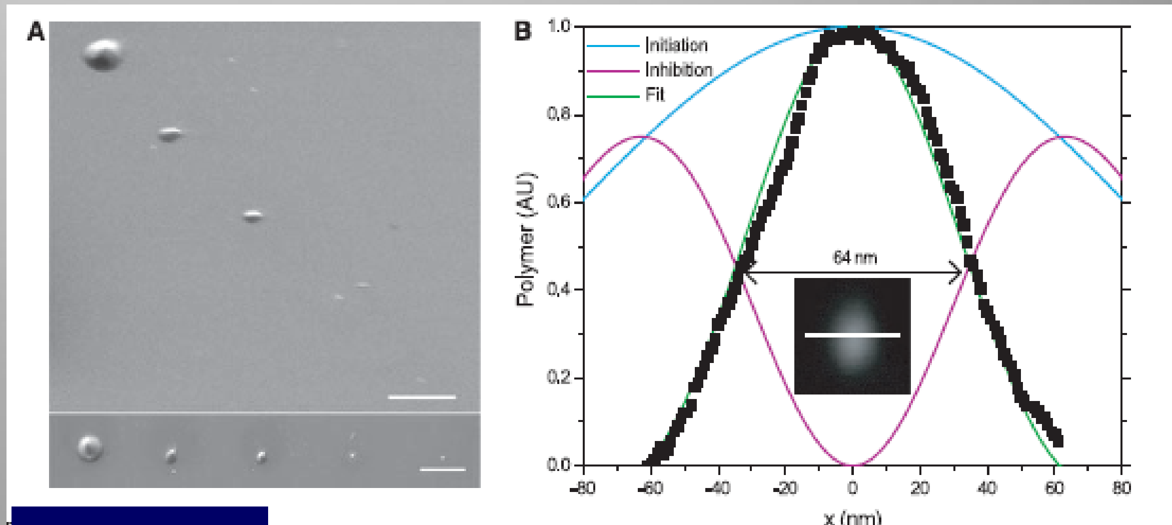


Fig. 2. Monomer, photoinitiator, co-initiator, and photoinhibitor used. (A) TEGDMA. (B) CQ. (C) EDAB. (D) TED. (E) UV-visible absorption spectra of CQ and TED in $CHCl_3$, demonstrating the complementary absorption spectra of the photoinitiator and the photoinhibitor, respectively.

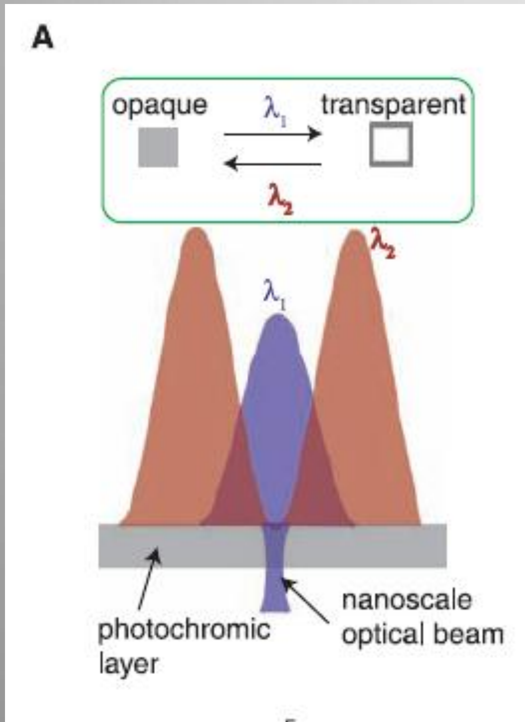


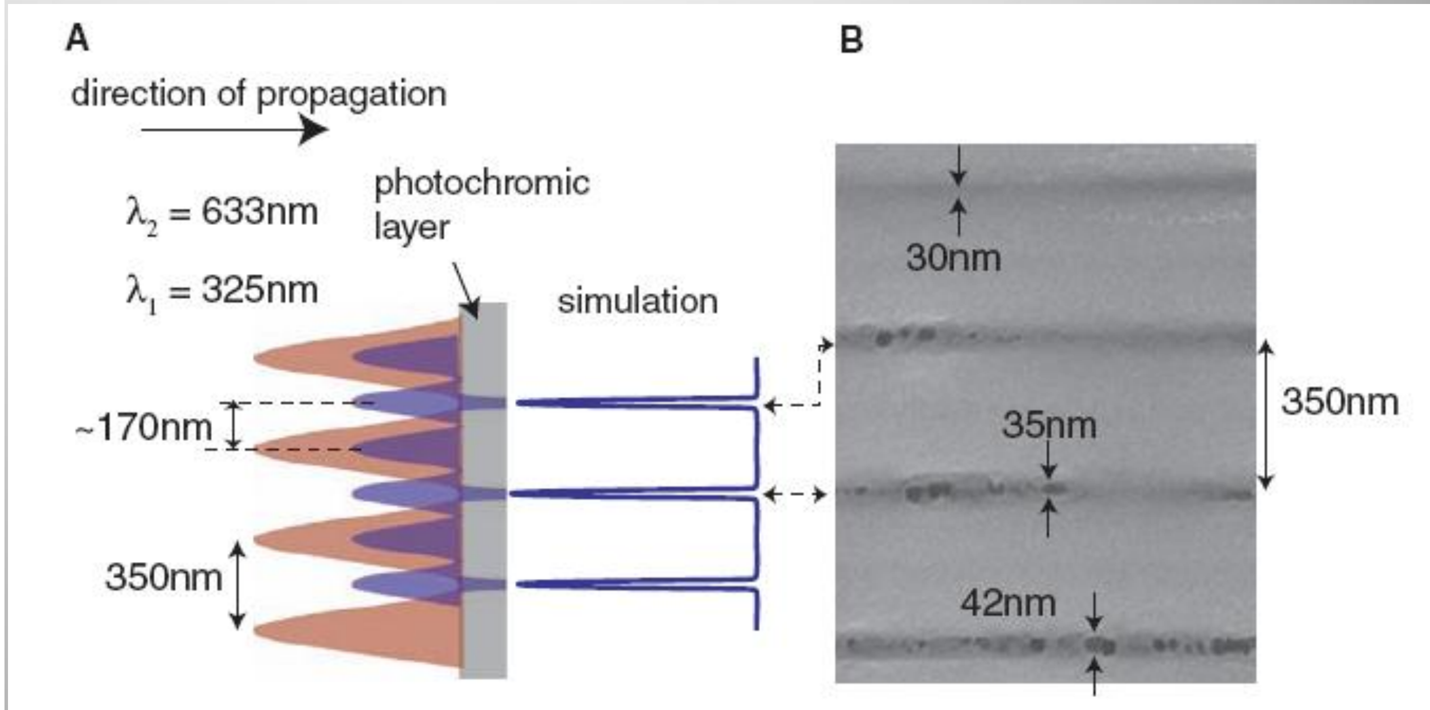
SCIENCE VOL 324 15 MAY 2009 917

Confining Light to Deep Subwavelength Dimensions to Enable Optical Nanopatterning

Trisha L. Andrew,1 Hsin-Yu Tsai,2,3 Rajesh Menon3,4*

Lines with an average width of 36 nanometers (nm), about one-tenth the illuminating wavelength l1 = 325 nm, made by applying a film of thermally stable photochromic molecules above the photoresist. Simultaneous irradiation of a second wavelength, l2 = 633 nm, renders the film opaque to the writing beam except at nodal sites, which let through a spatially constrained segment of incident l1 light, allowing subdiffractional patterning.





TIME FOR A BREAK

Holography