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Colorado State University

PhD Preliminary Exam

EUV Technology and Applications

Przemyslaw Wachulak

Thesis advisor:
Prof. M. C. Marconi

Committee Members:
Prof. C. S. Menoni
Prof. B. Parkinson
Prof. S. C. Reising

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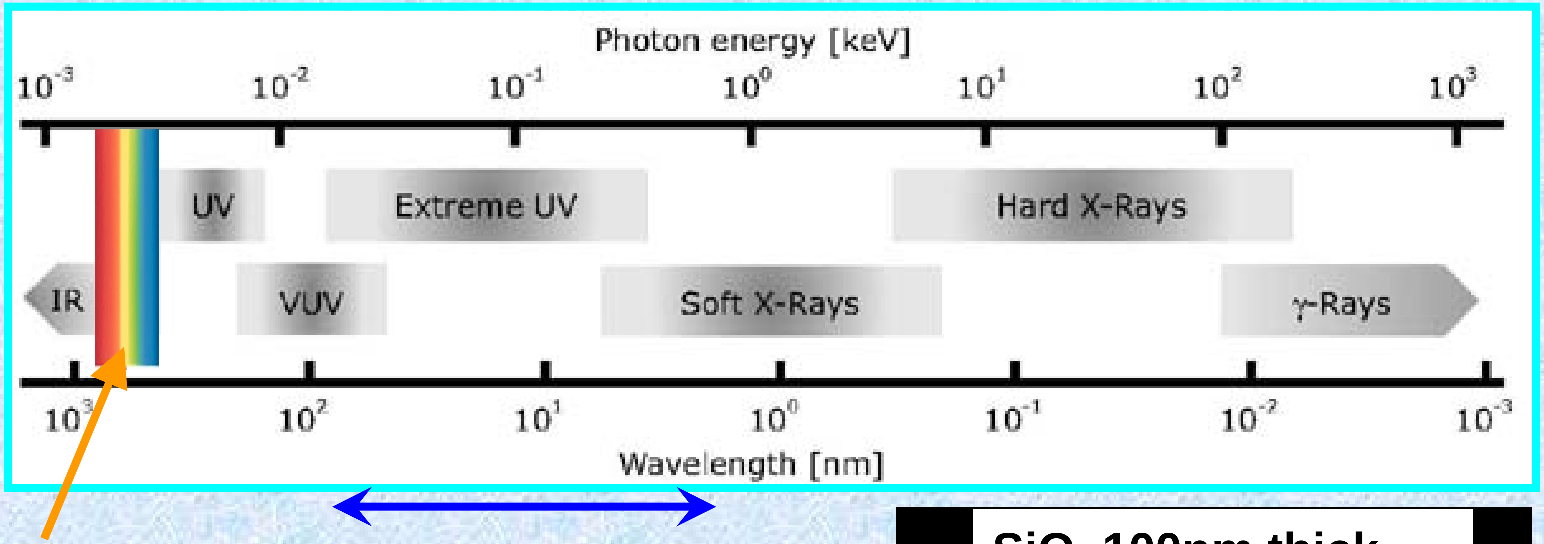
Outline

EUV Technology and applications

- *Motivations*
  - *EUV region of EM spectrum and EUV sources*
  - *EUV applications*
  - *Source: 46.9 nm discharge pumped table top laser*
- *Nanopatterning using Interference Lithography*
  - *Previous work*
  - *Compact tool*
  - *Printing different motifs*
  - *Photo-resists: PMMA and HSQ*
- *Table top extreme ultraviolet holography*
  - *Previous work*
  - *Setup description*
  - *Results*
  - *Resolution estimation*
  - *Parameters limiting the resolution*
- *Future work*
- *Summary and conclusions*

Motivations

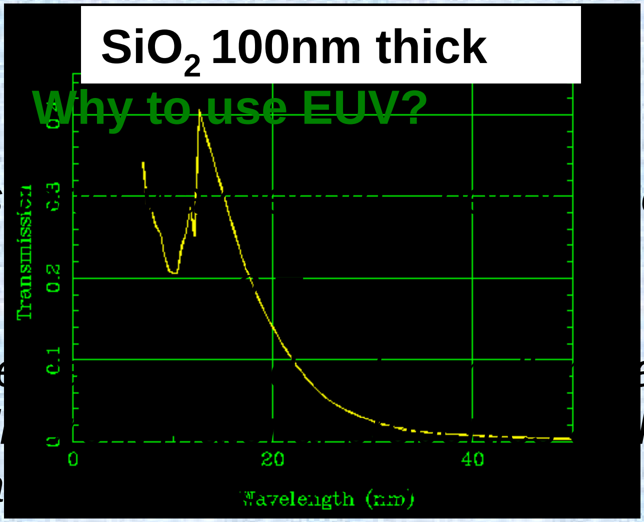
Electromagnetic Spectrum



Well known region

Still unexplored

- *wavelenght coincides with atomic and molecular resonance frequencies –* ***very high absorption,*** *almost everything is opaque*
- *difficult to find appropriate optics to change the beam properties*
- *lack of accessible coherent sources*



Why to use EUV?

- *s* *olution*

We *atures*

- *d* *hat*

wa

EUV Sources

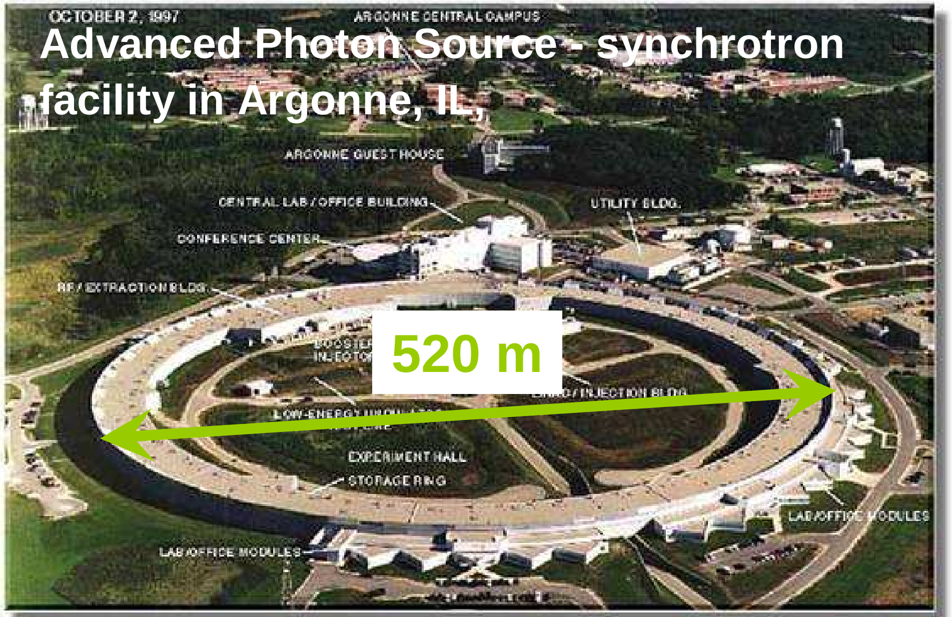
Synchrotrons:

Advantages:

- *tunable wavelength of the beam*
- *high flux*

Disadvantages:

- *pretty big facilities,*
- *not easily accessable*
- *low coherence, if not filtered*
- *multi-milion $ facility*



Advanced Photon Source - synchrotron facility in Argonne, IL,

EUV Plasma Sources:

Advantages:

- *small, easy to move,*
- *high power,*
- *cheaper than synchrotrons*
- *one can buy one –*

- accessable

Disadvantages:

- *not monochromatic,*
- *emission in large solid angle – impossible to collect all light*
- ***not coherent***

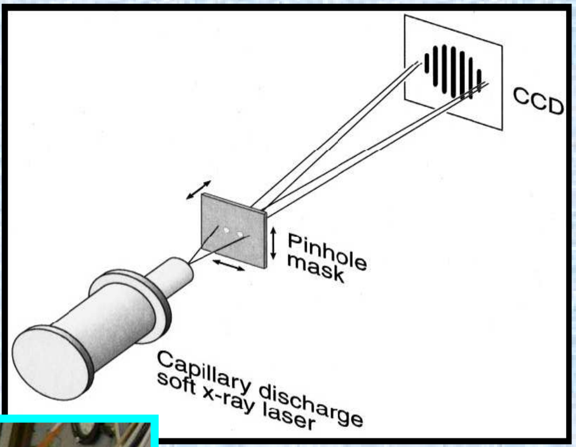
Energetiq plasma source

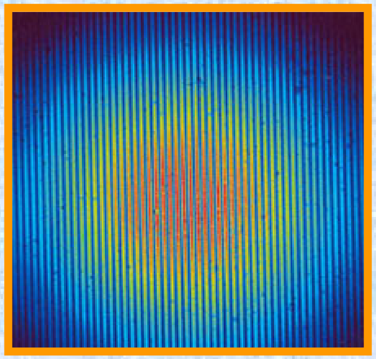
EUV Sources…

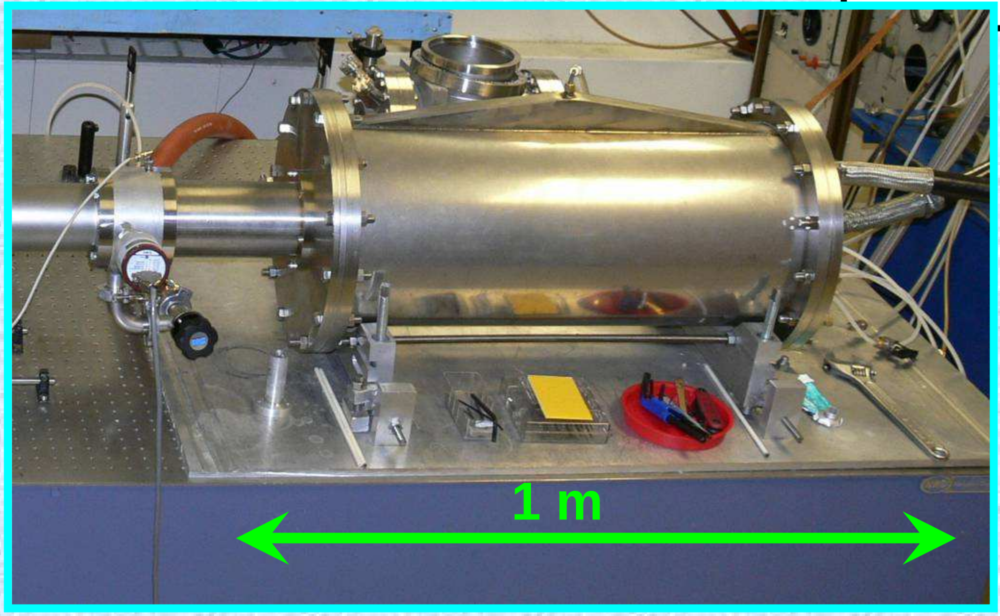
Discharge pumped EUV lasers:

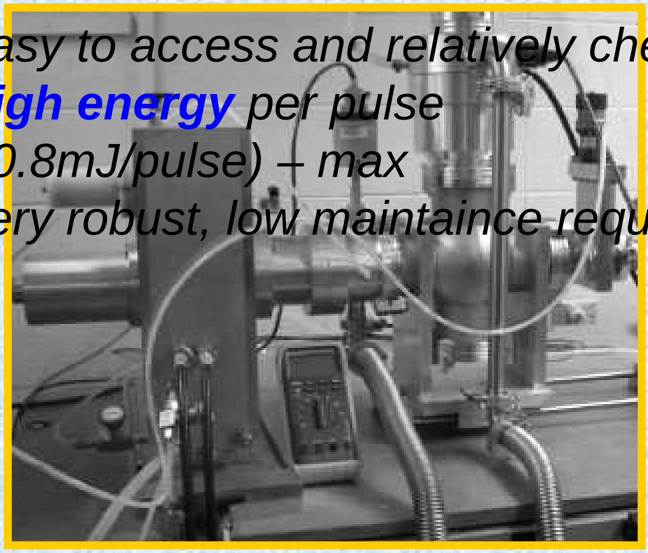
Advantages:

- *lasers – so are* ***highly coherent*** *(spatial and temporal) – good or specific applications*
- ***small*** *– table-top or even desk-top*







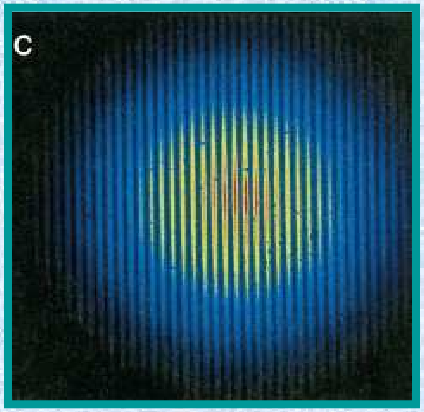


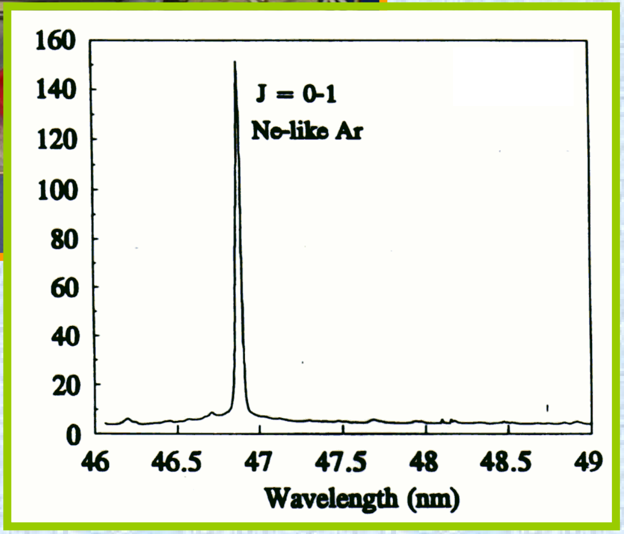
- *easy to access and relatively cheap*
- ***high energy*** *per pulse (~0.8mJ/pulse) – max*
- *very robust, low maintaince required,*

>>> Very useful for my applications <<<

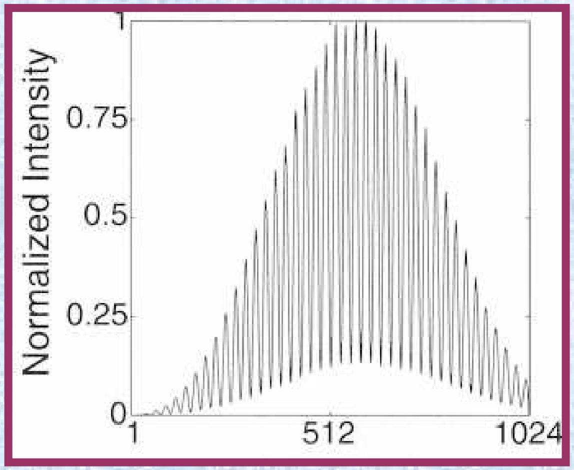
Capillary discharge laser – 46.9 nm

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





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



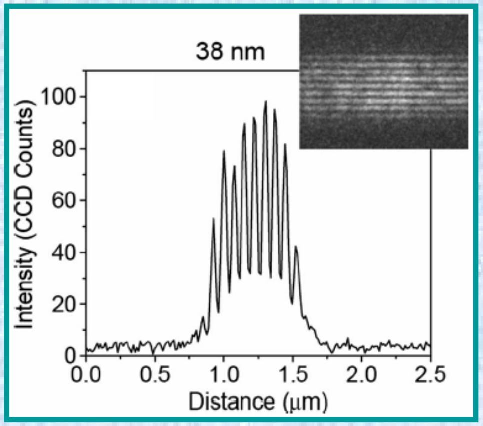
Y. Liu, et al. Phys. Rev. A, **63**, 033802 (2001).

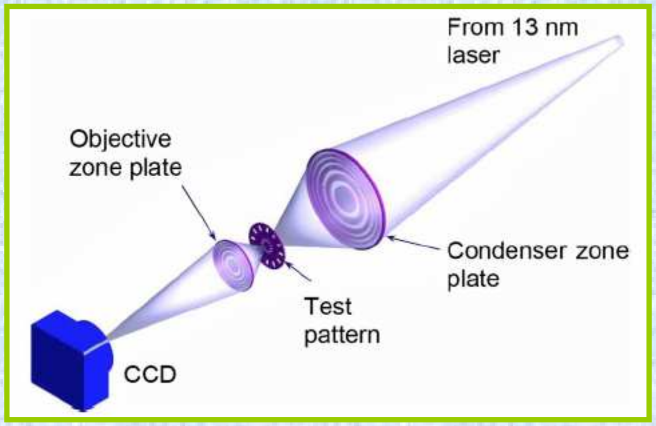
- *Repetition rate: 4 Hz*
- ***High energy per pulse max - 0.8 mJ***
- ***Average power ~ 3 mW***
- ***High monochromacity: $\Delta\lambda/\lambda=1\times10^{-4}$***
- ***Coherence radius: R_c = 550 μm***
  at 0.157m from 36cm capillary
- ***Very compact***

Some applications of EUV light

- **EUV Microscopy**

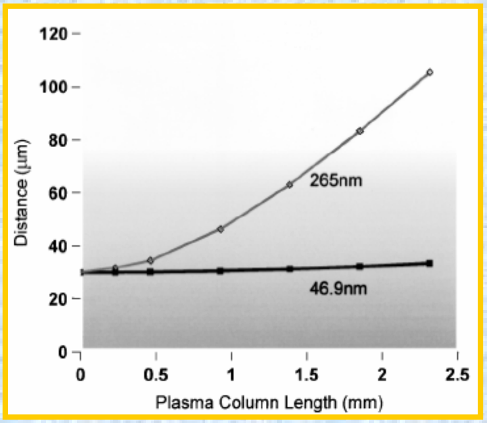
***38nm** resolution with 13.2nm Cd laser, ~70% modulation*

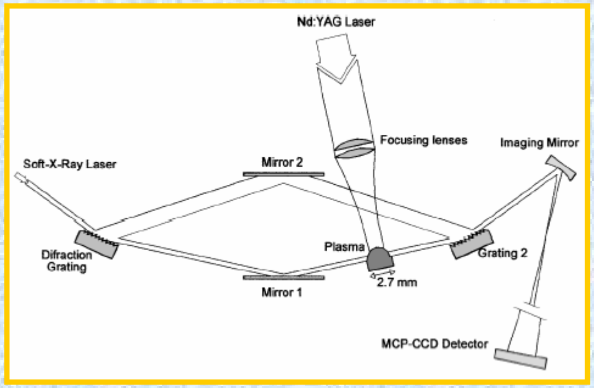


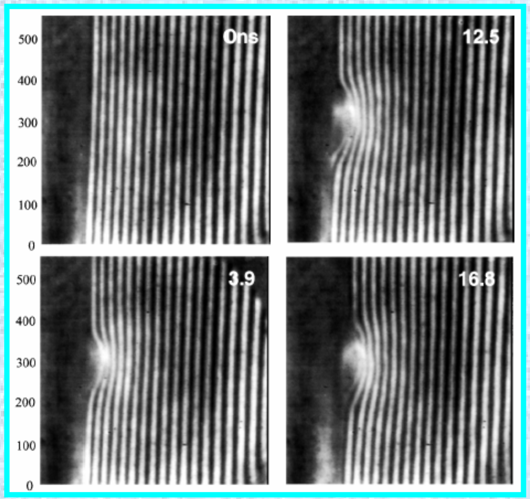


"Sub-38 nm resolution tabletop microscopy with 13 nm wavelength laser light" Vaschenko at. al., OPTICS LETTERS / Vol. 31, No. 9 / May 1, 2006

- **EUV Interferometry of dense plasmas**







"Dense plasma diagnostics with an amplitude-division soft-x-ray laser interferometer based on diffraction gratings", J. Filevich, et. al., OPTICS LETTERS / Vol. 25, No. 5 / March 1, 2000

Time resolved studies of dense plasmas

- *And many more…*

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Nanopatterning using Interference Lithography

Previous Work in Interferometric Lithography include:

Ar, F_2 and ArF lasers. Multiple exposures, immersion lithography:

1. *Savas et al. J. Vac. Sci. Technol. B 14 (6), Nov/Dec 1996*
2. *S.A. Zaidi and S.R.J. Brueck, J. Vac. Sci. Technol. B 11 (3), May/Jun 1993*
3. *M. Switkes et al. Appl. Phys. Lett, 77, (20), 3149, Nov 2000*
4. *B.W. Smith et al. J. Microlith, Microfab, Microsys. 3, 44, Jan 2001*
5. *W. Hinsberg et al. J. Vac. Sci. Technol. B, 16 (6), Nov/Dec 1998*
6. *Fernandez A et al. J. Vac. Sci. Technol. B, 15 (6), Nov/Dec 1997*

Synchrotron radiation:

1. *Solak et al. J. Vac. Sci. Technol. B, 17 (6), Nov/Dec 1999*
2. *Solak et al. Appl. Phys. Lett., 75 (15), 2328, Oct 1999*
3. *V.N. Golovkina et al. J. Vac. Sci. Technol. B, 22 (1), Jan/Feb 2004.*
4. *Solak, Microelectronic Engineering, 78-79, 2005, pp. 410-416,*

And many, many more…..

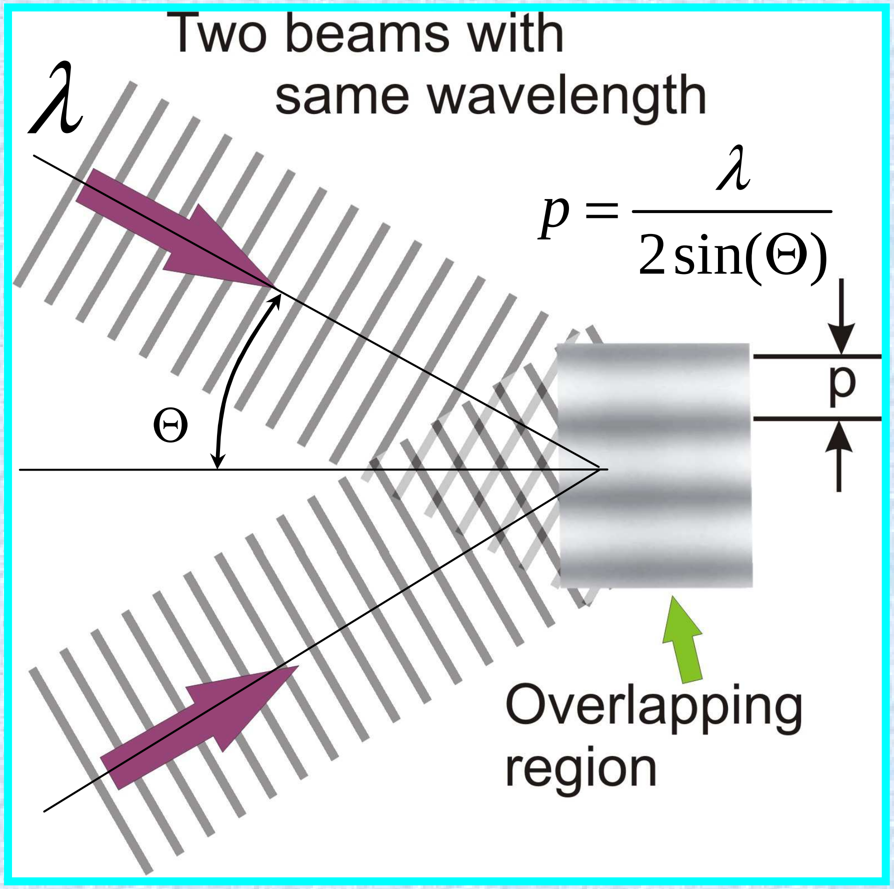
Interferometric Lithography
Periodic features

Interference creates an intensity modulation in the region of the overlapping of two or more coherent beams.

Advantages:
- *period limited mainly by λ*
- *parallel imprint process*
- *possible to write really small features*
- *simple scheme*

Requirements:
- *high spatial and temporal coherence of the source*

Applications:
- *characterization of photoresist*
- *production of nanochannel devices*
- *potential for fabrication of nanomagnetic structures*



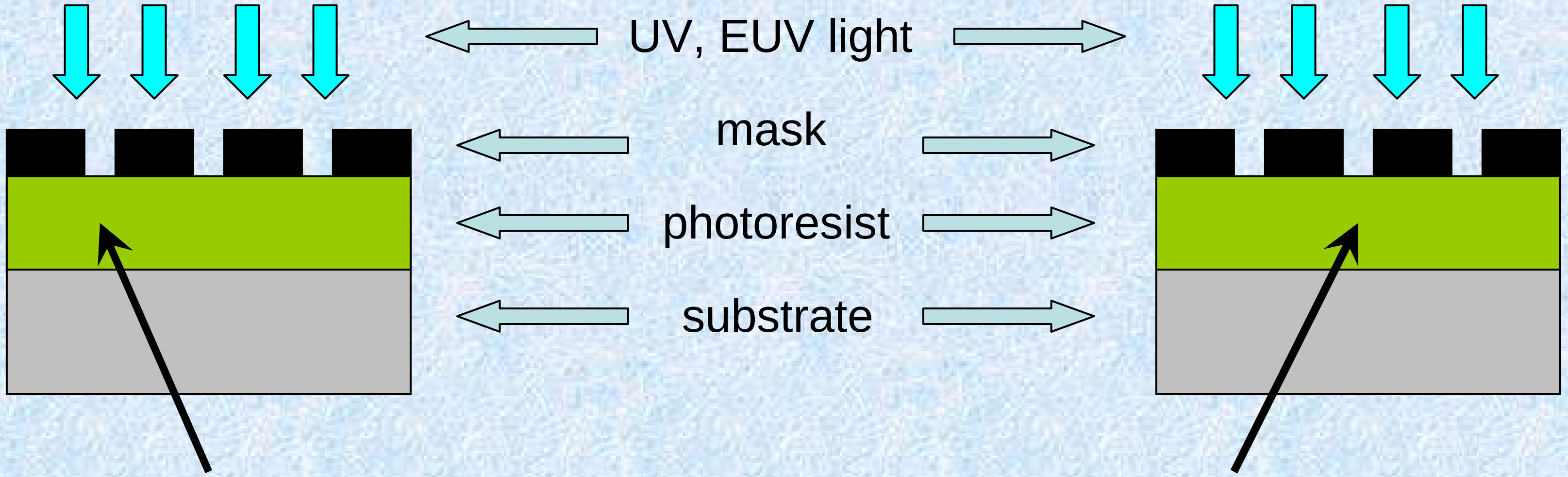
$$p = \frac{\lambda}{2\sin(\Theta)}$$

The Photoresist

Photoresist is a light-sensitive polymer used to form a patterned coating on a surface.

Positive

Negative



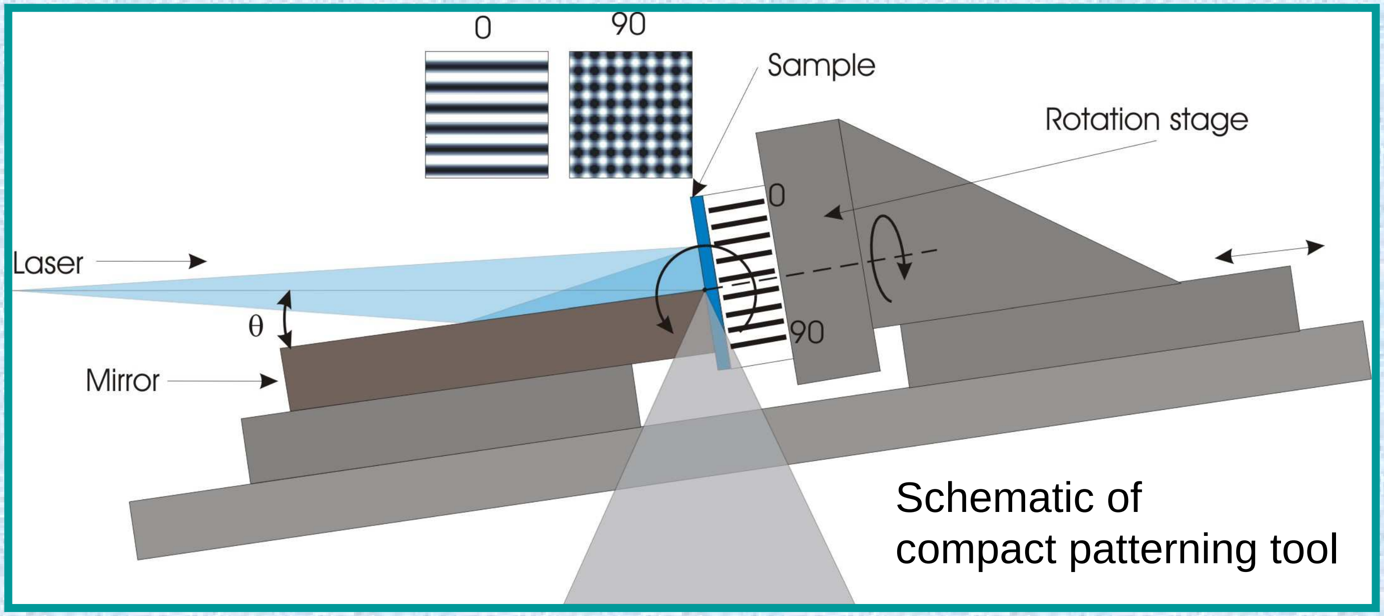
Exposed portion of the photoresist is soluable to the developer

Exposed portion of the photoresist remains after developing

PMMA - Polymethyl methacrylate

HSQ - hydrogen silsesquioxane

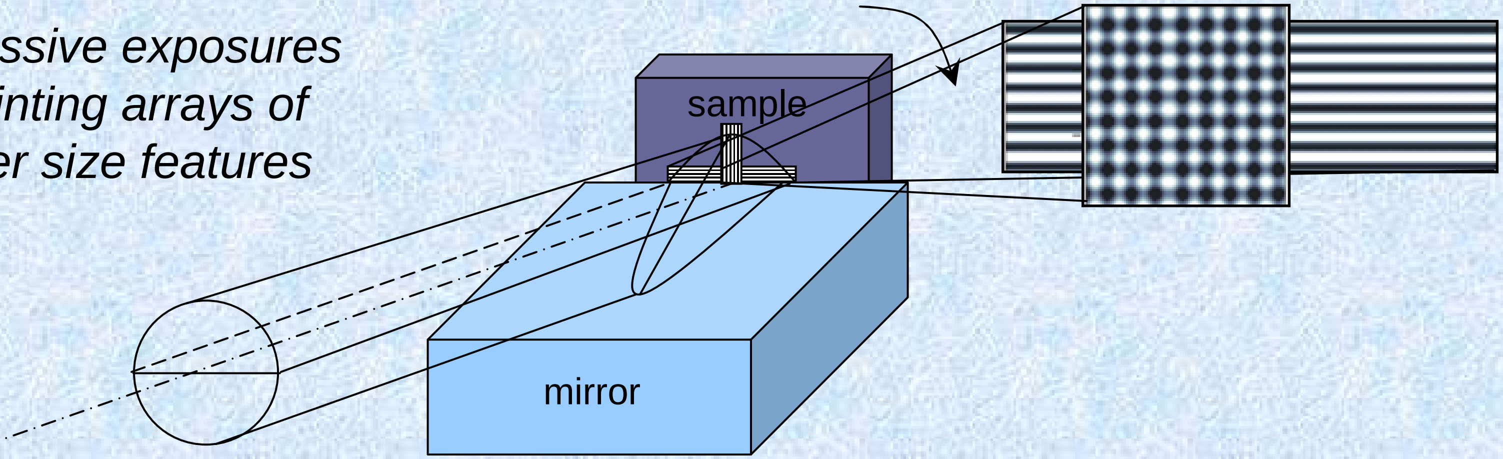
Table top Nanopatterning – Compact tool



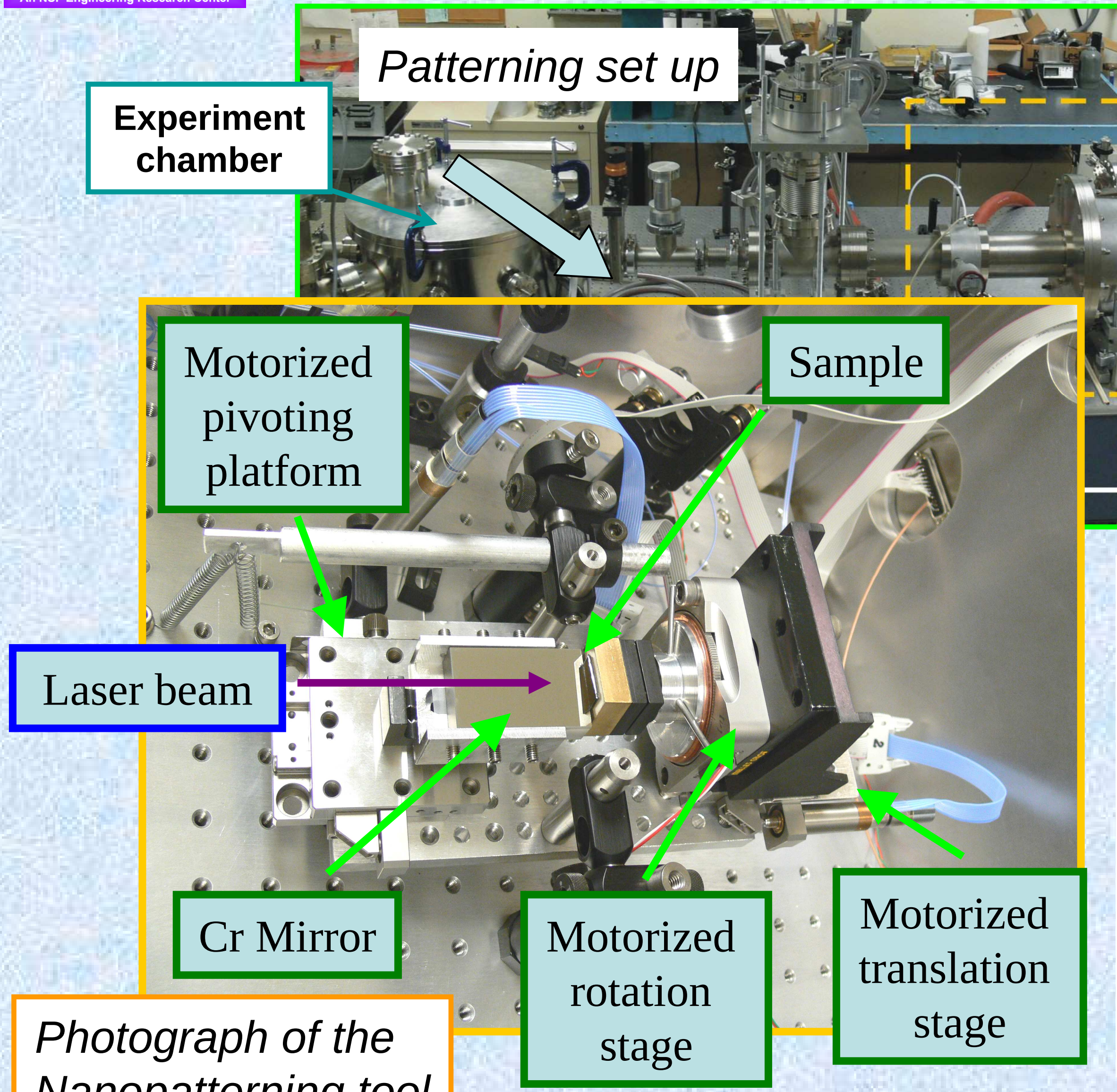
Schematic of
compact patterning tool

Double exposure set up with a Lloyd's mirror

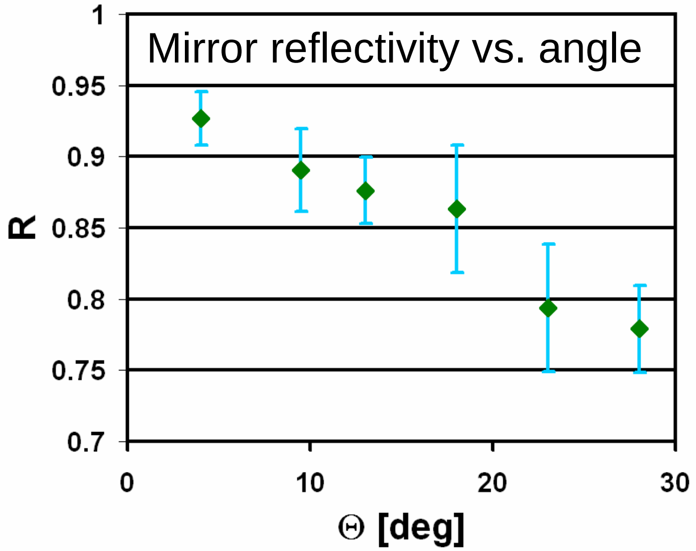
Two successive exposures allows printing arrays of nanometer size features



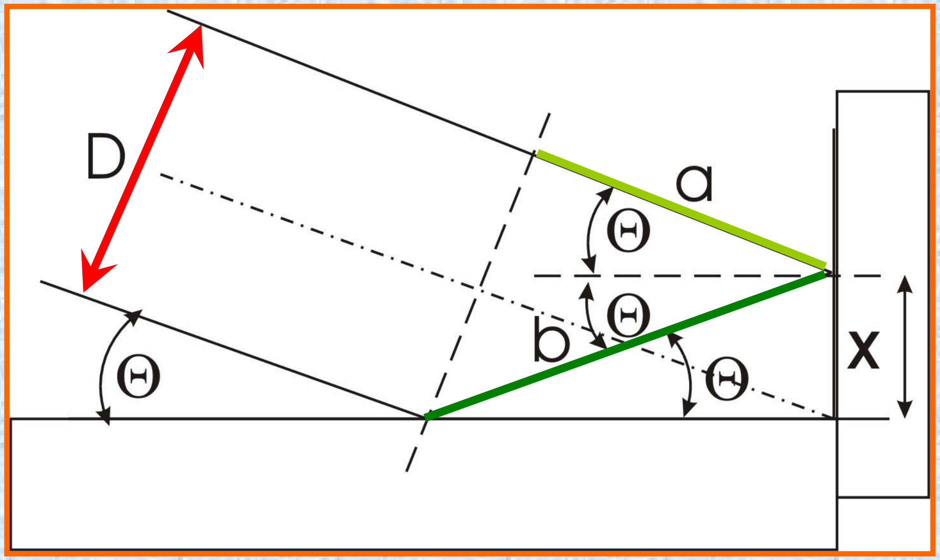
Nanopatterning tool



Photograph of the Nanopatterning tool



Coherence limitations to the printing area



- Spatial coherence:

Requirement: $D \leq 2R_c$

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

- Temporal coherence:

Requirement: $b - a \leq l_c$

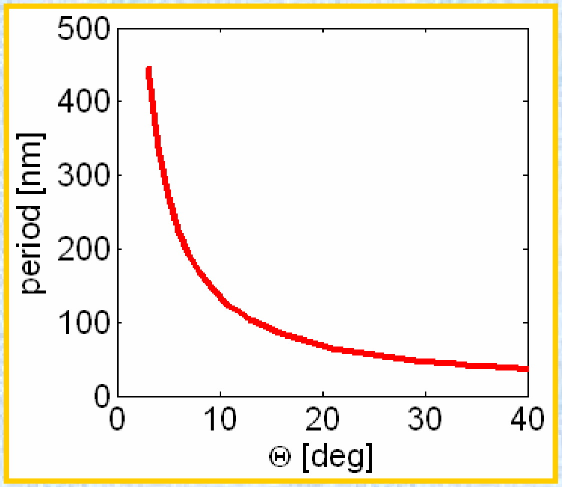
$$\boxed{x = \frac{l_c}{2\sin(\Theta)}}$$

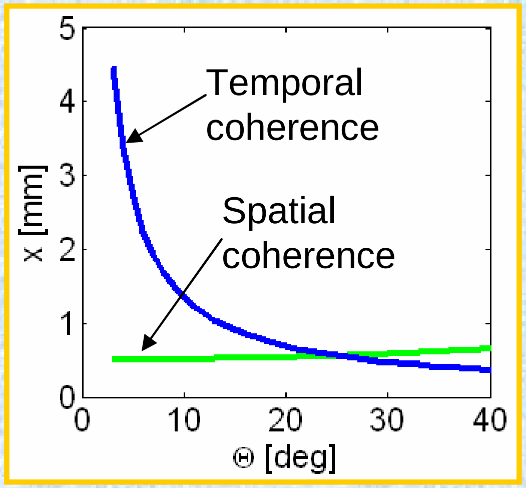
Radius of coherence:

$R_c \sim 0.5mm$

Coherence length:

$$l_c = \frac{\lambda^2}{\Delta\lambda} = 469\mu m$$





Lloyd's Mirror Nanopatterning Results - PMMA

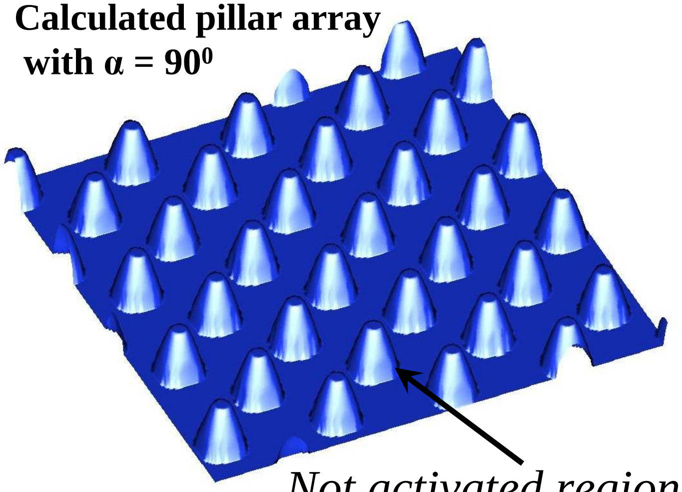
This approach allows to pattern areas typically ***500x500μm^2****.*

The pattern shape can be controlled by:

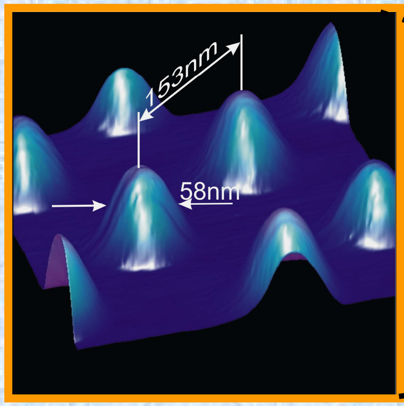
1. ***Changing the exposure dose*** *– pillars or holes*
2. ***Changing the angle between exposures (α)*** *– changes the geometry of the pattern*
3. ***Changing the interferometer angle (θ)*** *– changes the period in each exposure*

Different motifs – pillars or holes

Calculated pillar array with $\alpha = 90^0$

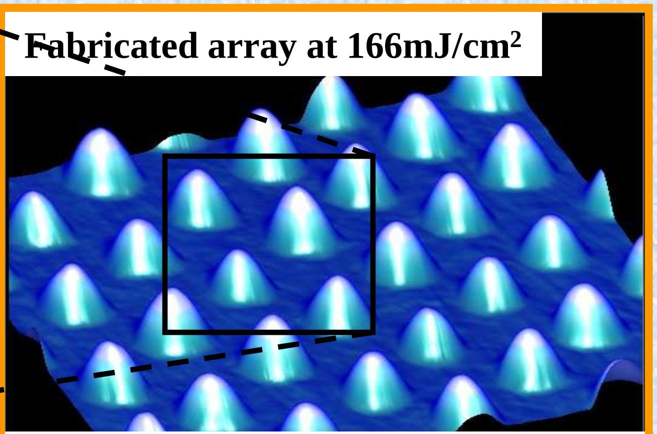


Not activated region



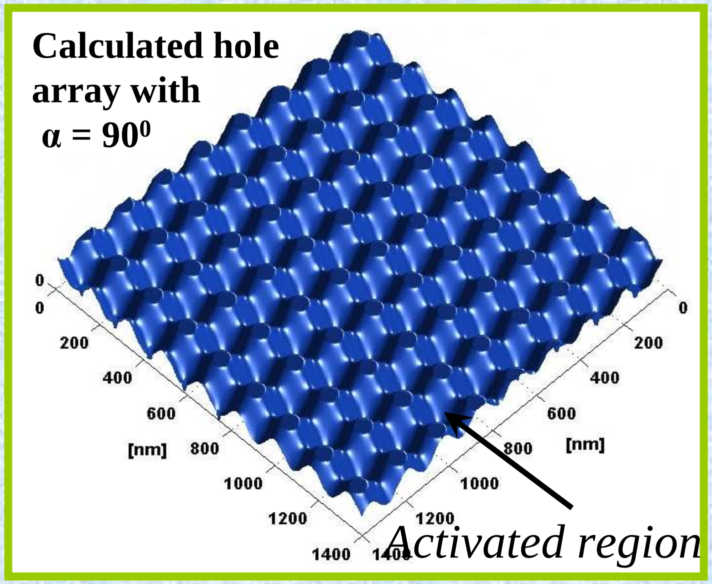
*Pillars with FWHM down to **58 nm (1.2λ)** were obtained with period **153nm** at high dose*

Fabricated array at 166mJ/cm^2

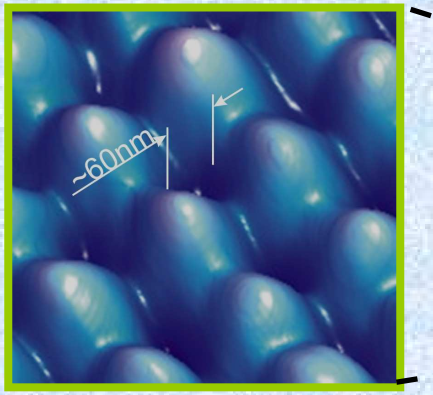


Feature size was close to the wavelength limit λ = 46.9nm

Calculated hole array with $\alpha = 90^0$

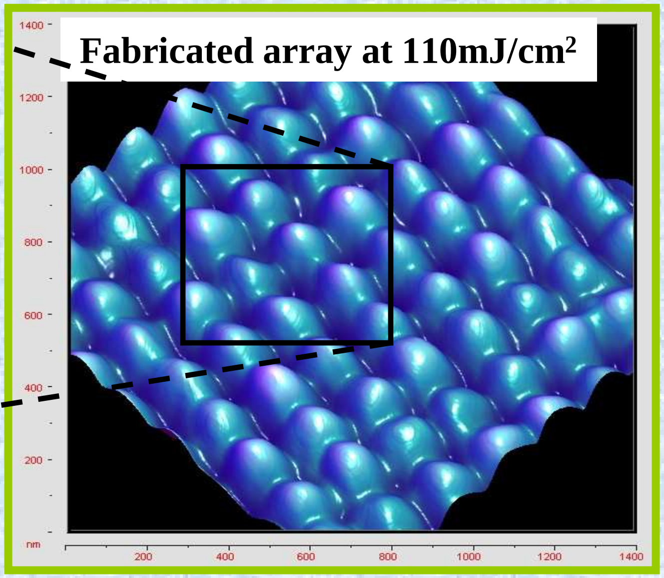


Activated region



*Holes were obtained at the low dose with FWHM ~**60 nm***

Fabricated array at 110mJ/cm^2



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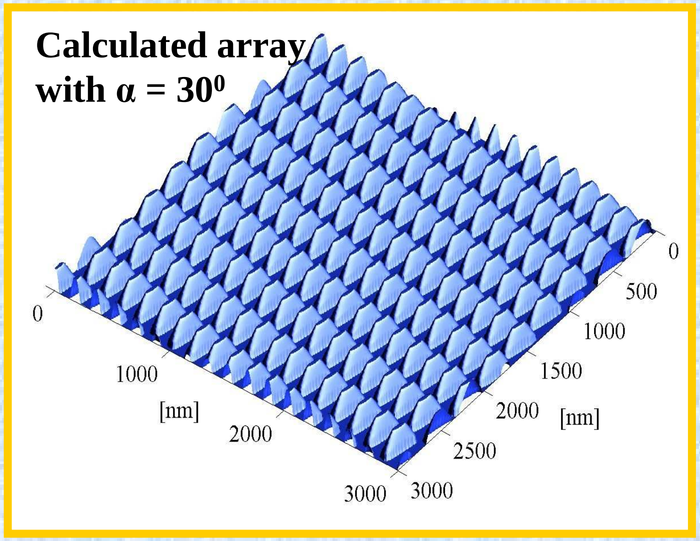
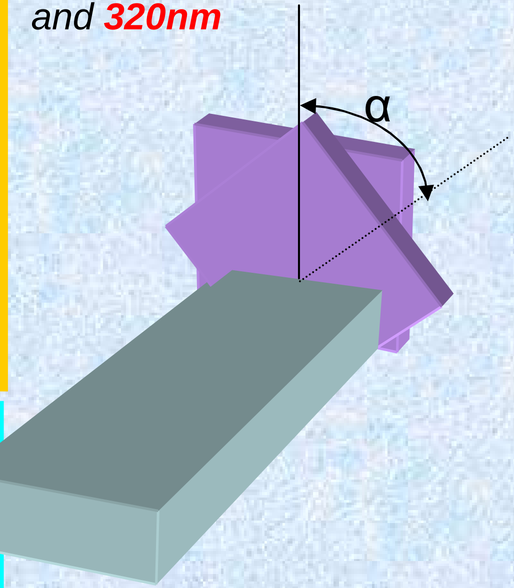
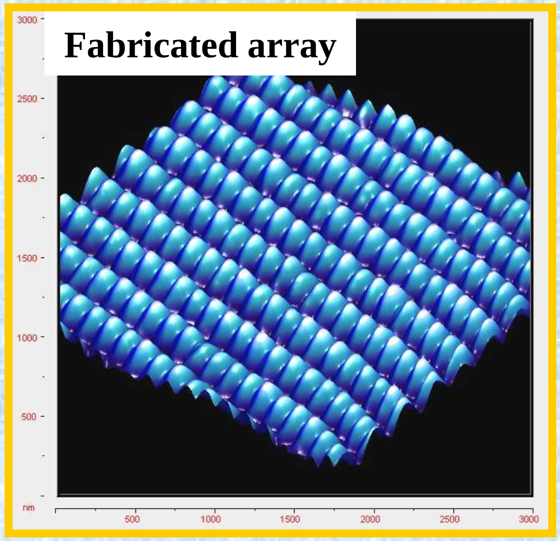
Different motifs – ovals

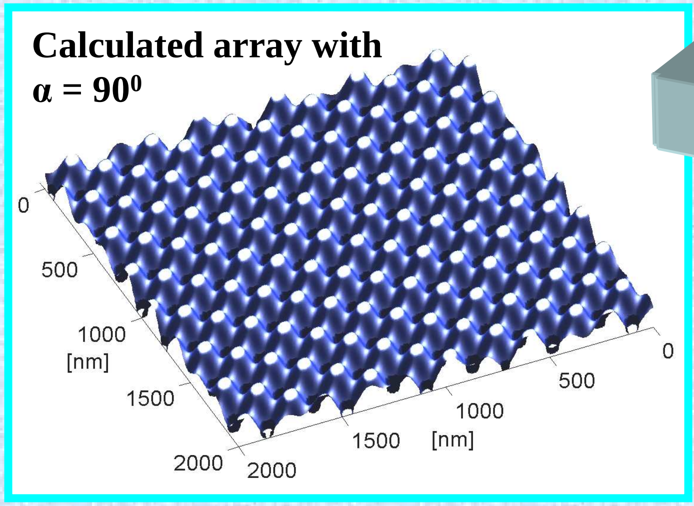
Different rotation angles allows printing different motifs


Calculated array with $\alpha = 30^0$

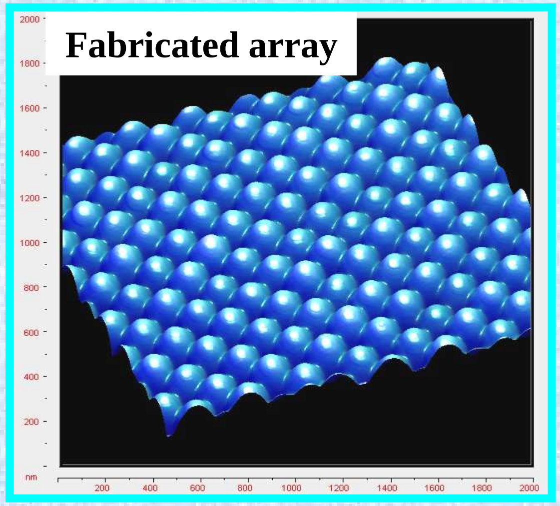
Pillars - FWHM ***80x160 nm^2*** *were obtained at the high dose with periods* ***160nm*** *and* ***320nm***




Fabricated array


Calculated array with $\alpha = 90^0$

Pillars FWHM ***75x110 nm^2*** *(1.6x2.3)λ were obtained with holes between ~**60nm** diameter*


Fabricated array

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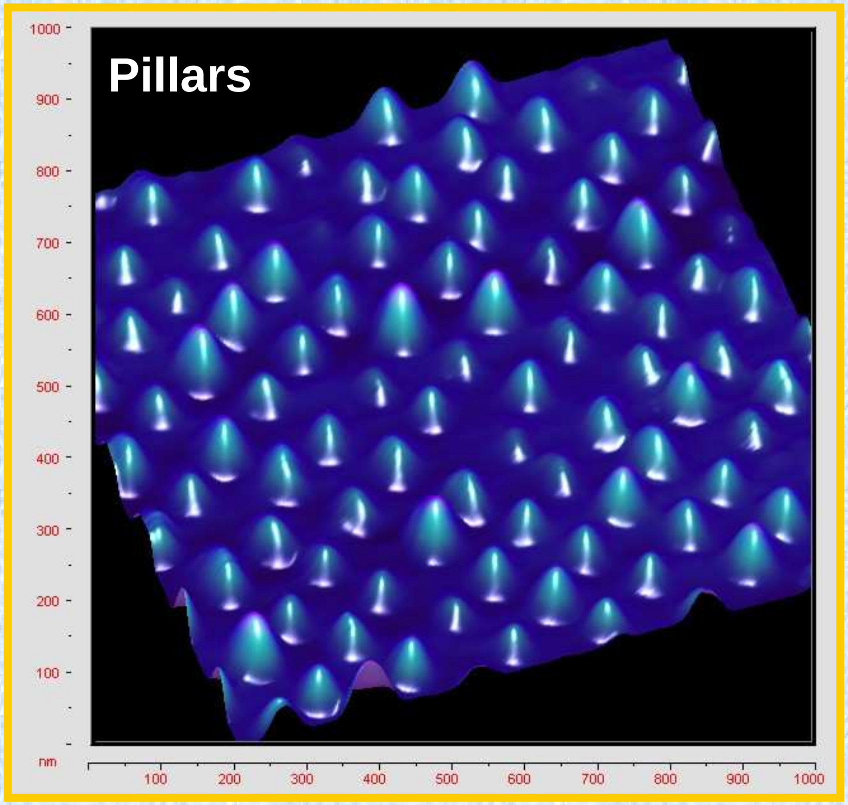
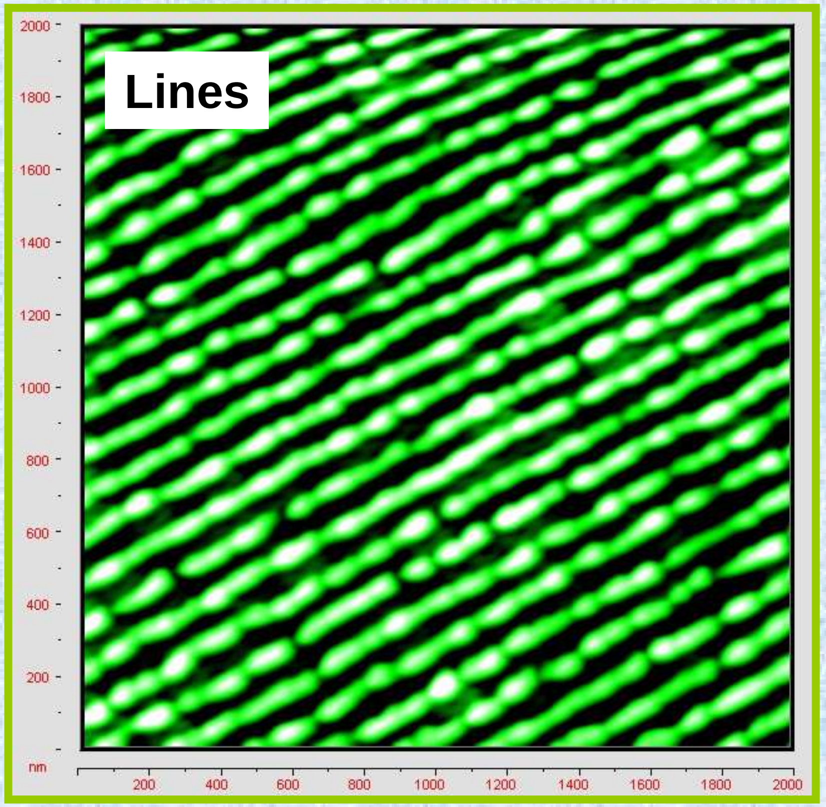
Smallest features

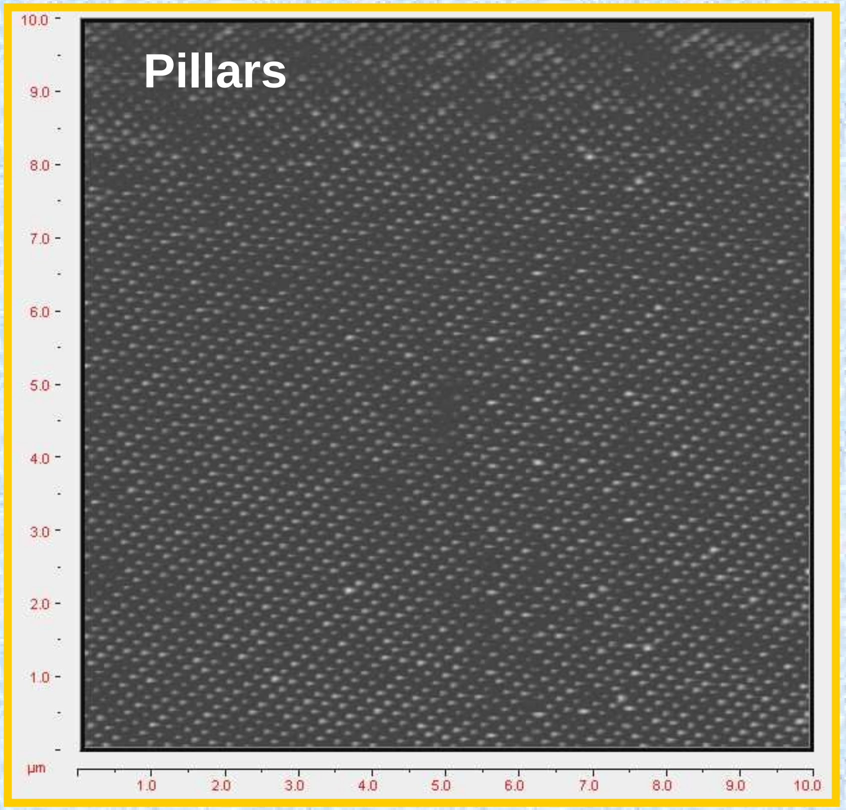


Period ***90nm****,*
pillars FWHM ***~45nm***

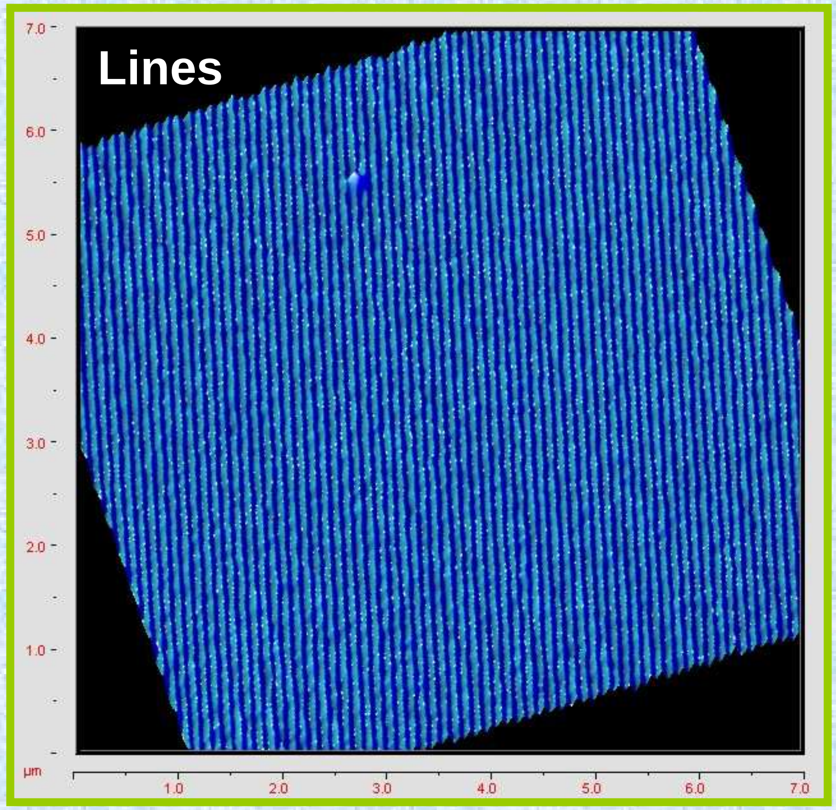


Period ***95nm****,*
lines FWHM ***~47nm***

Large areas

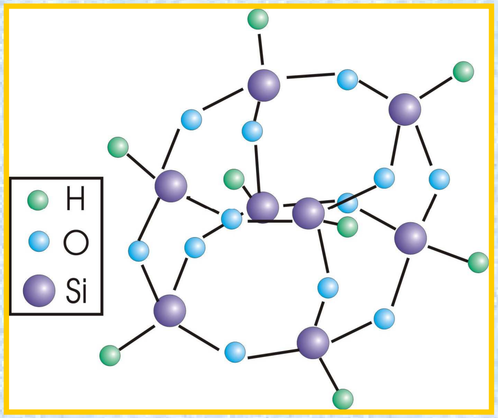


*Period **140nm**,*
*pillars FWHM **~70nm***
Scan size 10x10µm²



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

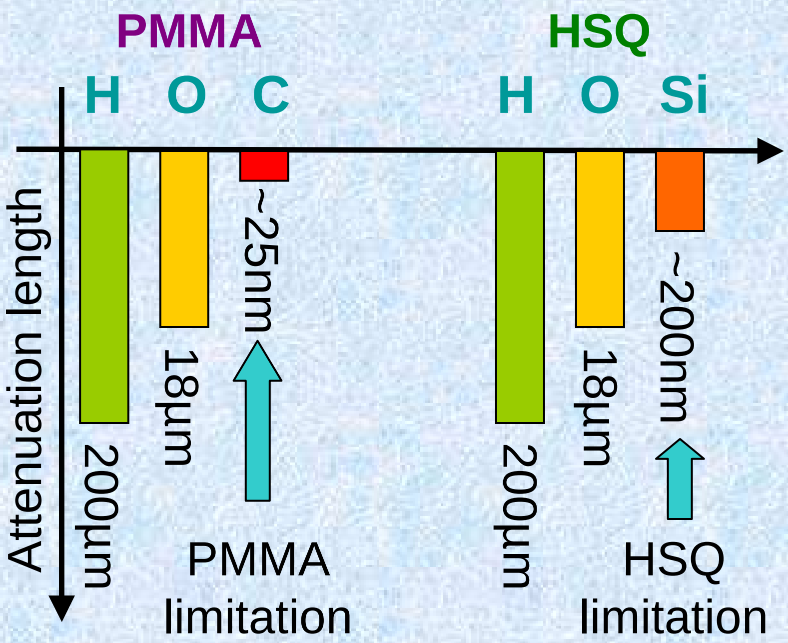
Table top Nanopatterning - HSQ photoresist



Why HSQ?

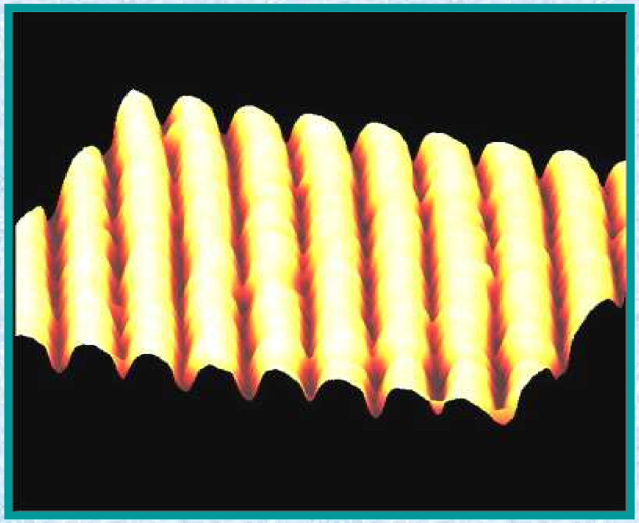
HSQ *- hydrogen silsesquioxane has some advantages over the PMMA photoresist:*

- *The penetration depth at 46.9nm wavelength is more than* ***150nm*** *(due to the chemical composition - H, O, Si)*
- *More resistant to ion beam etching: 1.22nm/s for PMMA,* ***0.47nm/s*** *HSQ with the same etching parameters*
- *High spatial resolution* ***~10nm****.*
- *Requires less dose for activation than PMMA*



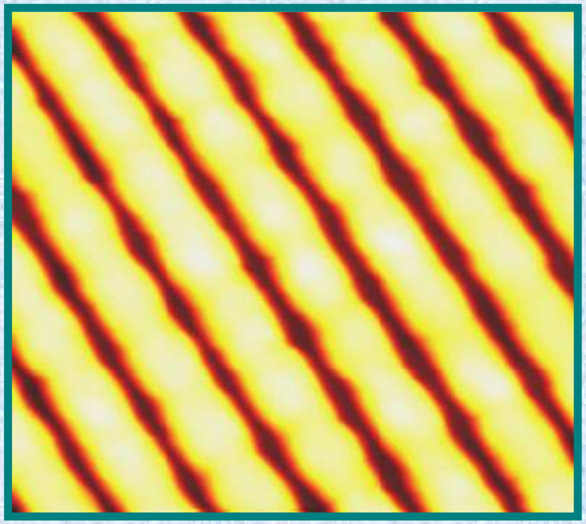
Attenuation lengths (1/e) for 30eV radiation (λ ~41.3nm)
www.cxro.lbl.gov

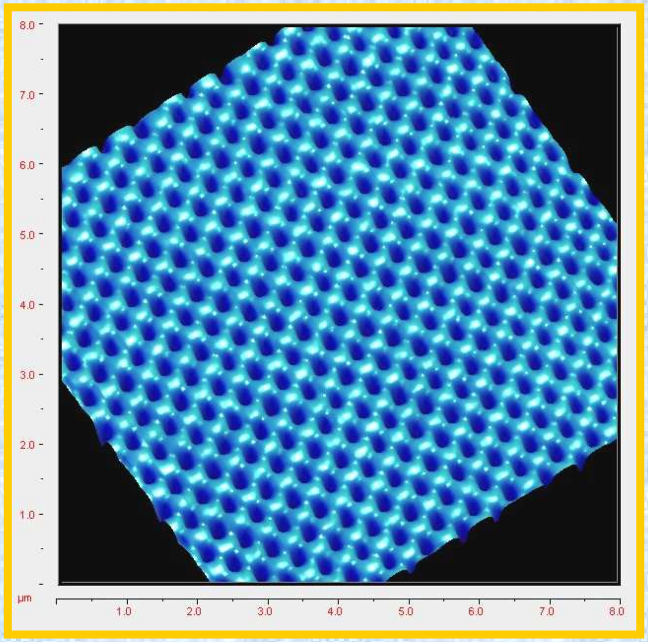
Different motifs with HSQ



***106nm** width lines patterned in HSQ photoresist*

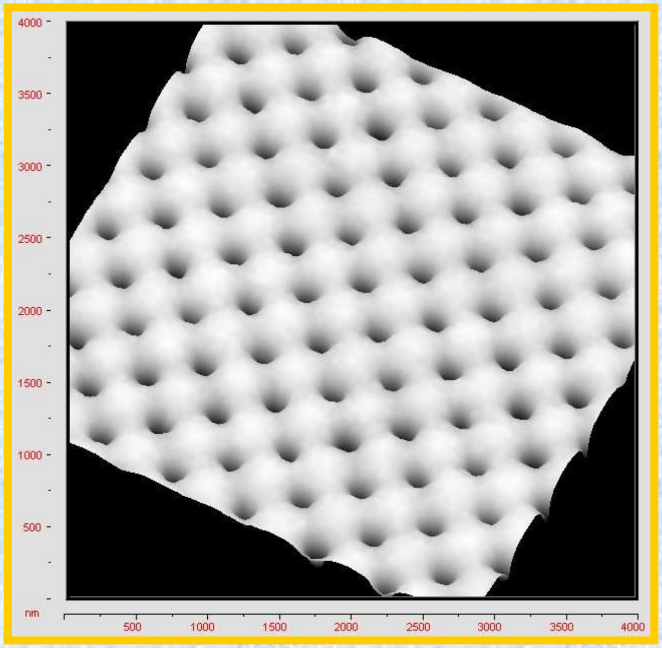
Dose: ~41mJ/cm^2



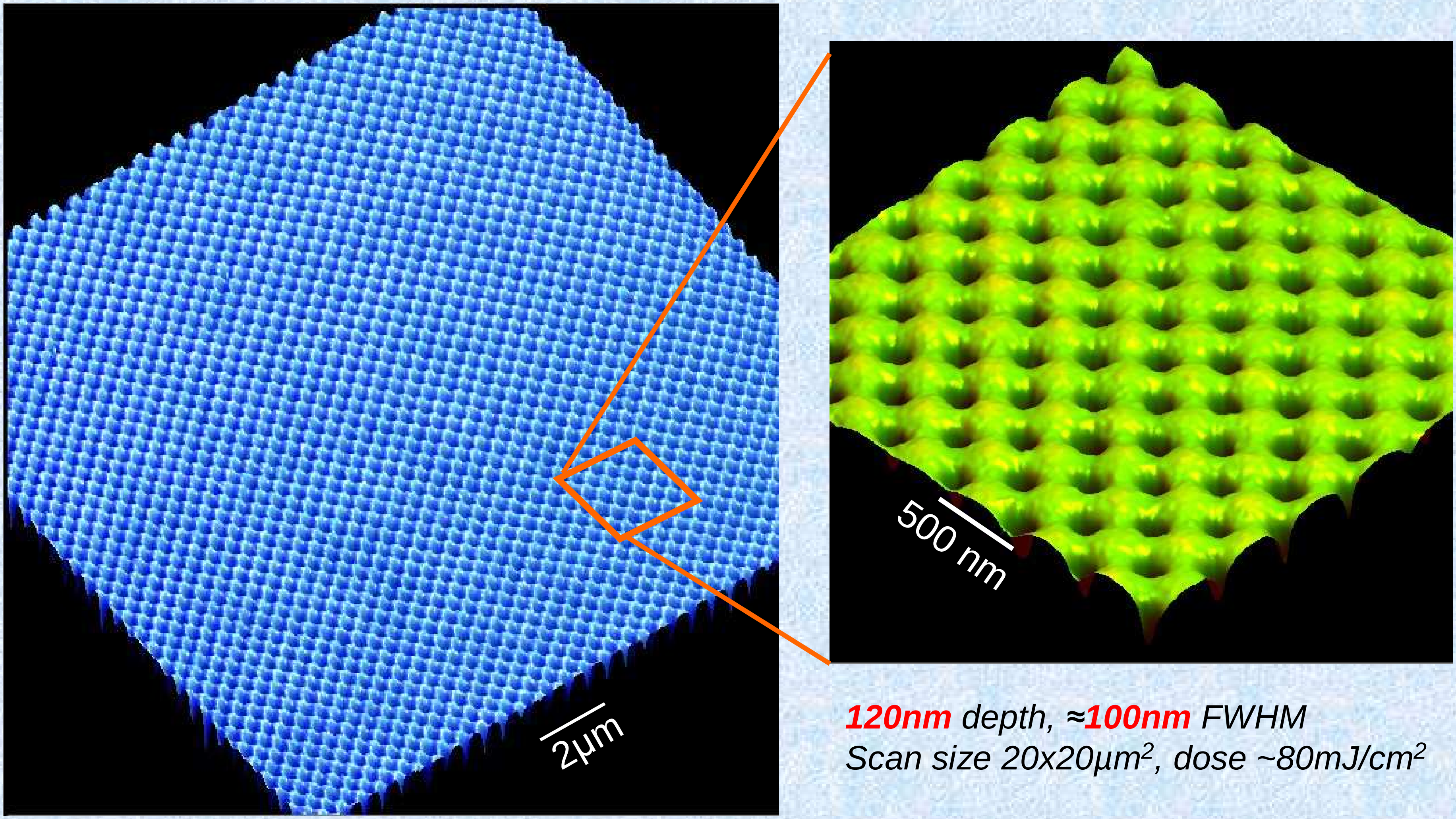


***130nm** diameter holes patterned in HSQ, depth ~110nm*

Dose: ~41mJ/cm^2

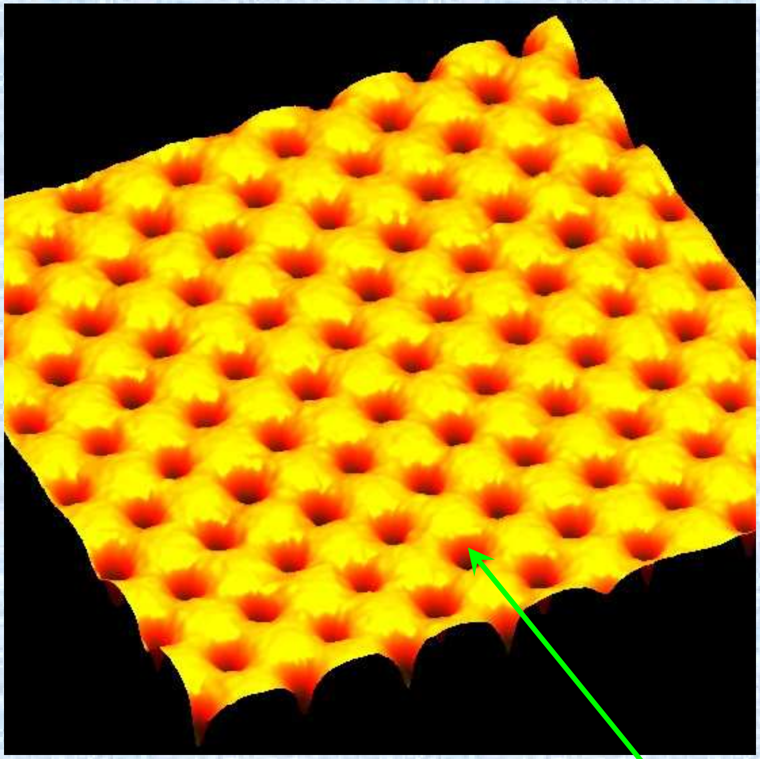


Large arrays of holes

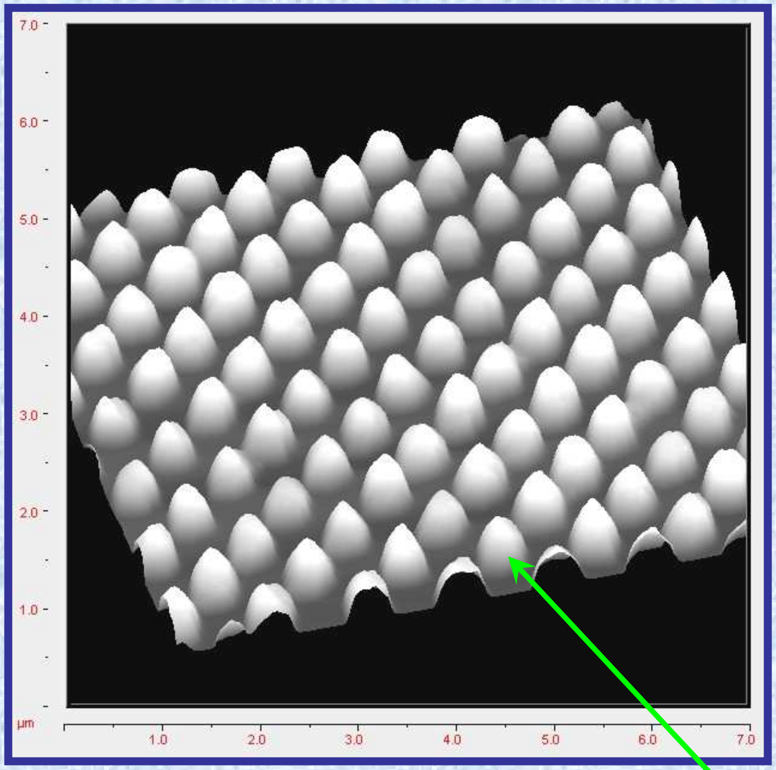


120nm *depth, ≈***100nm** *FWHM*
Scan size 20x20µm^2, dose ~80mJ/cm^2

Holes or Pillars



Dose ~41mJ/cm^2 *Not activated region*



Dose ~14mJ/cm^2 *Activated region*

For PMMA:

~110mJ/cm^2

~166mJ/cm^2

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    - ***Photo-resists: PMMA and HSQ***
  - ***Table top extreme ultraviolet holography***
    - ***Previous work***
    - ***Setup description***
    - ***Results***
    - ***Resolution estimation***
    - ***Parameters limiting the resolution***
  - ***Future work***
  - ***Summary and conclusions***

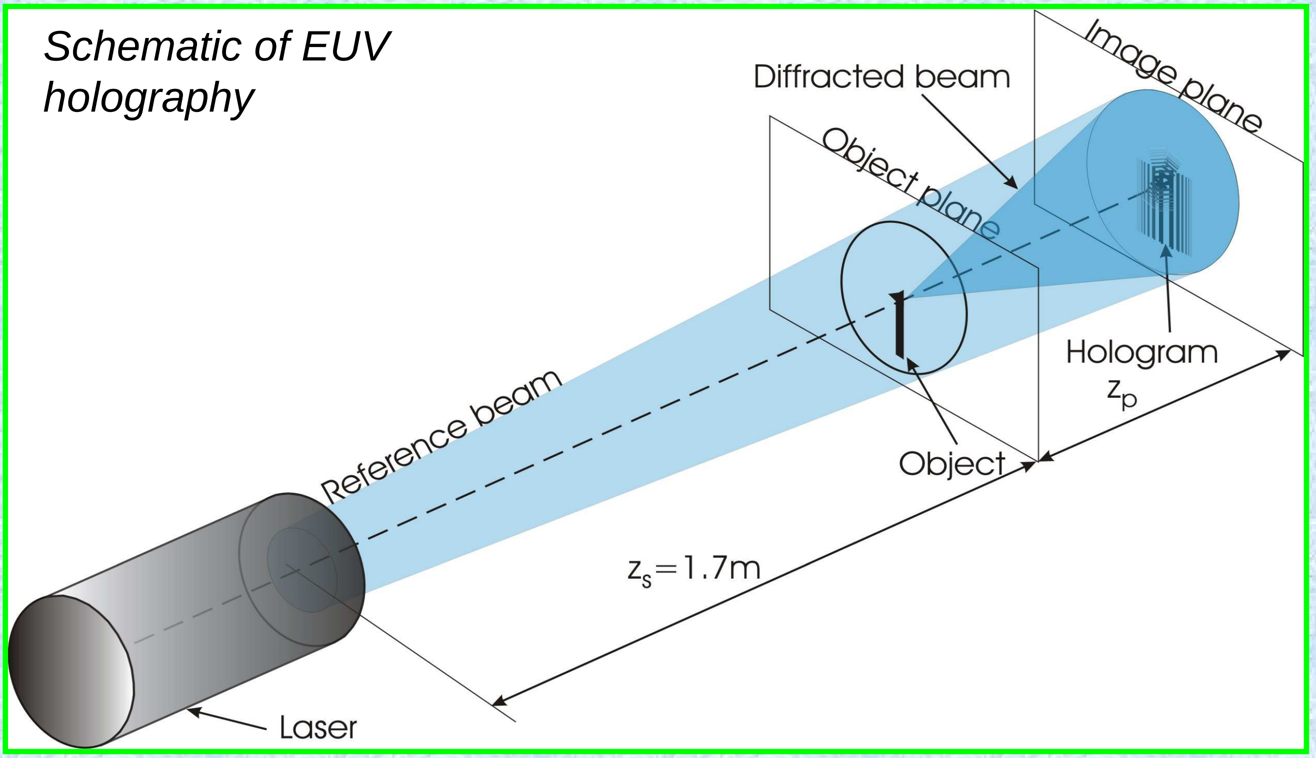
Previous work

Milestones in holography:

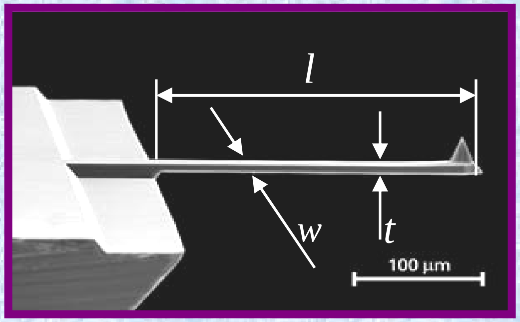
- *1948 - D. Gabor, “A new microscopic principle”, Nature (London), 161, pp. 777-778,*
- *1952 – A. V. Baez,”A study in diffraction microscopy with special reference to x-rays”, J. Opt. Soc. Am. 42, pp. 756-762,*
- *1963 – E.Leith, J.Upatnieks, “Wavefront reconstruction with a continuous-tone objects”, J. Opt. Soc. Am. 53,12, pp. 1377-1381,*
- *1969 – J. W. Giles, “Image reconstruction from a Fraunhoffer x-ray hologram with visible light”, J. Opt. Soc. Am. 59, pp. 1179-1188,*
- *1974 – S. Aoki, S. Kikuta,”X-ray holographic microscopy”, Jpn. J. Appl. Phys. 13, pp. 1385-1392,*
- *1987 – J. E. Trebes et al., “Demonstration of X-ray holography with an x-ray laser”, Science 238, pp. 517-519,*
- *1990 – C. Jacobsen et al., “X-ray holographic microscopy using photoresist”, J. Opt. Soc. Am. A 7, pp. 1847-1861,*
- *S. Lindaas et al., “X-ray holographic microscopy by means of photoresist recording and atomic-force microscope readout”, J. Opt. Soc. Am. A, 13, 9, 1996, pp. 1788-1800,*

And many, many more…..

EUV Holography Setup



Schematic of EUV holography

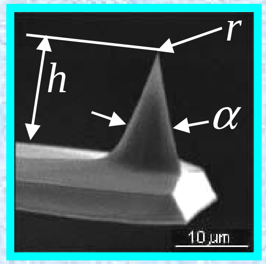


http://www.spmtips.com/nsc16/al-bs

Object characteristics:

Tip characteristics (according manufacturer):

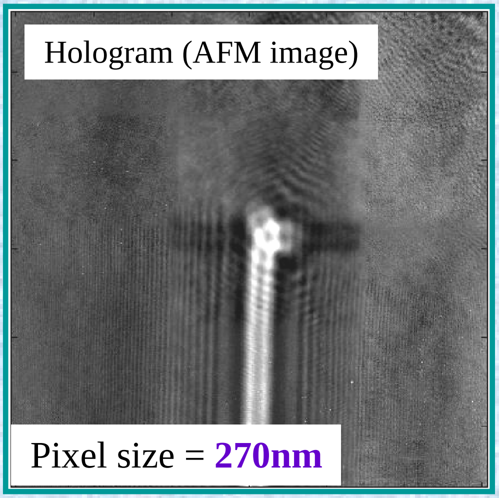
- *cantilever length l =230µm,*
- *width w = 40µm,*
- *thickness t = 7µm,*
- *full tip cone angle a = 30°*
- *tip height h = 20 - 25 µm,*
- *typical tip curvature radius r of uncoated probe* ***<10.0 nm***

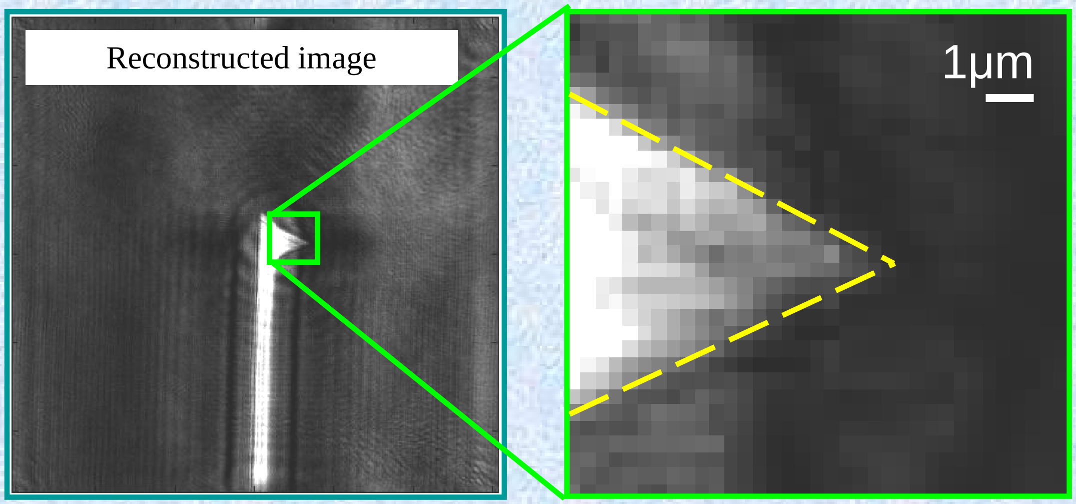


S. Lindaas et al., “X-ray holographic microscopy by means of photoresist recording and atomic-force microscope readout”, J. Opt. Soc. Am. A, 13, 9, 1996, pp. 1788-1800

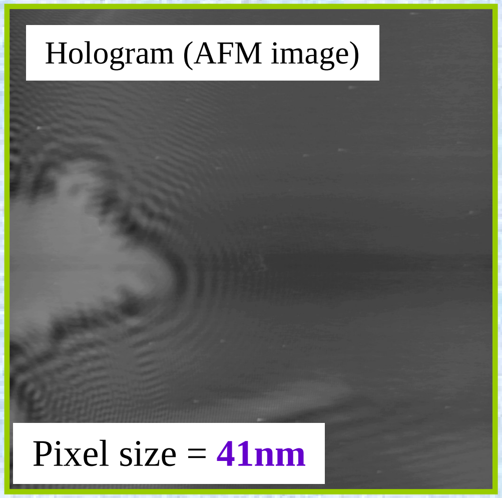
AFM digitized holograms and reconstructions

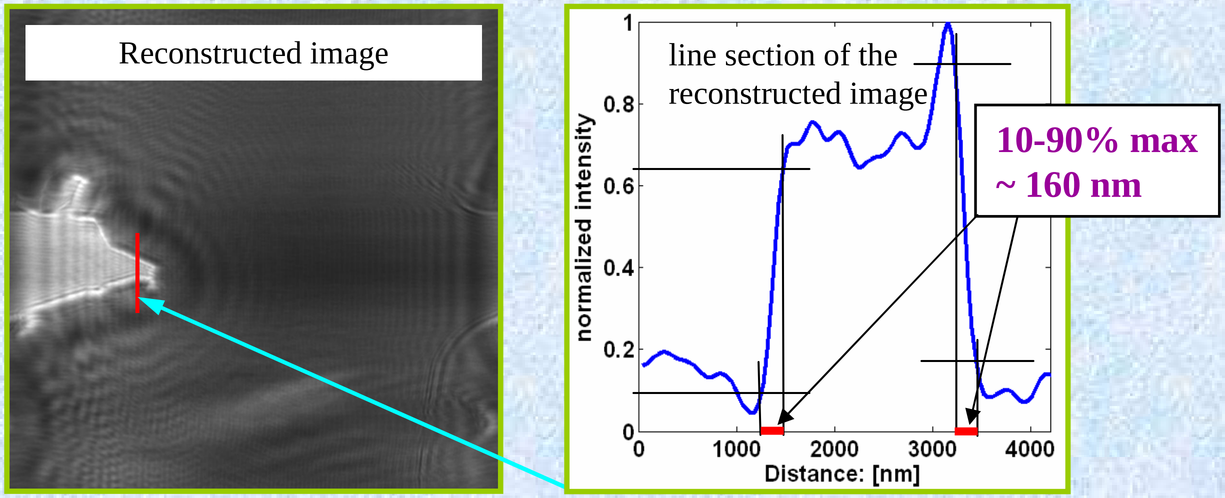
- *Hologram and reconstructed image obtained at z_p =4mm, digitized with AFM, pixel size = 270nm*





- *Hologram and reconstructed image obtained at z_p =120µm, digitized with AFM, pixel size = 41nm*

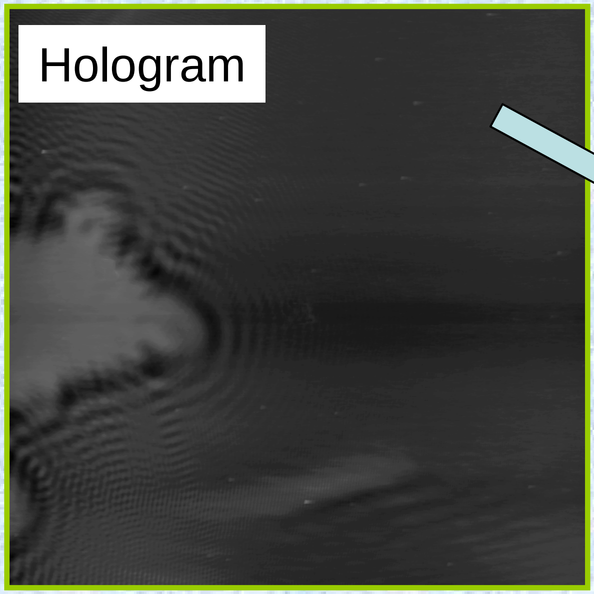


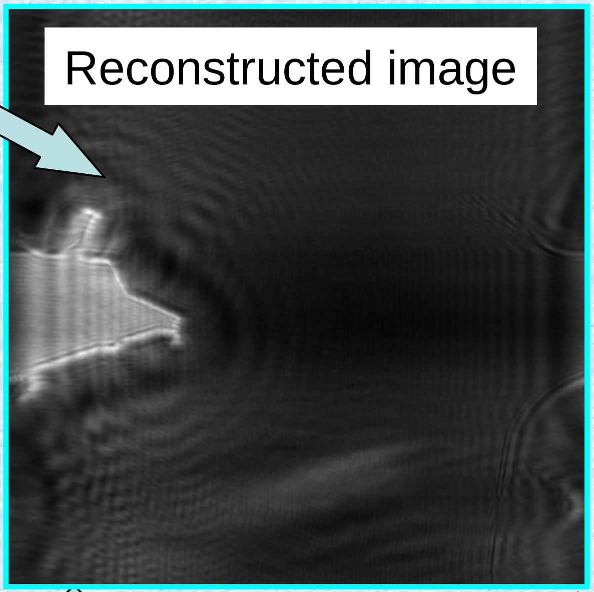


10-90% max ~ 160 nm

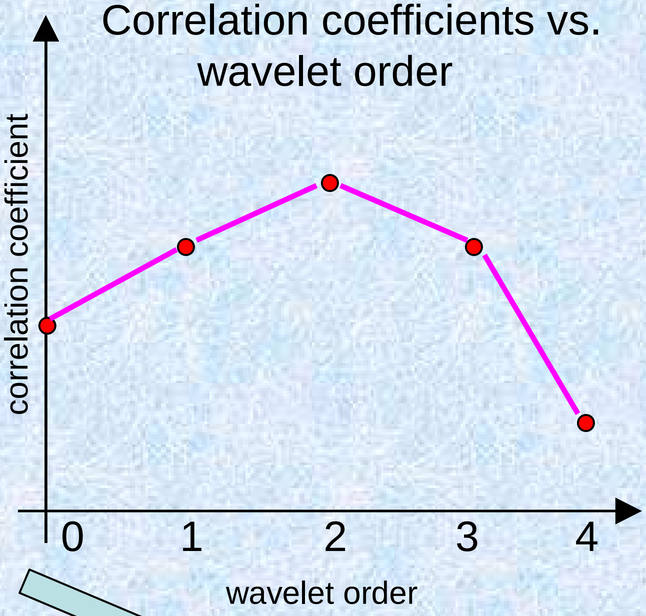
Method of Resolution estimation

Hologram and reconstructed image obtained at z_p =120μm, digitized with AFM, pixel size = 41nm

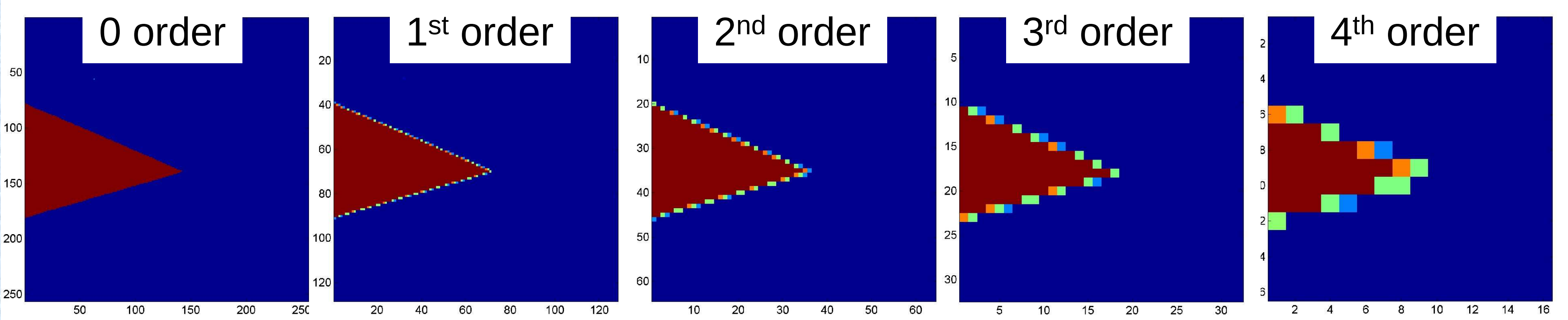




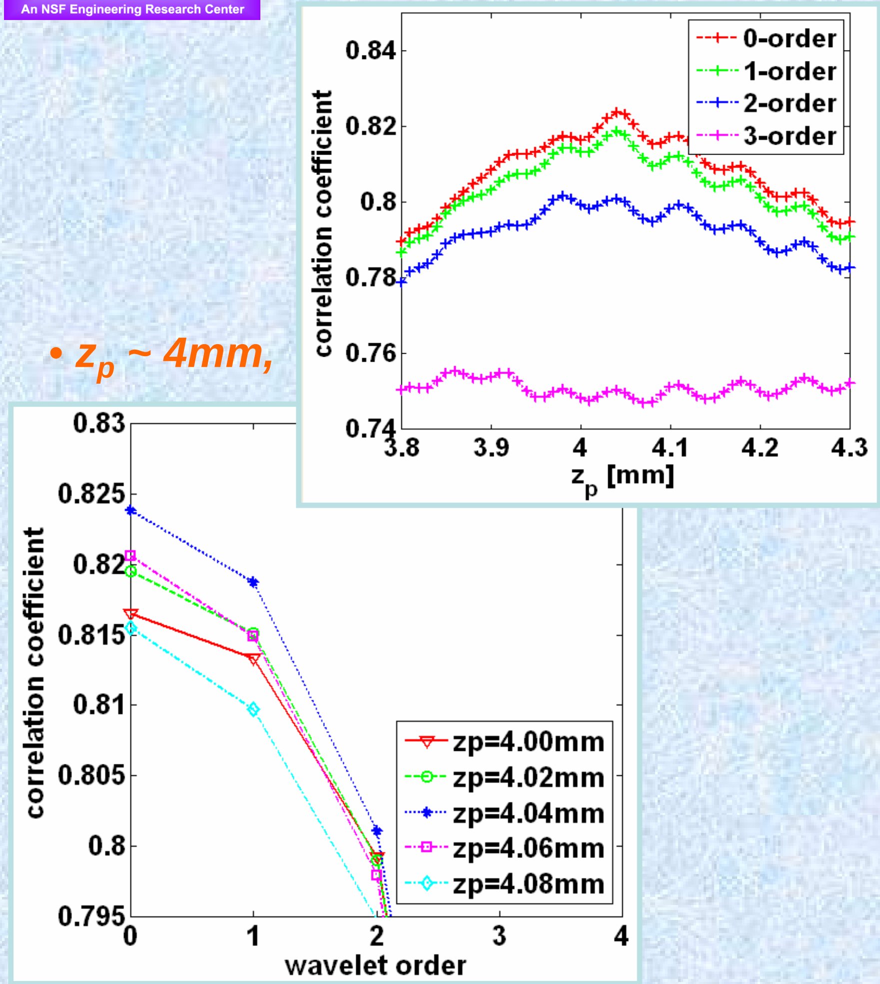
Correlation coefficients vs. wavelet order



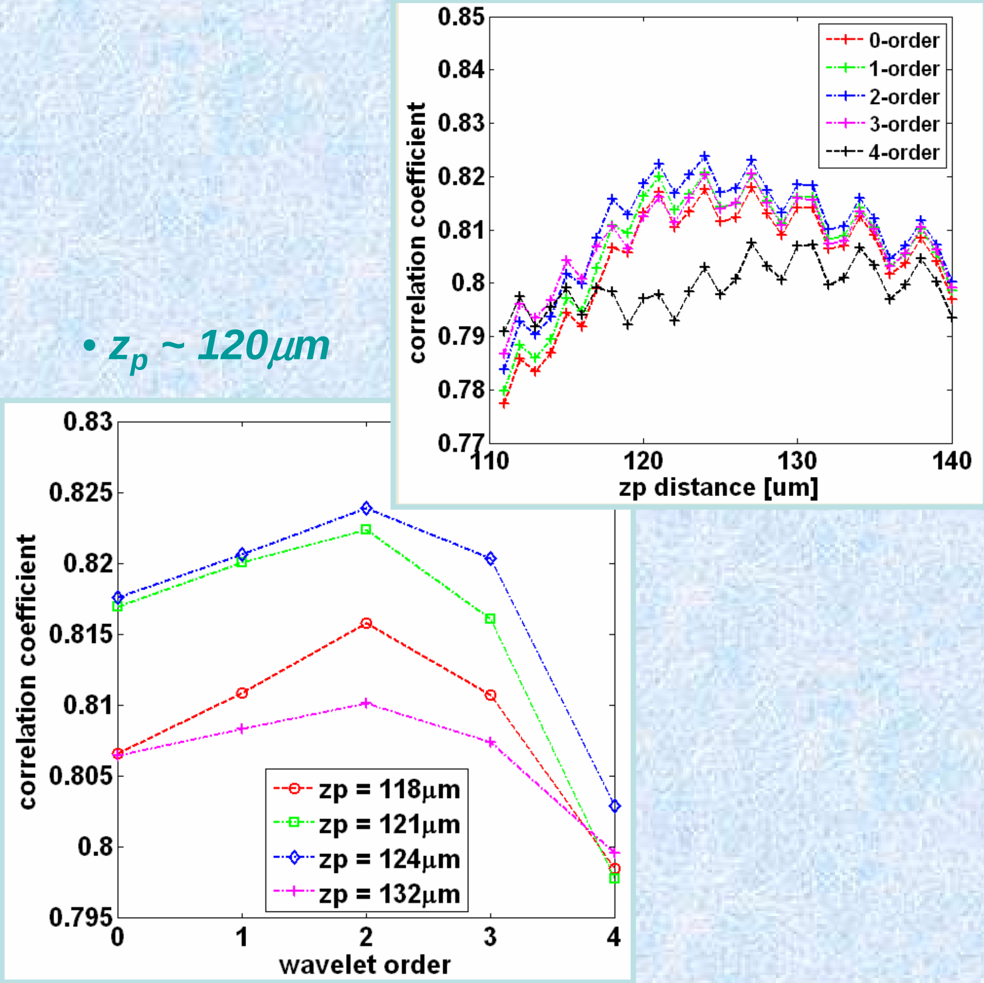
Lower resolution Wavelet Image Approximations



Correlation Analysis Results



- z_p ~ 4mm,



- z_p ~ 120μm

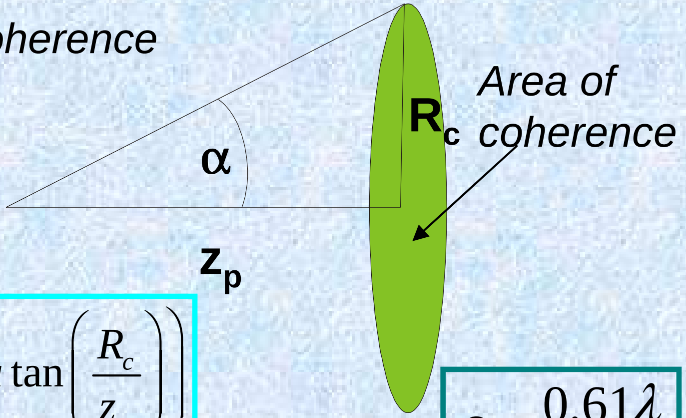
- *pixel size:* ***270nm***
- *optimum reconstruction* z_p = ***4.04 mm***
- *resolution:* $2^{0.5}$*·270nm =* ***381 nm***

- *pixel size:* ***41nm***
- *optimum reconstruction* z_p = ***124 μm***
- *resolution:* 2^2*·41nm =* ***164 nm***

Resolution due to EUV laser coherence parameters

Coherence limitations:

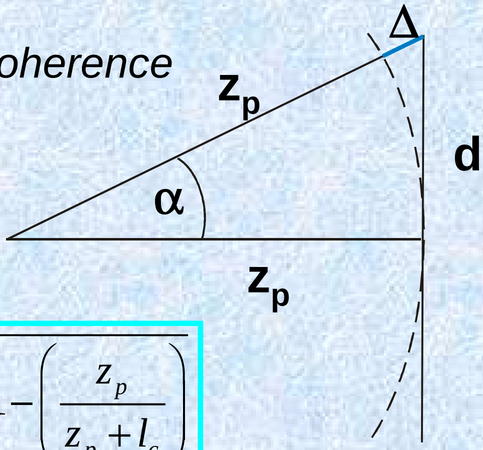
- *spatial coherence*



$$NA_{\max} = \sin\left(a\tan\left(\frac{R_c}{z_p} \right) \right)$$

$$\delta = \frac{0.61\lambda}{NA_{\max}}$$

- *temporal coherence*



$$NA_{\max} = \sqrt{1 - \left(\frac{z_p}{z_p + l_c} \right)}$$

Rayleigh criterion for resolution

Table with resolutions for…	*Transversal coherence*	*Longitudinal coherence*	*Experimental resolution*
z_p = 4 mm	*337.8 nm*	*64.1 nm*	*381 nm*
z_p = 120 µm	*30.4 nm*	*29.2 nm*	*164 nm*

Hologram scanning limitations:

$$N_{total} = \left(N_{samples} / line \right)^2 \sim \left(\frac{\lambda \cdot z_p}{\delta^2} \right)^2$$

$$NA = \sin\left(a\tan\left(\frac{d}{z_p} \right) \right) \qquad NA \le NA_{max}$$

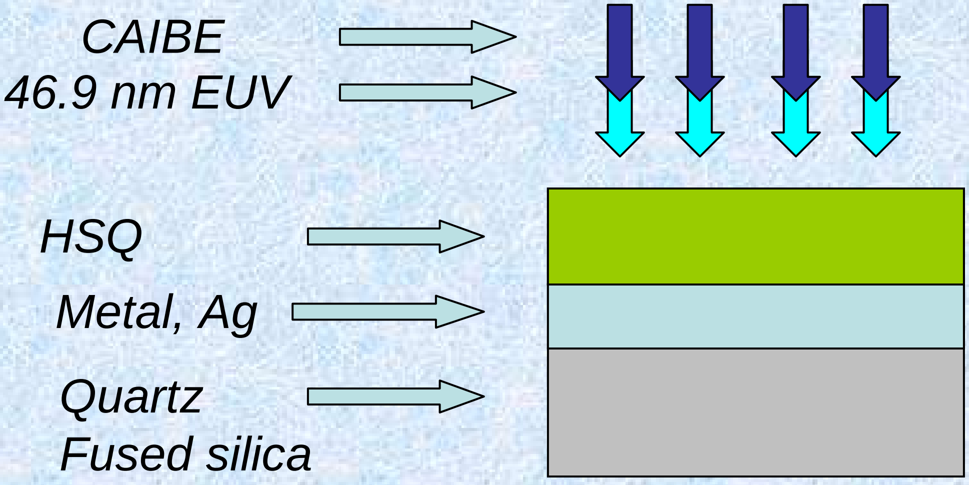
If δ=λ=46.9nm, at z_p=4mm, N_{total}= 7.27G samples

Real limitation to the resolution.

z_p has to be smaller

Future work

- Transferring the pattern to metalic substrates



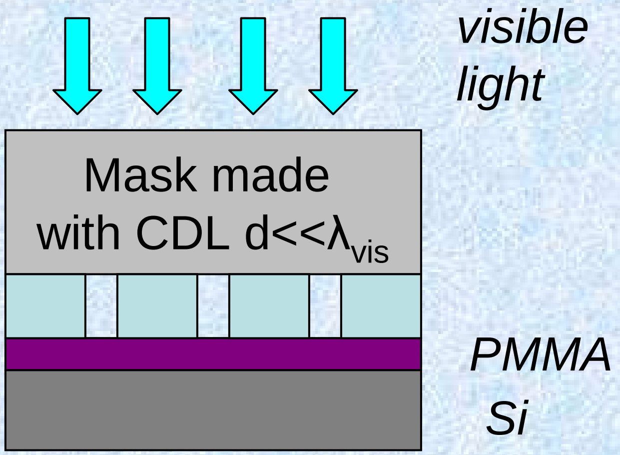
CAIBE
46.9 nm EUV

HSQ

Metal, Ag

Quartz
Fused silica

- Nanopatterning using plasmonic resonances



visible light

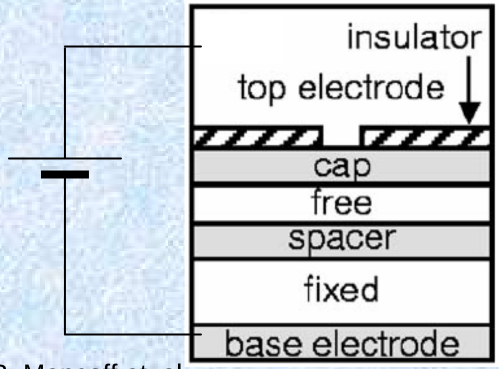
Mask made with CDL $d \ll \lambda_{vis}$

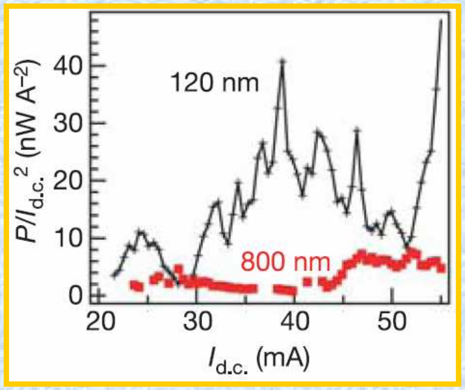
PMMA

Si

- Nanopatterning of magnetic materials

Cap	*2nm Cu/3.5nm Pd*
Free	*4.5nm $Ni_{80}Fe_{20}$*
Spacer	*6nm Cu*
Fixed	*20nm $Co_{81}Fe_{19}$*
Base electrode	*5nm Pd/25nm Cu*





“Phase-locking in double-point-contact spin-transfer Devices”, F. B. Mancoff et. al., NATURE, vol 437, 15 September 2005

EUV
An NSF Engineering Research Center

Summary - Nanopatterning

Colorado State University

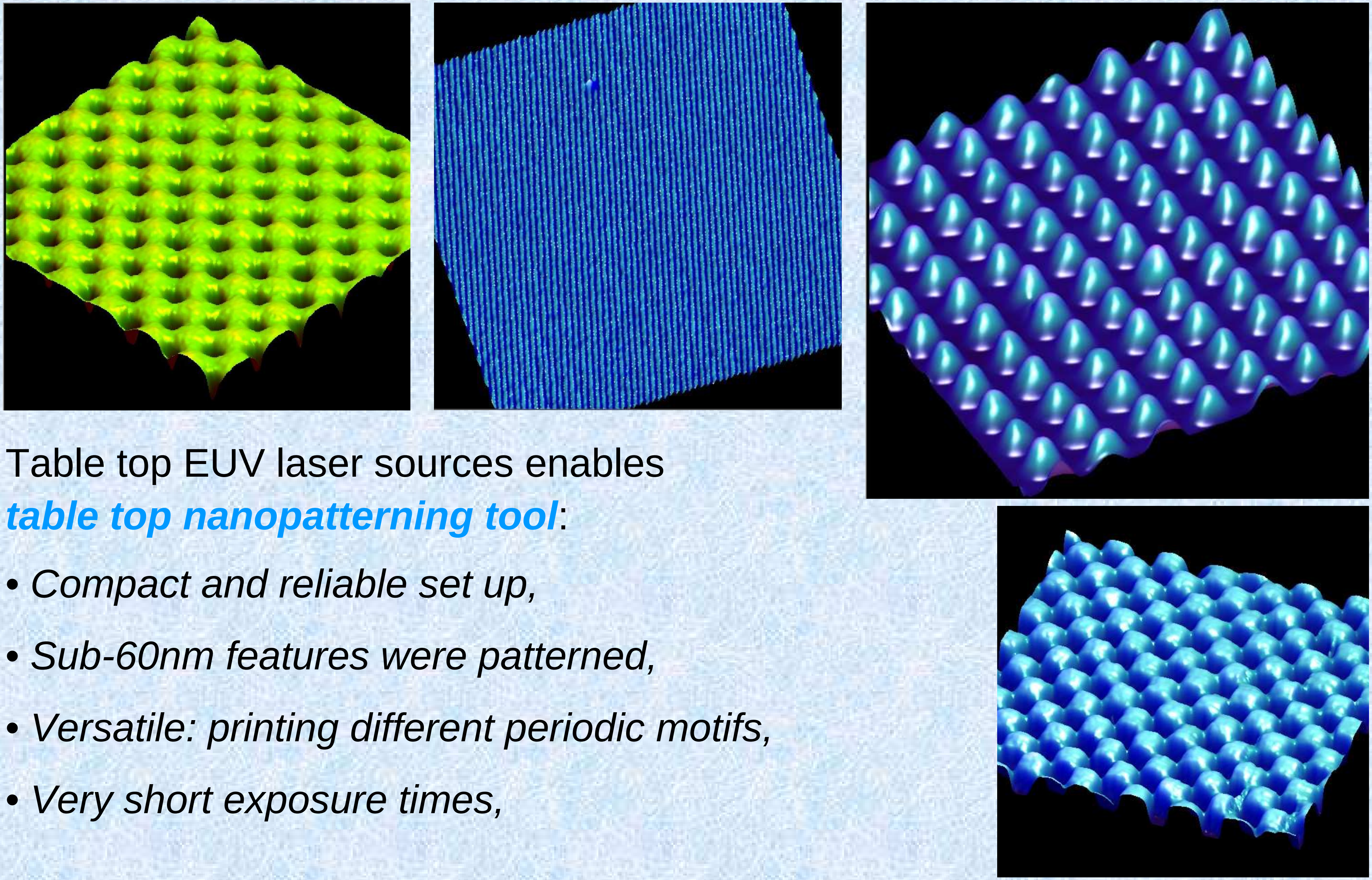
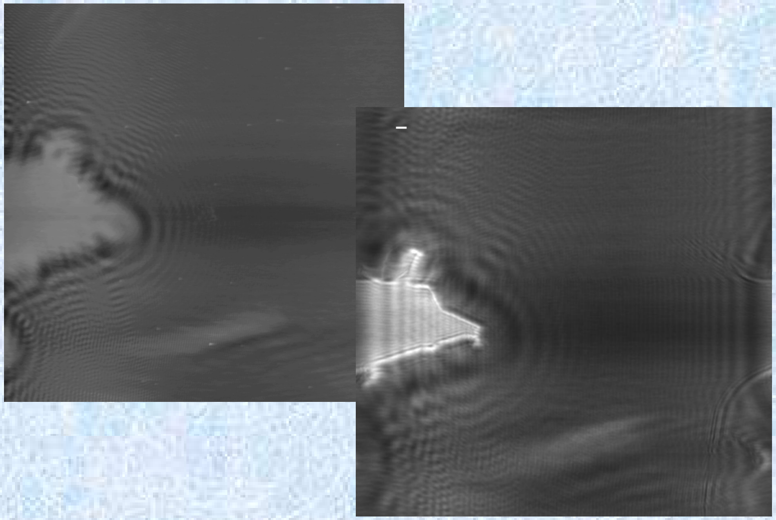


Table top EUV laser sources enables ***table top nanopatterning tool***:

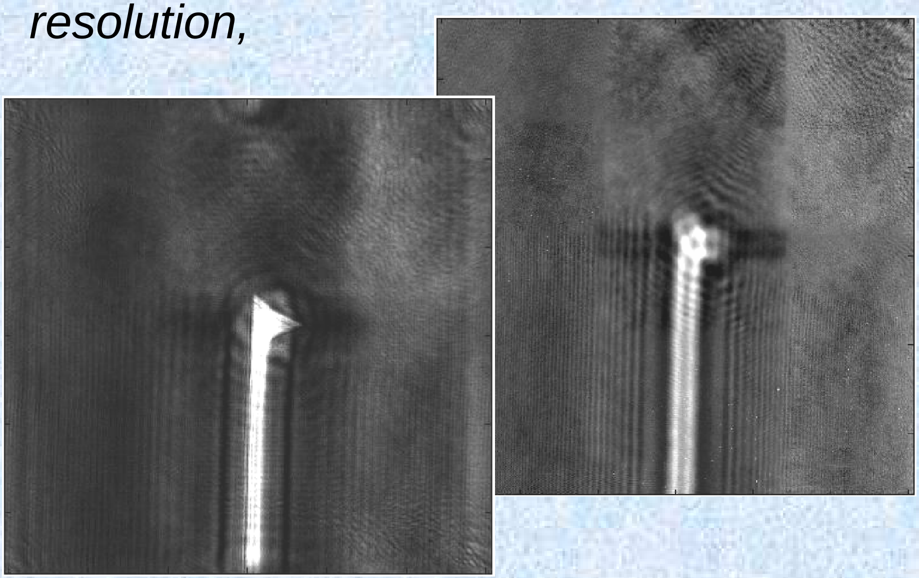
- *Compact and reliable set up,*
- *Sub-60nm features were patterned,*
- *Versatile: printing different periodic motifs,*
- *Very short exposure times,*

Summary - EUV Holography



- ***Sub-200 nm*** *resolution in the recording and reconstruction of a holographic image obtained in the Gabor’s geometry with a table top EUV laser was demonstrated,*

- *Demonstrated resolution analysis shows that the temporal and spatial coherence of the 46.9 nm laser do not limit the NA of the hologram allowing for* ***sub 100 nm*** *resolution,*



- *To determine the optimum reconstruction parameters and assess the spatial resolution of the holographic recording we used a* ***wavelet decomposition and correlation analysis****,*

List of publications

Journal publications:

1. *"Sub 400 nm spatial resolution extreme ultraviolet holography with a table top laser", **P. W. Wachulak**, R. A. Bartels, M. C. Marconi, C. S. Menoni, J. J. Rocca, Y. Lu, and B. Parkinson, , Optics Express, Vol. 14, Issue 21, pp. 9636-9642*
2. *"Patterning of nano-scale arrays by table-top extreme ultraviolet laser interferometric lithography", **P. W. Wachulak**, M. G. Capeluto, M. C. Marconi, C. S. Menoni, and J. J. Rocca, Optics Express, Vol. 15, Issue 6, pp. 3465-3469*
3. *"Table top nanopatterning with extreme ultraviolet laser illumination", M. G. Capeluto, **P. Wachulak**, M.C. Marconi, D. Patel, C.S. Menoni, J.J. Rocca, C. Iemmi, E.H. Anderson, W. Chao, D.T. Attwood, , Microelectronic Engineering (2007), doi:10.1016/j.mee.2007.01.018*
   M.G. Capeluto et al. Microelectr. Eng. (2007), doi:10.1016/j.mee.2007.01.018
4. *“Nanoscale patterning in high resolution HSQ photoresist by interferometric lithography with table top EVU lasers”, **P. W. Wachulak**, M. G. Capeluto, M. C. Marconi, D. Patel, C. S. Menoni, J. J. Rocca, submitted*
5. *“Volume extreme ultraviolet nano-holographic imaging with numerical optical sectioning”, **P. W. Wachulak**, M.C. Marconi, R. A. Bartels, C. S. Menoni, J.J. Rocca, submitted*

Conference Proceedings:

1. *“Table top EUV holography with sub 200 nm spatial resolution”, **Przemyslaw Wachulak**, Mario C. Marconi, Randy A. Bartels, Carmen S. Menoni, Jorge J. Rocca, SPIE Proceedings, 26 - 30 August 2007, San Diego 6702-18*
2. *“Interferometric lithography with sub 100 nm resolution using a table top λ=46.9 nm laser”*
   *Mario C. Marconi , **Przemyslaw Wachulak**, Dinesh Patel, Maria Gabriela Capeluto, Carmen S. Menoni, Jorge J. Rocca, SPIE Proceedings, 26 - 30 August 2007, San Diego, 6702-17*
3. *“Development of a table top nanopatterning tool with Extreme Ultraviolet Lasers”, Mario C. Marconi, **Przemyslaw Wachulak**, Carmen S. Menoni, Maria G. Capeluto, Erik Anderson, Proceedings of 2006 NSF Design, Service, and Manufacturing Grantees and Research Conference, St. Louis, Missouri.*
4. *“Nanopatterning and nanomachining with table-top extreme ultraviolet lasers”, M.C. Marconi , M.G. Capeluto, **P. Wachulak**, G. Vaschenko, H. Bravo, C.S. Menoni, J.J. Rocca , E.H. Anderson, W. Chao, D.T. Attwood, O. Hemberg, B. Frazer, and S. Bloom, Material Research Society Proceedings, Paper #: 0961-O06-05,*
5. *“Soft X-ray laser holographic imaging with sub micron resolution”, **P. W. Wachulak**, M. C. Marconi, R. Bartels, C. S. Menoni, J.J. Rocca, Proceedings of the 10th International Conference on X-Ray Lasers, August 20-25, 2006, Berlin, Germany.*
6. *“Table Top Nanopatterning using Soft X-Ray Lasers”, M. G. Capeluto, **P. Wachulak**, D. Patel, M. C. Marconi, C. S. Menoni, J. J. Rocca, E. H. Anderson, W. Chao, D. T. Attwood, Proceedings of the 10th International Conference on X-Ray Lasers, August 20-25, 2006, Berlin, Germany.*

Thank you