EUV
An NSF Engineering Research Center

Colorado State University

Center for Functional Nanomaterials
Brookhaven National Laboratory

COHERENT EUV LITHOGRAPHY WITH TABLE-TOP LASER

Lukasz Urbanski
Advisor: Mario C. Marconi
PhD Final
Sept 27 2012

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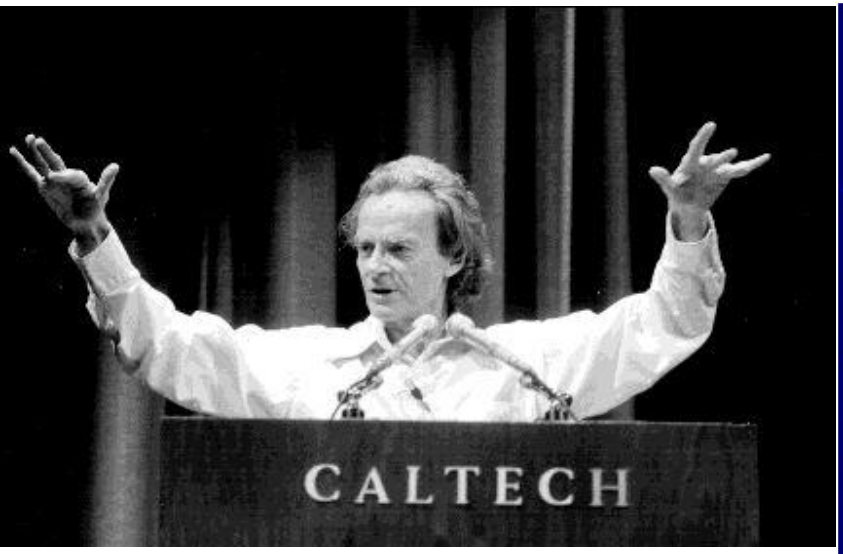
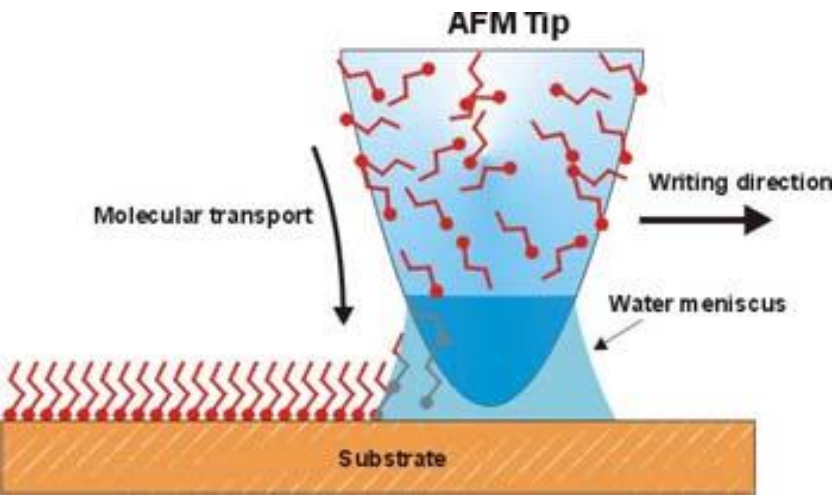
Outline

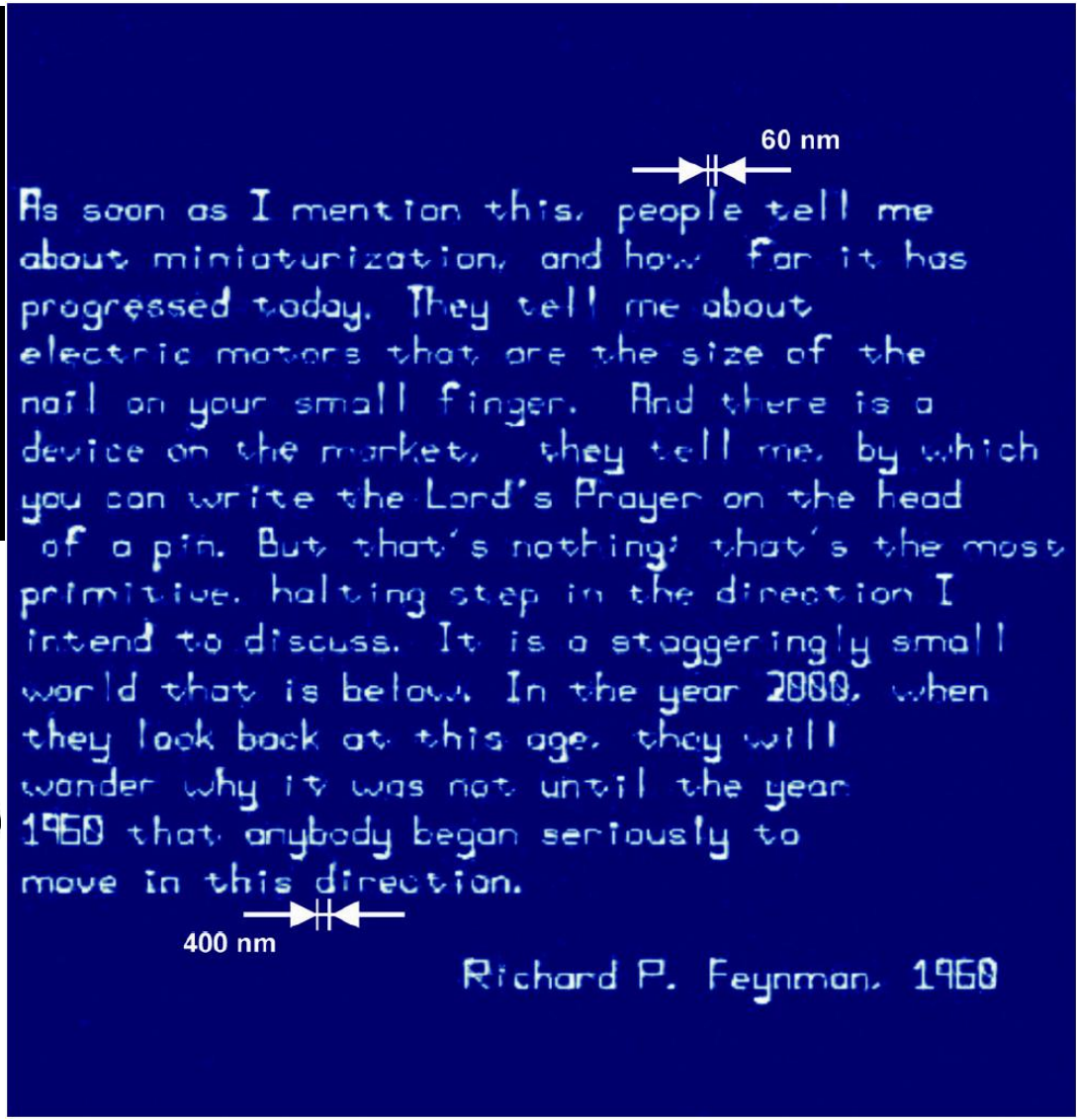
- Nanotechnology, applications, techniques
- Capillary Discharge Laser
- Holographic projection lithography
- Generalized Talbot Imaging lithography
- De-magnified Generalized Talbot Imaging lithography
- Defect Tolerance in the Generalized Talbot Imaging
- Summary

“There is plenty of room at the bottom”



Source: Caltech

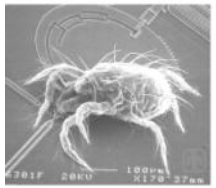




Source: http://mrsec.wisc.edu/Edetc/SlideShow/slides/lithography/dip_pen.html

The Scale of Things – Nanometers and More

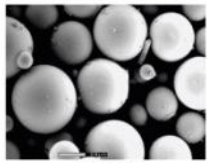
Things Natural



Dust mite
200 μm

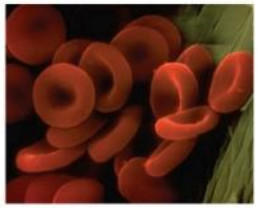
Ant
~ 5 mm

Human hair
~ 60-120 μm wide

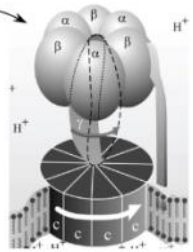


Fly ash
~ 10-20 μm

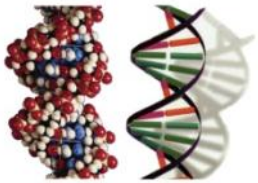
Red blood cells
(~7-8 μm)



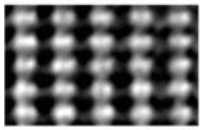
~10 nm diameter



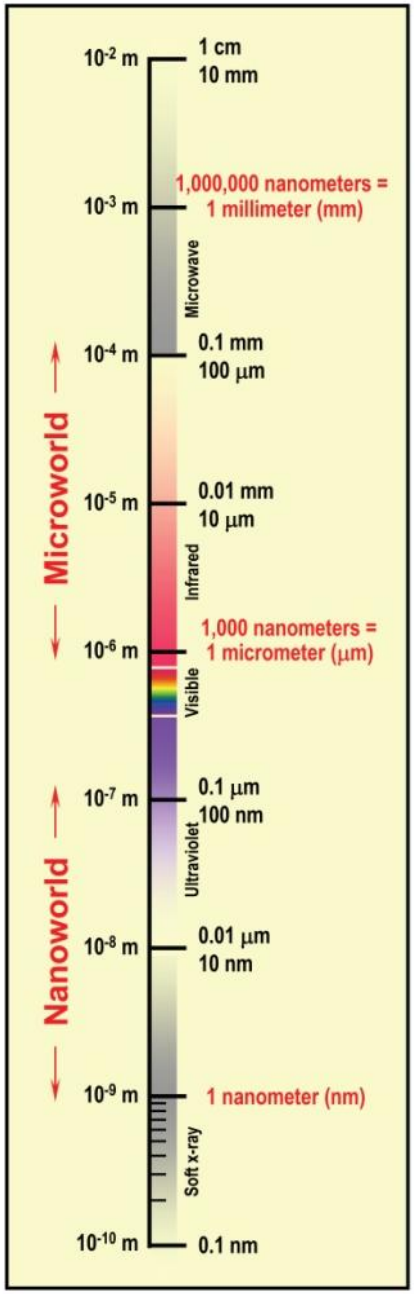
ATP synthase



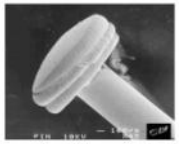
DNA
~2-1/2 nm diameter



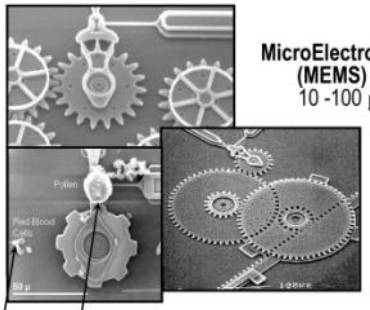
Atoms of silicon
spacing 0.078 nm



Things Manmade

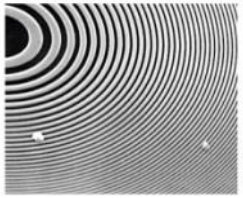


Head of a pin
1-2 mm

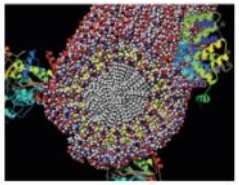


MicroElectroMechanical
(MEMS) devices
10 -100 μm wide

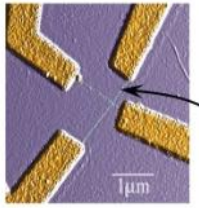
Pollen grain
Red blood cells



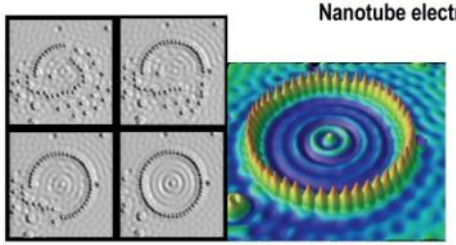
Zone plate x-ray "lens"
Outer ring spacing ~35 nm



Self-assembled,
Nature-inspired structure
Many 10s of nm

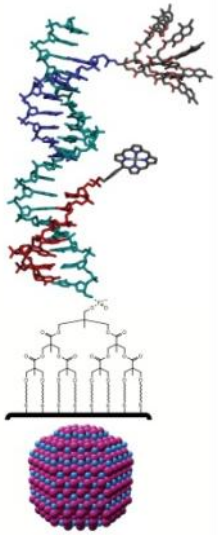


Nanotube electrode

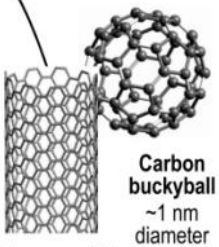


Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm

The Challenge



Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.



Carbon buckyball
~1 nm
diameter

Carbon nanotube
~1.3 nm diameter

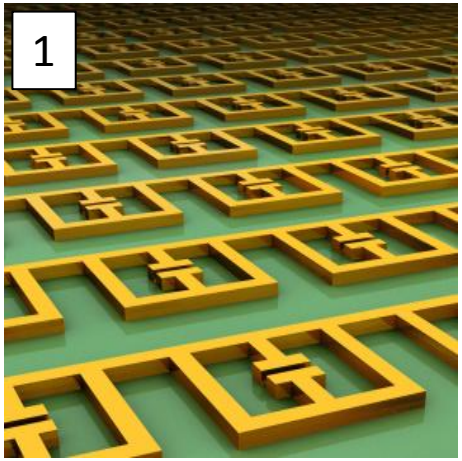
Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-26-06, pmd

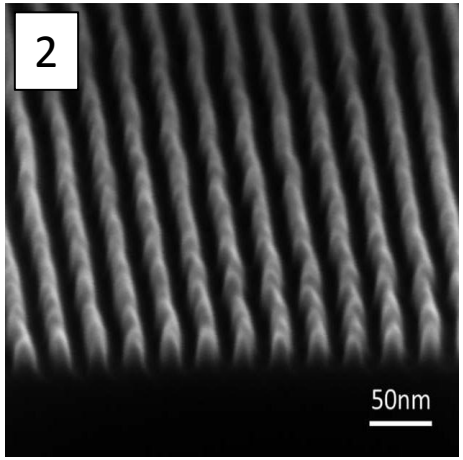
Nanotechnology

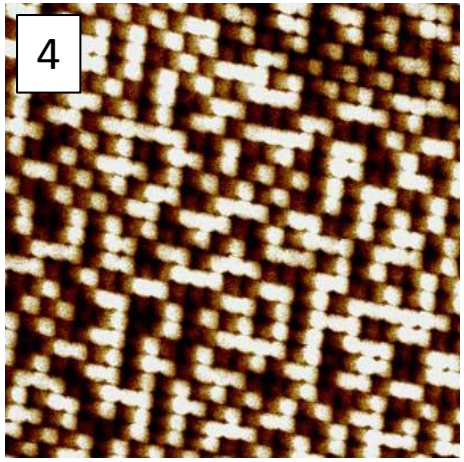
"ability of engineering materials precisely at nanometer scale"

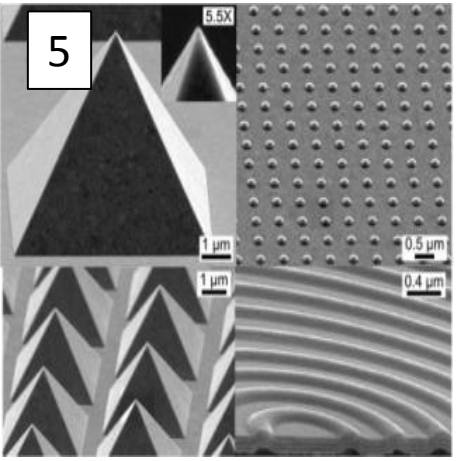
Norio Taniguchi, 1974

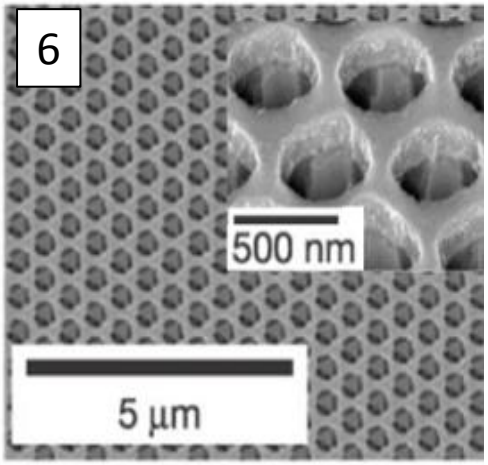
Applications

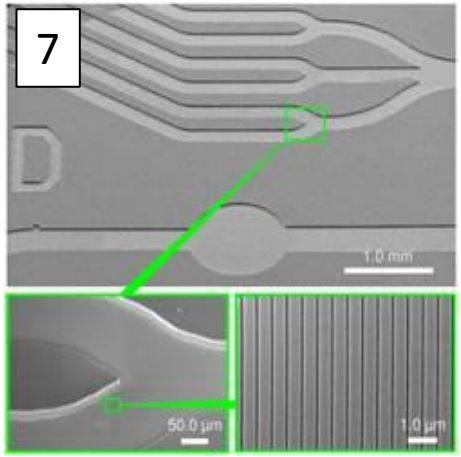


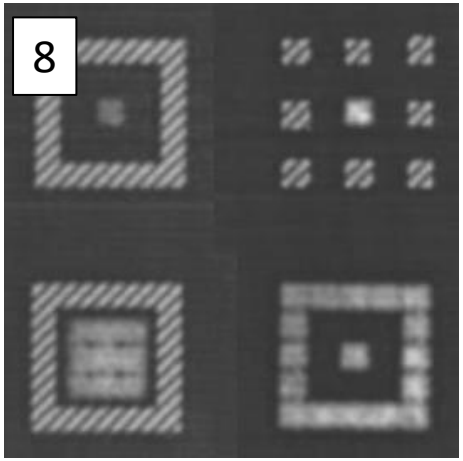






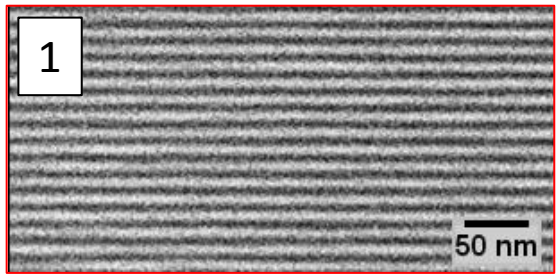




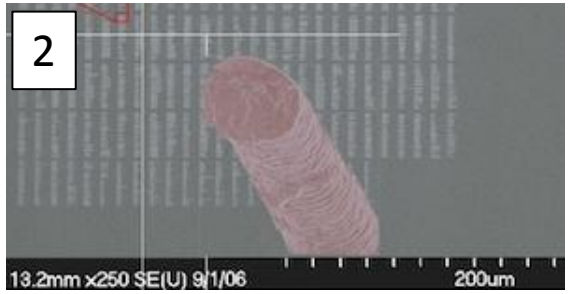


1. Dynamical electric and magnetic metamaterial response at terahertz frequencies, W. J. Padilla, A. J. Taylor, C. Highstrete, Mark Lee, and R. D. Averitt, Phys. Rev. Lett. 96, 107401 (2006).
2. Integration of block copolymer directed assembly with 193 immersion lithography, Chi-Chun Liu, Paul F. Nealey, Alex K. Raub, Philip J. Hakeem, Steve R. J. Brueck, Eungnak Han, and Padma Gopalan, J. Vac. Sci. Technol. B 28, C6B30 (2010).
3. MEMS, P.N. Mahalik, McGraw-Hill Education (2008).
4. Origins of switching field distributions in perpendicular magnetic nanodot arrays, J.M. Shaw, W.H. Rippard, S.E. Russek, T. Reith, and C.M. Falco. Journal of Applied Physics, 101, 023909 (2007).
5. Ultrasmooth Patterned Metals for Plasmonics and Metamaterials, P. Nagpal, N.C. Lindquist, S.H. Oh, and D.J. Norris. Science, 325, 594 (2009).
6. A three-dimensional optical photonic crystal with designed point defects, MH Qi, E. Lidorikis, P.T. Rakich, S.G. Johnson, J.D. Joannopoulos, E.P. Ippen, and H.I. Smith. Nature, 429, 538 (2004).
7. Single-step fabrication and characterization of photonic crystal biosensors with polymer microfluidic channels, C.J. Choi and B.T. Cunningham. Lab Chip, 6, 1373 (2006).
8. Biological lithography: Improvements in DNA synthesis methods, C. Kim, M. Li, M. Rodesch, A. Lowe, K. Richmond, and F. Cerrina, J. Vac. Science Technol. B, 22, 3163 (2004).

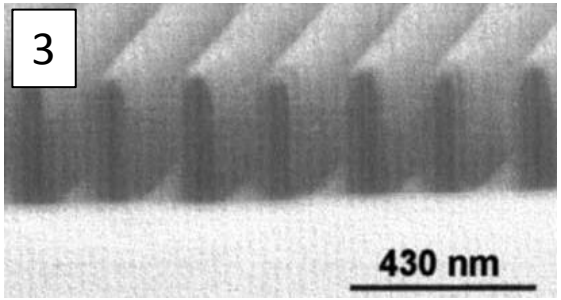
Techniques of nanofabrication



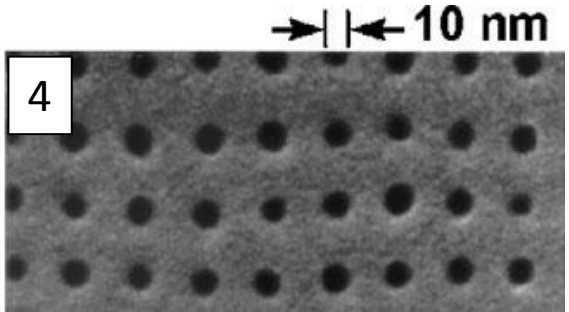
EUV lithography 8nm



Electron beam lithography 2.5nm

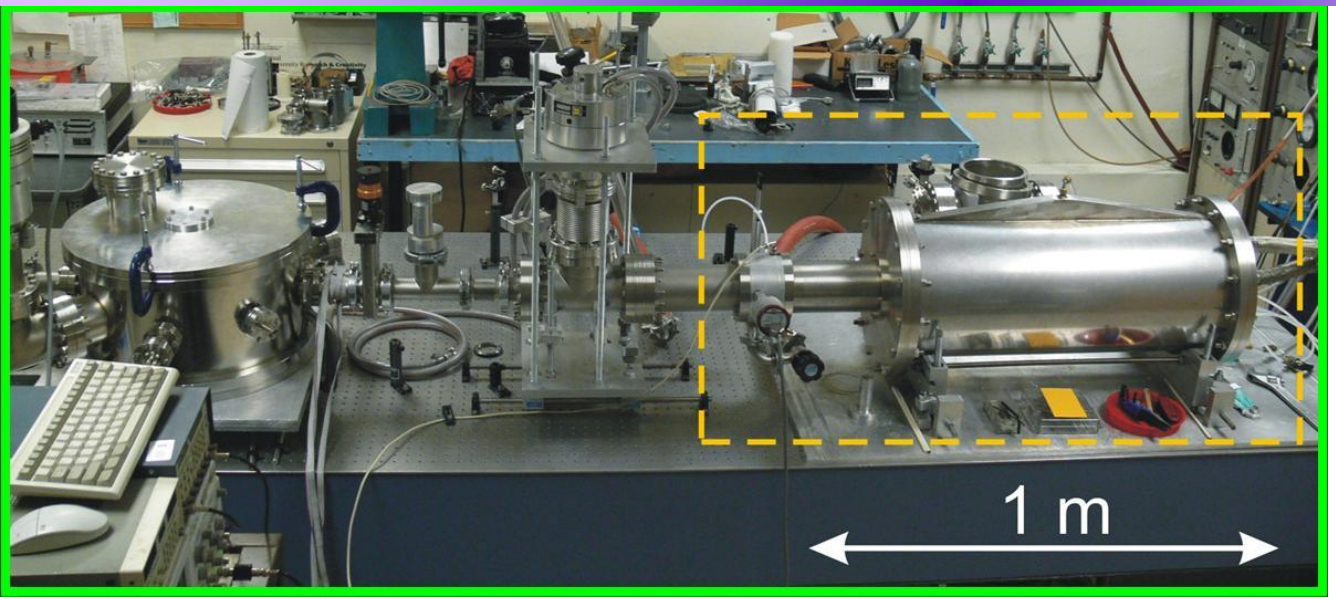


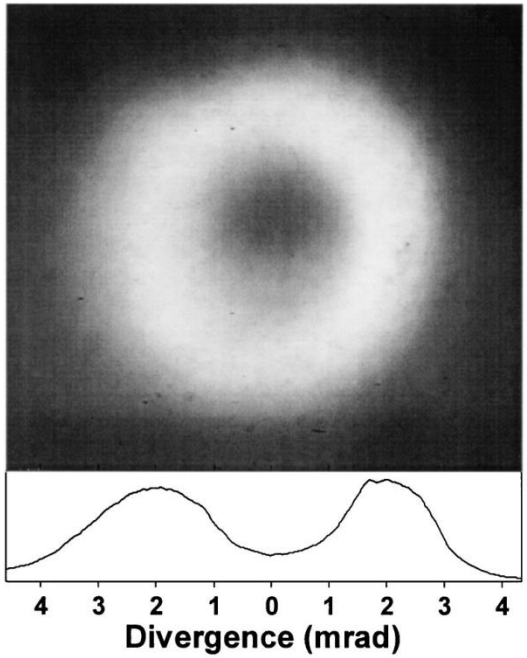
Scanning probe lithography 6nm



Nano imprint lithography 10nm

Capillary discharge EUV Laser





J.J. Rocca, V.N. Shlyaptsev, F.G. Tomasel, O.D. Cortazar, D. Hartshorn, and J.L.A. Chilla, "Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser", Physical Review Letters **73**, 2192, (1994)

Parameters of the Capillary discharge laser @ 46.9 nm

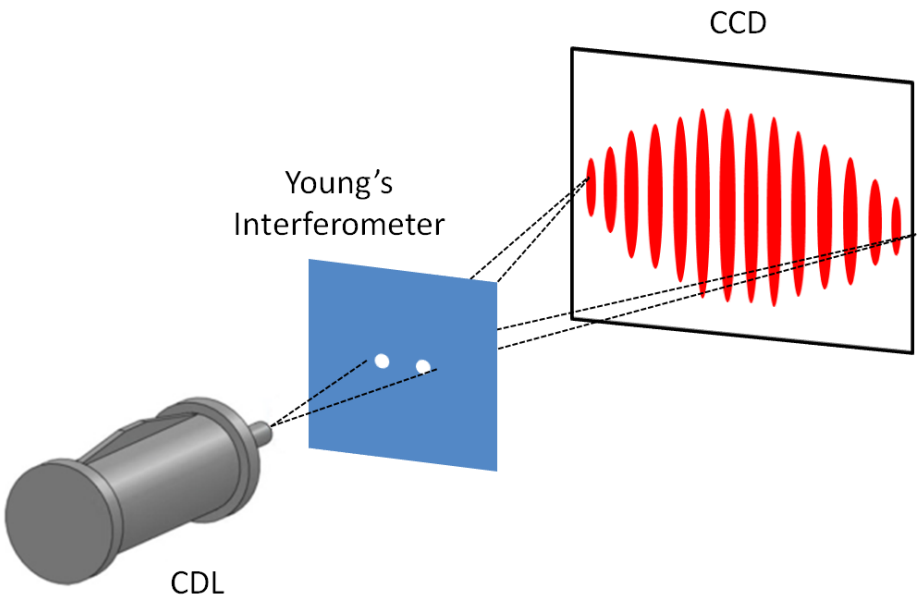
- Spectral bandwidth: $\Delta\lambda/\lambda = 3.5\ 10^{-5}$
- Power: miliwatts range
- Energy: typ. 0.1mJ-0.8mJ

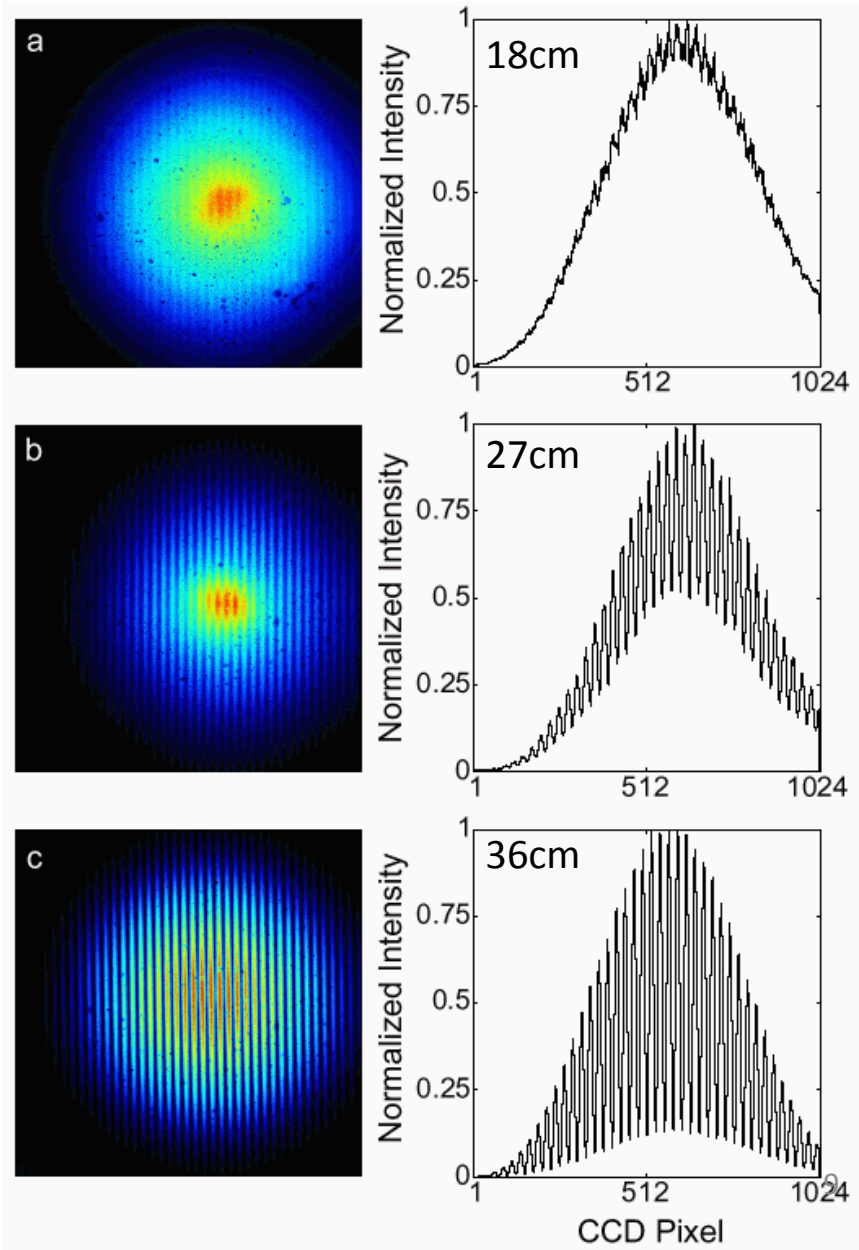
B.R. Benware, C.D. Macchietto, C.H. Moreno and J.J. Rocca, "Demonstration of a High Average Power Tabletop Soft X-Ray Laser," Phys. Rev. Lett. 81, 5804 (1998).

Spatial coherence

Characterization of spatial coherence:

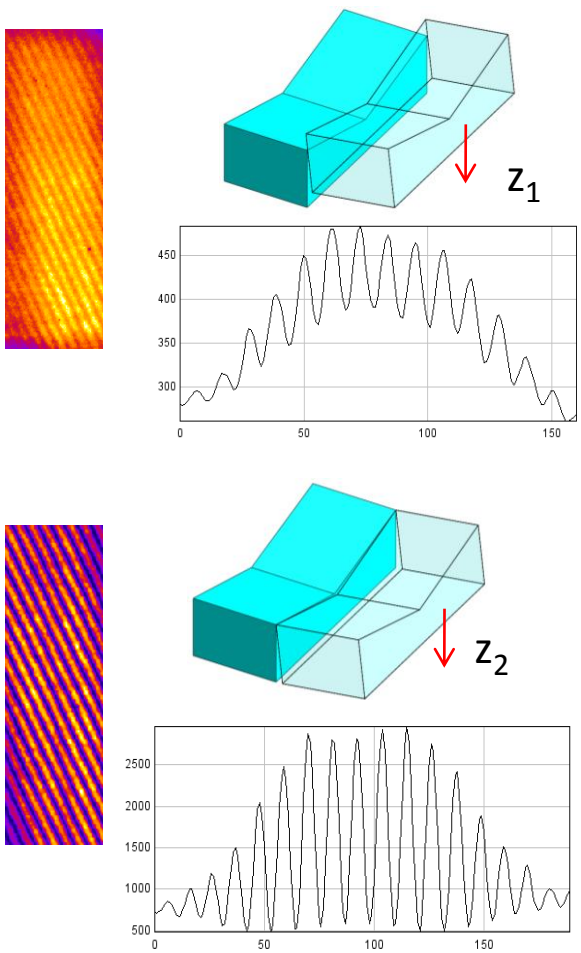
Young's interferometer

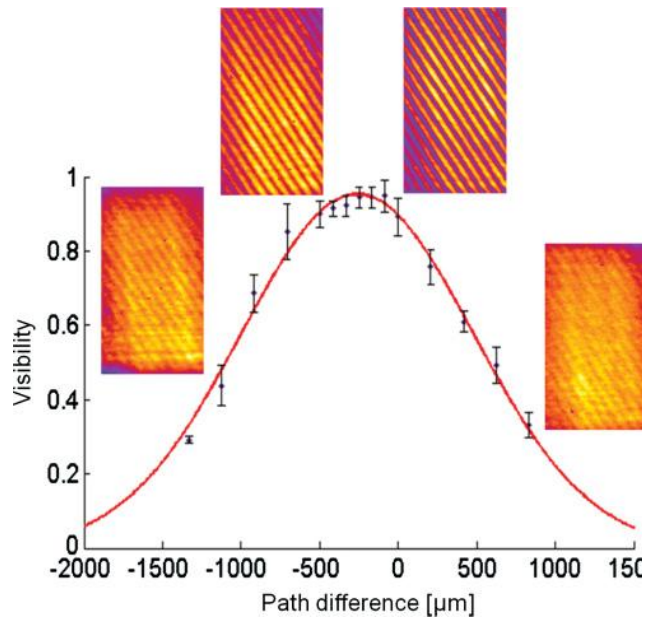


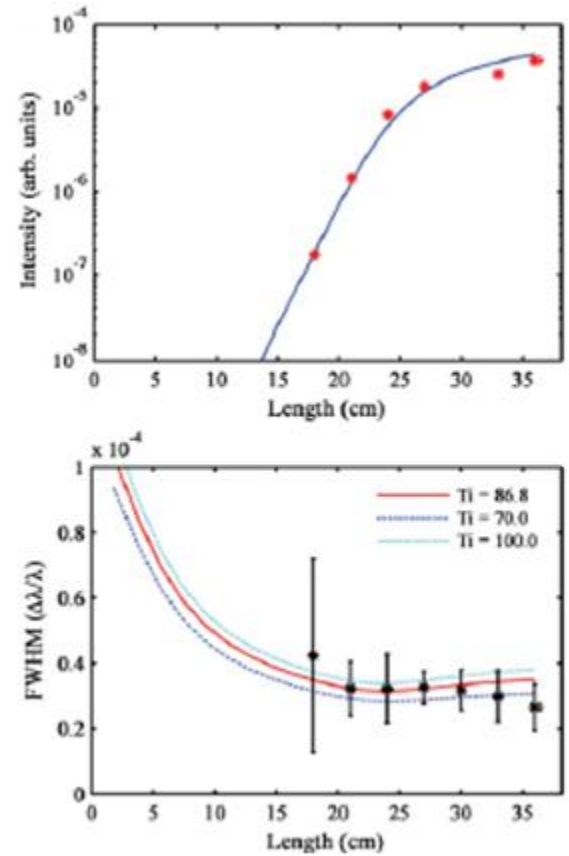


Y. Liu, et.al. *Phys. Rev. A,* **63**, 033802 (2001).

Temporal coherence







$\Delta\lambda/\lambda \sim 3.5\times10^{-5}$

L. Urbanski, et.al. *Phys. Rev. A*, ***85***, 033837 (2012)

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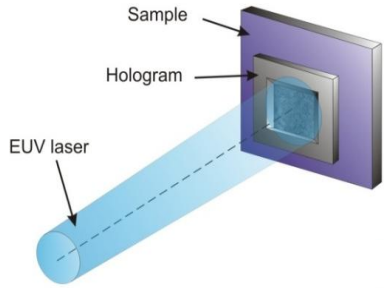
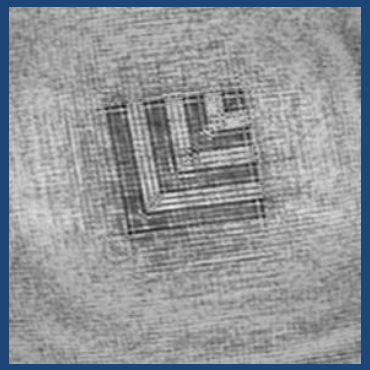
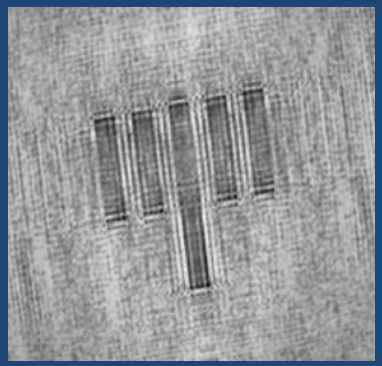
Nanoscale coherent lithography with table top EUV laser

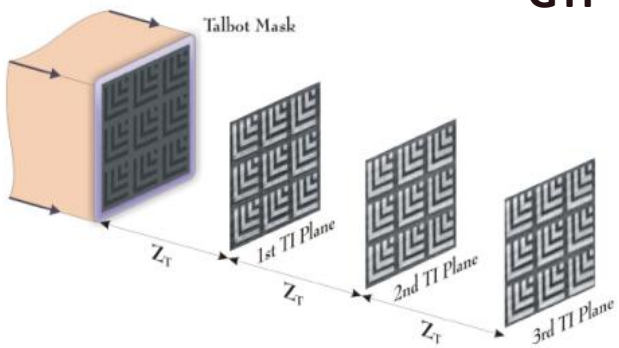
Holographic projection lithography

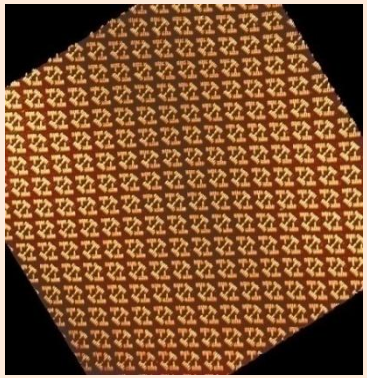


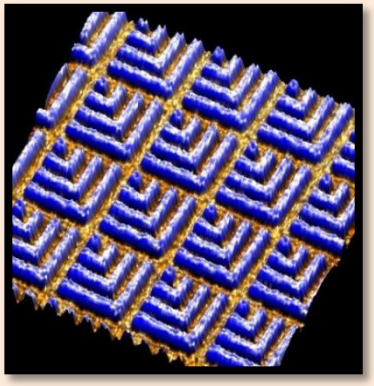




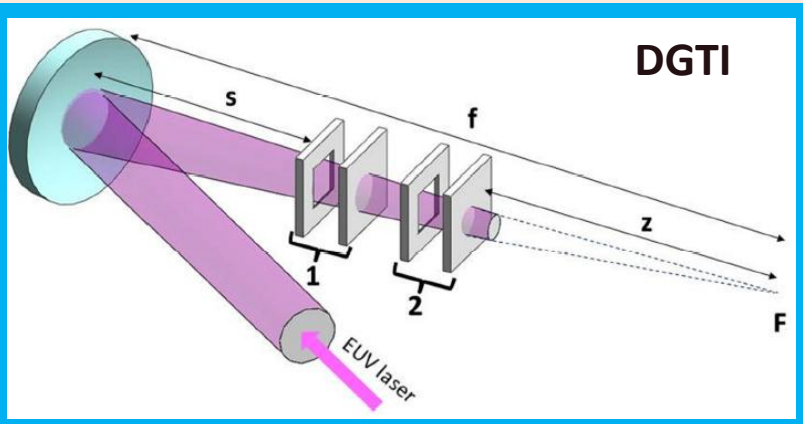
GTI

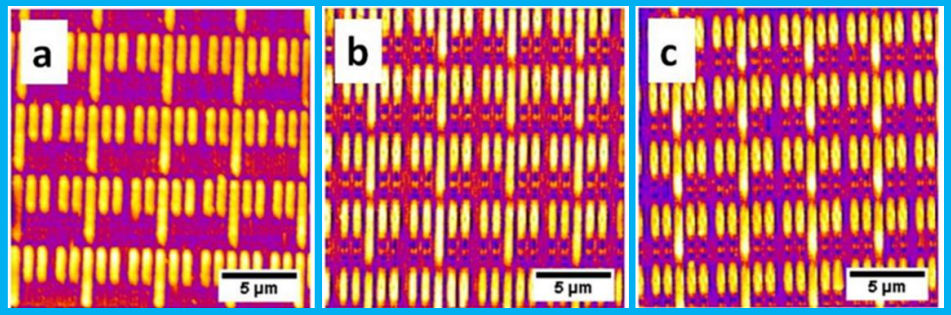






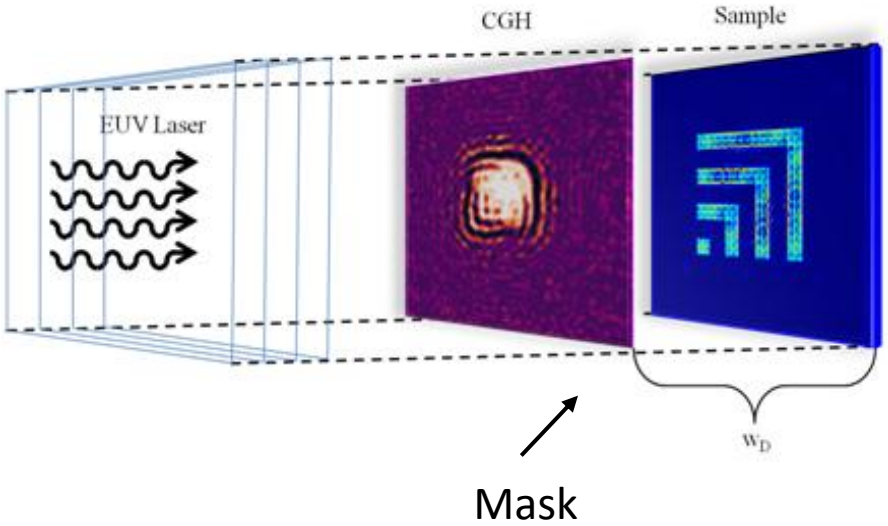
DGTI





Diffractive mask design and fabrication for EUV wavelengths

Holographic projection



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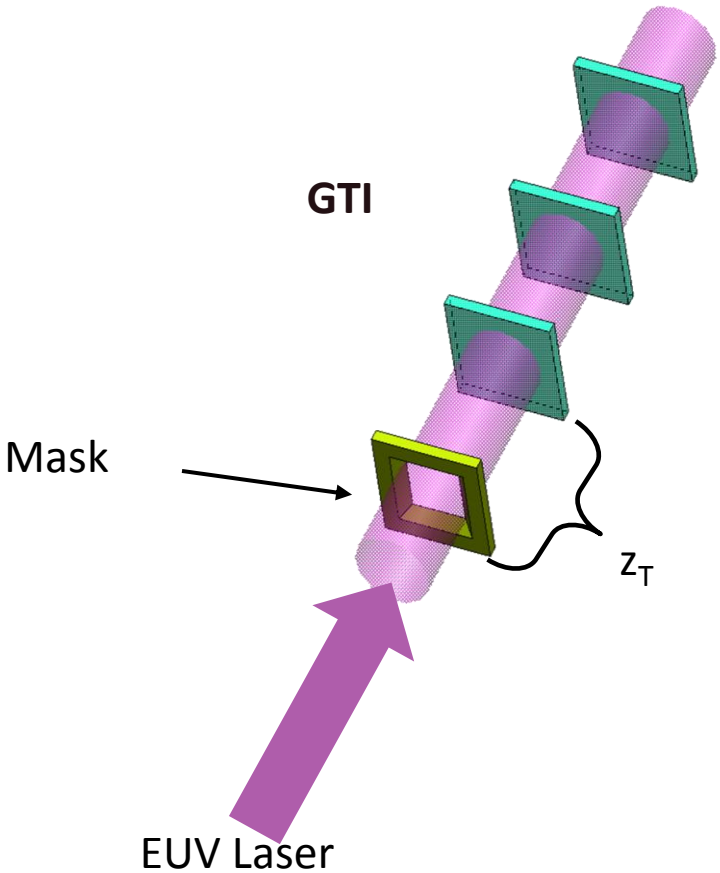
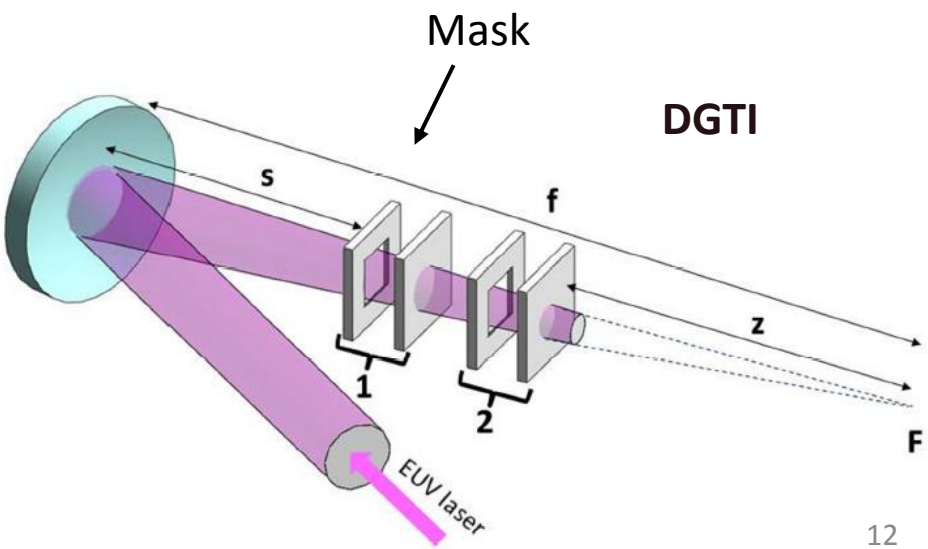
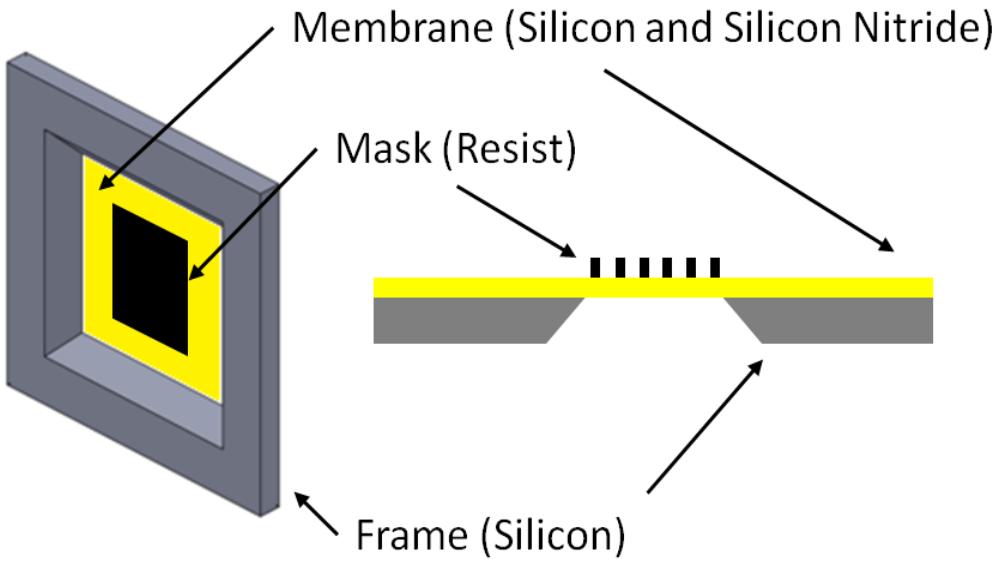
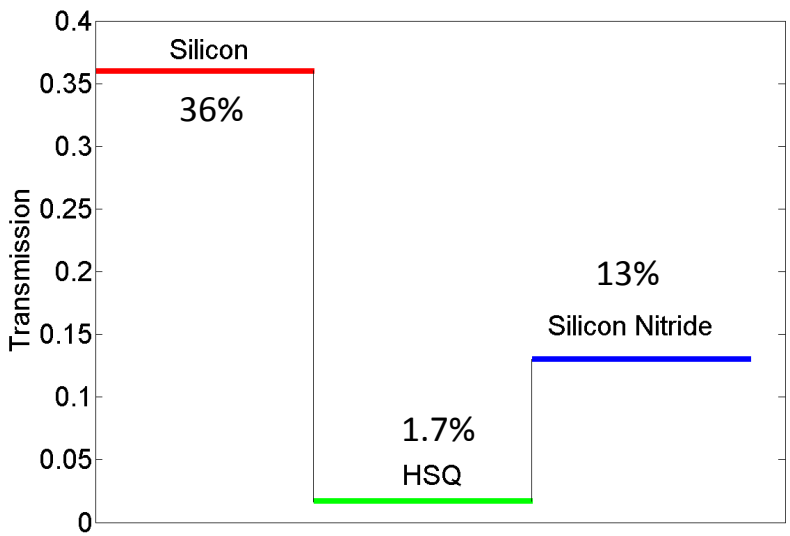


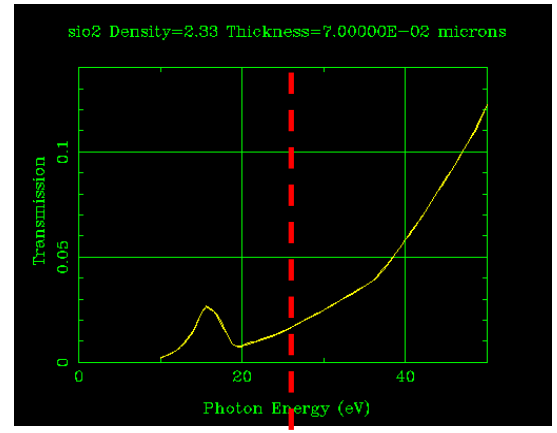


EUV Diffractive Mask

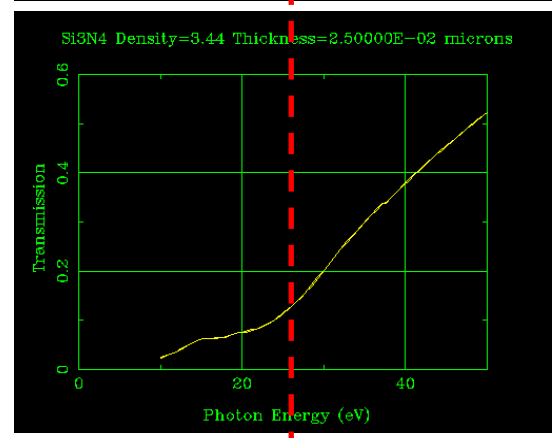




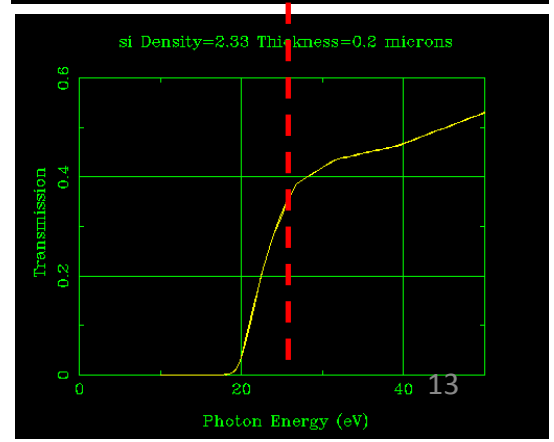
~70nm



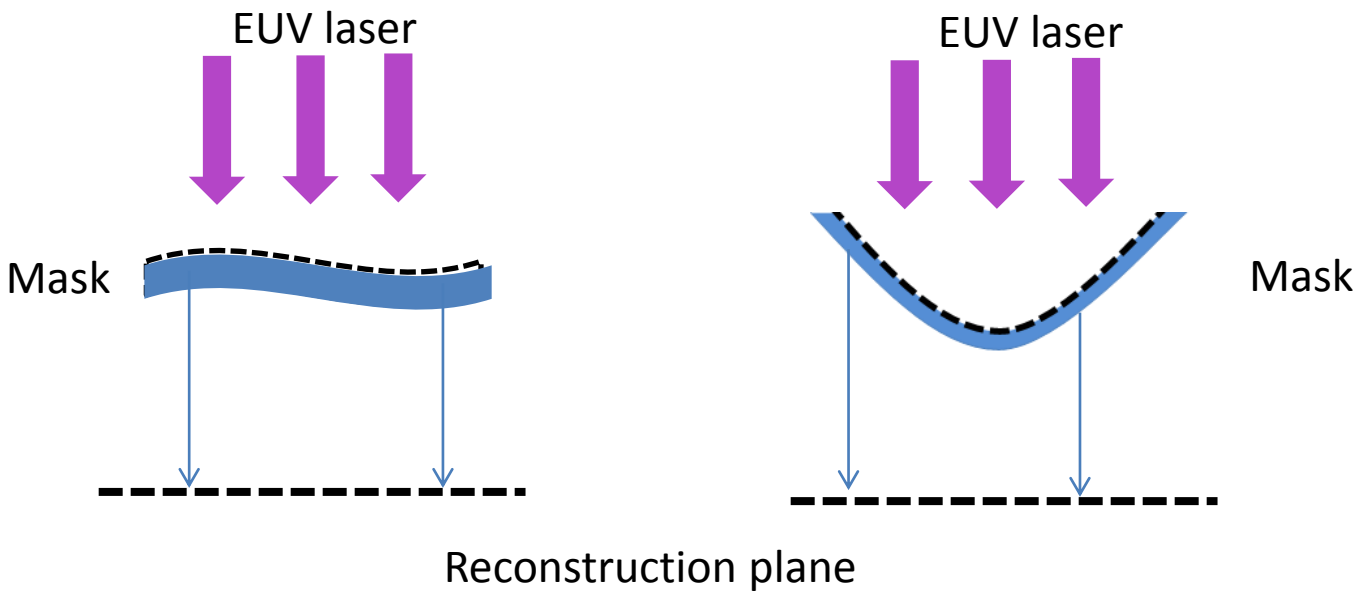
~25nm



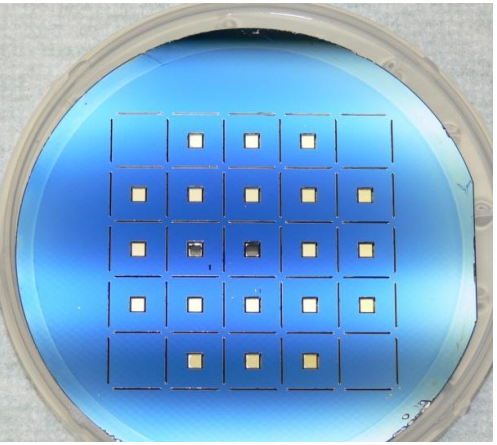
~200nm

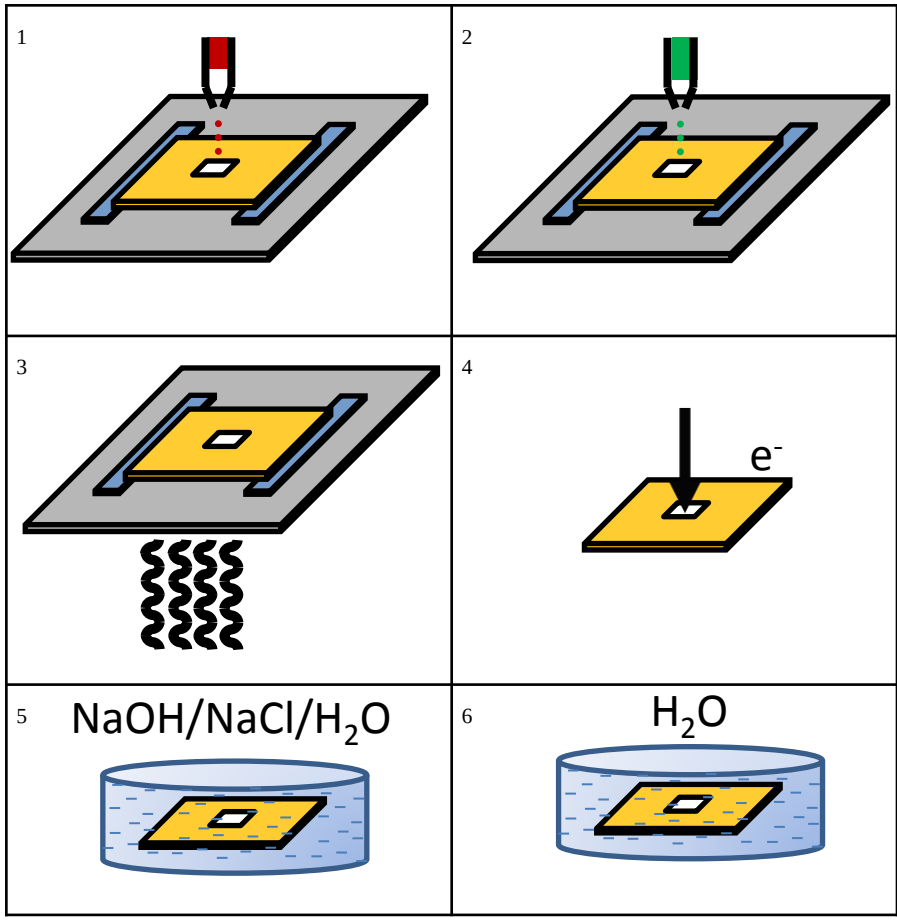


EUV Diffractive Mask – fabrication challenges



Mask Fabrication Protocol





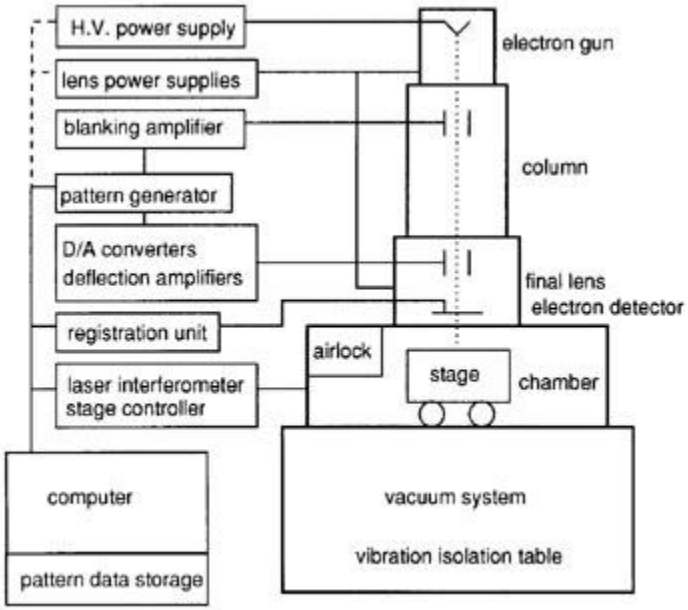
1. Spin Coating HSQ
2. Spin Coating ESPACER
3. E-beam lithography
4. Developing
5. Rinsing

EUV
An NSF Engineering Research Center

Colorado State University

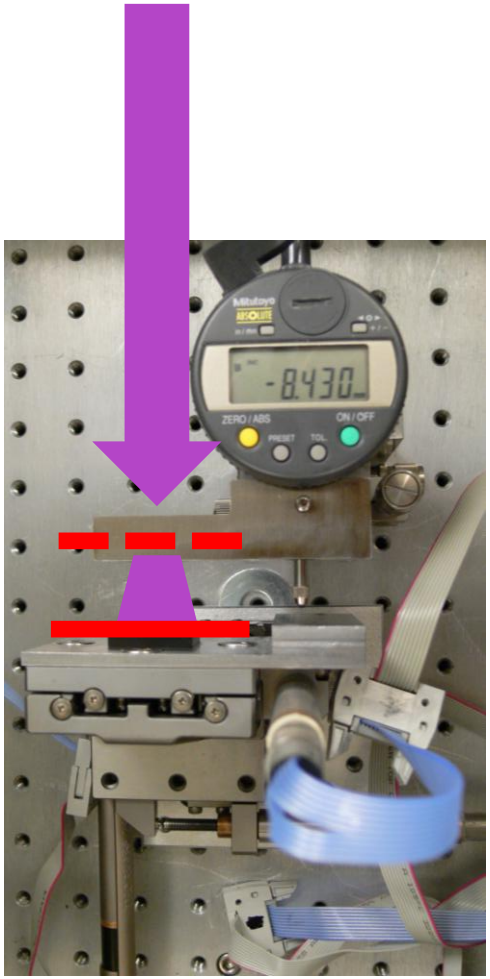
Center for Functional Nanomaterials
Brookhaven National Laboratory

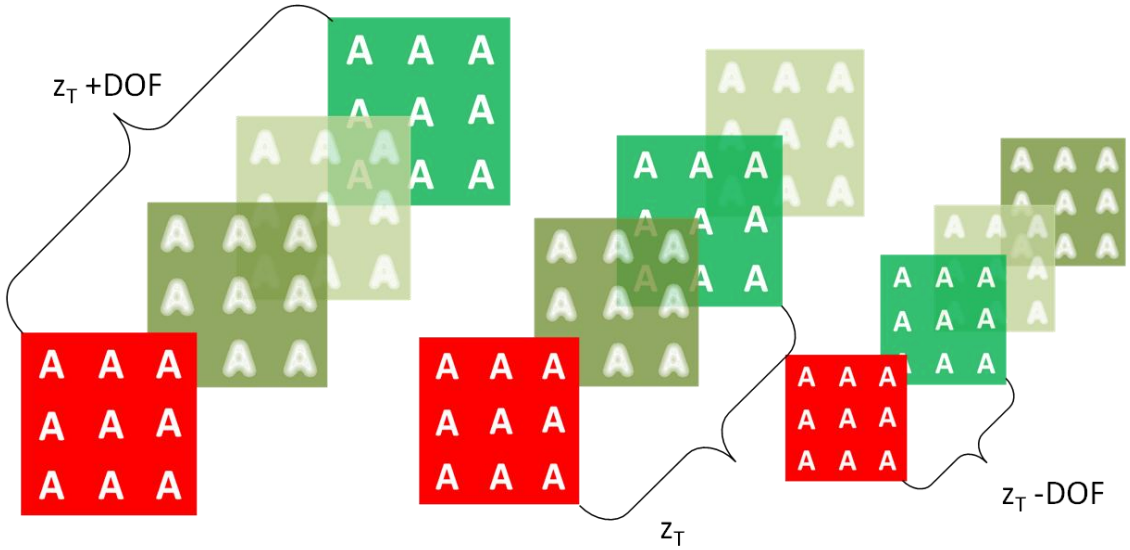
Mask Fabrication EBL

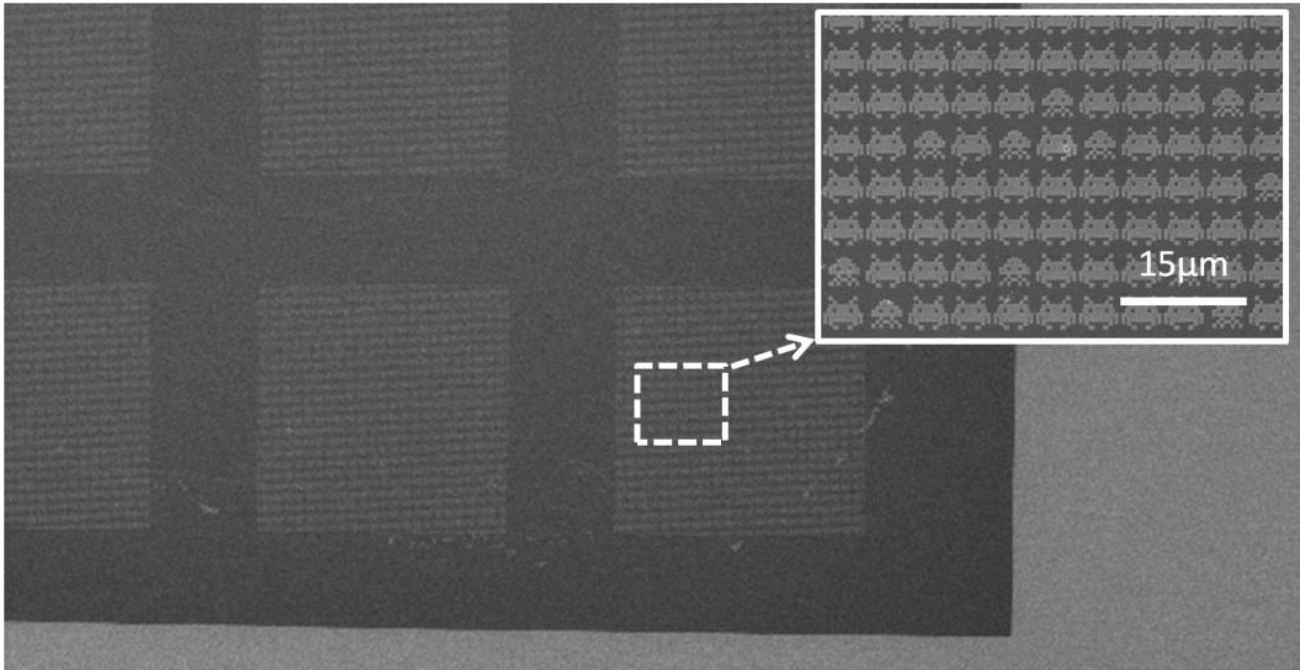


http://www.cnf.cornell.edu/image/spiefig1.jpg

Overpassing mechanical tolerances

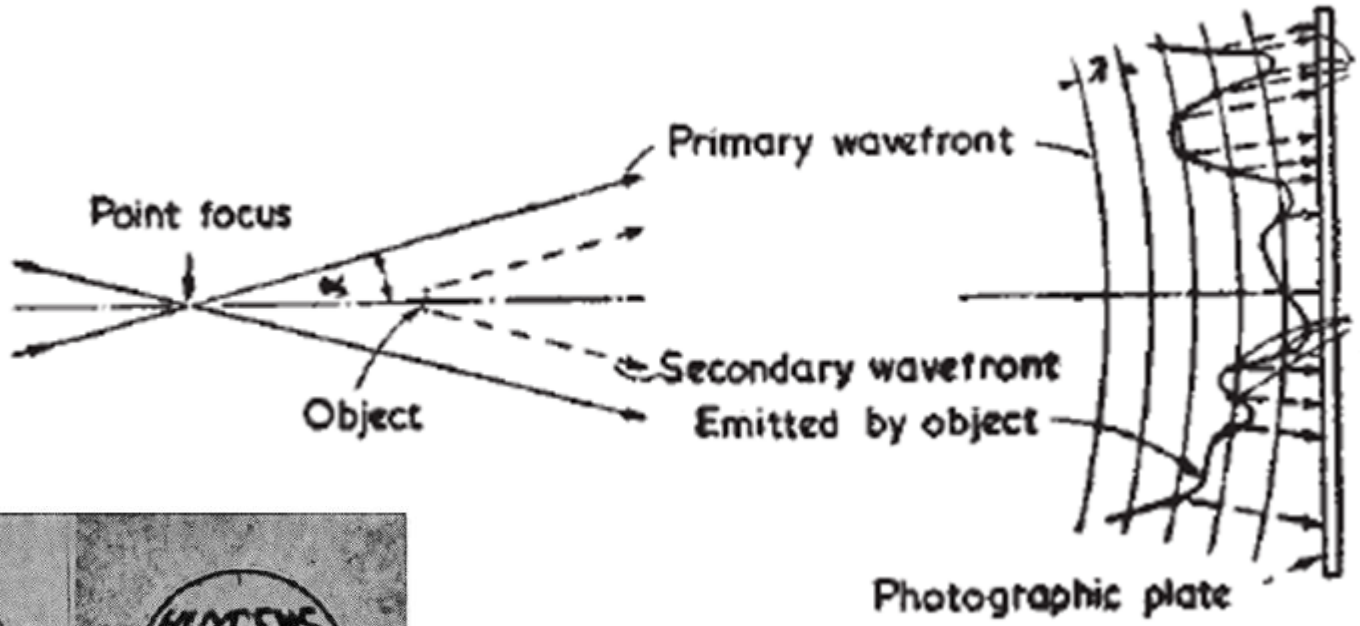


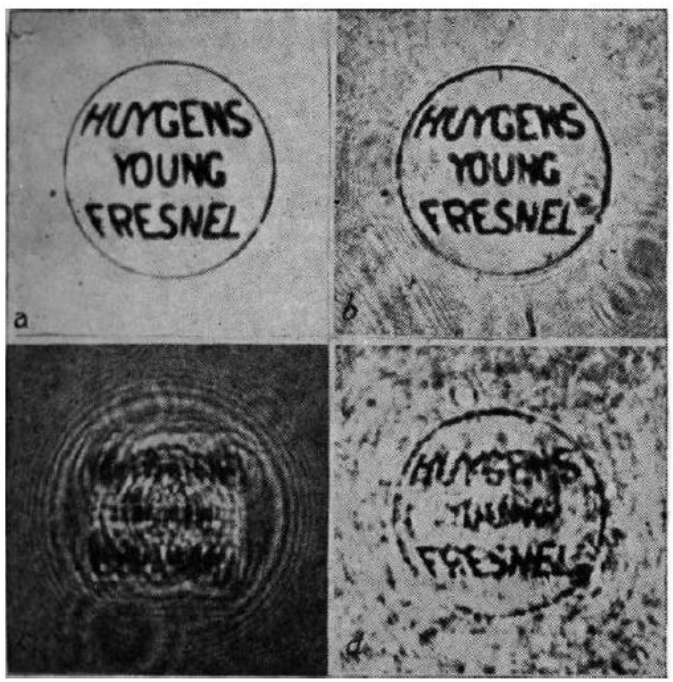




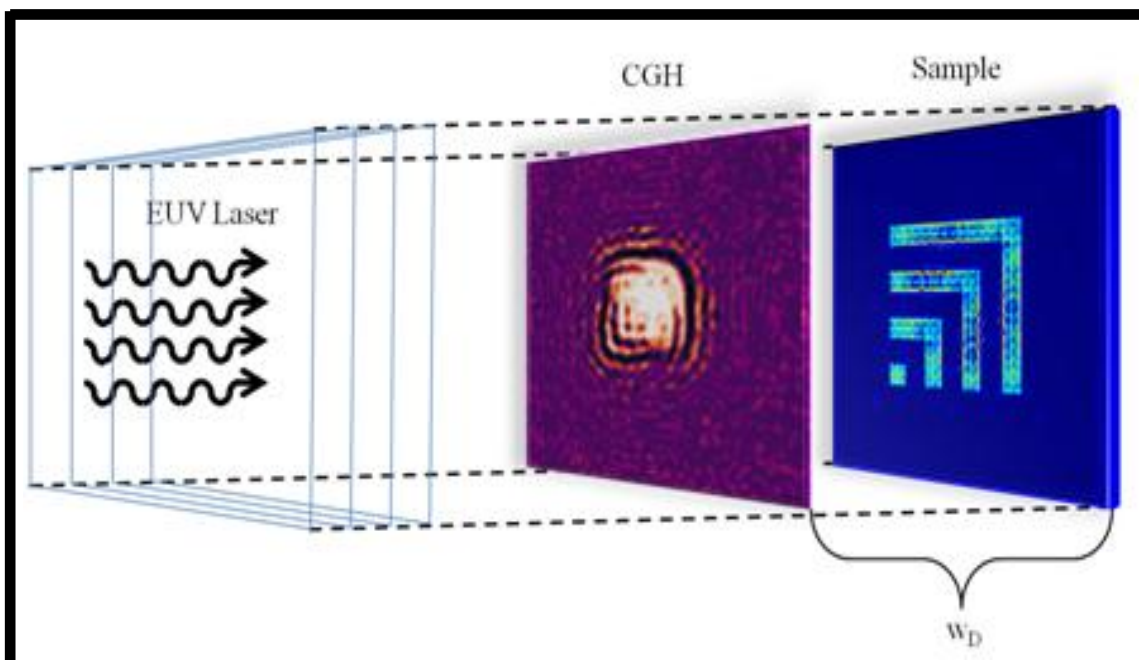
Holographic projection lithography

Holographic projection lithography

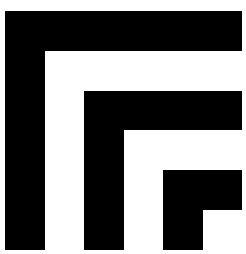


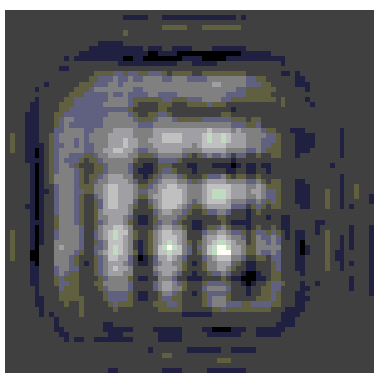


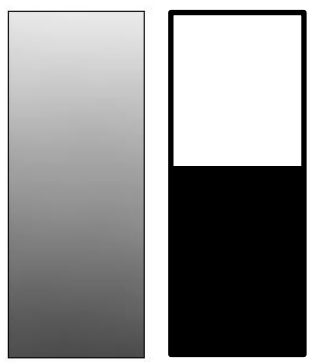
D. Gabor, Nature, **15**, 777 (1948)

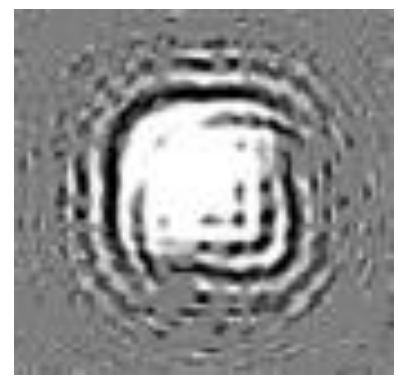


CGH calculation steps



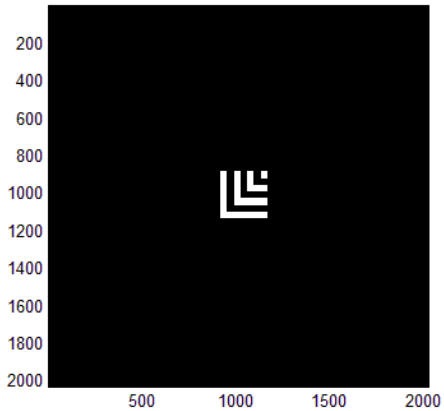




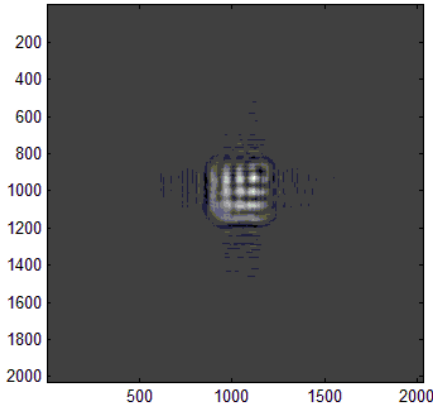


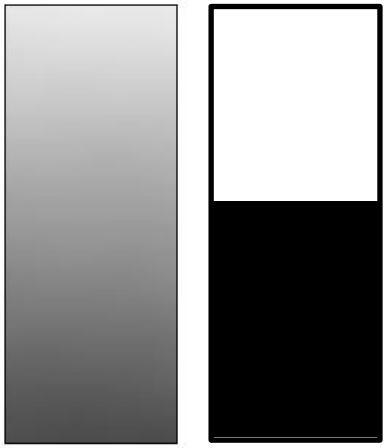
Hard threshold

Binary object

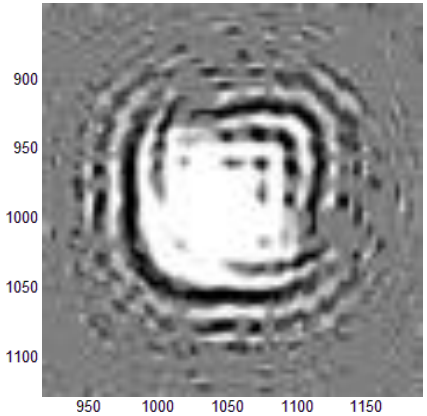


Fresnel propagation
(cont. tone hologram)

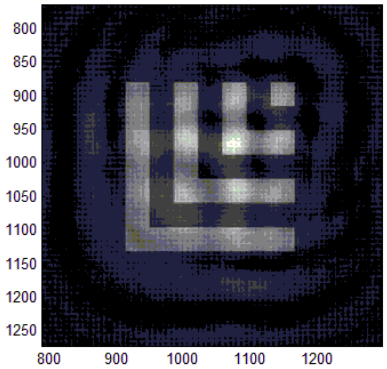




Half-toning

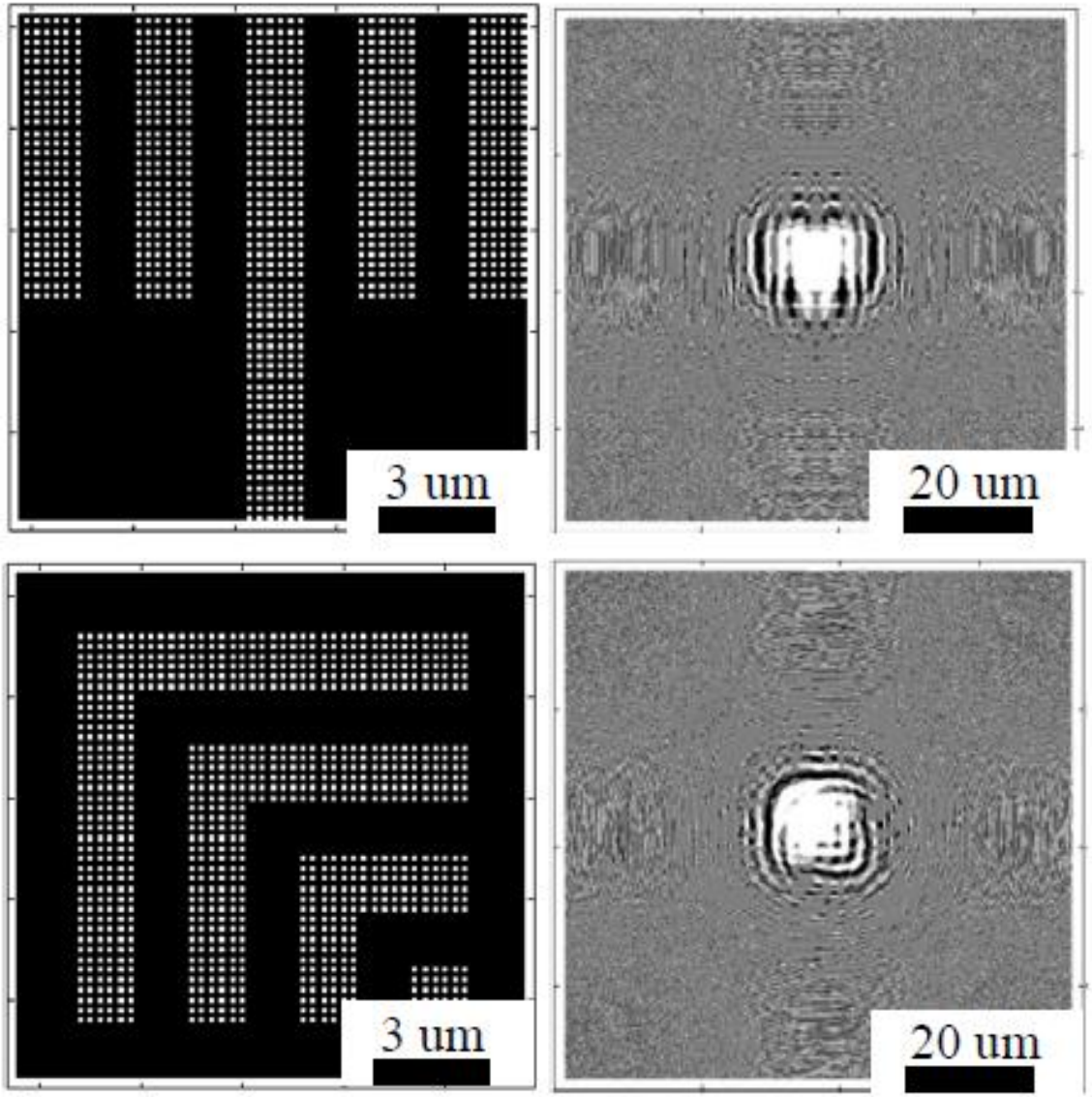


Binary
hologram



Reconstruction

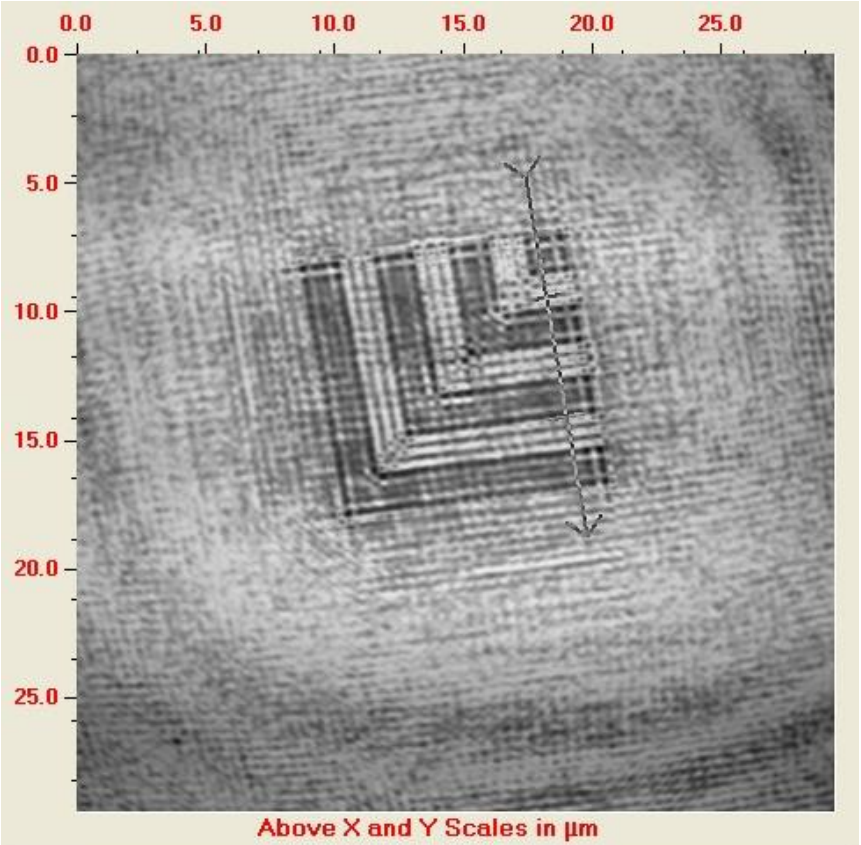
Half-toning by hard threshold

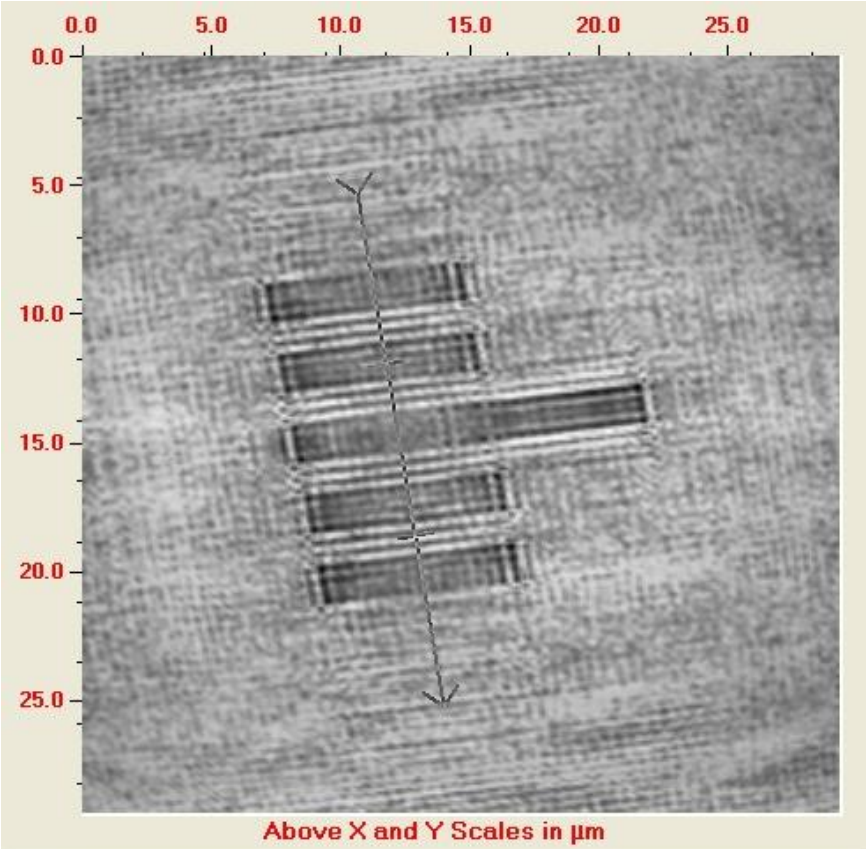


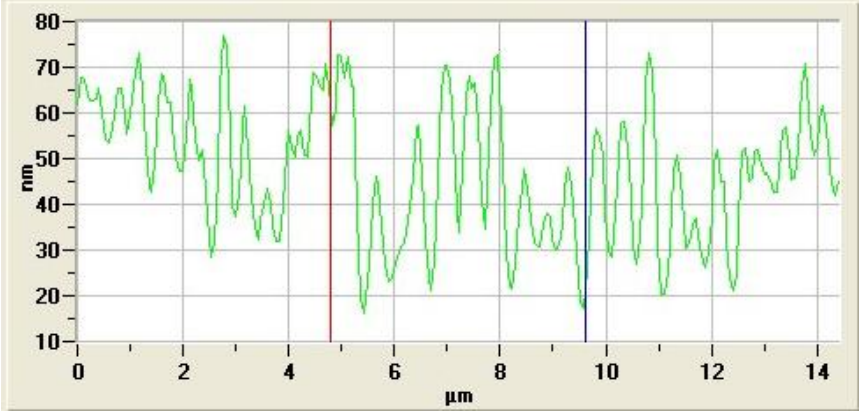
λ=46.9nm
Pixel Size=140nm
Z=500μm
Field=102.9μm
NA=0.102
DOF=4.5μm

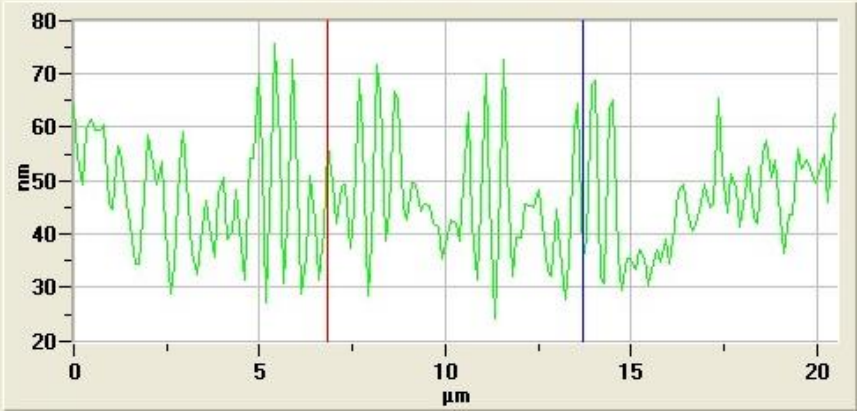
Binary objects and corresponding binary CGHs

Holographic projection lithography



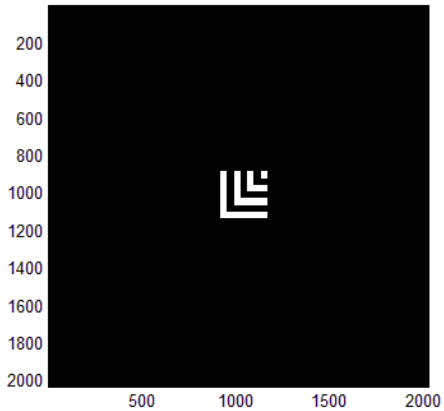




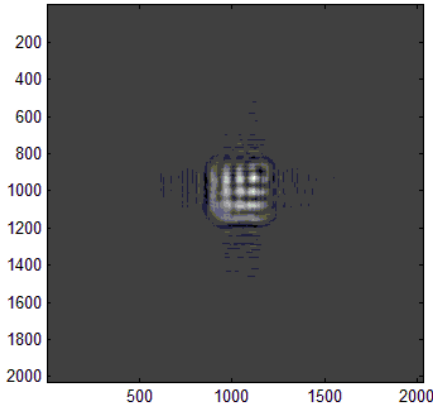


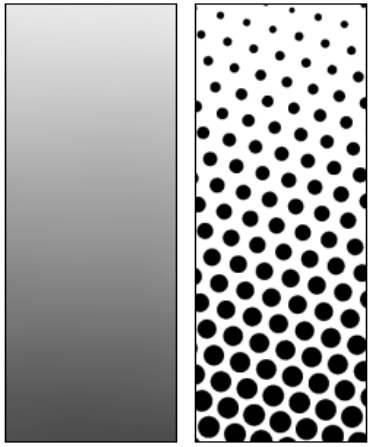
Screening

Binary object

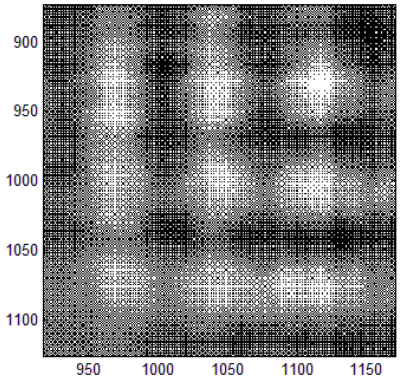


Fresnel propagation
(cont. tone hologram)

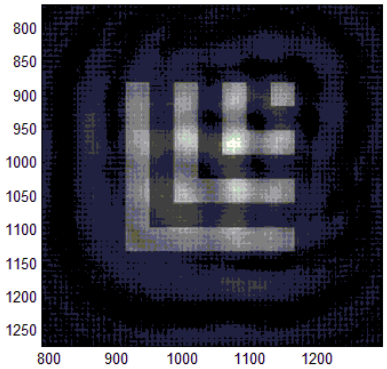




Half-toning

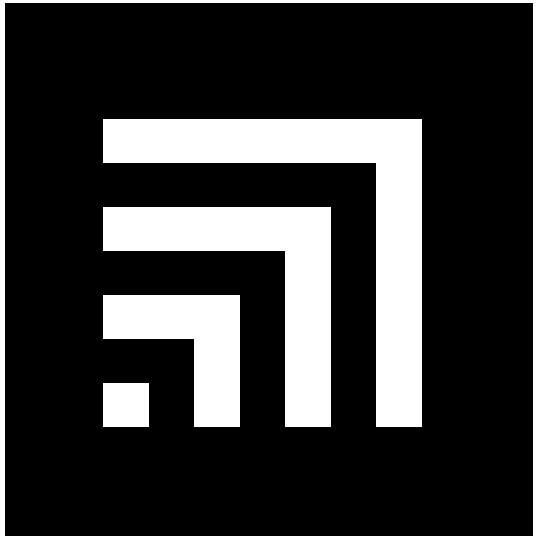


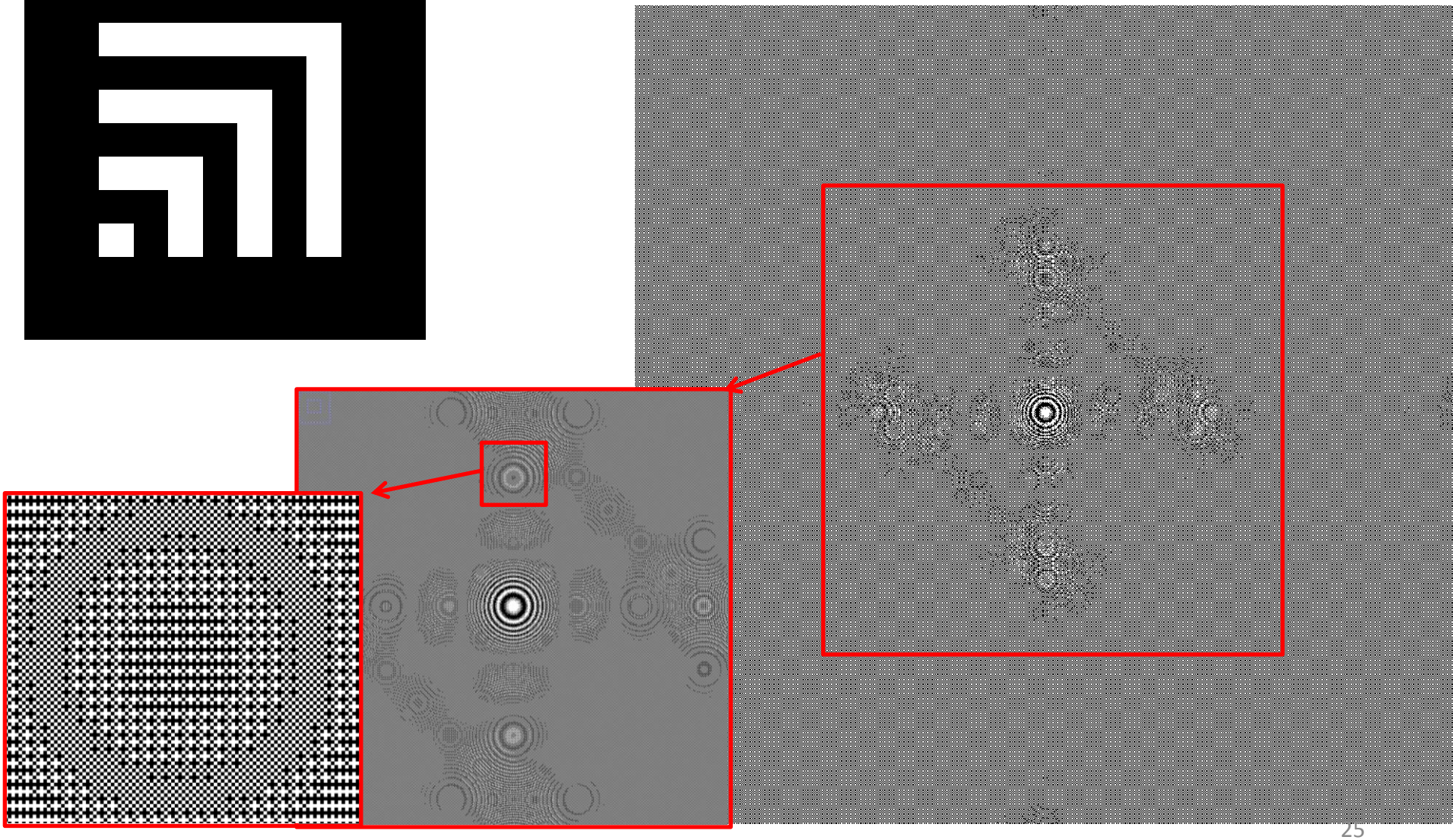
Binary
hologram



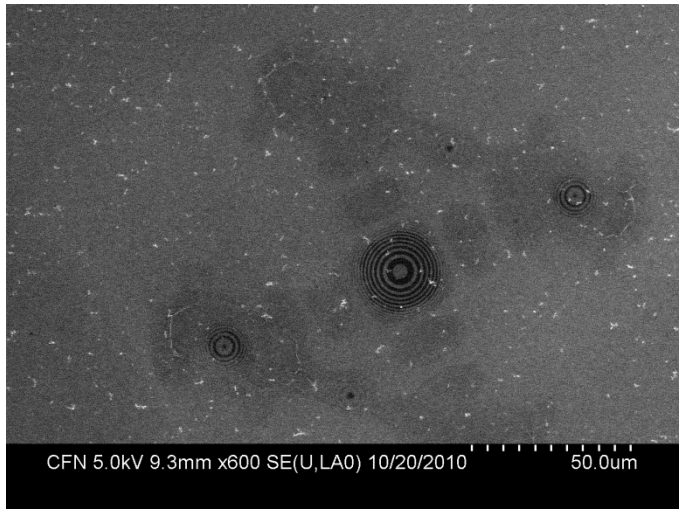
Reconstruction

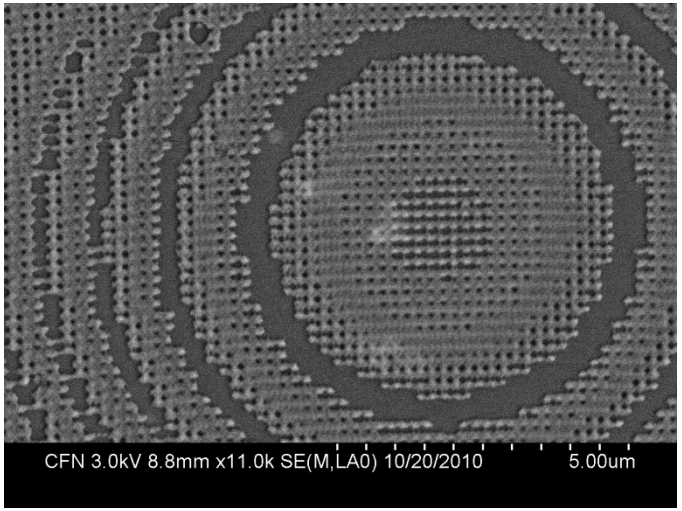
Computer Generated Hologram - dithering

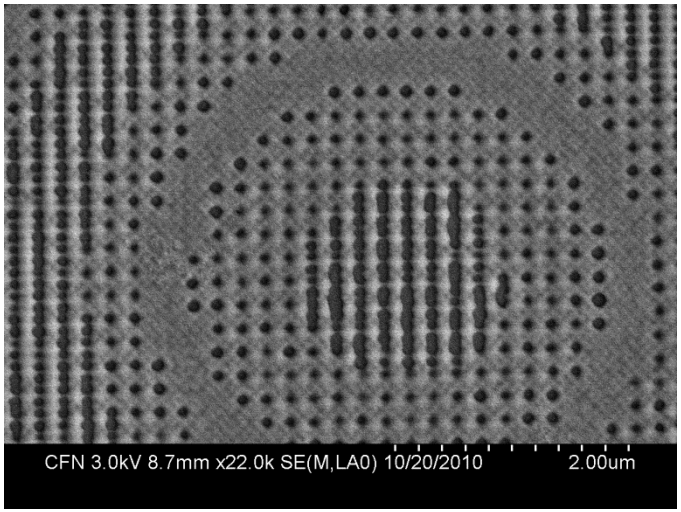


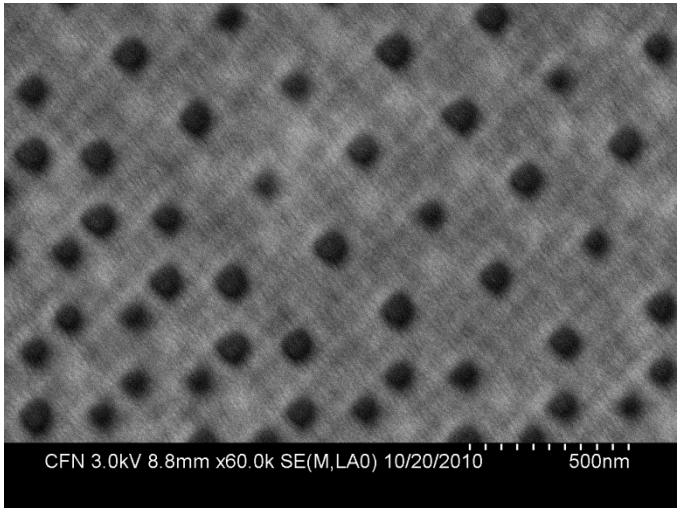


Computer Generated Hologram

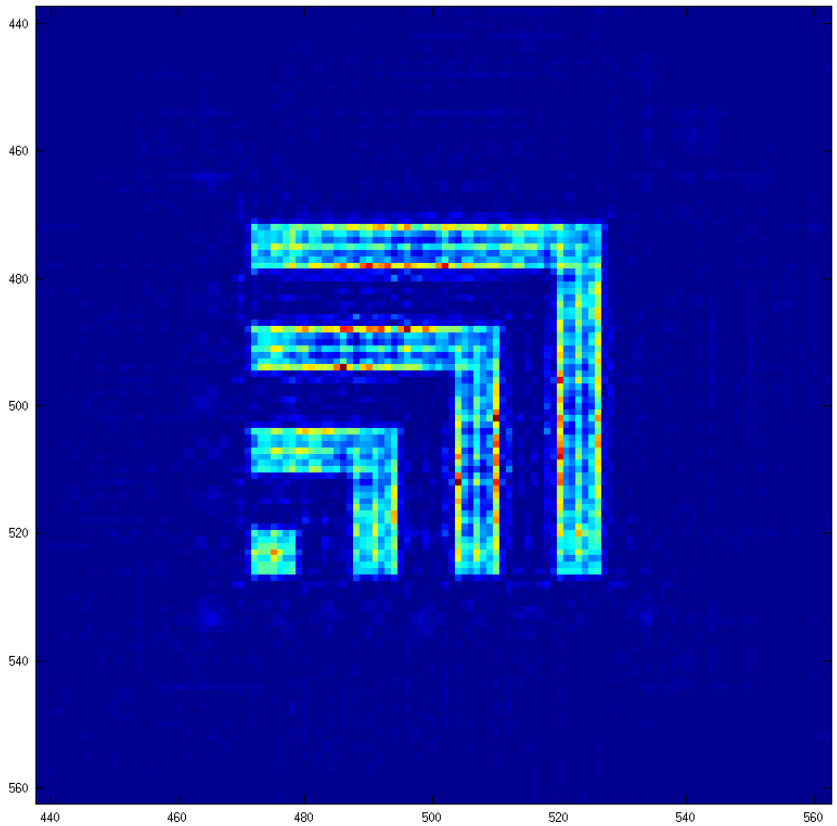








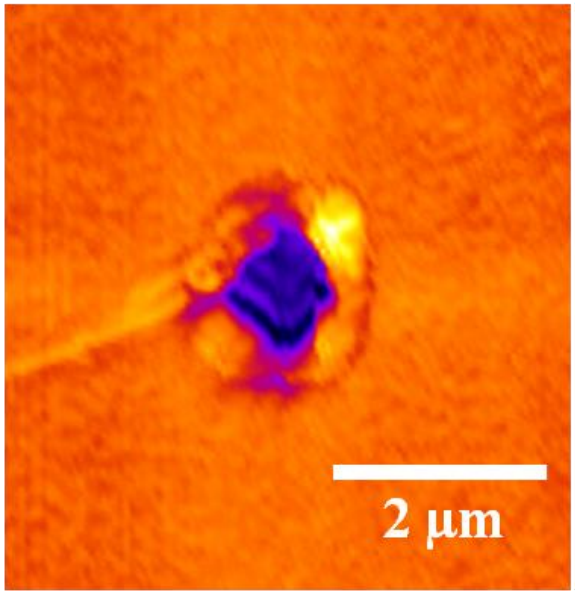
Computer Generated Hologram

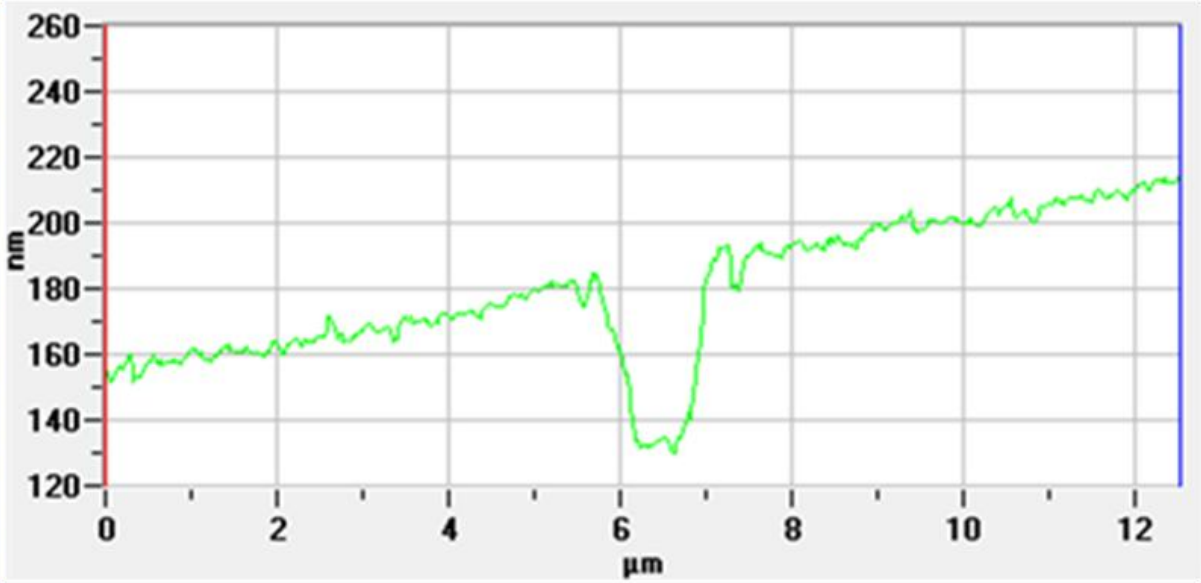


λ=46.9nm
pix size=50nm
Field=325µm
Z=~250µm
NA= ~0.6
Res= ~82nm
DOF= ~143nm

Numerical reconstruction of a CGH

Reconstruction in a photoresist



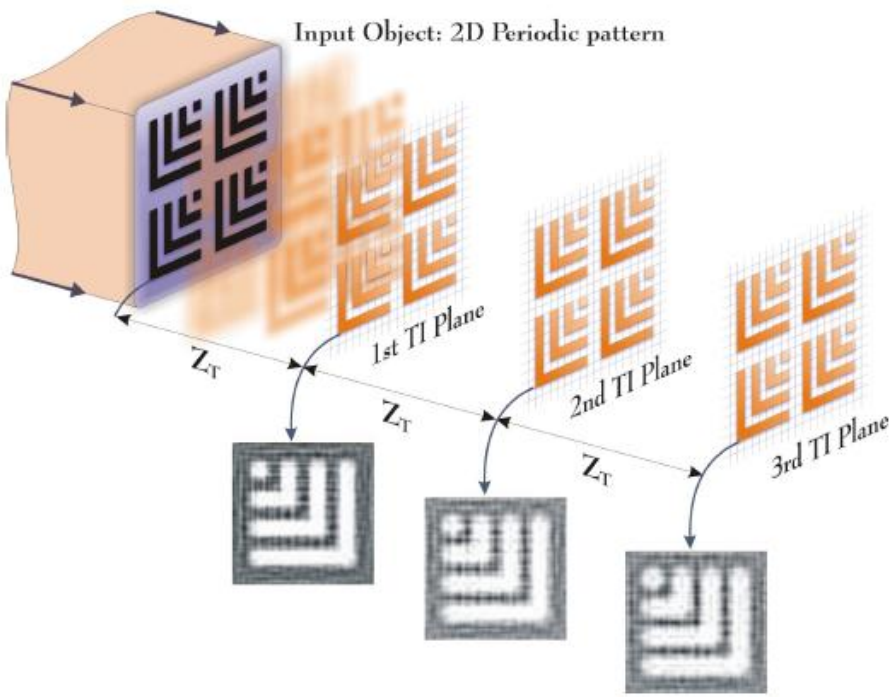


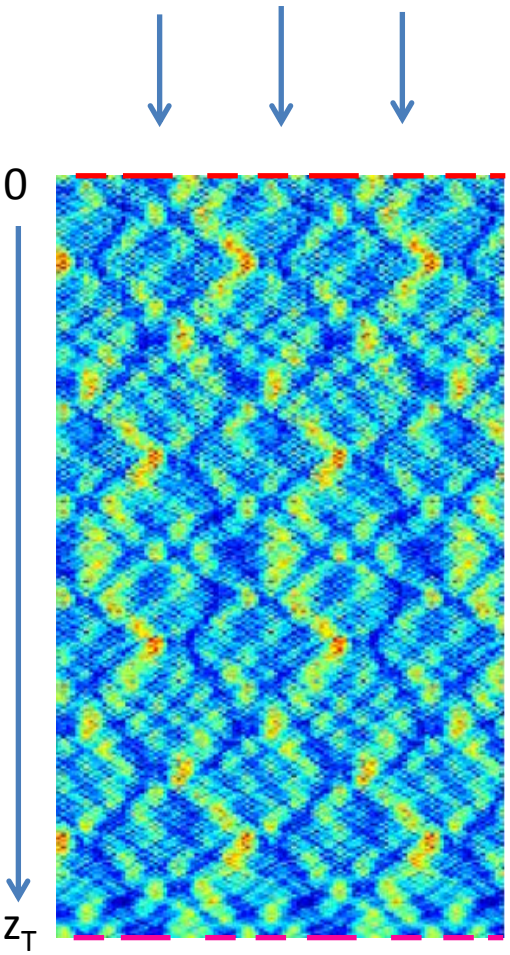
Summary

- Non-periodic features,
- Simple system,
- Small areas,
- Size is the limitation practical limit,
- Impractical for nanofabrication

Generalized Talbot imaging lithography

Generalized Talbot Imaging lithography





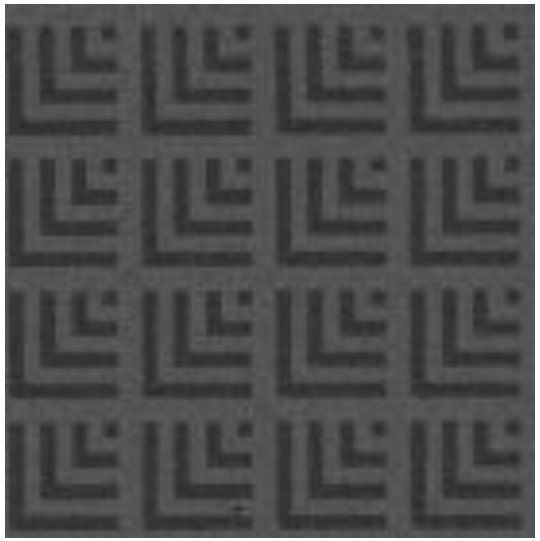
$$z_T = 2M\frac{p^2}{\lambda}$$

•H. F. Talbot, *"Facts relating to optical science" No. IV, Philos. Mag.* ***9****, 401 (1836).*

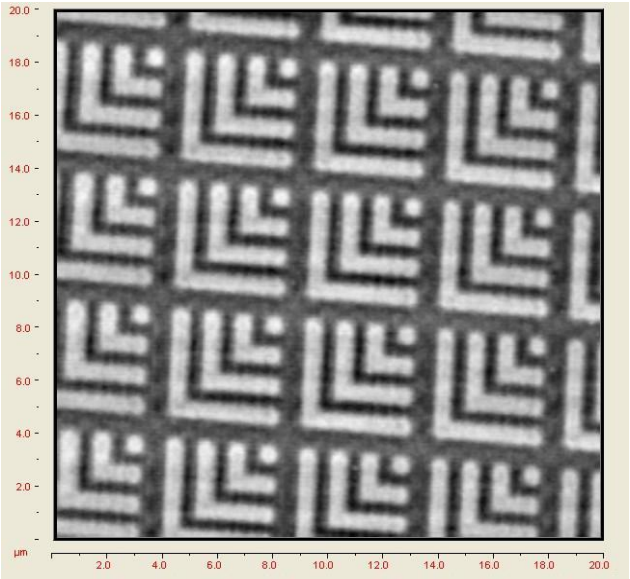
•F.R.S Rayleigh, *"On copying diffraction gratings and on some phenomenon connected therewith", Philos. Mag.* ***11****, (1881).*

Previous results

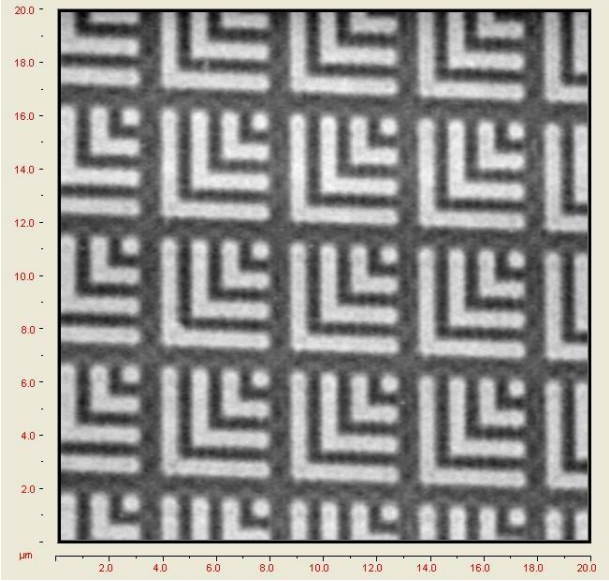
Talbot Mask



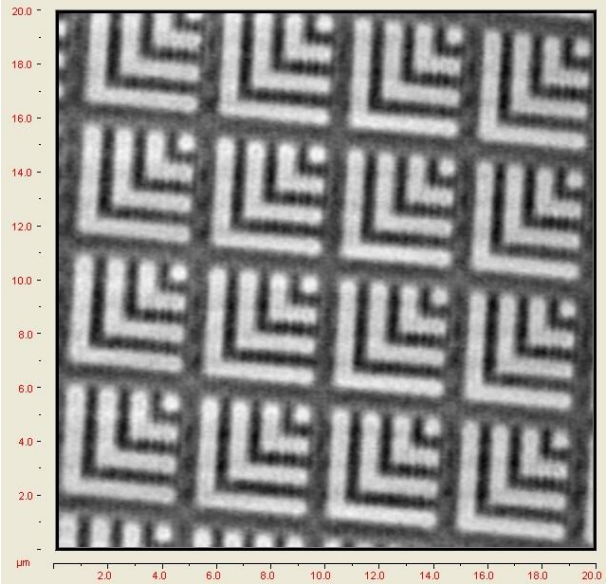
1st Talbot Plane



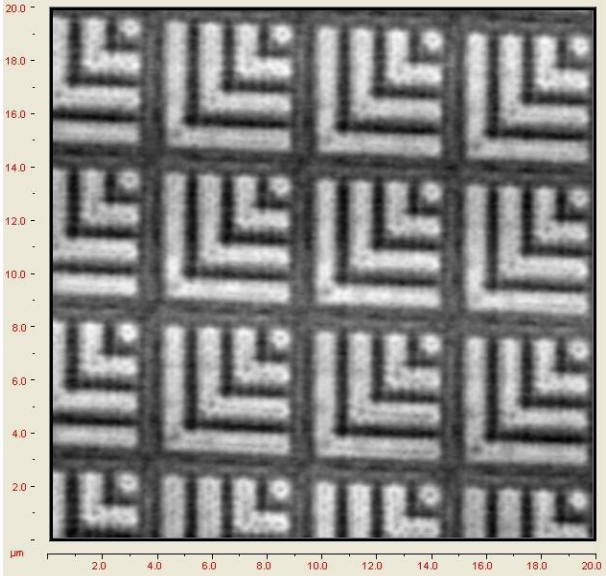
2nd Talbot Plane



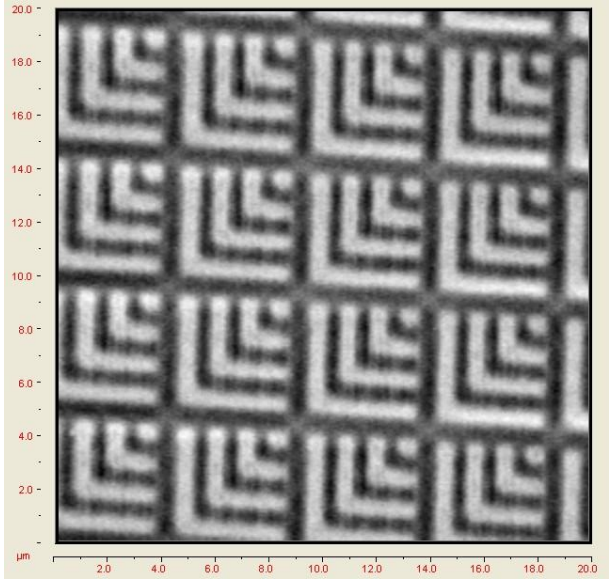
3rd Talbot Plane



4th Talbot Plane



5th Talbot Plane

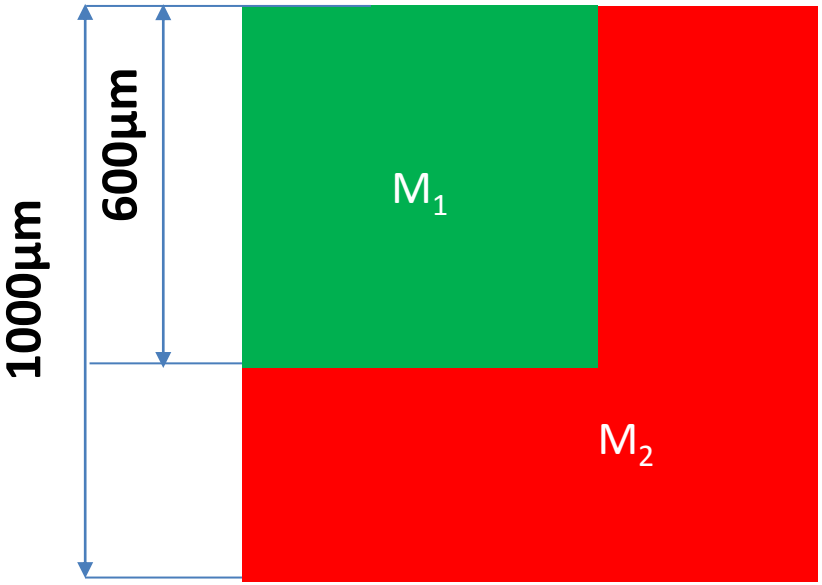


High NA GTI Lithography

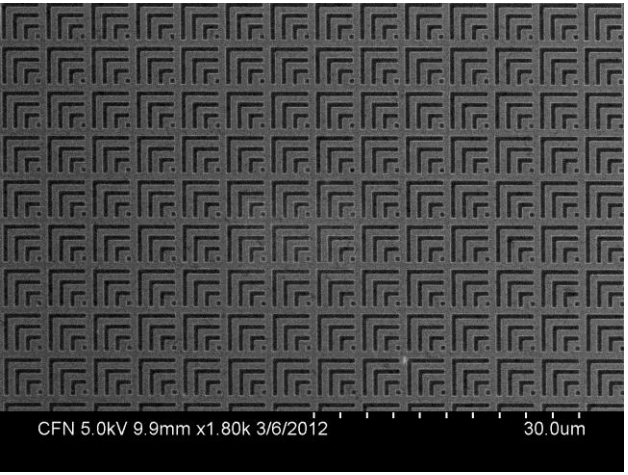
$$\Delta = 0.61\frac{\lambda}{NA} = 0.61\lambda\sqrt{1+\left(\frac{z_T}{W}\right)^2}$$

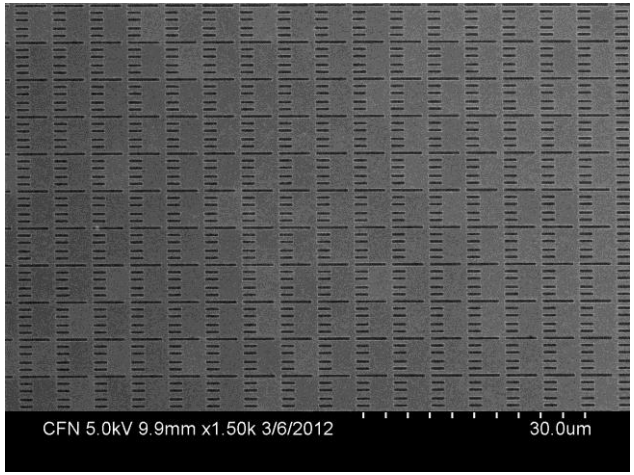
W=600μm
Δ=99.5nm

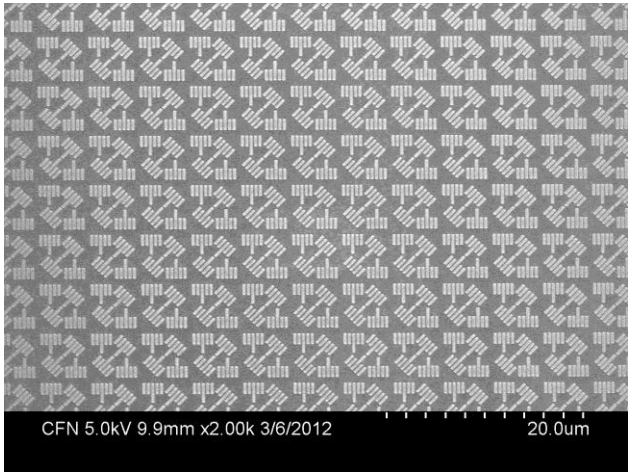
W=1000μm
Δ=63.8nm

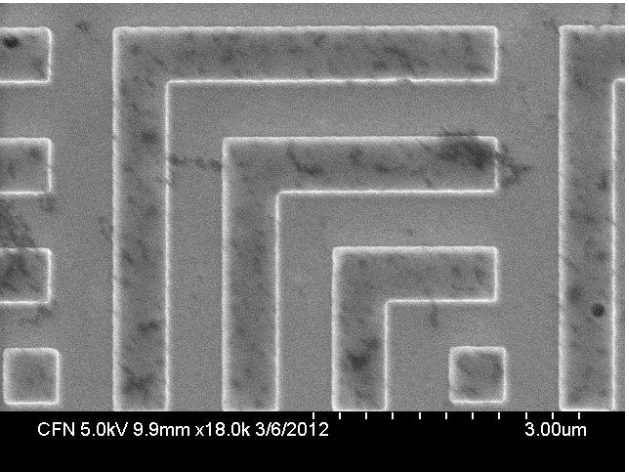


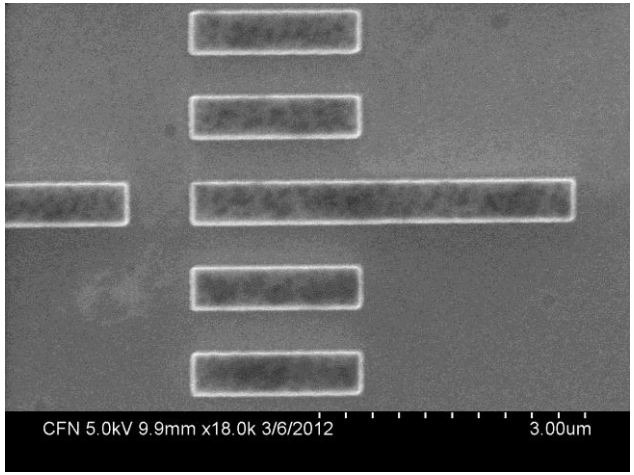
High NA GTI Lithography

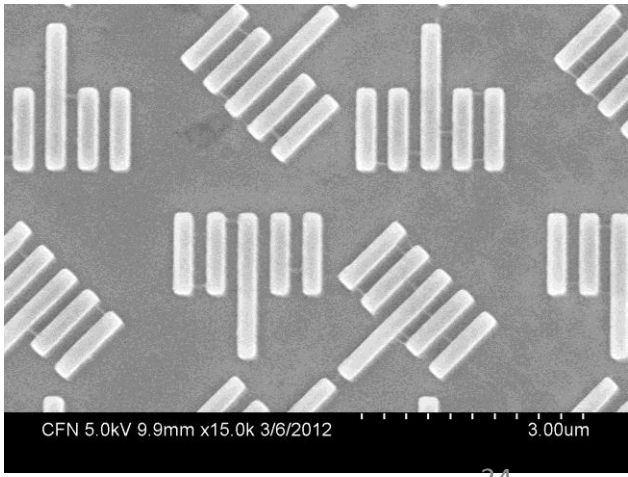




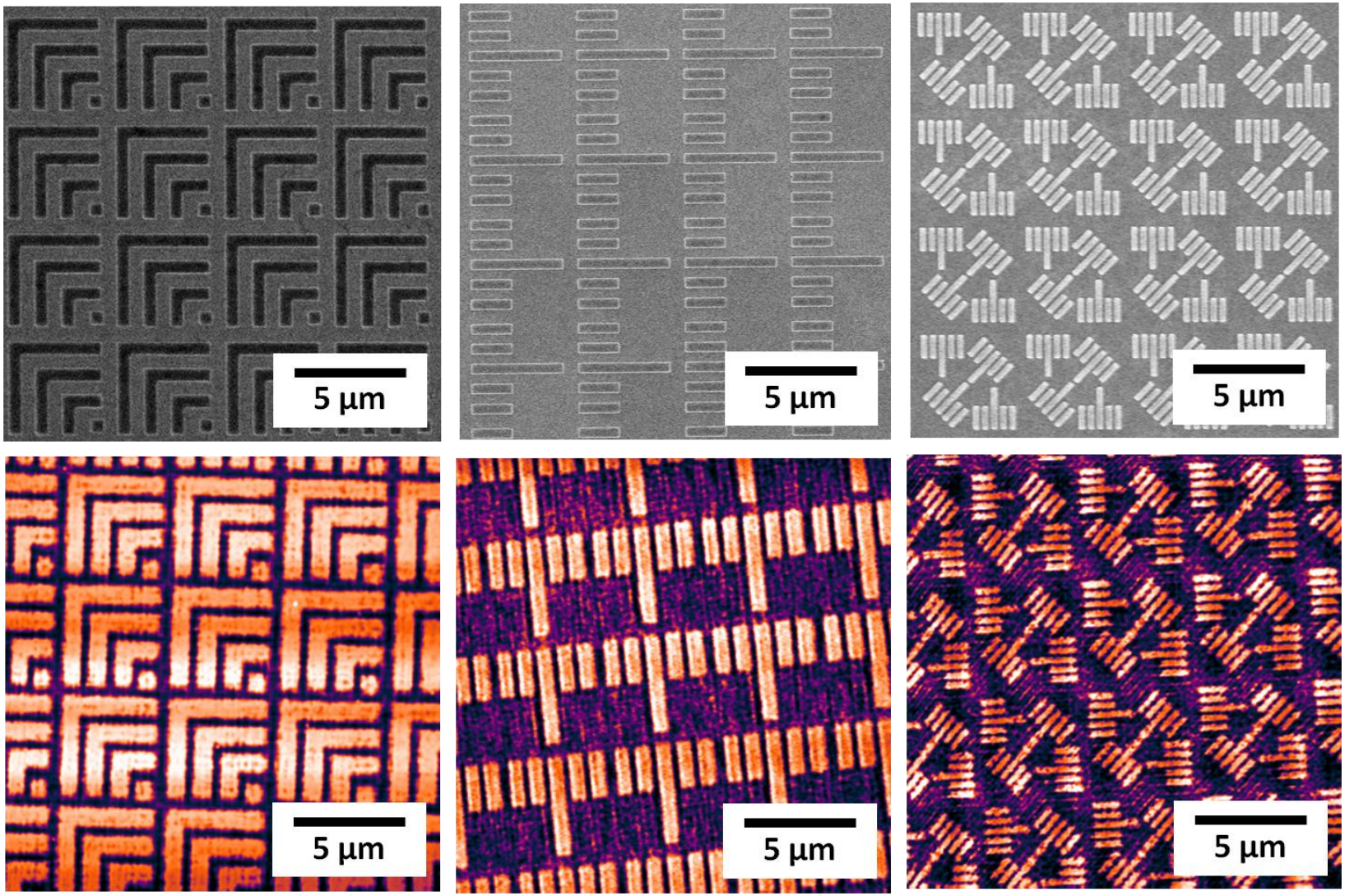






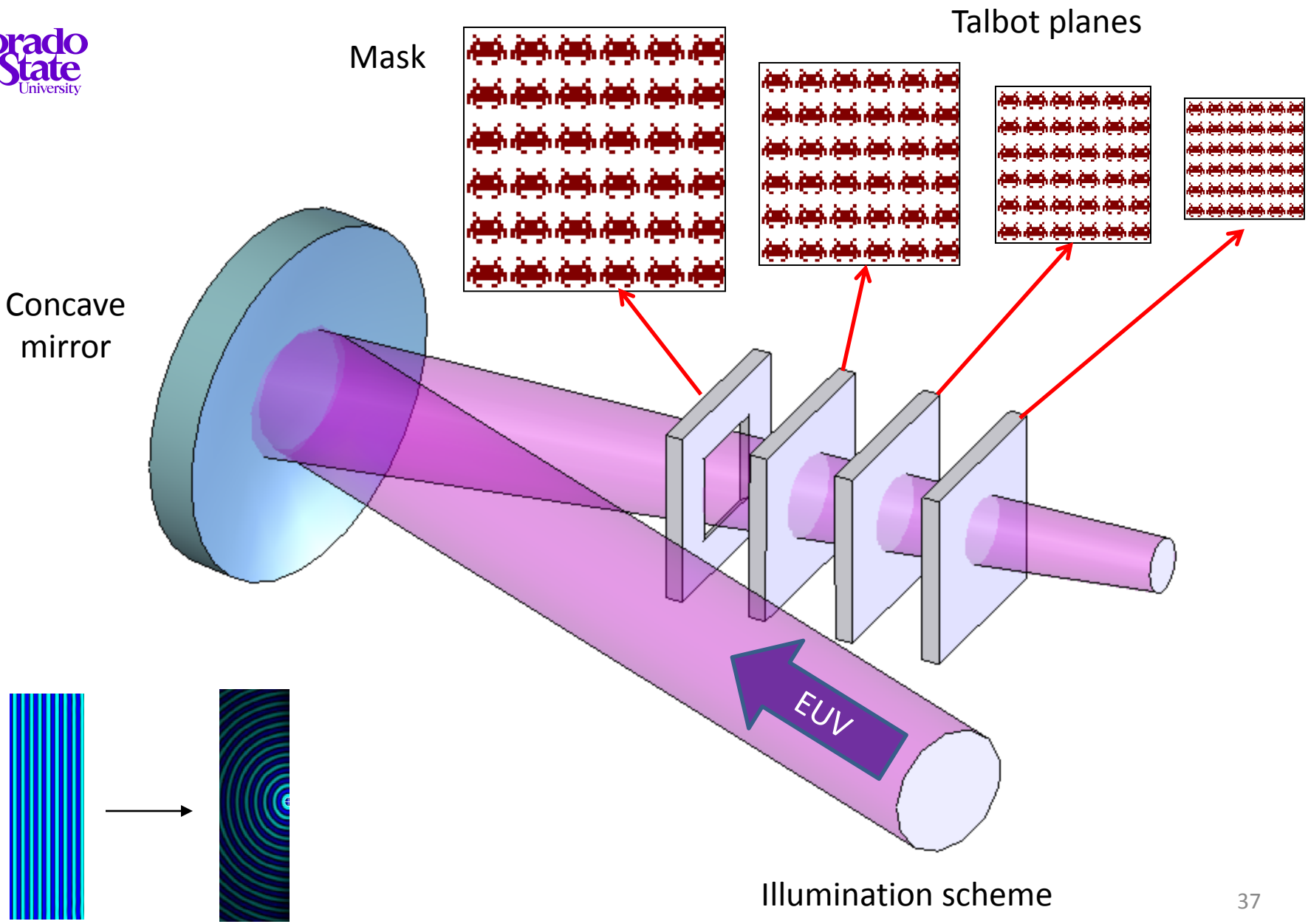


High NA GTI Lithography

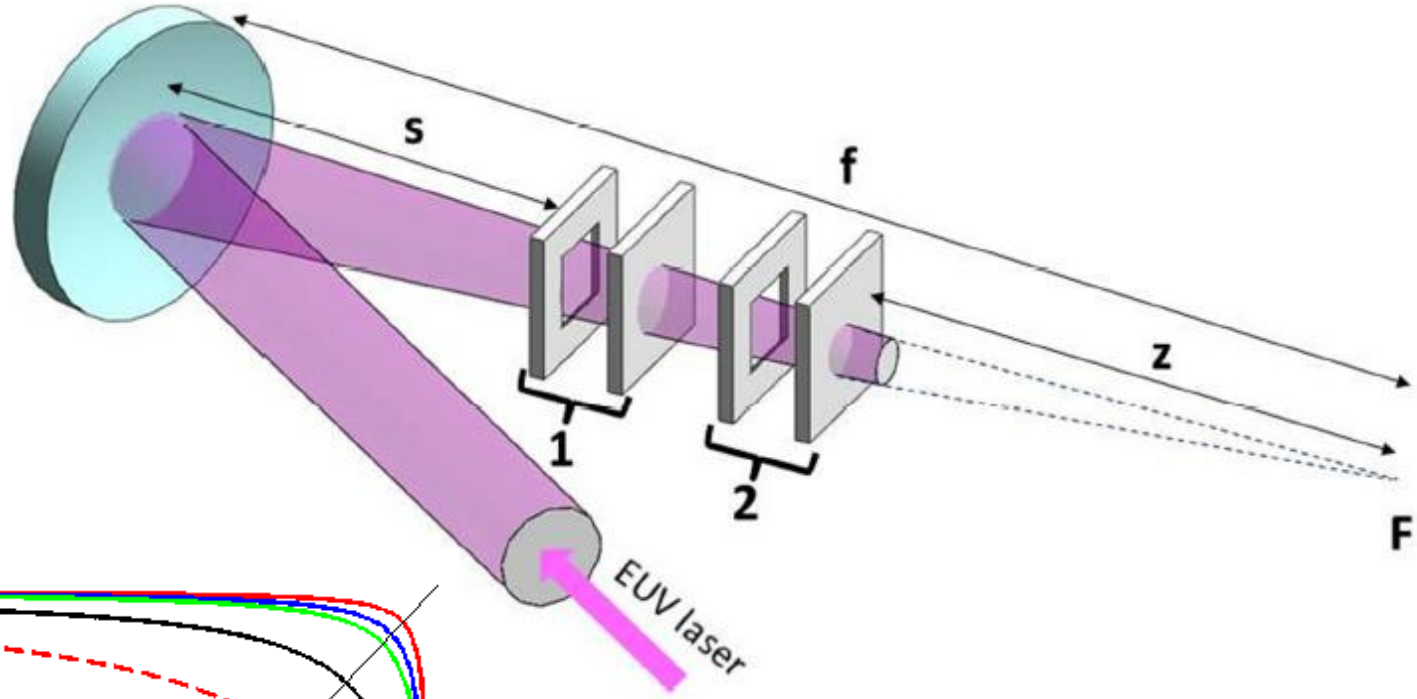


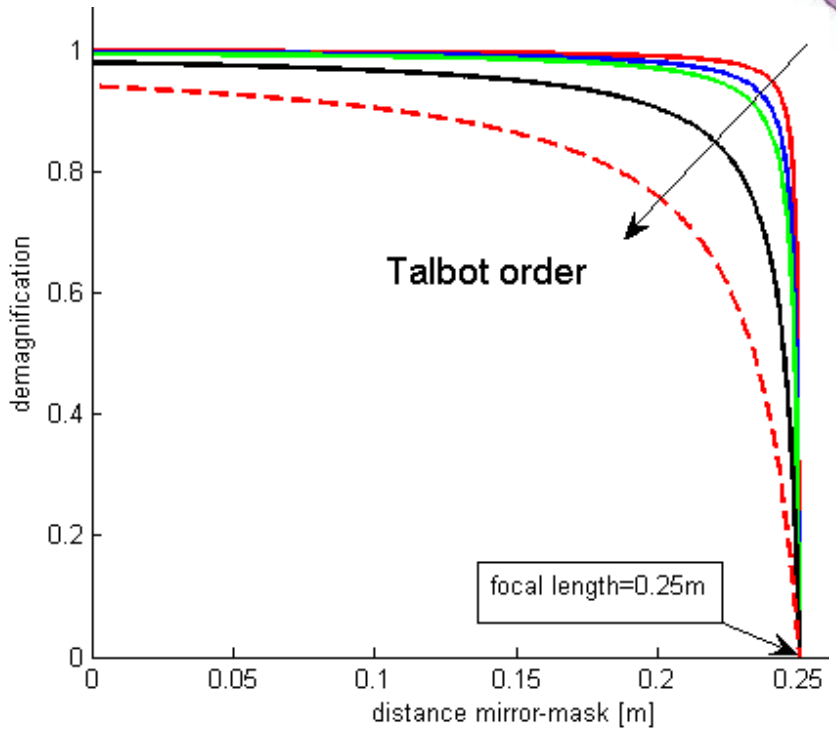
Demagnified Generalized Talbot imaging lithography

De-magnified Talbot Imaging



De-magnified Talbot Imaging: Schematic

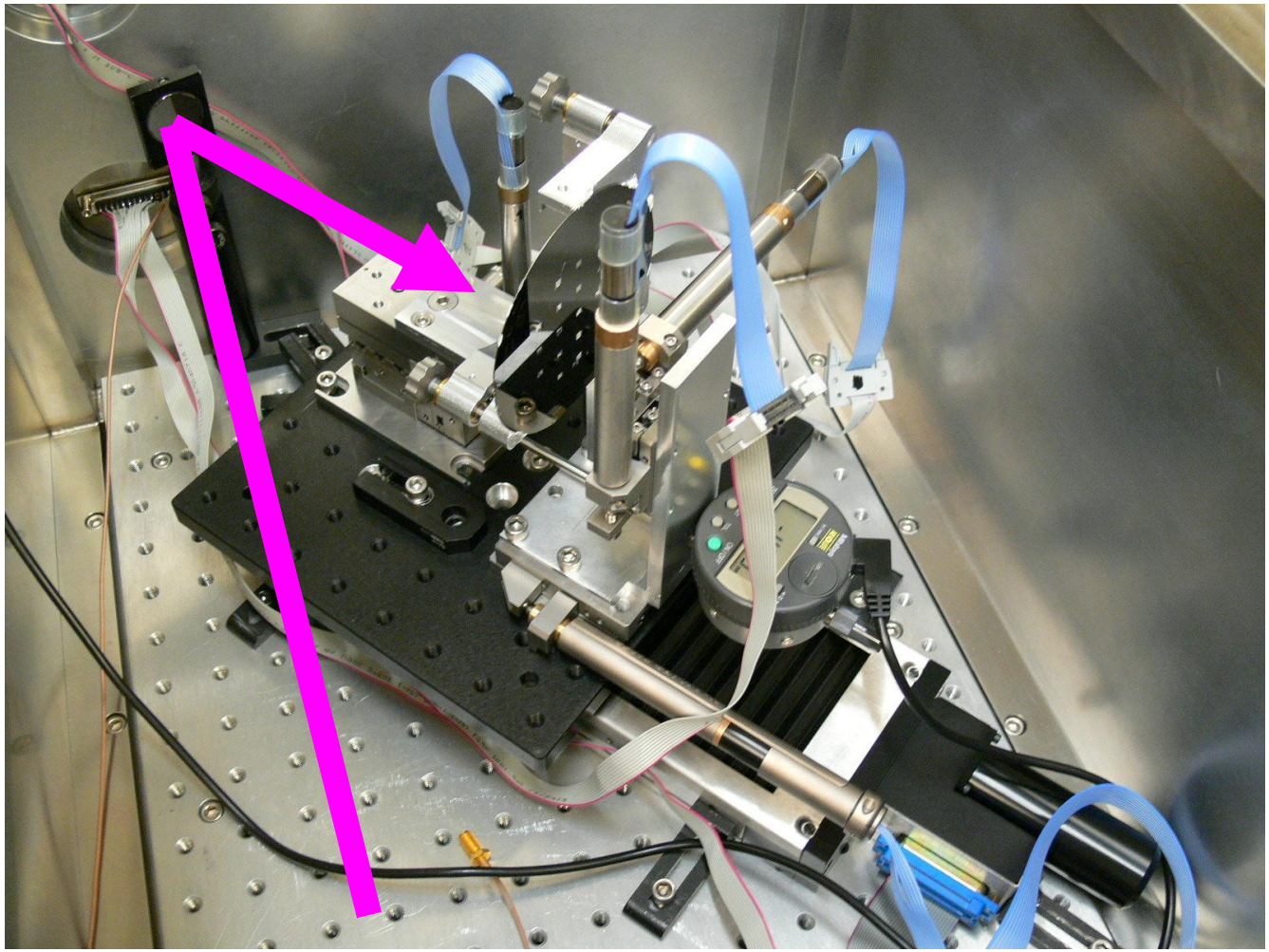




$$p' = p\left[\frac{z}{(f-s)}\right]$$

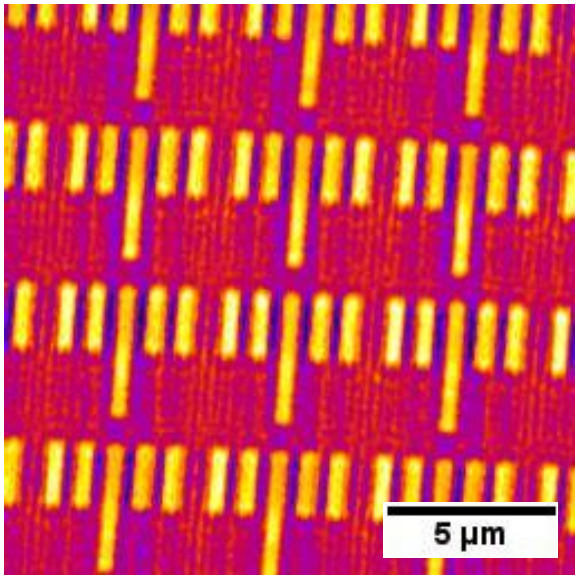
$$z_T = \frac{2np^2(f-s)}{2np^2 + \lambda(f-s)}$$

De-magnified Talbot Imaging: Experimental setup

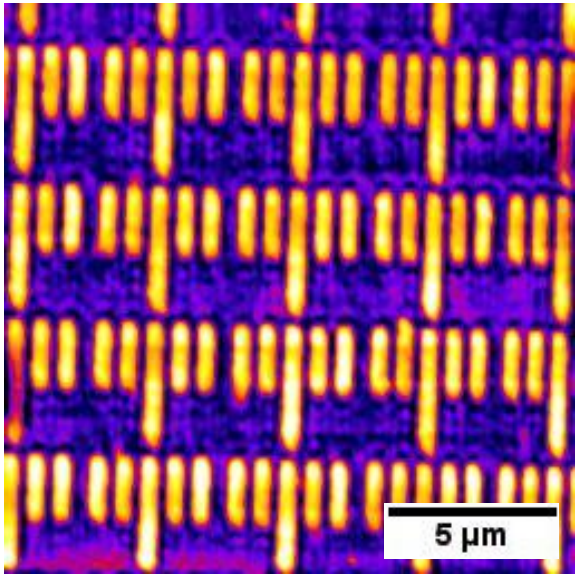


EUV Laser

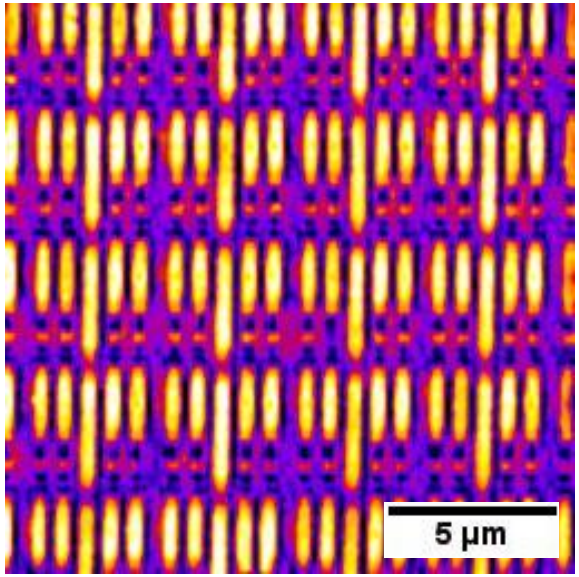
De-magnified Talbot Imaging: Results



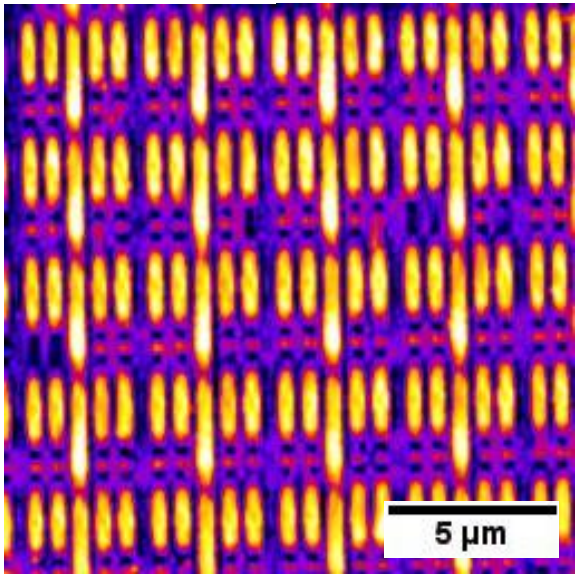
p'/p = 0.98



p'/p = 0.887

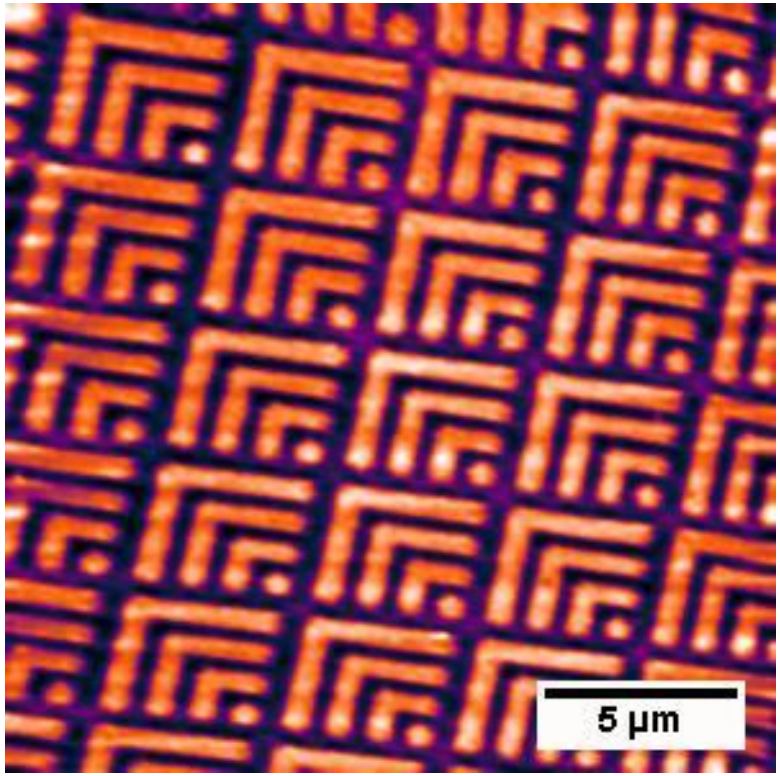


p'/p = 0.867

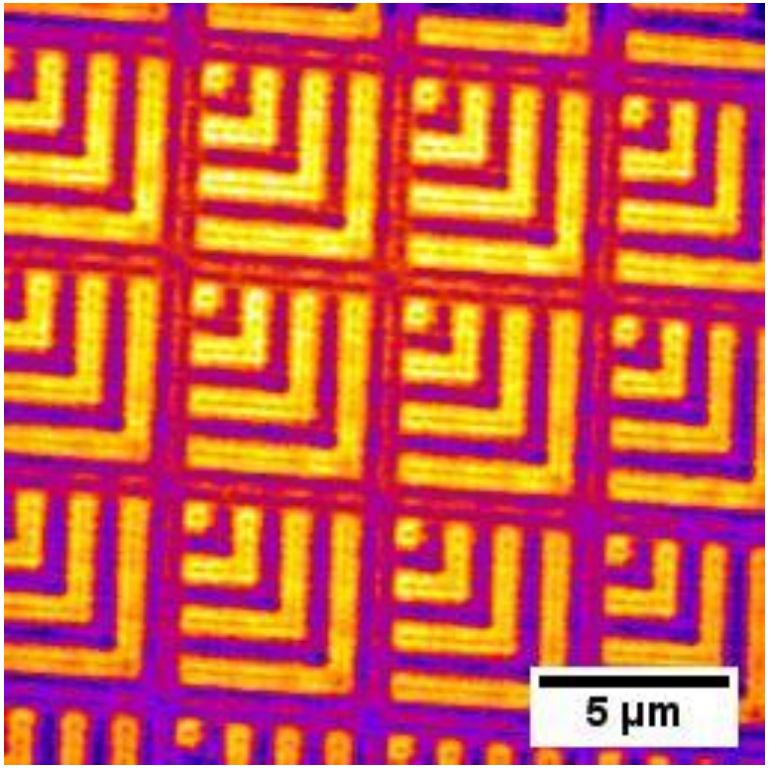


De-magnified Talbot Imaging: Results cont.

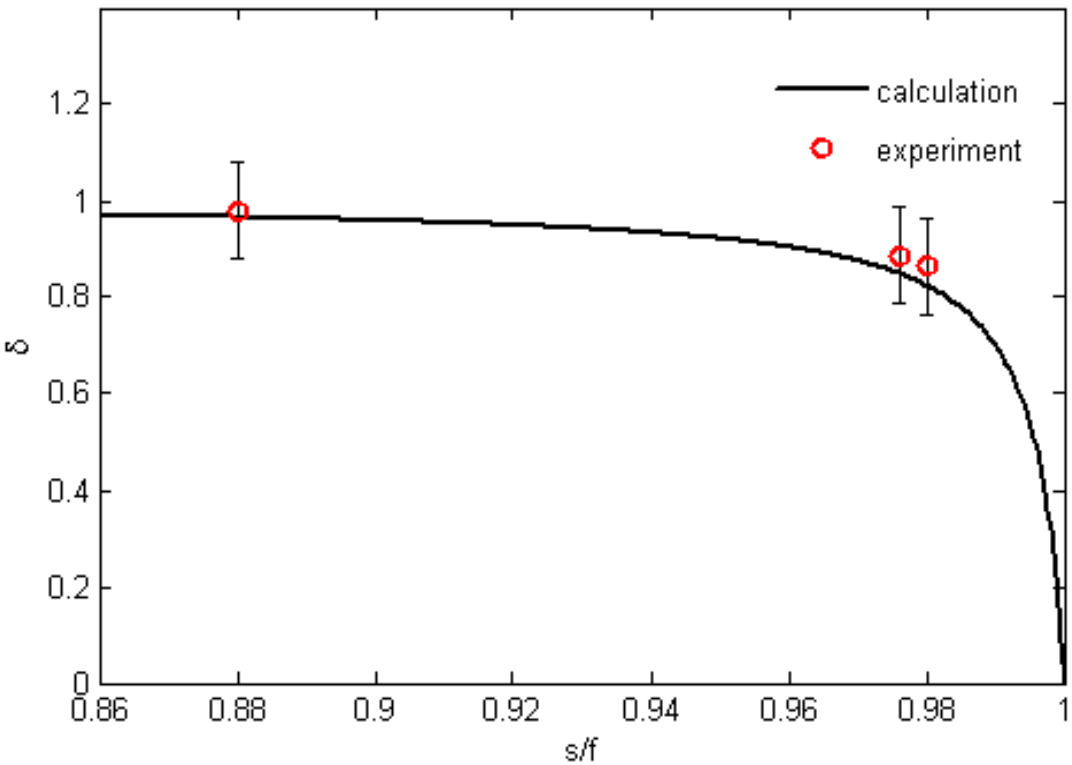
Reconstruction with de- magnification



Reconstruction without de-magnification



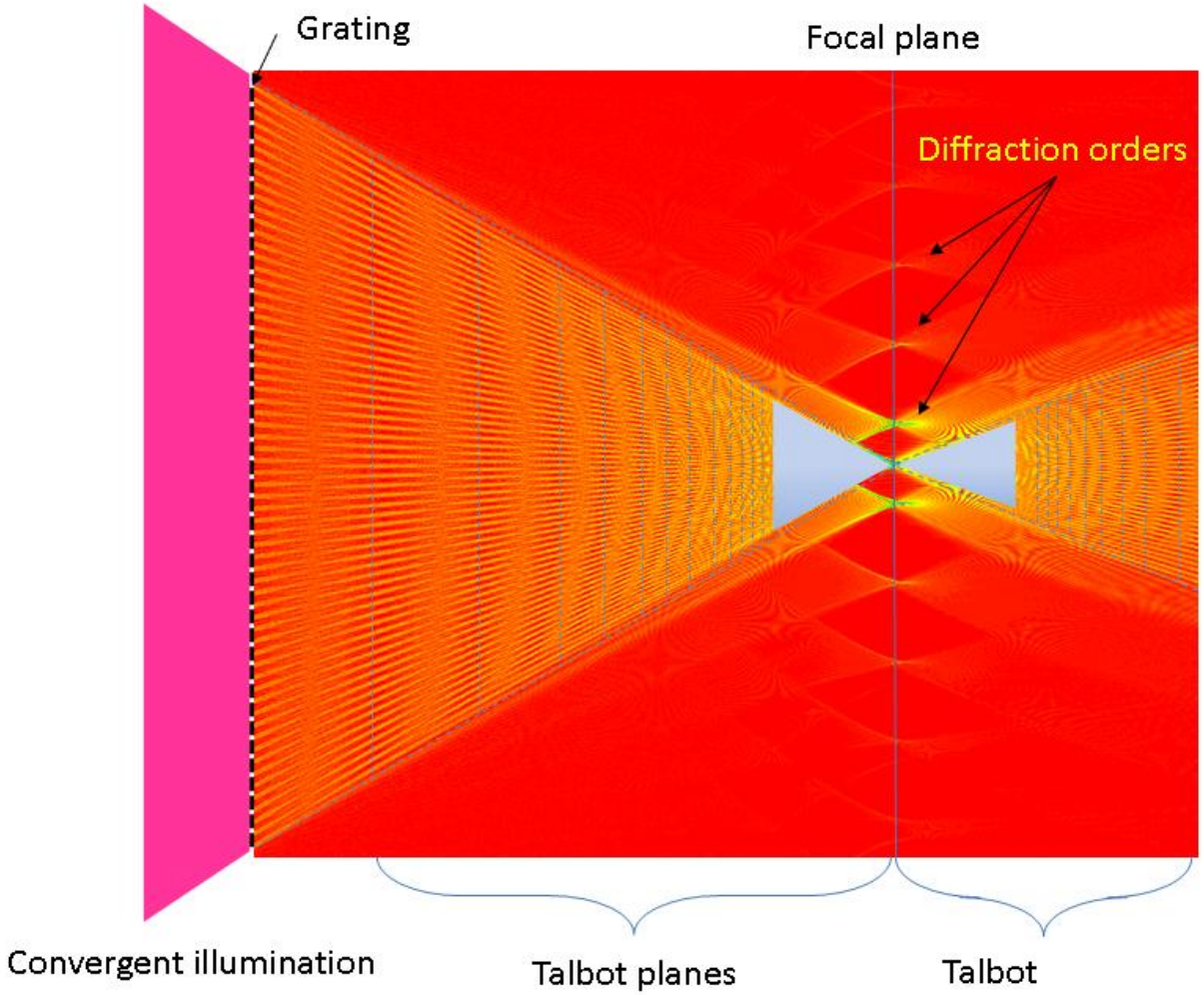
De-magnified GTI: Summary

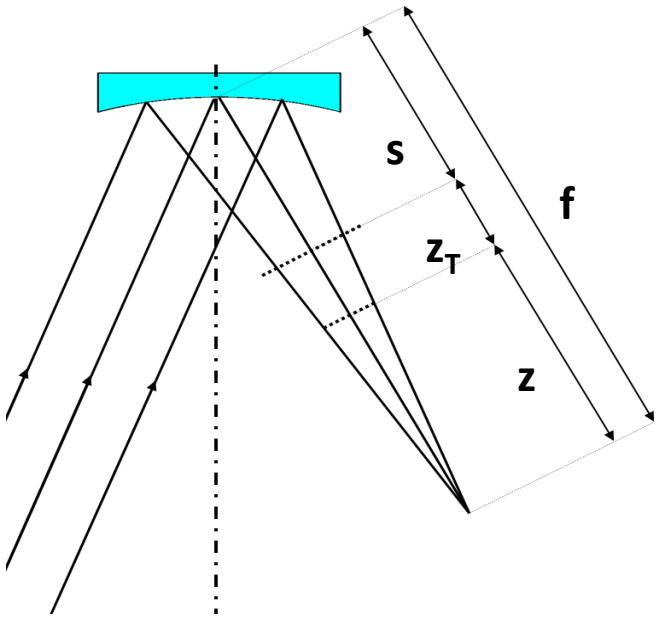


Calculated de-mag.	Measured de-mag.
0.96	0.980
0.86	0.887
0.82	0.865

Comparison between measured and calculated values of de-magnification

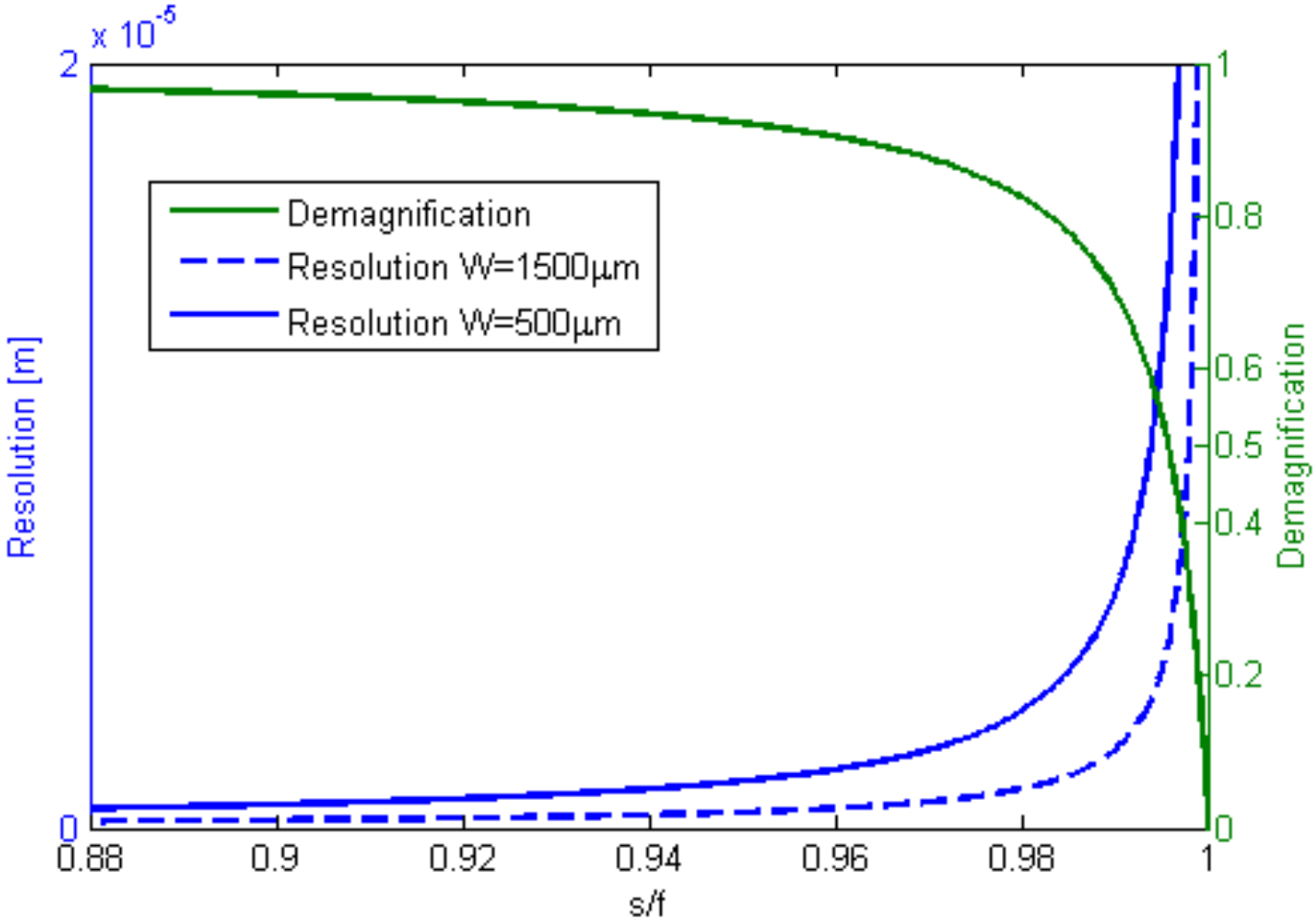
De-magnified GTI: Limitation to de-magnification





L. Urbanski, et.al. „Analysis of a scheme for de-magnified Talbot lithography", *J. Vac. Sci. Technol. B*, ***29***, 06F504 (2011).

De-magnified GTI: Limitation to de-magnification

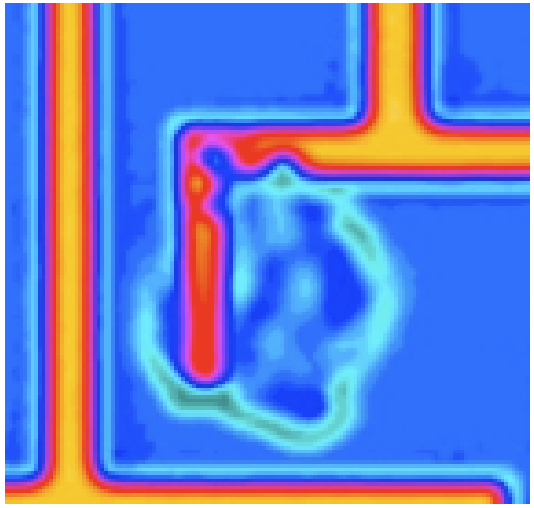


$$NA = \left[\sqrt{1 + \left(\frac{2(f-s)p^2 mf}{(2p^2 m + \lambda(f-s))(f-d-s)W} \right)^2} \right]^{-1}$$

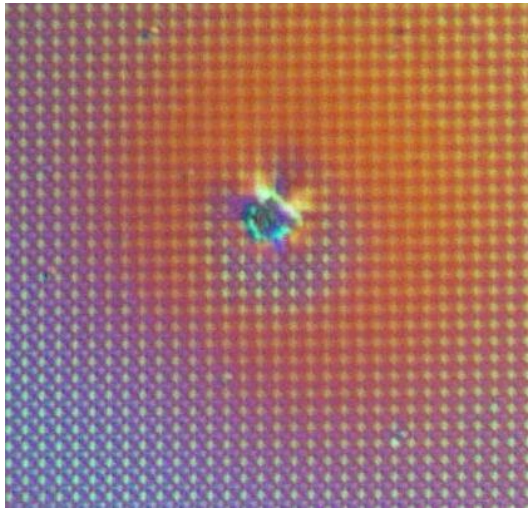
$$\Delta = 0.61 \frac{\lambda}{NA}$$

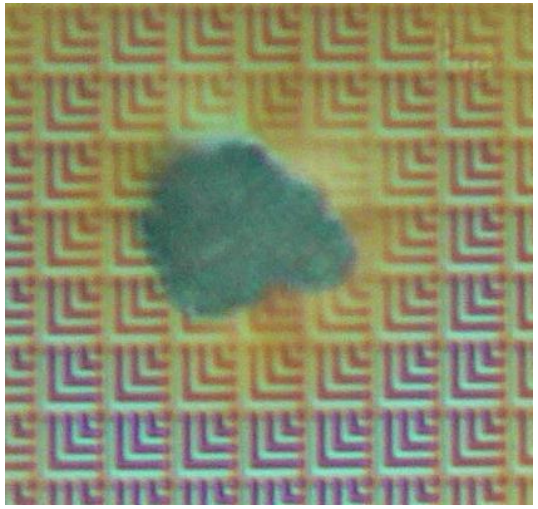
Defect tolerance in the Generalized Talbot imaging lithography

Typical Defects in a Mask



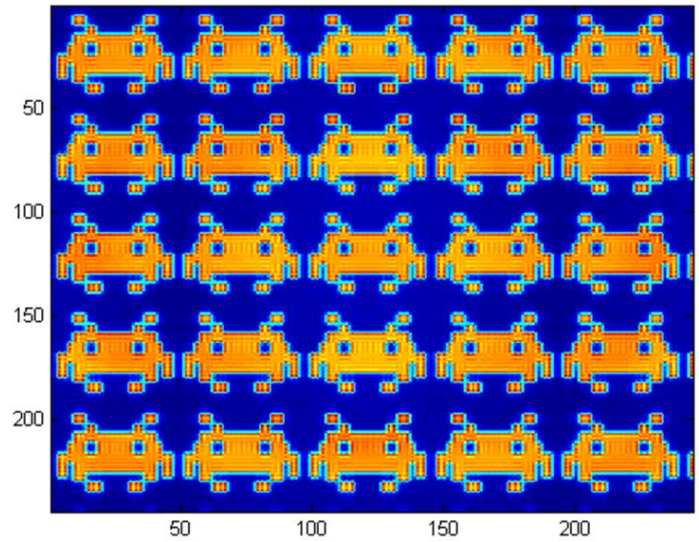
http://www.als.lbl.gov/als/science/sci_archive/213-EUVLithography.html





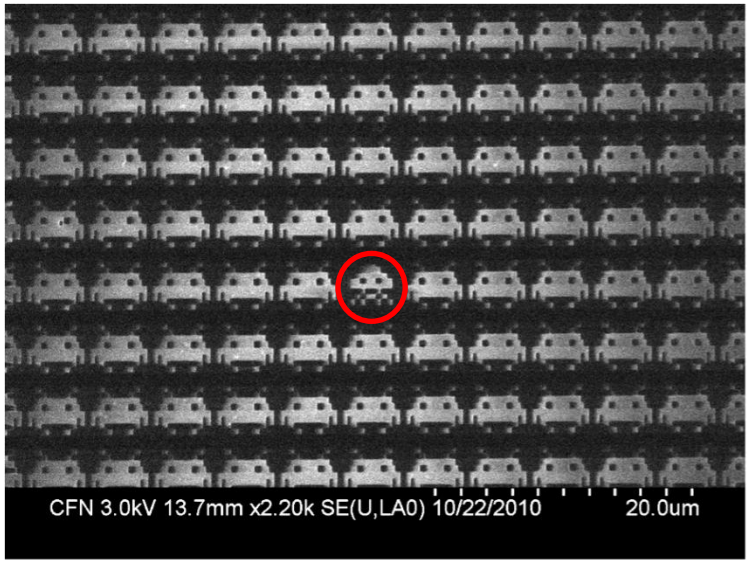
My Experience

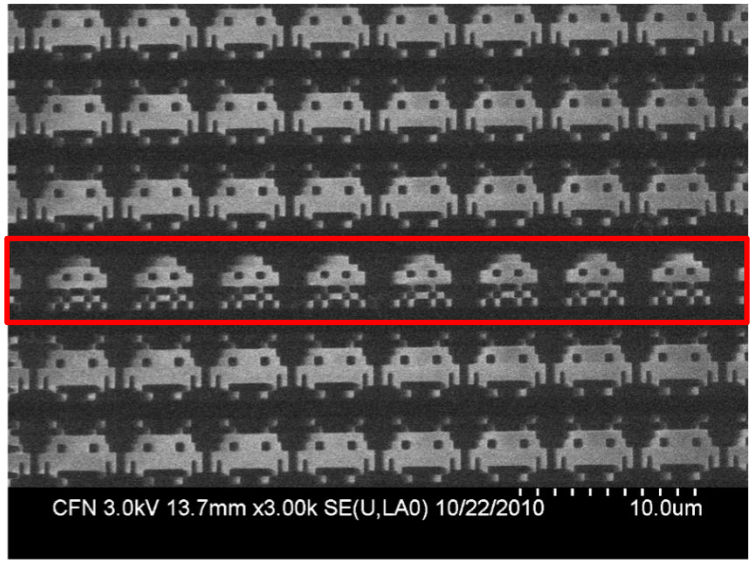
Mask with a defect: Numerical Simulation

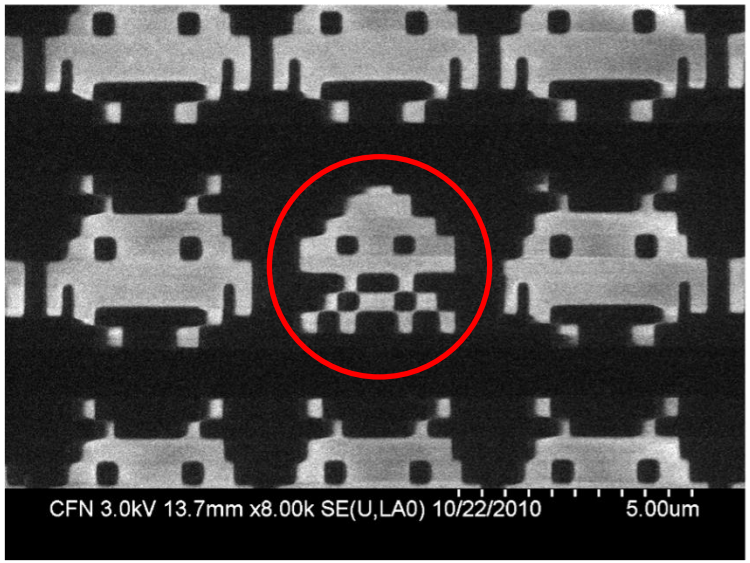


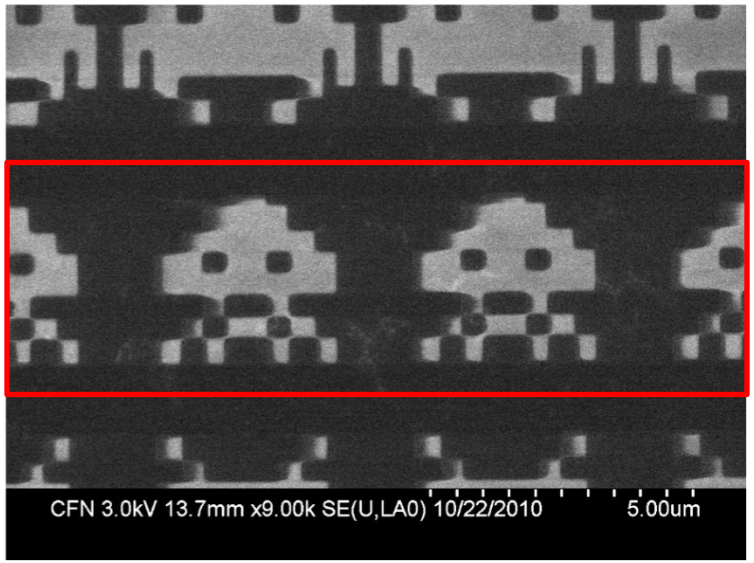
$$u(x) = i\frac{e^{\frac{ikx^2}{z}}}{\lambda z}\cdot\int_{-\infty}^{\infty}\hat{u}(\xi)e^{\frac{ik(x-\xi)^2}{z}}d\xi$$

Experimental Verification: Mask Design

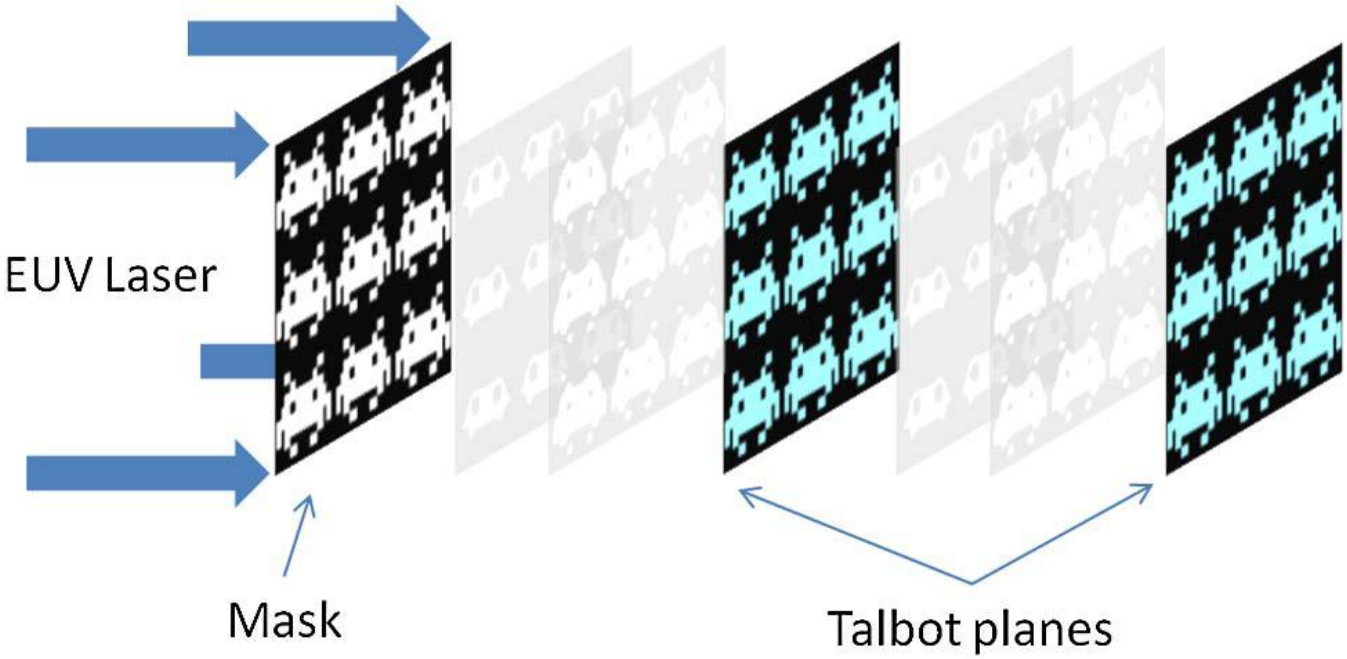








Generalized Talbot Imaging: Defect Tolerance



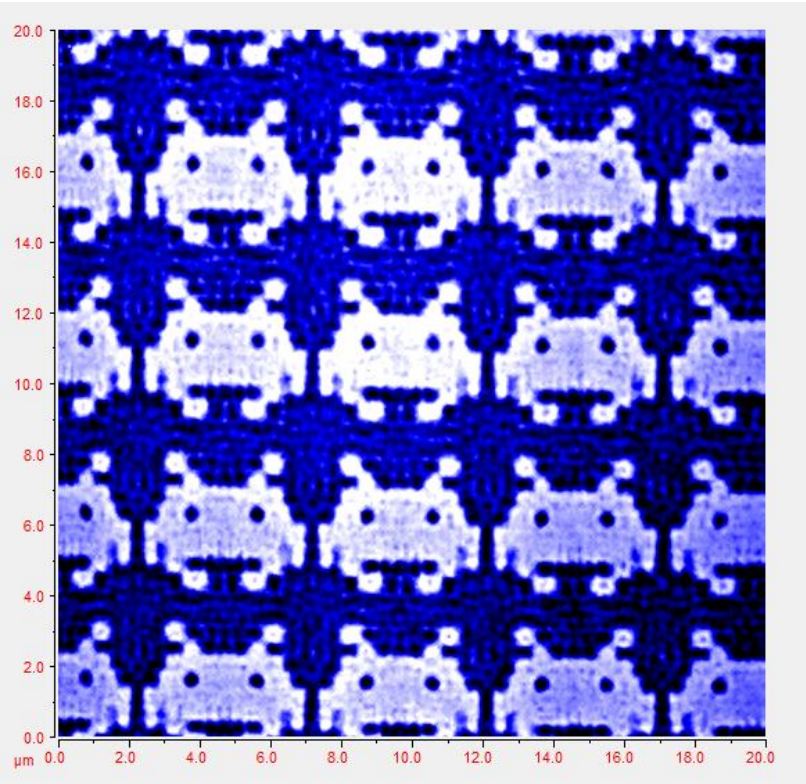
EUV
An NSF Engineering Research Center

Colorado State University

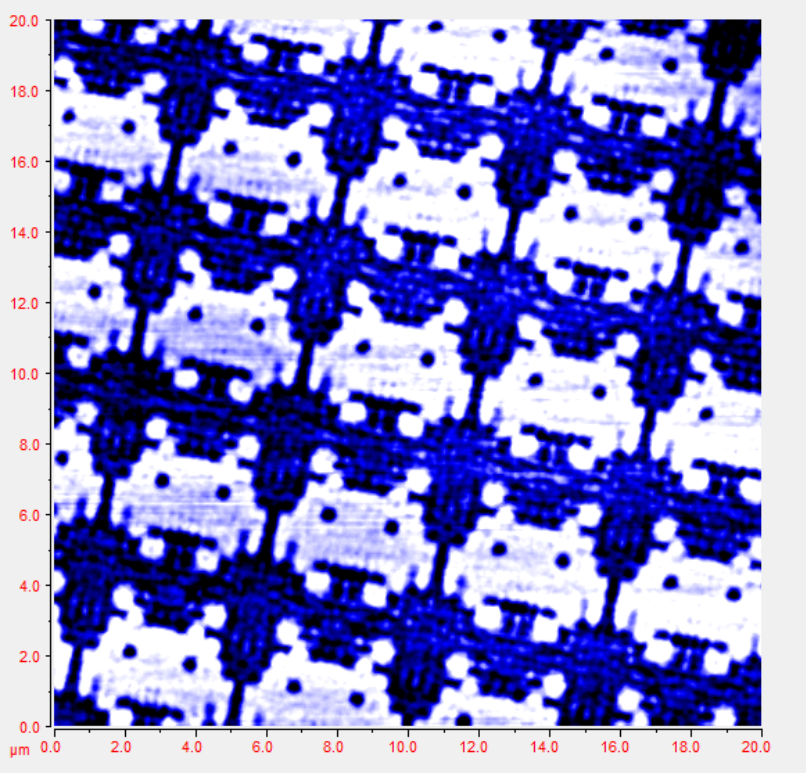
Center for Functional Nanomaterials
Brookhaven National Laboratory

Experimental Verification: Results for 0.01% and 1% of defect concentration

0.01%

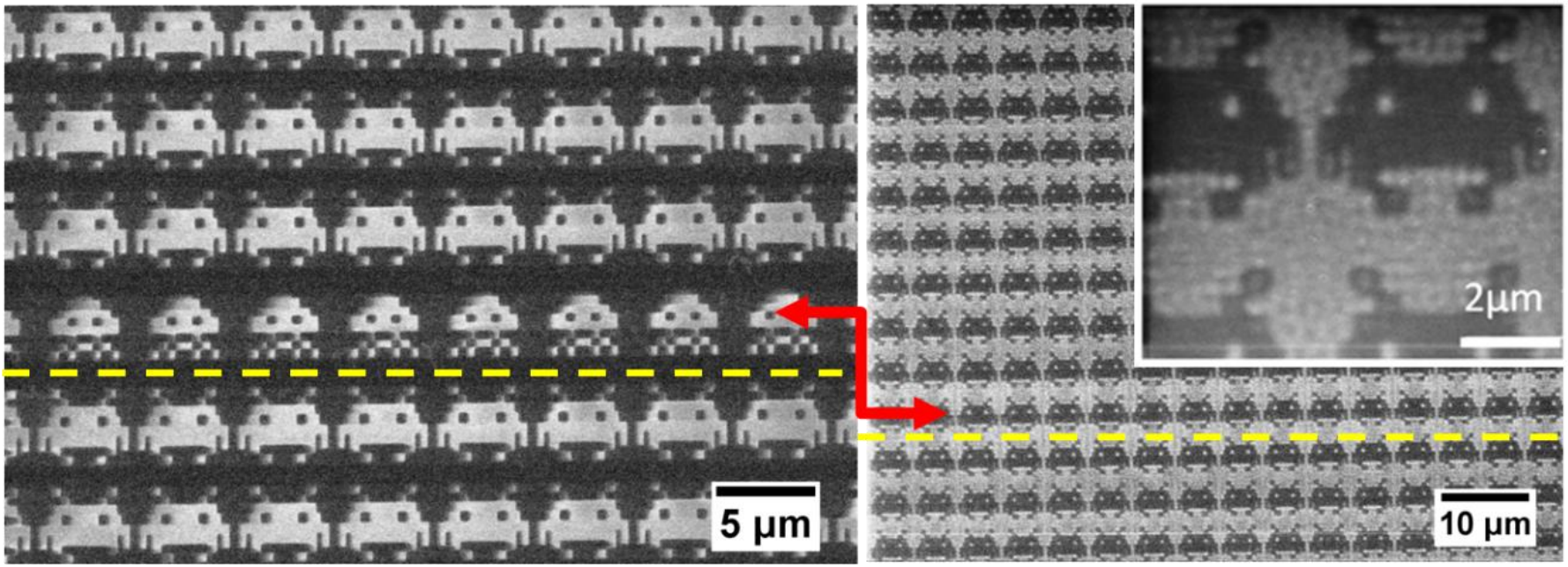


1%



Atomic Force Microscope Scan of patterned resist (PMMA) 20x20micron^2

Experimental Verification: Results for 1% of defect concentration



Mask

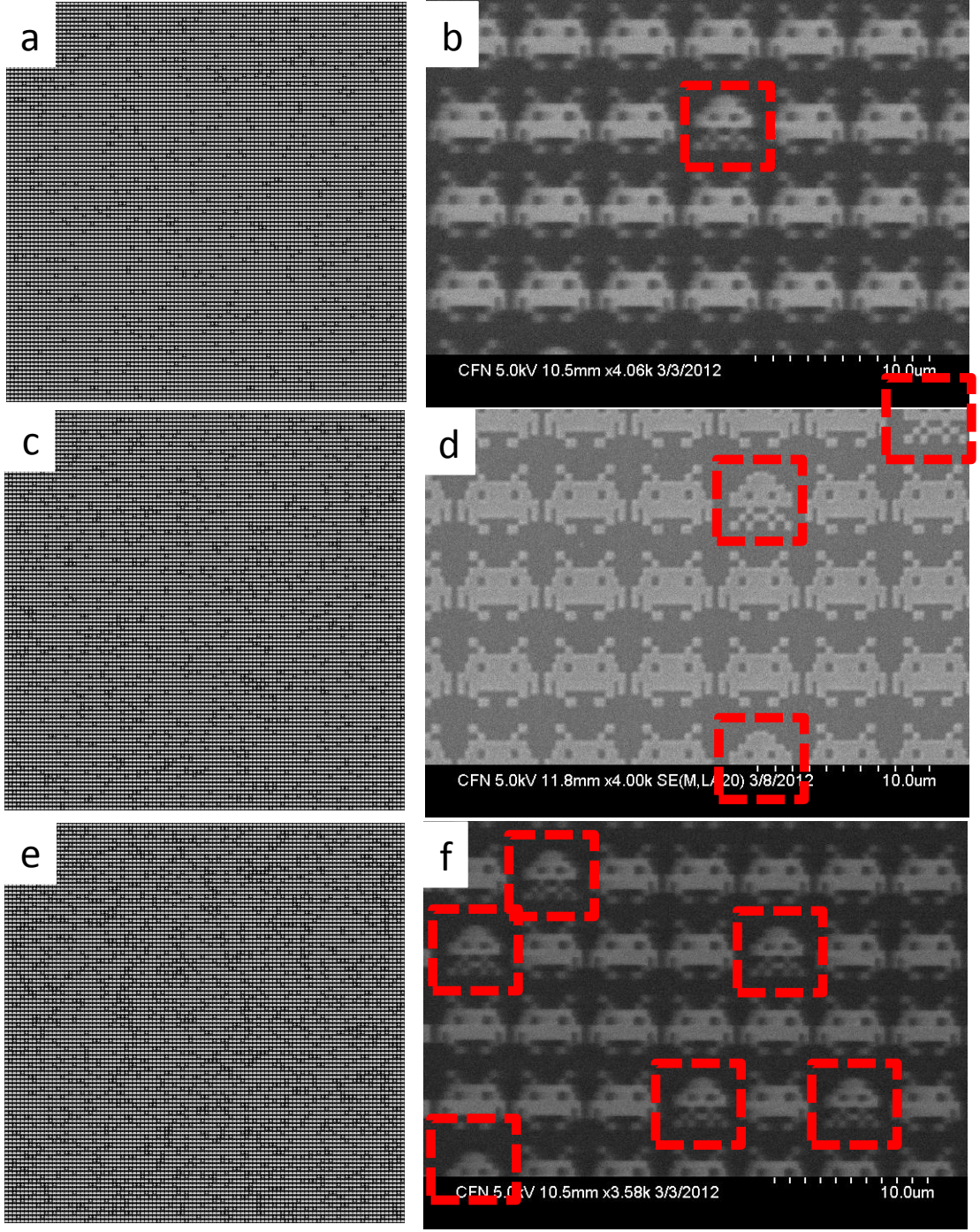
Replica

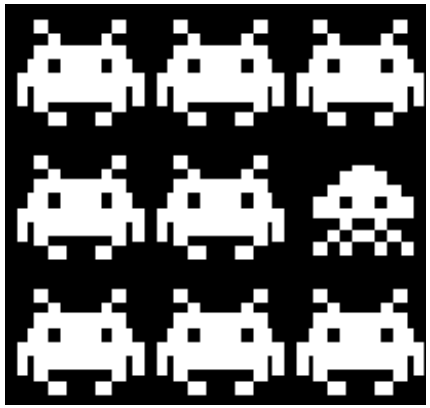
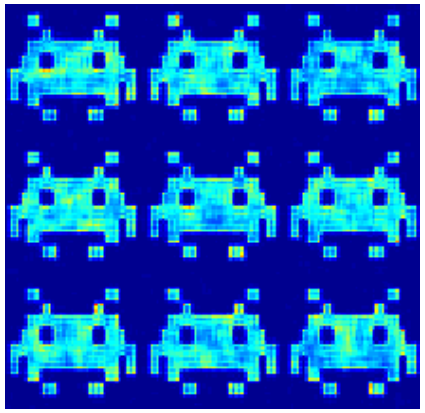
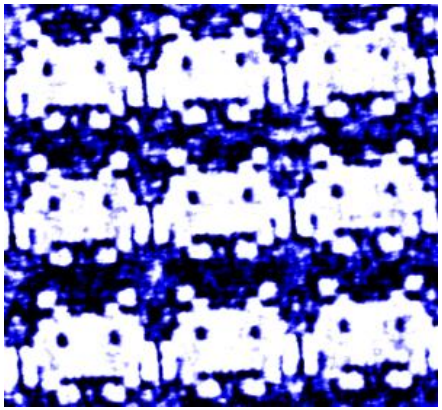
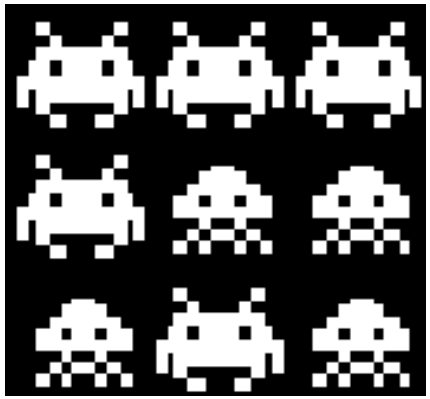
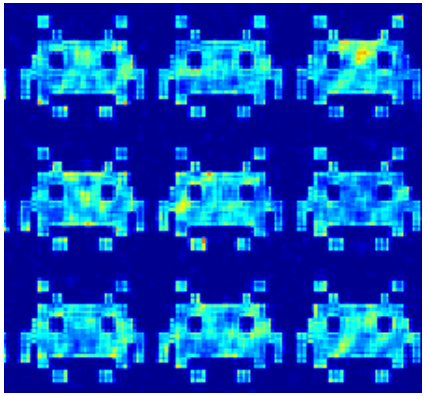
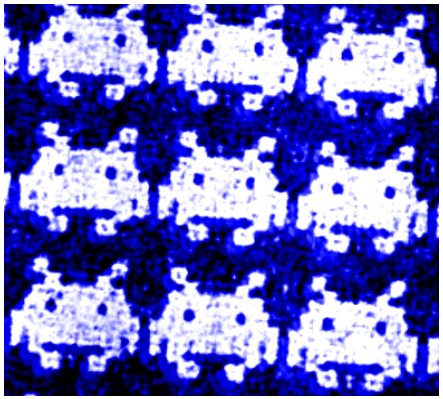
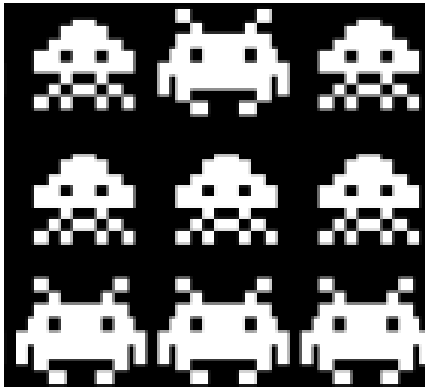
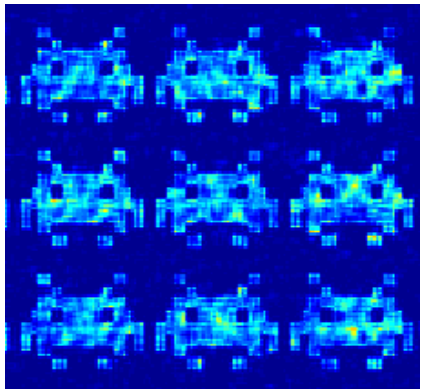
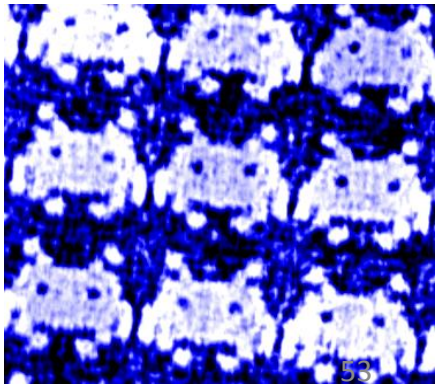
Electron Microscope Scan of patterned resist (PMMA)

5%

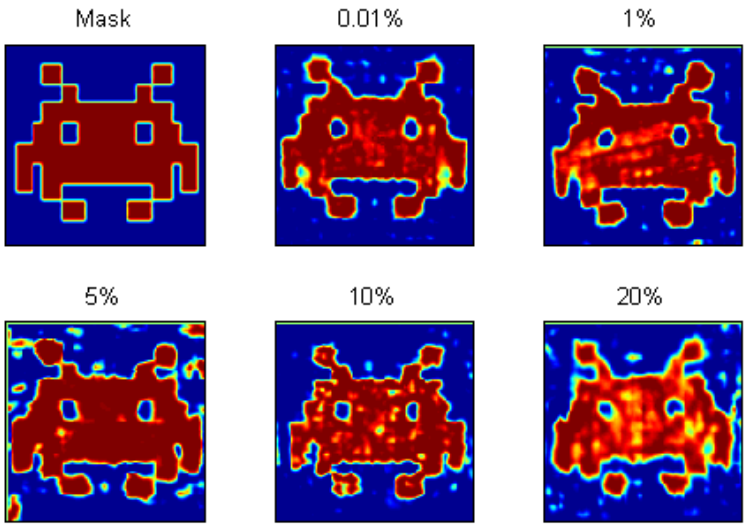
10%

20%


a
b
CFN 5.0kV 10.5mm x4.06k 3/3/2012
c
d
CFN 5.0kV 11.8mm x4.00k SE(M,L
20) 3/8/2012
10.0um
e
f
CFN 5.0
V 10.5mm x3.58k 3/3/2012
10.0um

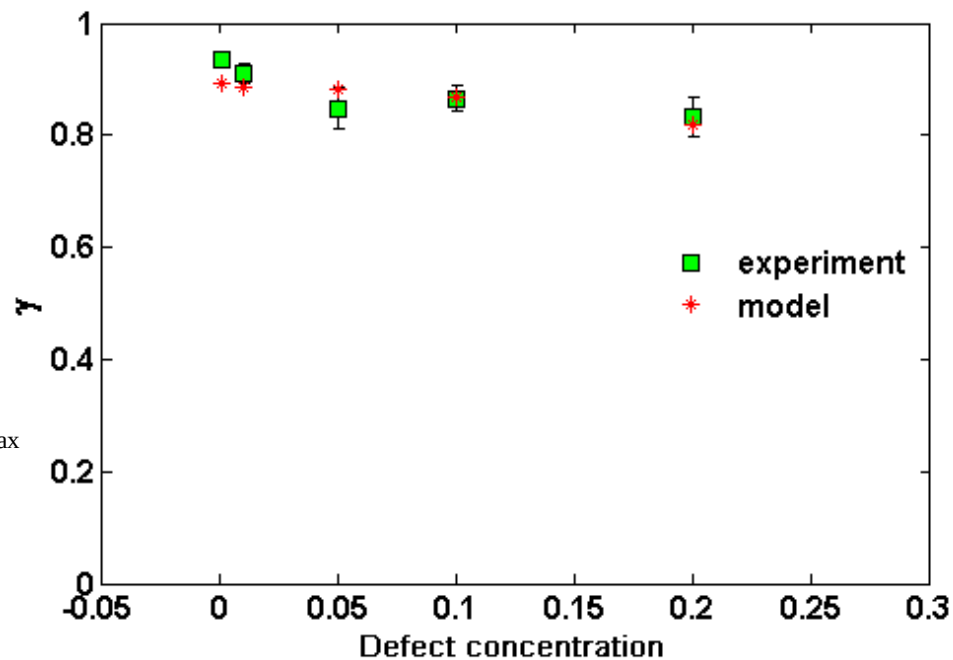
Defect concentration	Mask	Numerical reconstruction	Reconstructions in resist
5%			
10%			
20%			

Analysis of the replica quality for different defect concentration



	0.01%	*1%*	*5%*	*10%*	*20%*
Simul.	***0.89***	***0.88***	***0.88***	***0.86***	***0.81***
Exp. (mean)	***0.93***	***0.90***	***0.84***	***0.86***	***0.83***

$$\gamma(u,v)=\left|\frac{\sum_{x,y}\left[f(x,y)-\bar{f}_{u,v}\right]\left[t(x-u,y-v)-\bar{t}\right]}{\left\{\sum_{x,y}\left[f(x,y)-\bar{f}_{u,v}\right]^2\sum_{x,y}\left[t(x-u,y-v)-\bar{t}\right]^2\right\}^{0.5}}\right|_{\max}$$

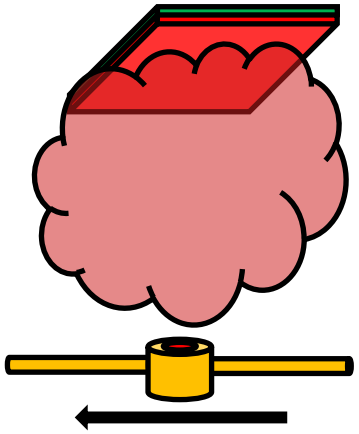


Technique Summary

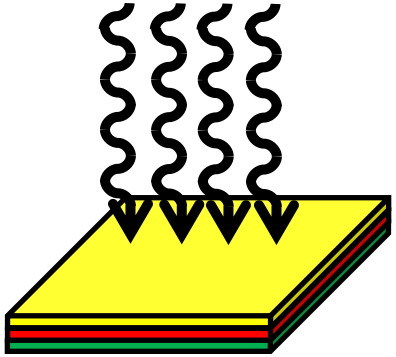
- Optical imprint lithography
- Non contact
- High fidelity
- High resolution
- Size scalable
- Defect tolerant

Functionalization of the nanostructures: Sacrificial mask method

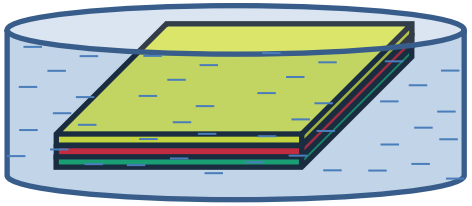
Deposition of a thin metallic layer

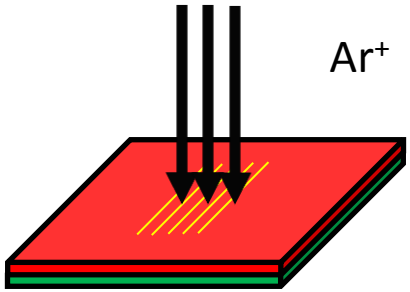


EUV-L

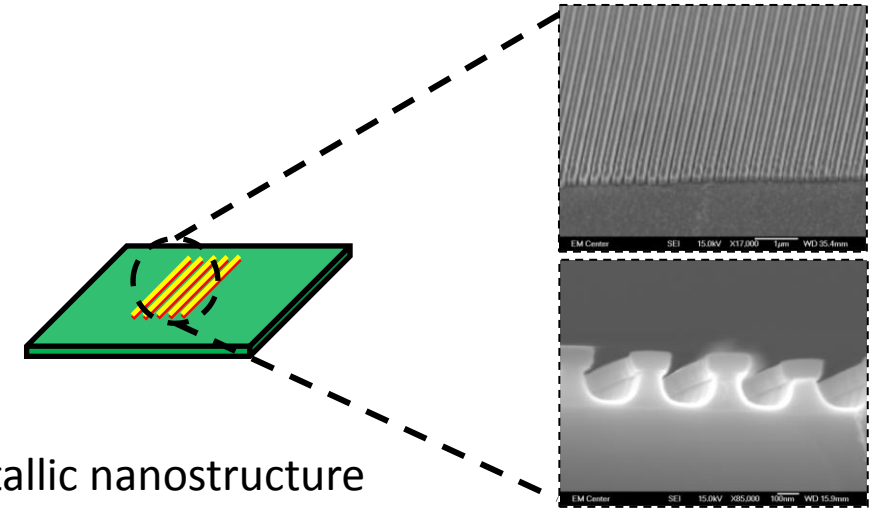


Developing



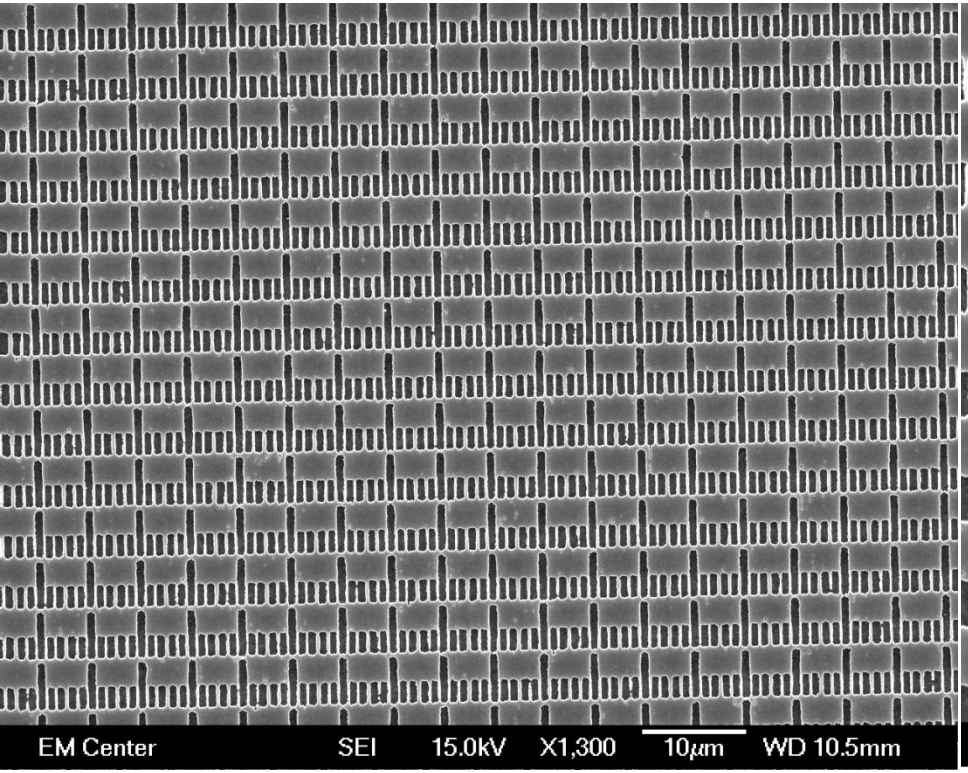


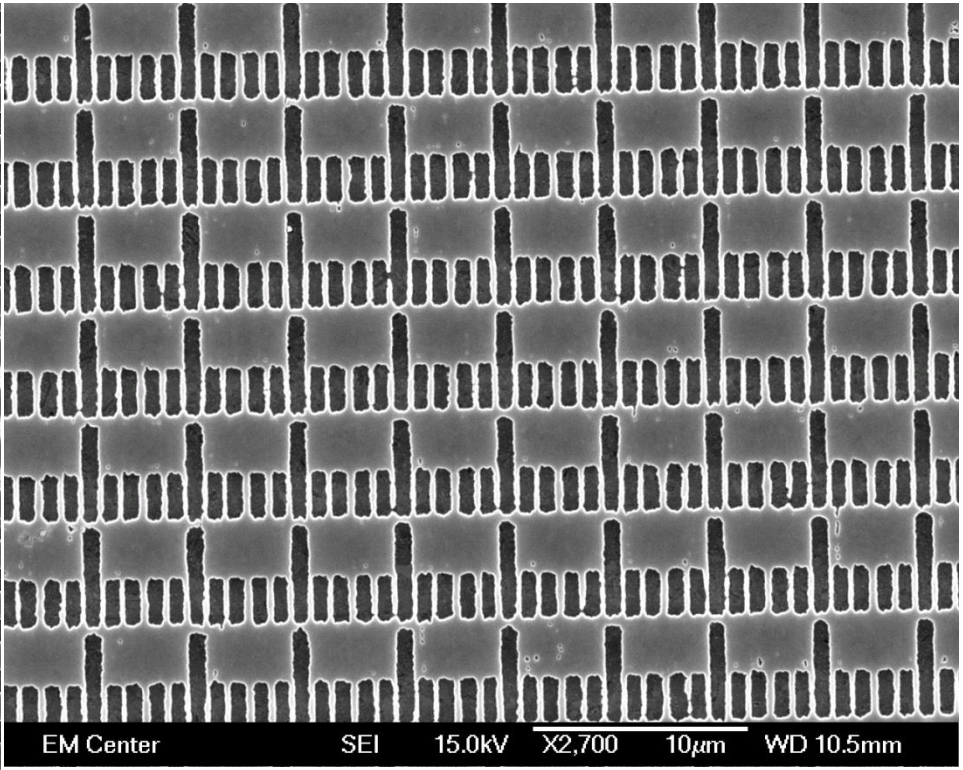
Argon plasma etching



Metallic nanostructure

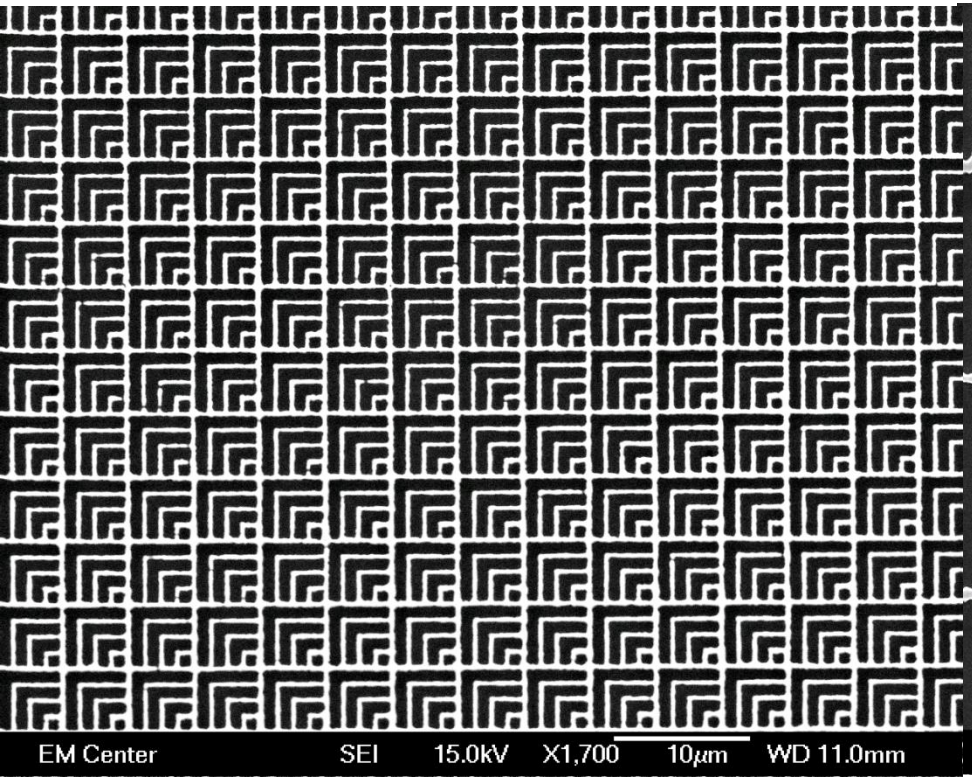
Functionalization of the nanostructures: Sacrificial mask method

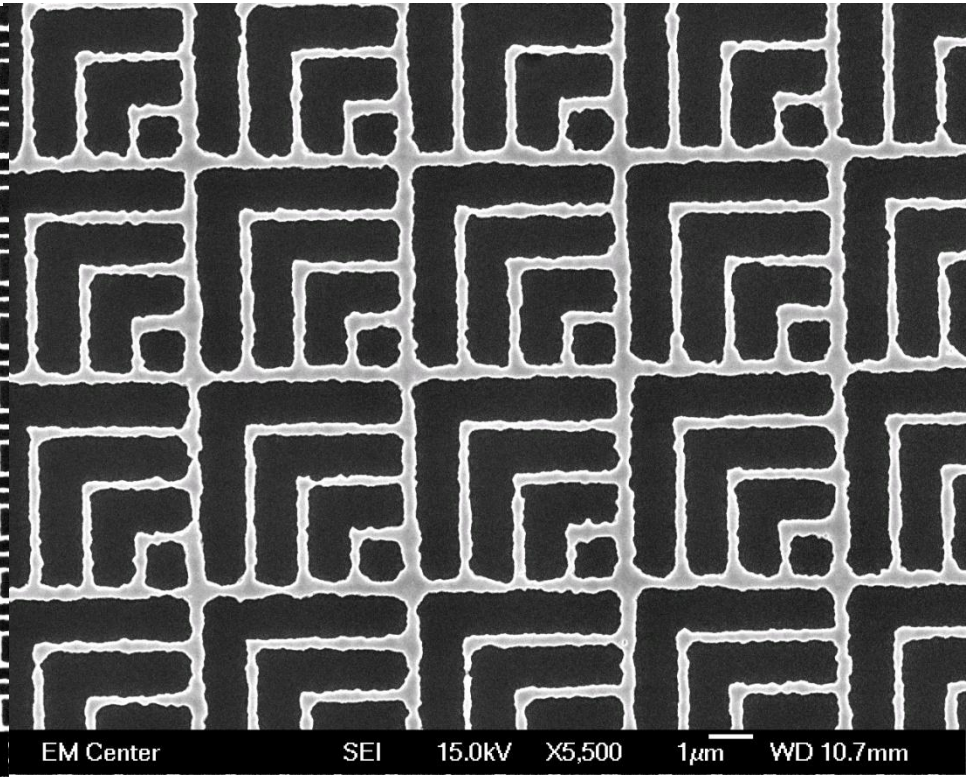




Silver on silicon

Functionalization of the nanostructures: Sacrificial mask method





Gold on silicon

Summary

- Holographic lithography
- GTI
- DGTI
- Defect Tolerance
- Optical imprint technique for mask copying

Publications

- L. Urbanski, M. C. Marconi, L. M. Meng, M. Berrill, O. Guilbaud, A. Klisnick, and J. J. Rocca, Phys. Rev. A **85**, 033837 (2012).
- L. Urbanski, M.CMarconi, A. Isoyan, A. Stein, C. S. Menoni, and J. J. Rocca, *J. Vac. Sci. Technol. B* ***29***, 06F504 (2011).
- A. Isoyan, F. Jiang, Y. C. Cheng, F. Cerrina, P. Wachulak, L. Urbanski, J. J. Rocca, C.S. Menoni, and M.C. Marconi, , *J. Vac. Sci. Technol. B* ***27***, 2931 (2009).
- L. Urbanski ,L. M. Meng, M. C. Marconi, M. Berril, O. Guilbaud, A. Klisnick, J. J. Rocca , *SPIE Proc. 8140* (2011).
- M. C. Marconi, P. Wachulak, L. Urbanski, C.S Menoni and J. J. Rocca, A. Isoyan, F. Jiang, Y. Cheng, F. Cerrina SPIE Proc. **7271**, 72713O-3 (2009).
- L. Urbanski, A. Isoyan, A. Stein, C.S. Menoni, J. J. Rocca , and M. C. Marconi, „Defect Tolerant EUV Lithography Technique". Opt. Lett. **37**, 3633 (2012).
- L. Urbasnki, W. Li, A. Isoyan, A. Stein, C.S. Menoni, J. J. Rocca, and M.C Marconi , J. Vac. Sci. Technol. B, (in press).

US Patent

- Non-contact, scalable And Defect Free Optical Nano-patterning By Demagnified Talbot Effect,

Conferences

- L. Urbanski, M. Marconi, et al."Line width measurement of a capillary discharge soft x-ray laser", ICXRL 2012.
- L. Urbanski, M. Marconi, et al."Defect Tolerant EUV lithography", ICXRL 2012.
- L. Urbanski, M. Marconi, et al."Defect Tolerant EUV lithography", CLEO 2012.
- L. Urbanski, L. Meng, M. Marconi, et al."Line width measurement of a capillary discharge soft x-ray laser." SPIE Proceedings, 05 Oct 2011.
- L. Urbanski, P. Wachulak, A. Isoyan, et al. (Proceedings Paper) Published: 14 Dec 2010.
- L. Urbanski , A. Klisnik , L. Meng , M. C. Marconi, J.J. Rocca, American Physical Society 4 Corners Fall Meeting. Ogden, UT, October 15-16 2010.
- M. C. Marconi; P. W. Wachulak; L. Urbanski; A. Isoyan; Fan Jiang; Yang Chun Cheng; J. J. Rocca; C. S. Menoni; F. Cerrina, (Proceedings Paper), 28 September 2009.
- L. Urbanski, P. Wachulak, F. Cerrina, A. Isoyan, F. Jiang, Y. C. Cheng, C.S. Menoni, J.J. Rocca and M.C. Marconi, International Conference on X-ray Lasers. Korea, 2010.
- L. Urbanski, P. Wachulak, A. Isoyan, F. Jian, Y. Cheng, J.J. Rocca, C.S. Menoni, F. Cerrina, M. C. Marconi, American Physical Society 4 Corners Fall Meeting. Golden, CO, Oct. 24-25 2009.
- L. Urbanski, Isoyan, F. Jian, Y. Chung-chen, P. Wachulak, J.J. Rocca, C.S. Menoni, M.C. Marconi, F. Cerrina, Colorado Photonics Industry Association, Boulder 2010.
- L. Urbanski, P. Wachulak, J.J. Rocca, C.S. Menoni, M.C. Marconi, Colorado Photonics Industry Association, Boulder 2008.
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