ME290R: Topics in Manufacturing

Fall 2017

Nanoscale manipulation of materials

Lecture 13.1: Emerging X-ray and Optically-based Lithography Techniques I

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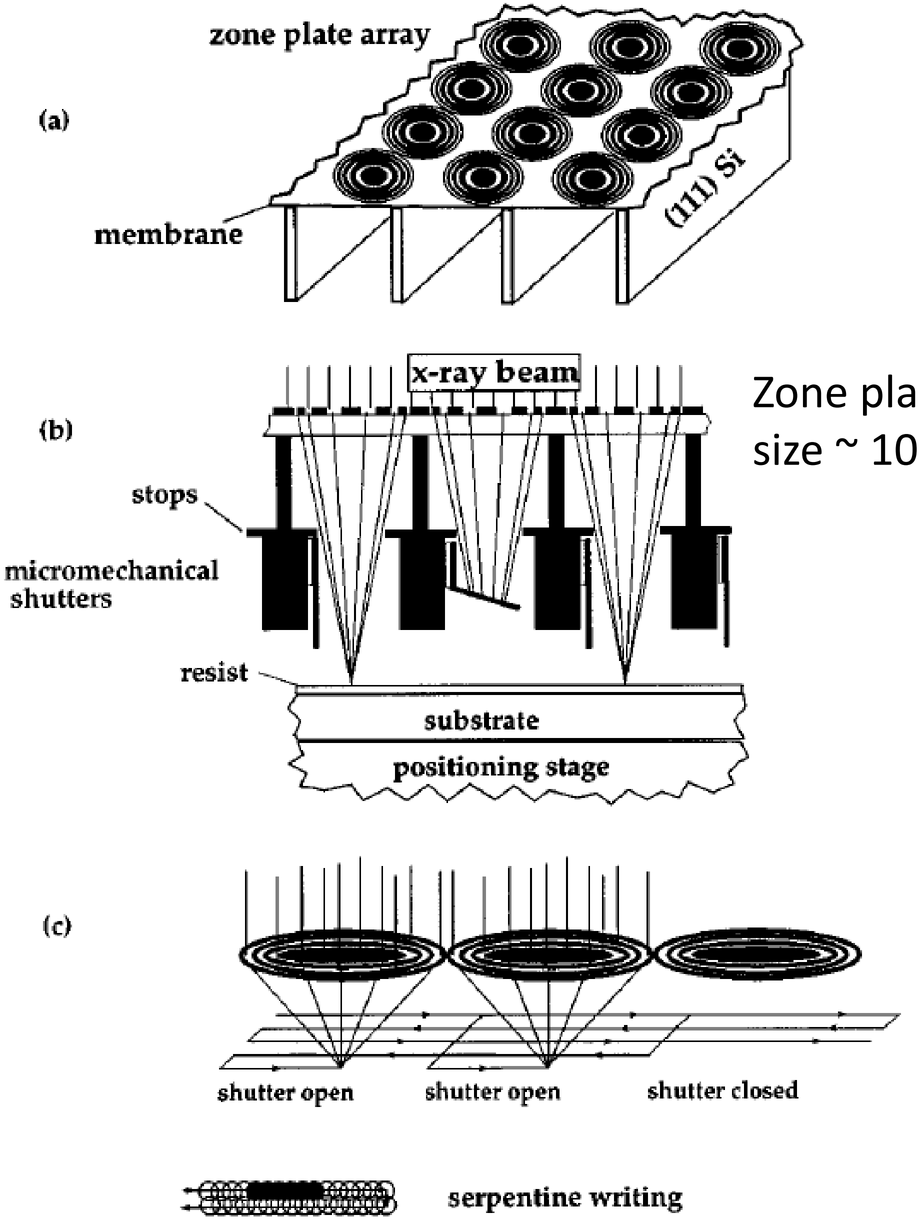
Emerging optical/x-ray based methods

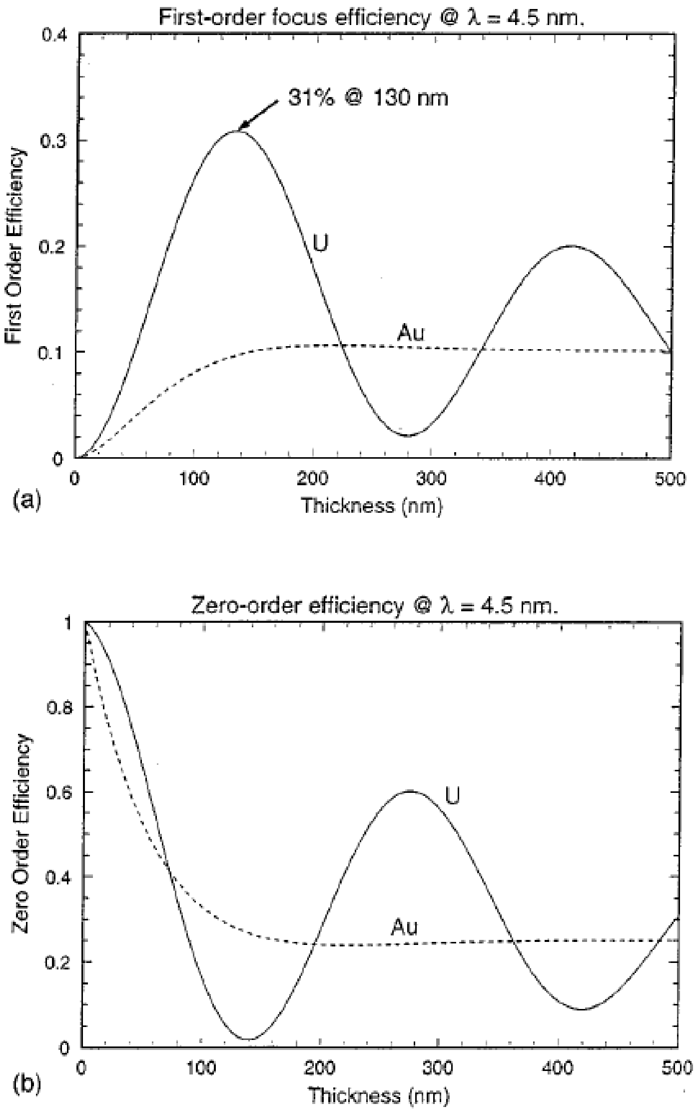
- Zone plate arrays
- Harnessing diffraction at mask edges
  - Near-field lithography, and roll-to-roll photolith
- Interference lithography
- 3D lithography
  - Projection-based
  - Holographic methods
  - Grayscale optical lithography
- Device-integrated lithography
  - Integrated lenses
  - Stop-flow and continuous-flow lithography

X-ray zone plate array lithography



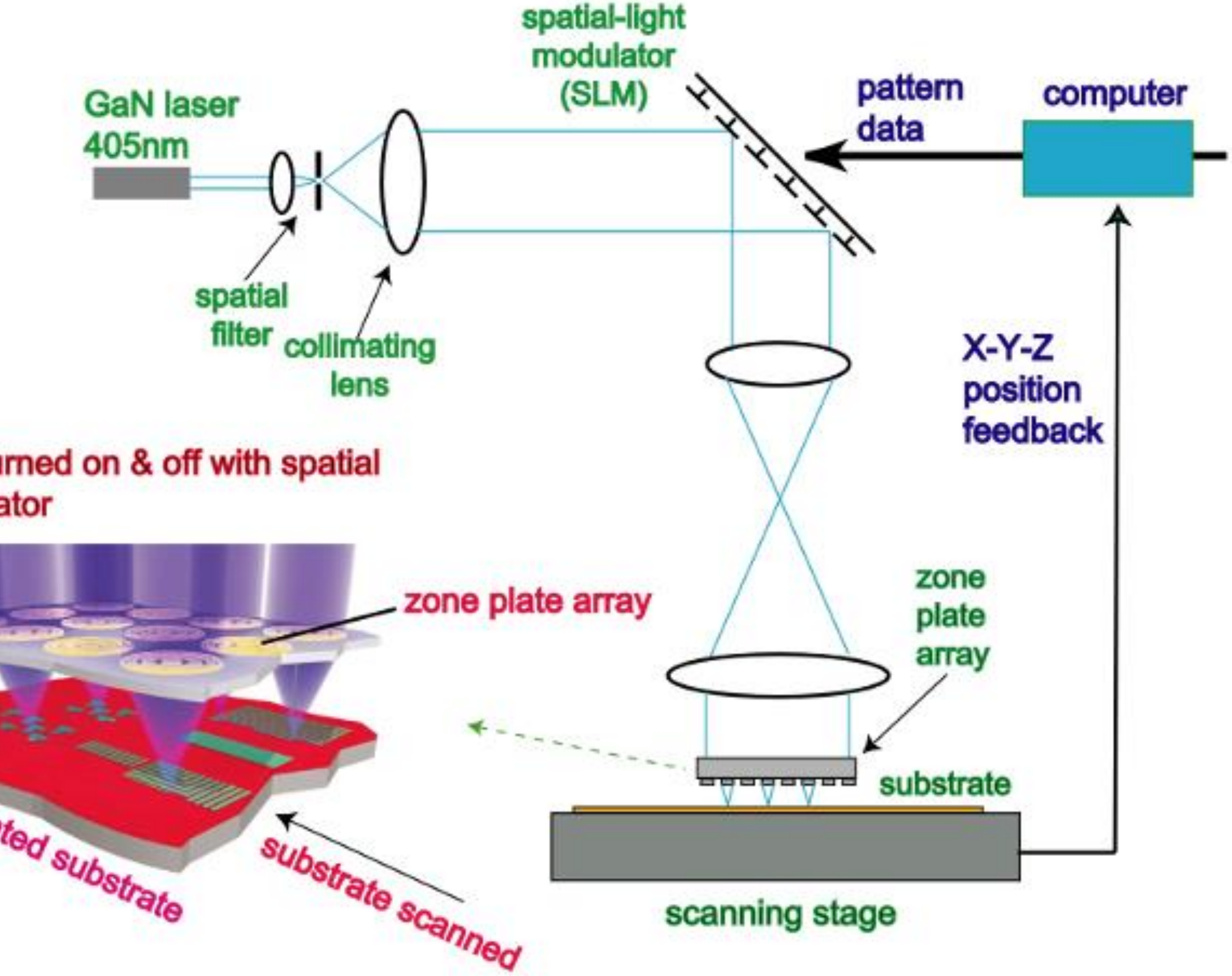
Zone plate size ~ 10 µm

Uranium proposed as zone plate material



Smith, JVST B 14 4318, 1996.

Zone plate array lithography with light



beamlets turned on & off with spatial light modulator

- ~1000 lenses
- NA = 0.85
- 405 nm light
- Resolution 150-200 nm in dense patterns

Lumarray.com

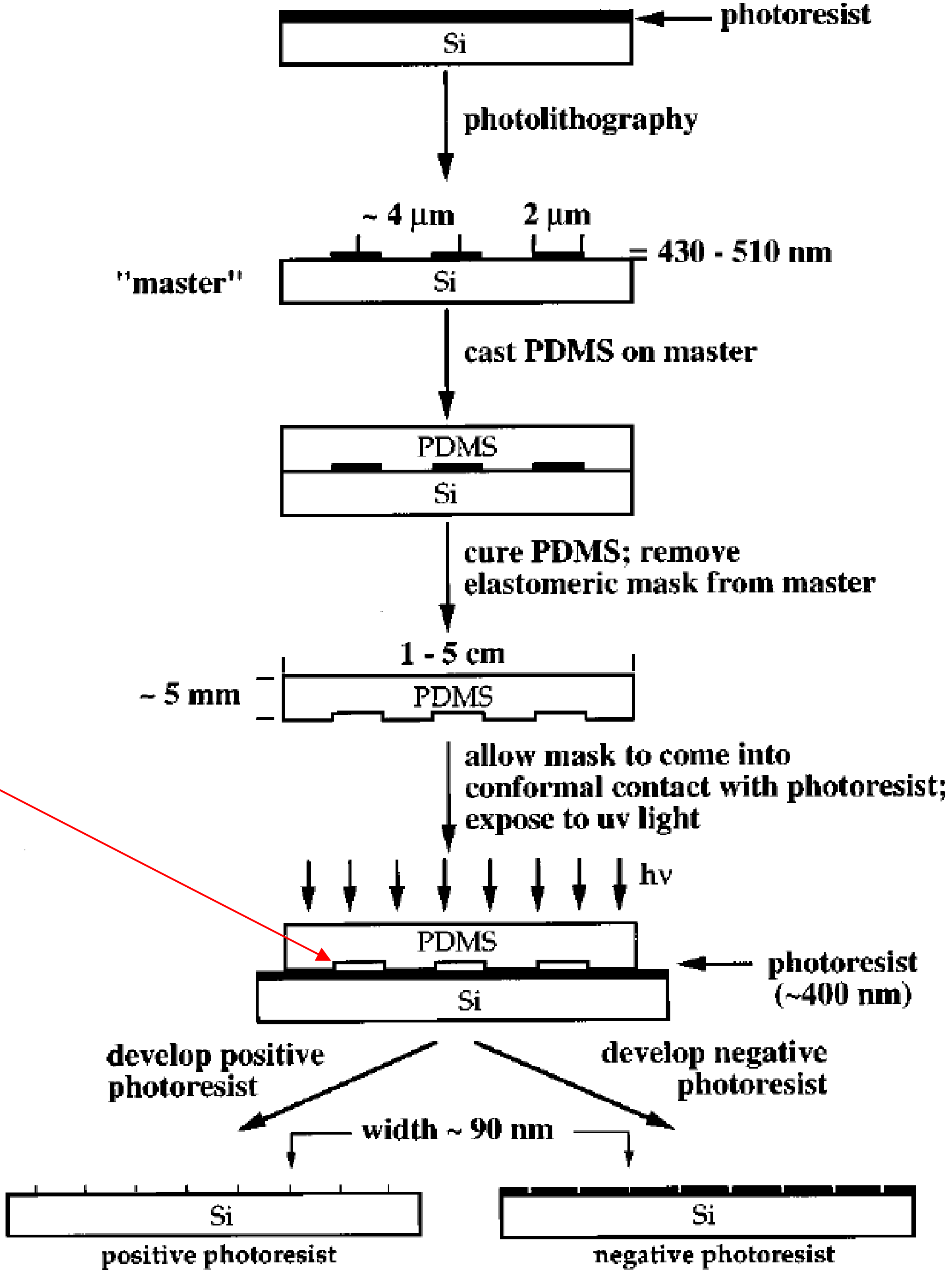
Zone plate arrays

- Applicable to X-rays and photons
- Advantages: parallelizable and customizable pattern transfer
- Disadvantage: still slow compared to full mask-based processes

Near-field techniques

- "Contact" lithography with rigid masks does not really involve perfect contact (because of particles and mask/wafer non-planarity)
- Why not make the optical mask conformable?
- Pattern curved substrates
- Exploit predictable near-field diffraction

Intensity “dip” near each phase edge is ~ 0.25 times the wavelength of illumination in the resist – hence sub-100 nm for UV light



Rogers *et al.*, *Appl. Phys. Lett.*, Vol. 70, No. 20, 19 May 1997

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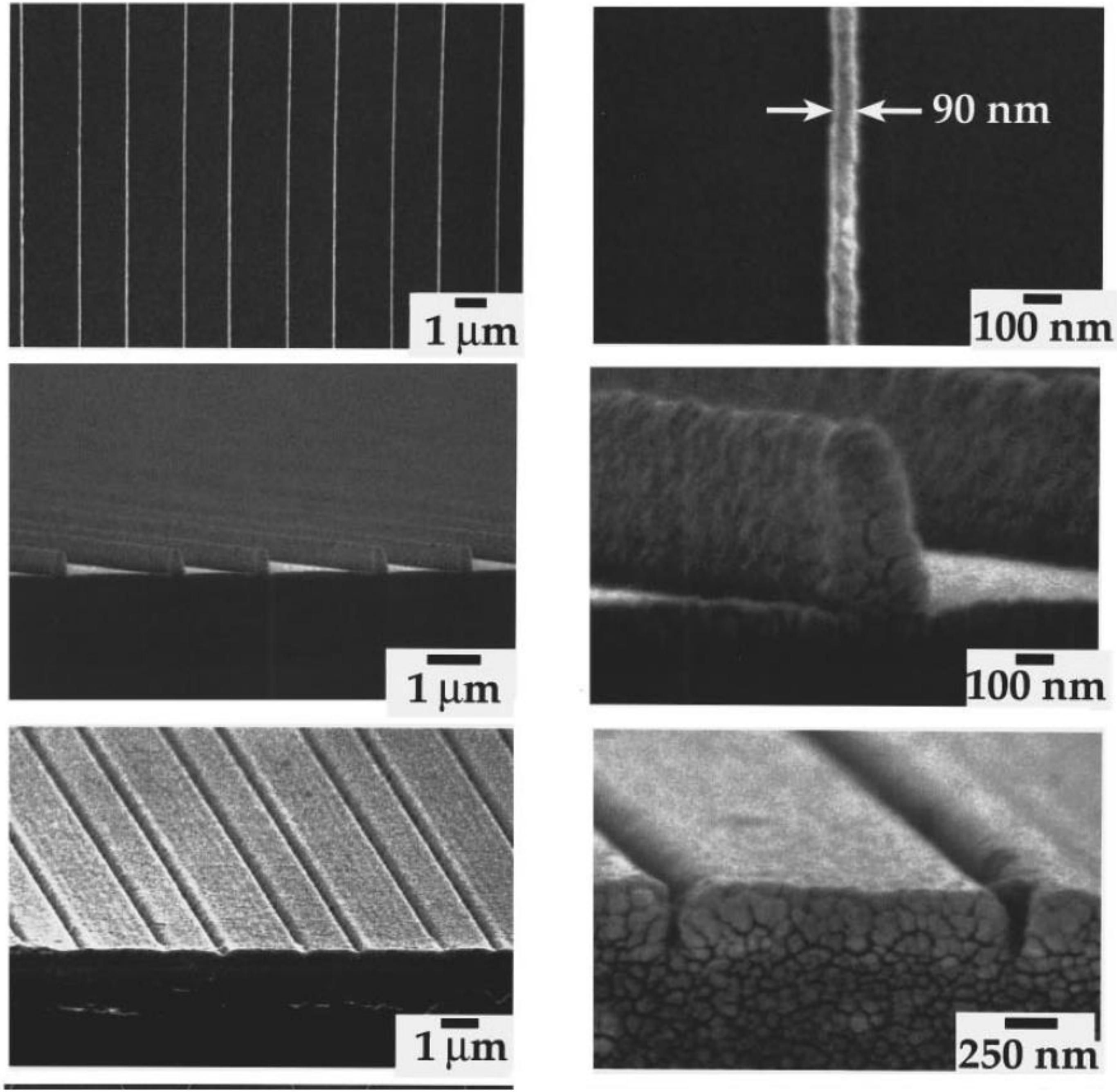
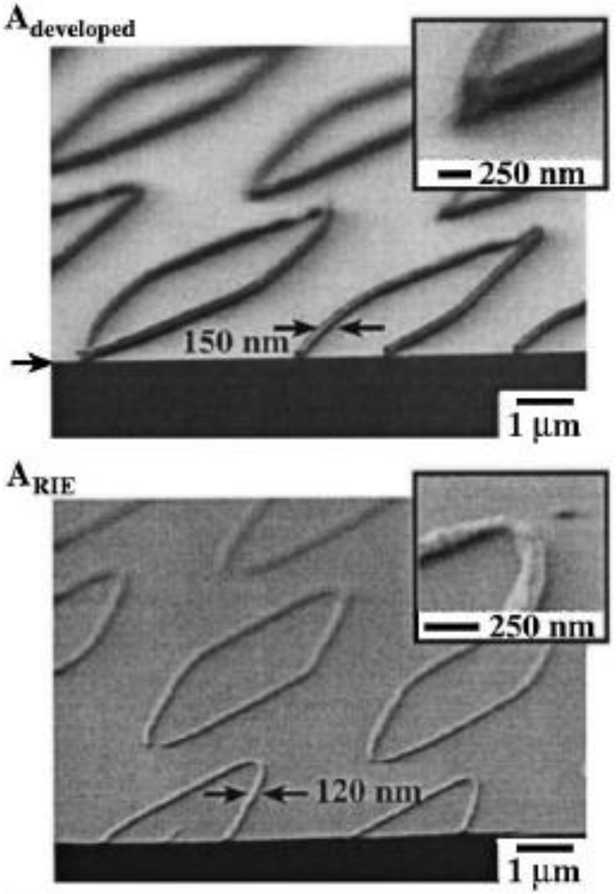


Rogers *et al*., *Appl. Phys. Lett*., Vol. 70, No. 20, 19 May 1997

Embossed resist as its own optical element



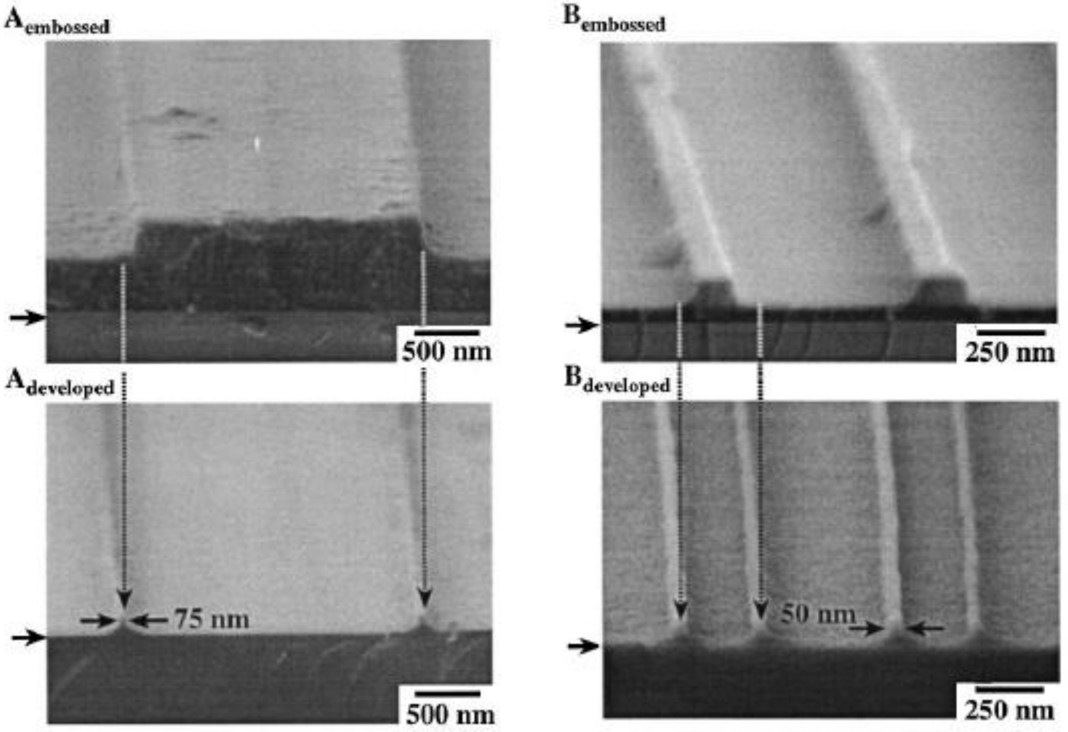
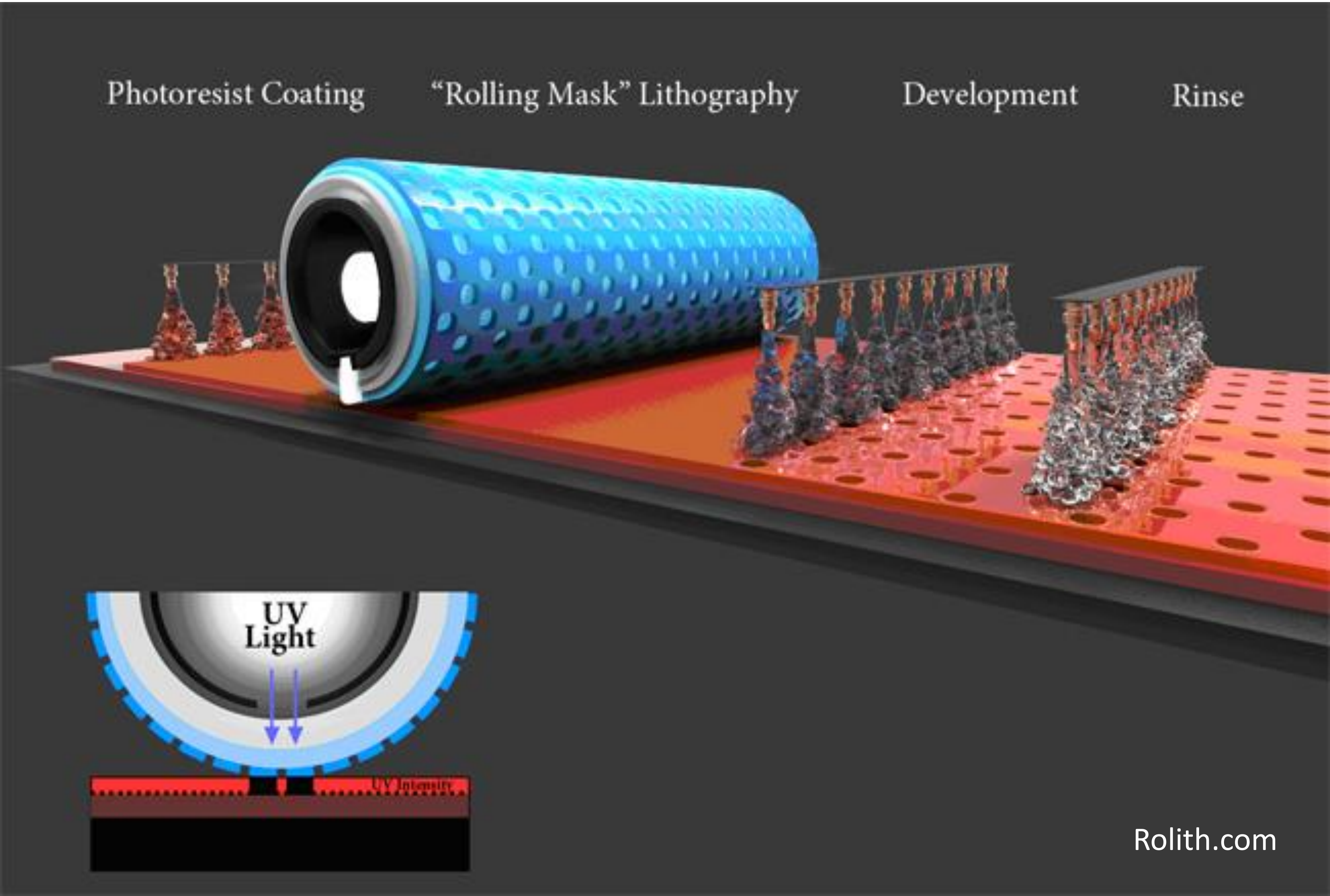


FIG. 3. Features generated using rectangular topographies. All samples were developed for 1 min. The black arrow at the left of the images indicates the photoresist/substrate interface. (A_{embossed}): lines with 2-μm width and 4-μm periodicity embossed on a 0.50 μm layer of photoresist. ($A_{\mathrm{developed}}$): exposed (A_{embossed}) (3 s); width of features is ~75 nm. (B_{embossed}): lines (150-nm wide, with periodicity 800 nm) embossed on a ~200 nm layer of photoresist. ($B_{\mathrm{developed}}$): exposed (B_{embossed}) (0.85 s); features are ~50-nm wide.

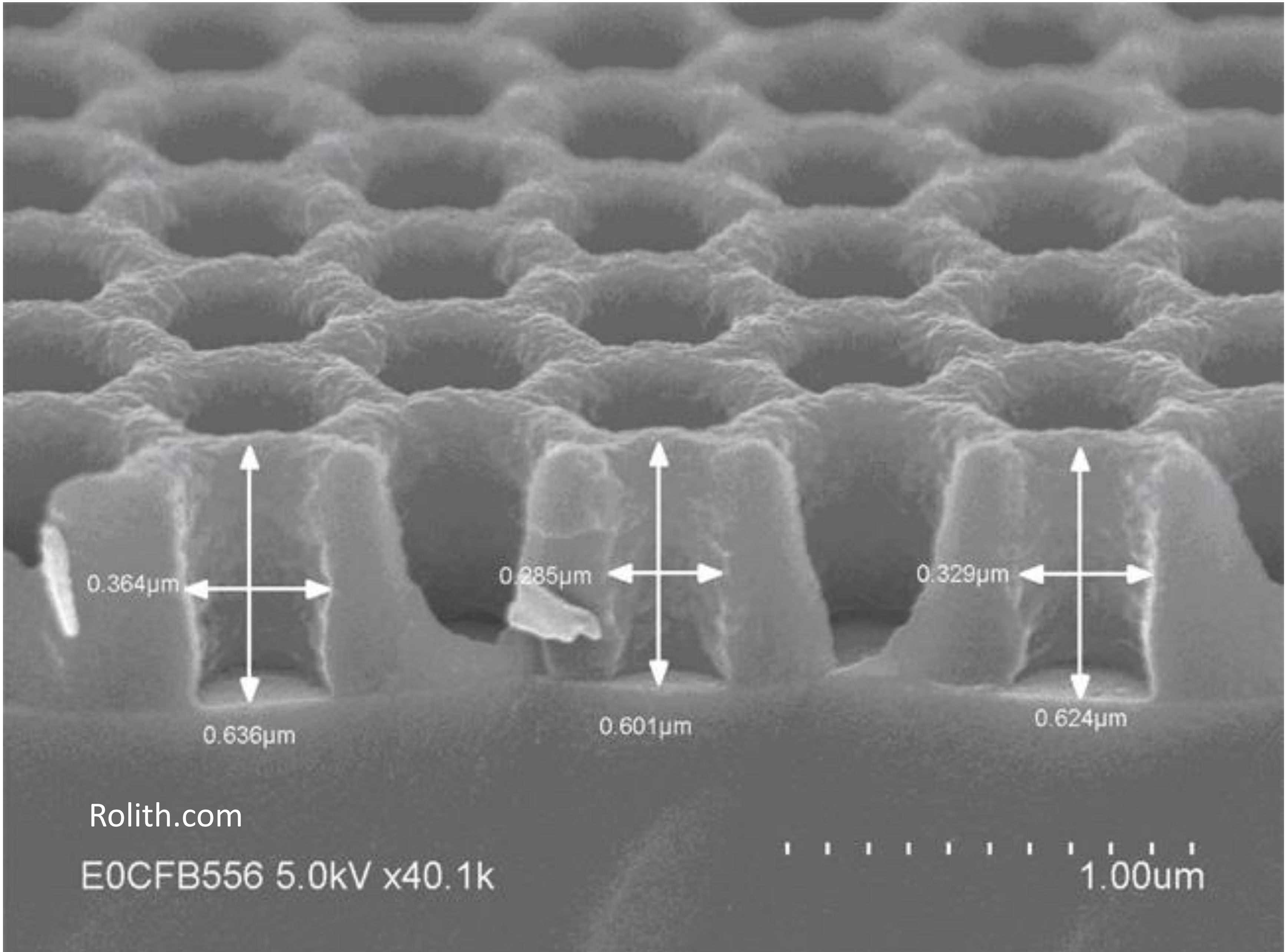
Paul *et al.*, *Appl. Phys. Lett.*, Vol. 73, No. 20, 1998

Roll-to-roll photolithography



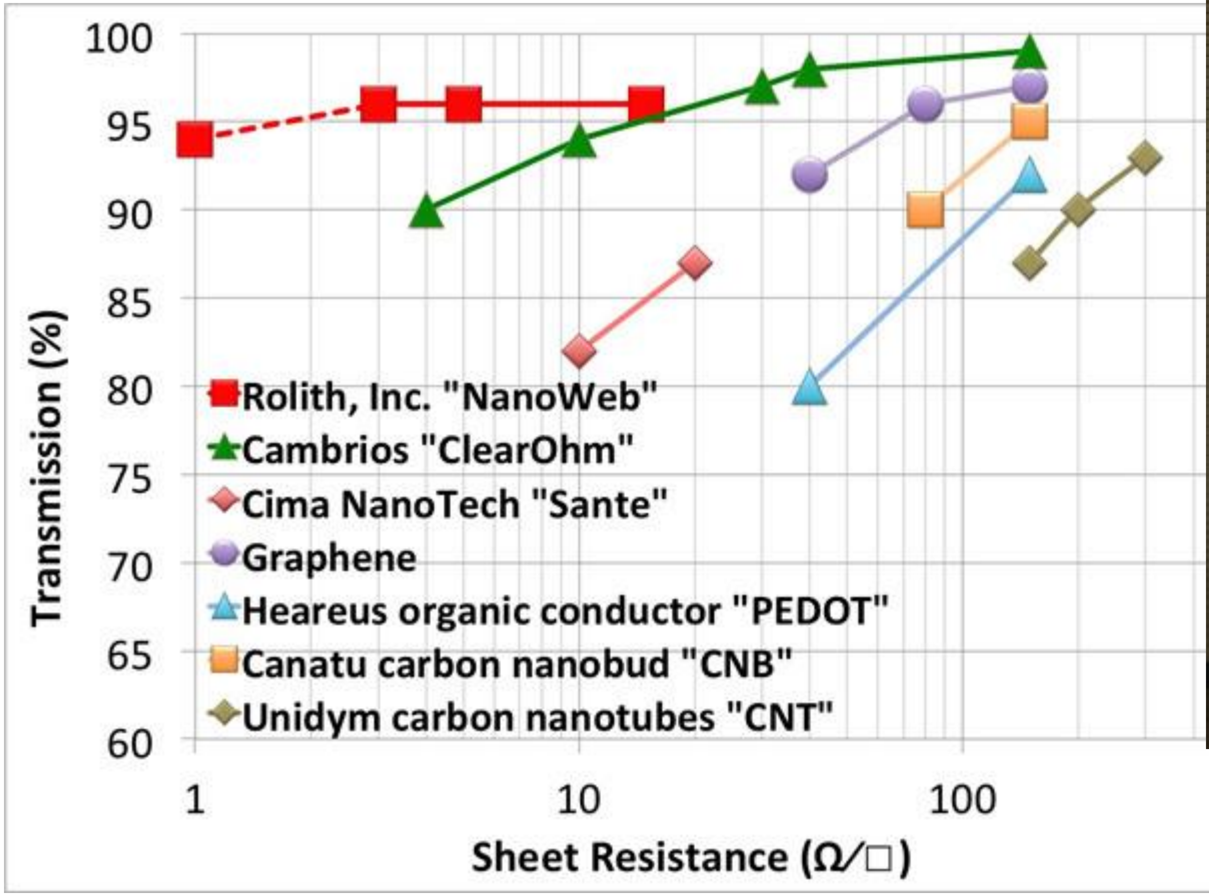
Rolith.com

Roll-to-roll photolithography



Roll-to-roll photolithography

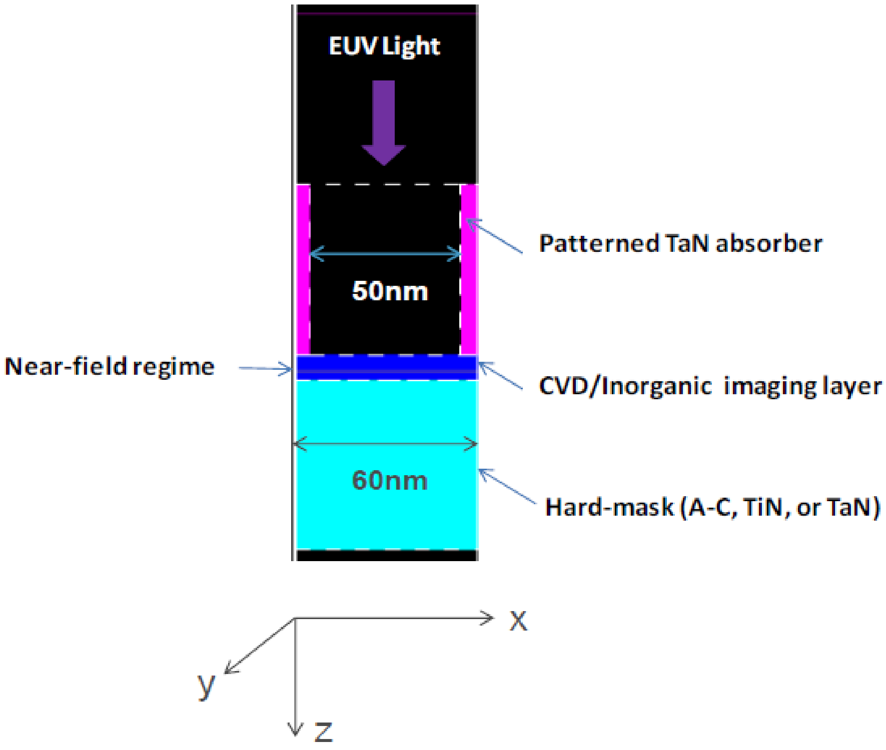
- Claimed by Rolith:
  - Cost down to \$2/m^2
  - Throughout up to 3 m^2/min



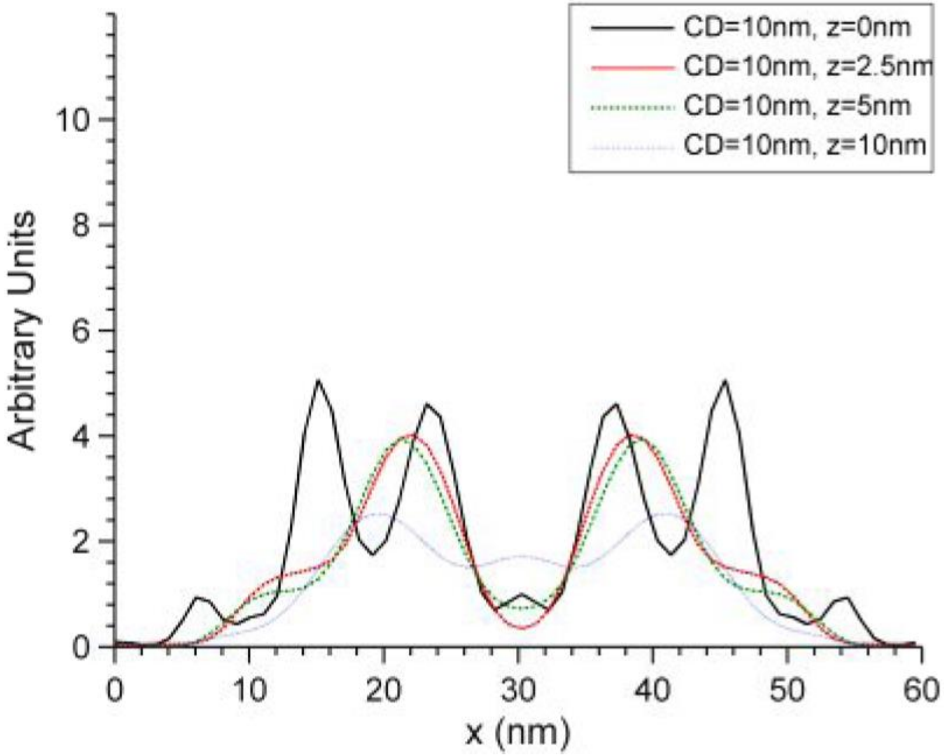
Rolith.com

Frequency multiplication based on EUV near-field imaging

- EUV propagates laterally, as an evanescent wave, within the imaging layer

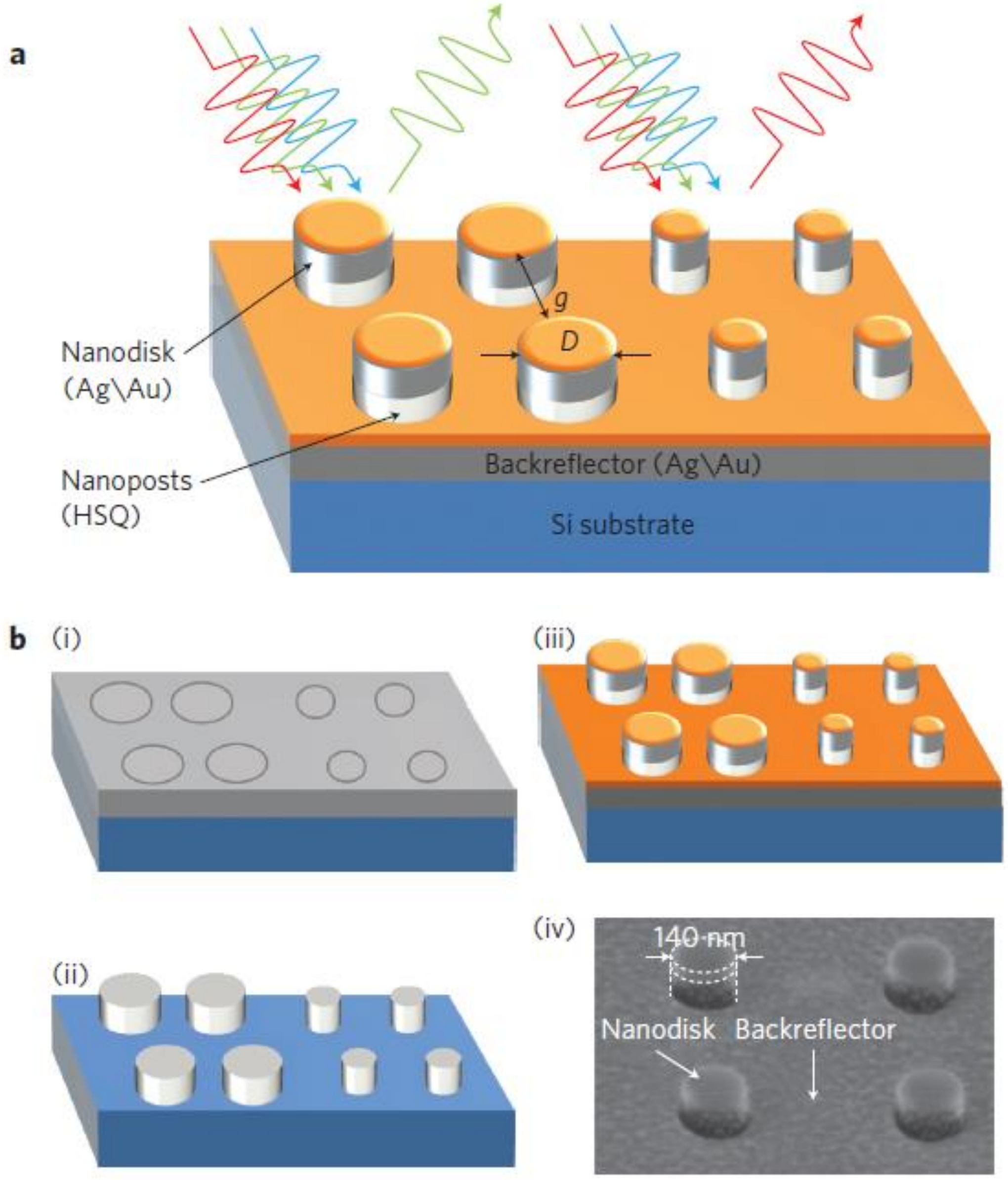


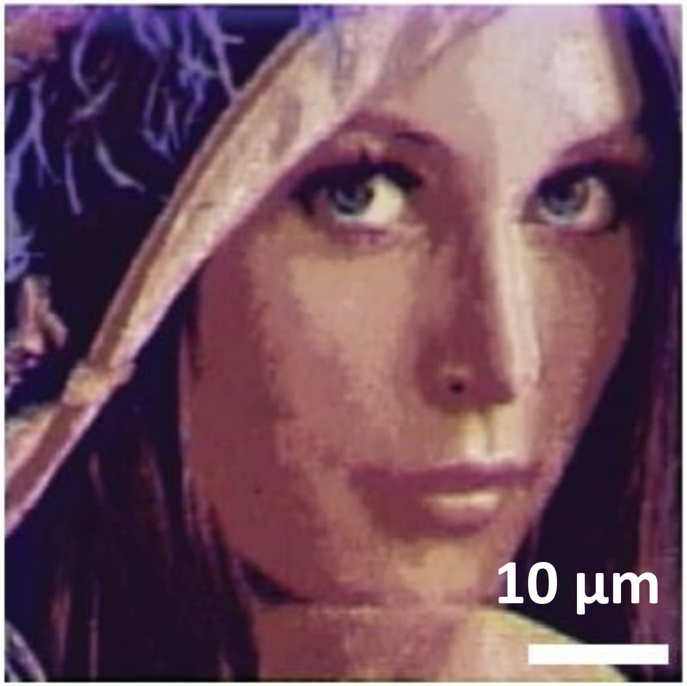
TE wave with TaN absorber and hard mask (absorber CD 10 nm; gap 50 nm; imaging layer 10 nm thick)

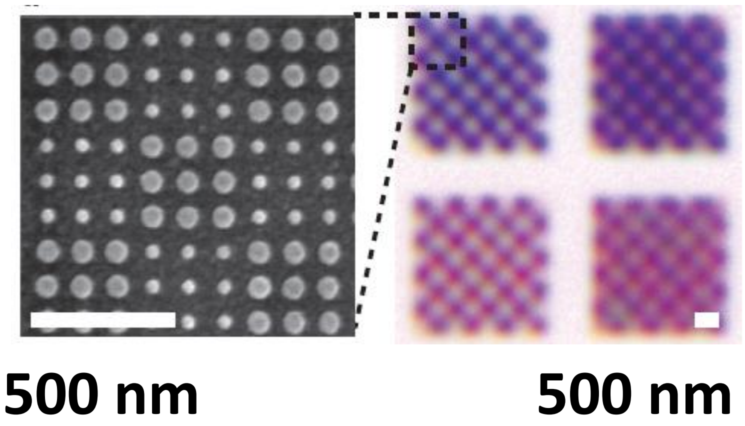


Chen *et al.*, *Proc SPIE* vol. 9049, 90490D, 2014

Printing color at the nanoscale

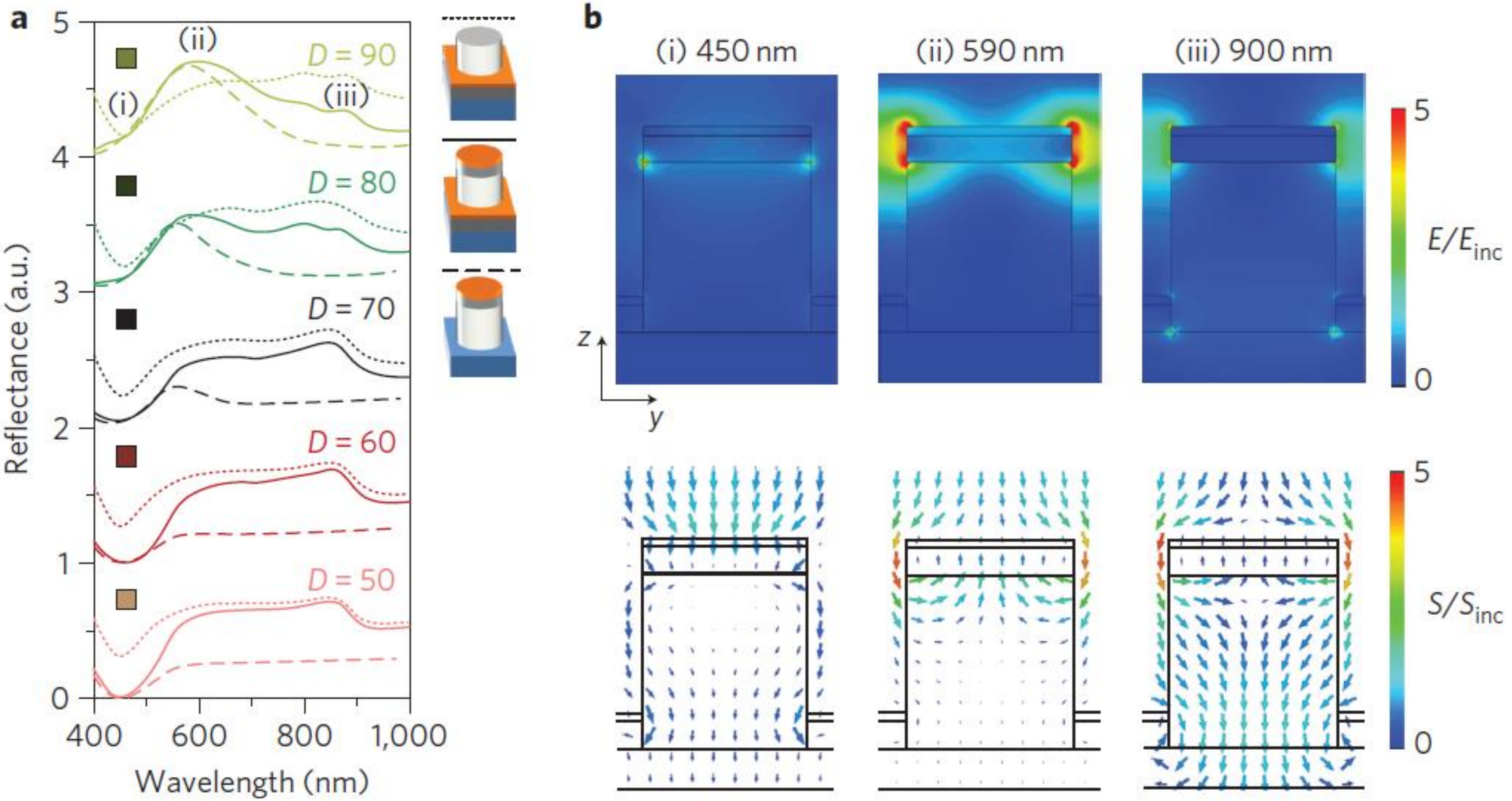






Kumar et al., Nature Nanotech, vol. 7, p. 557, 2012

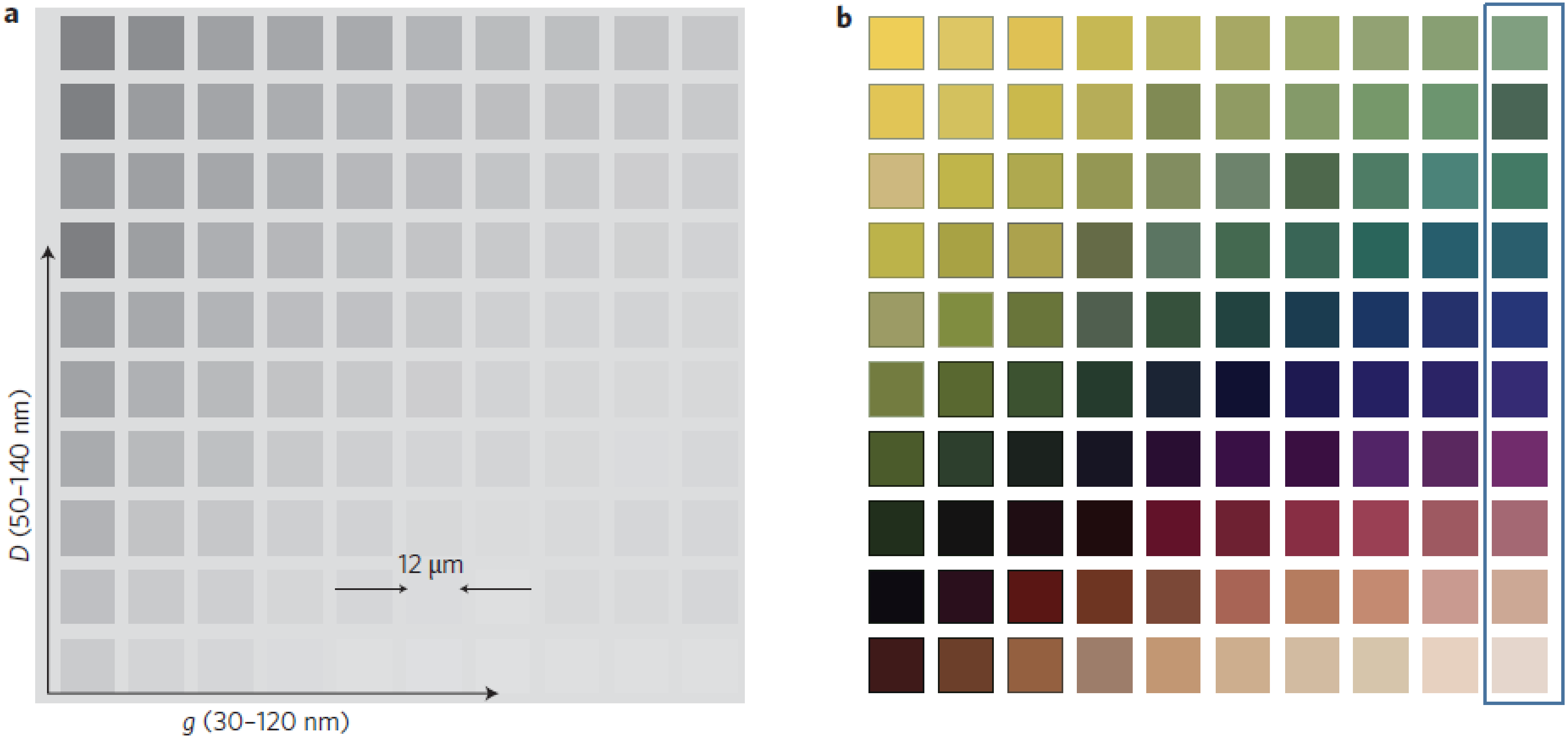
Printing color at the nanoscale



Electric field enhancement

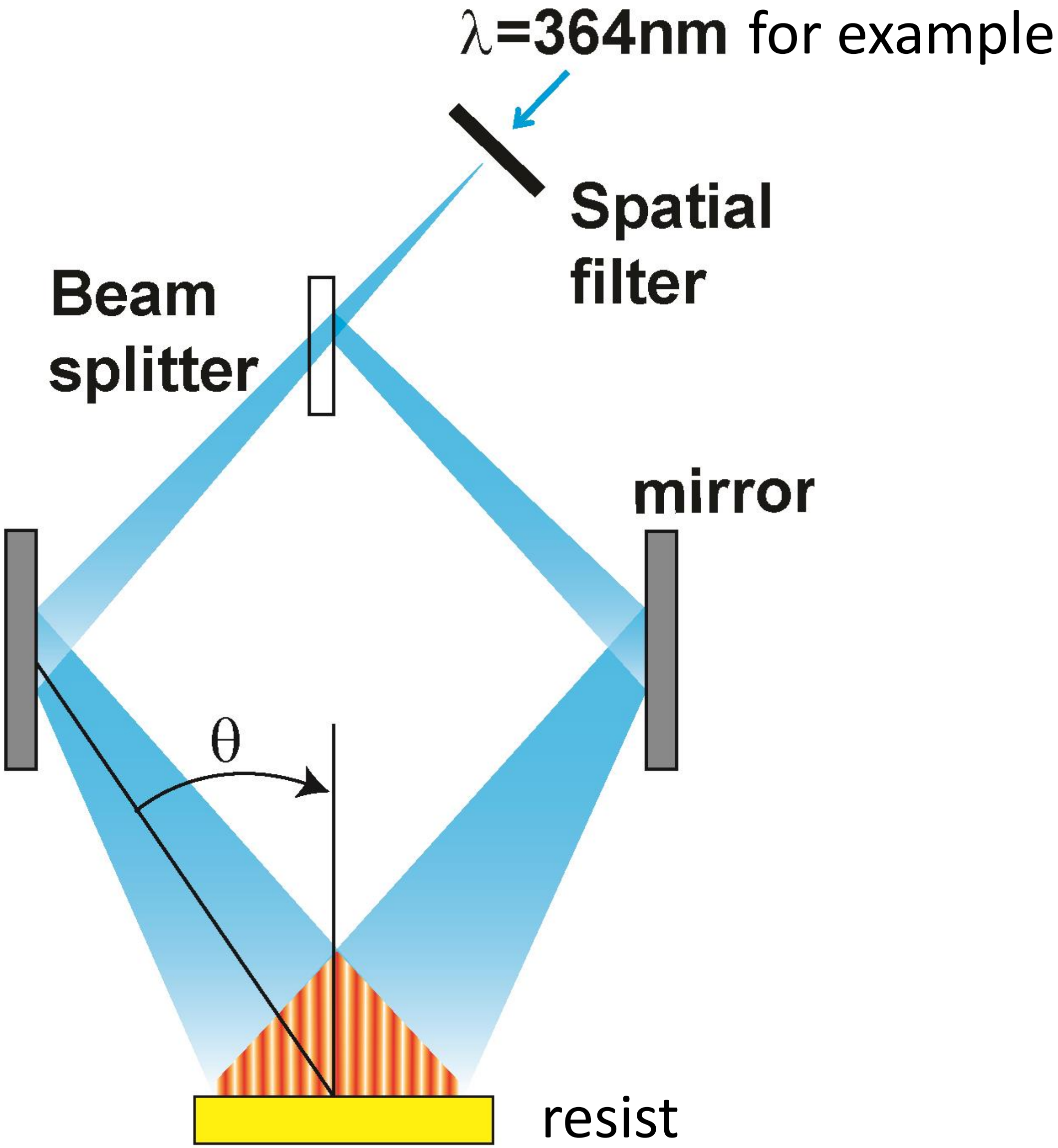
Kumar et al., Nature Nanotech, vol. 7, p. 557, 2012

Printing color at the nanoscale



Kumar et al., Nature Nanotech, vol. 7, p. 557, 2012

Interference lithography



- Regular patterns over wafer-sized areas with extremely simple optics – no mask
- Requires spatially and temporally coherent light
- Small θ: no upper limit to period of pattern
- $\theta \rightarrow 90°$:

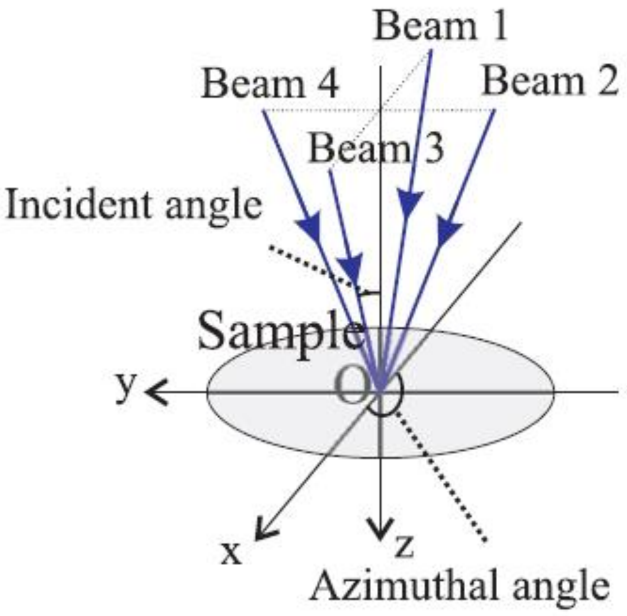
$$\text{period}, \Lambda \rightarrow \frac{\lambda_0}{2n}$$

- where *n* is resist's refractive index

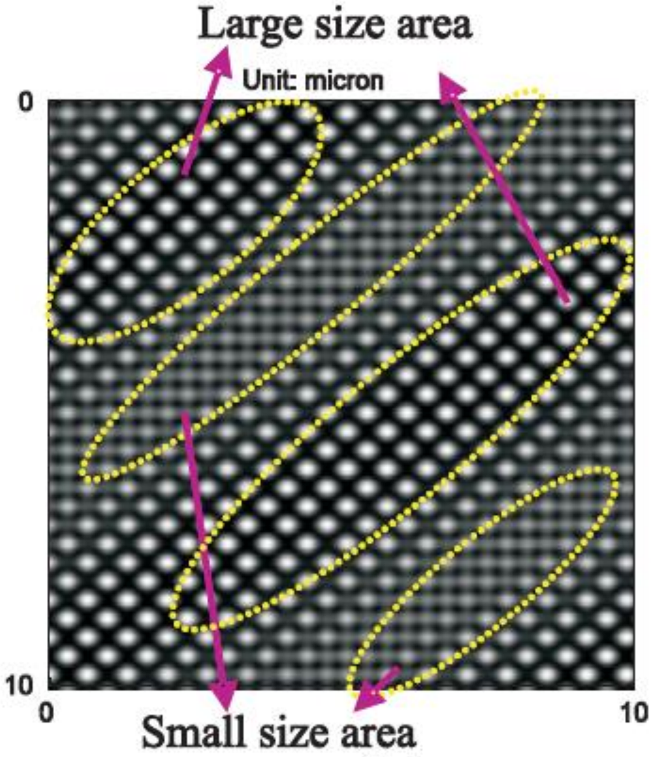
Mok *et al.*, Ch 21 of *Nanowires: Implementations and Applications*, Intech

2D arrays are possible by interfering multiple beams

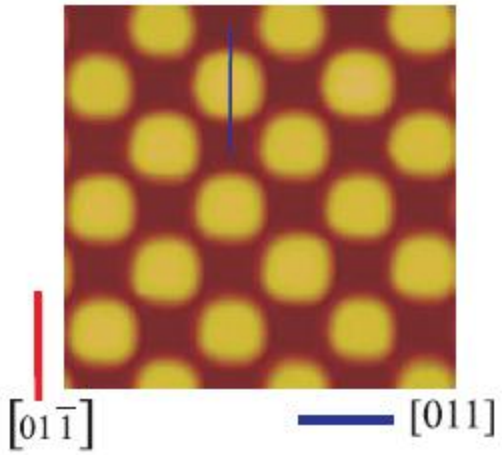
- Three beams: honeycomb structure
- Four beams: square array of, e.g., contact holes
- High intensity illumination: can directly pattern the substrate



(a)



(b)



Direct patterned
SiO_2/GaAs
~640 nm pitch structure

Tan *et al.*, *Nanotechnology* **20** (2009) 125303

Sequential exposures with a single beam pair and substrate rotation between steps

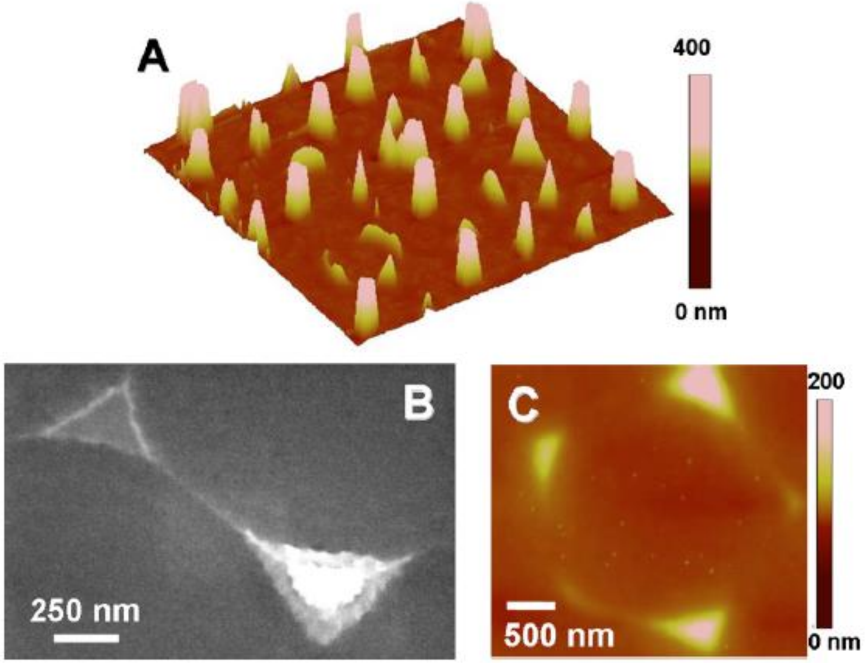


FIG. 4. (Color online) (a) AFM images of a tenfold symmetry silicon mater (the size is 12×12 μm^2). (b) SEM zoom in small features on (a) silicon master, (c) AFM images of the pure silica replica after sintering.

Letailleur *et al.* J. Appl. Phys. **109**, 016104 2011

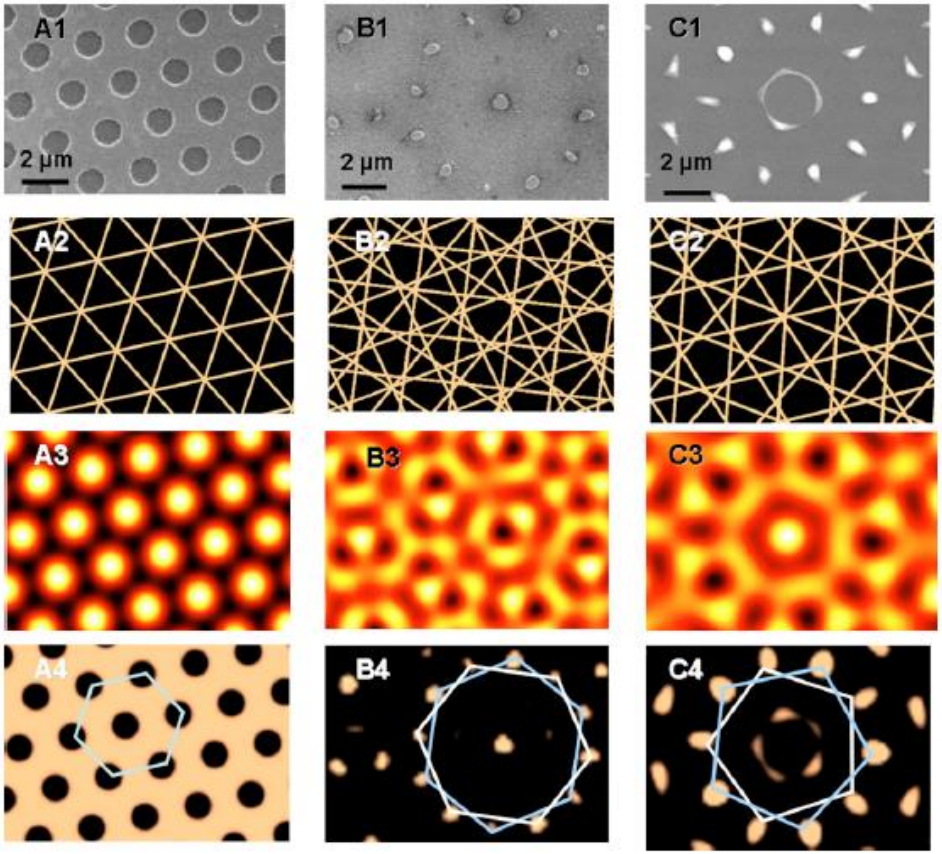
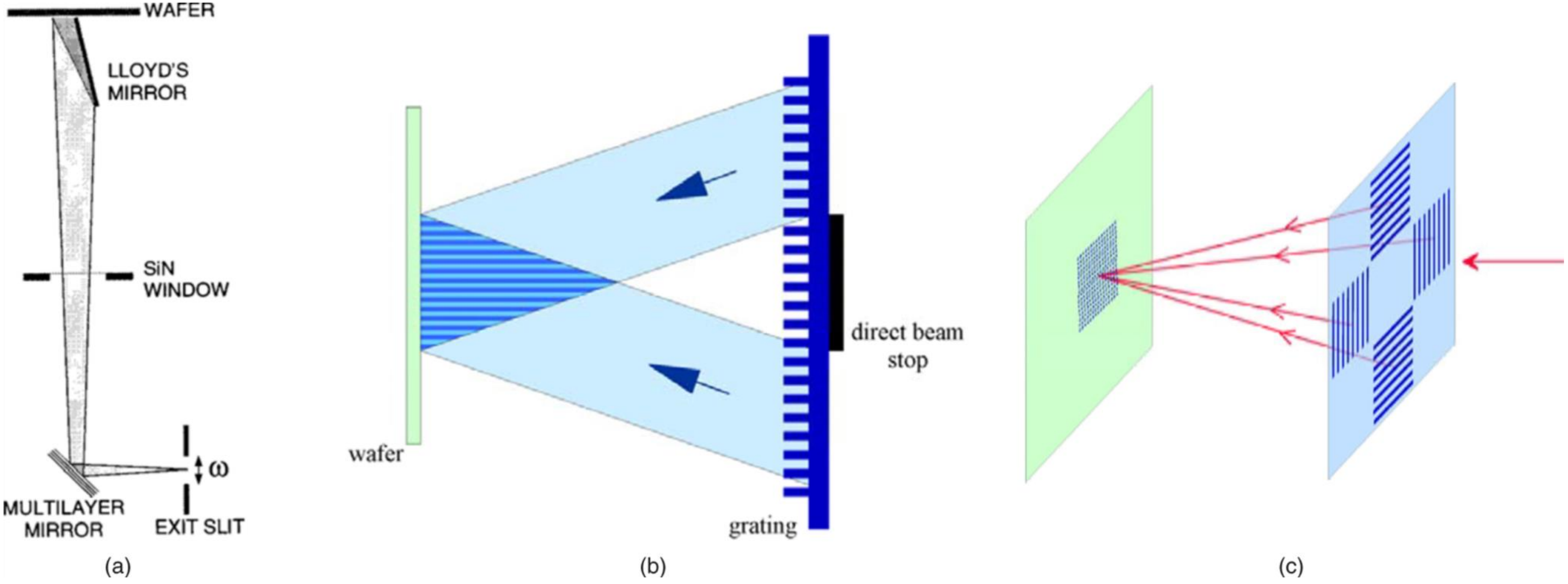


FIG. 2. (Color online) First row: SEM pictures of different silicon masters. Depth of the structures: (a) and (b) 150 nm (c) 450 nm. Symmetry order: (a) 3, (b) 6, (c) 5. Second row: corresponding directions of the interference patterns during the n exposures. Third row: simulated exposure dose on each point of the surface, obtained by summing up the intensity of the n interferences patterns. Fourth row: simulated resist height profiles. The results were obtained using the simulated doses and initial layer thicknesses. Pentagons and hexagons are guide for the eyes.

Interference lithography for EUV



Single pitch per field

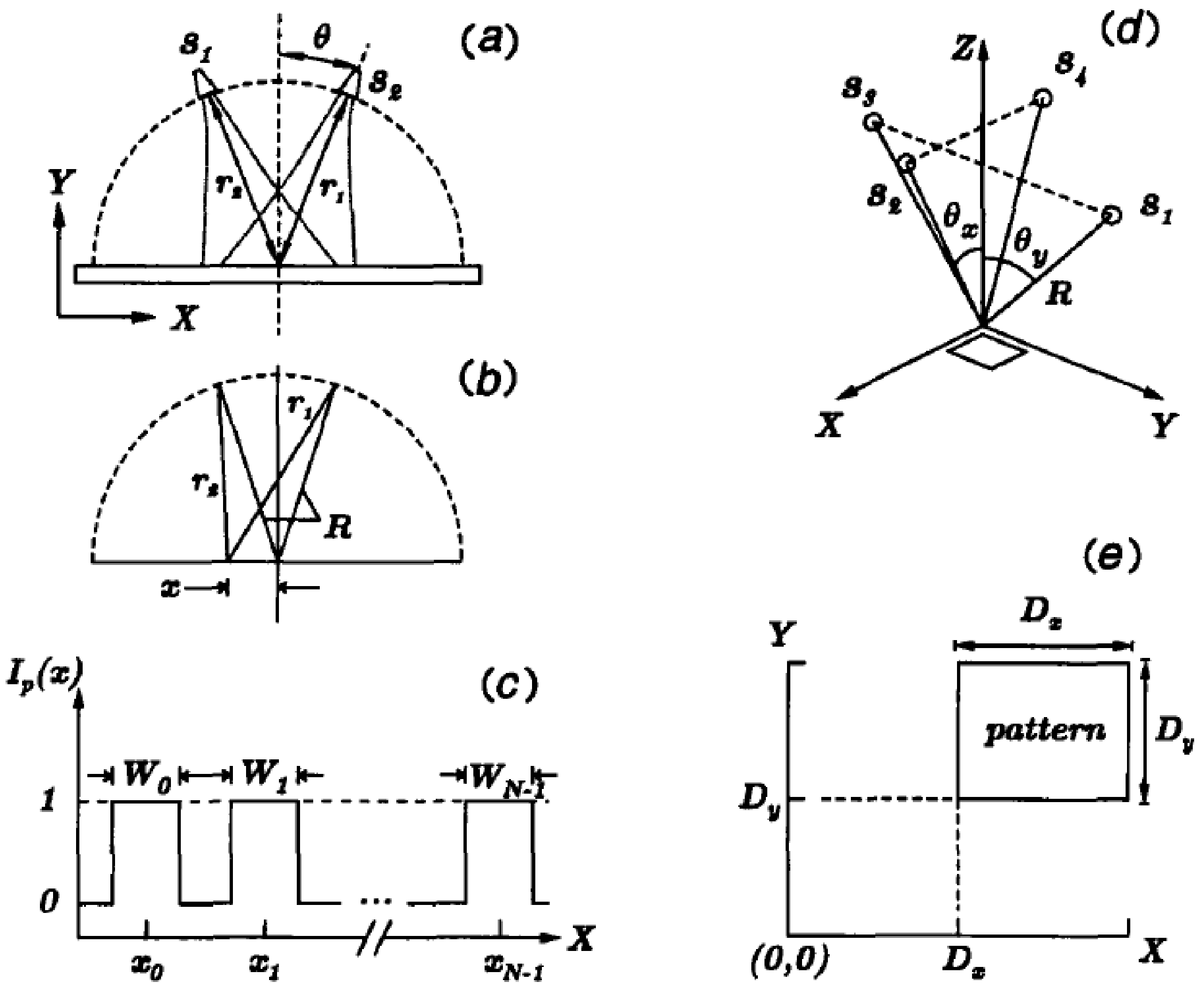
Pairs of gratings to generate interference

Perpendicular gratings for contact hole arrays

Gronheid, *Micro/Nanolith. MEMS MOEMS*. 8(2), 021205

Printing arbitrary patterns by interference lithography

- Sweep angle of incidence of two beams
- Vary intensity and relative phase as angle varies
- Build up arbitrary 1D intensity history pattern on substrate
- Resist integrates illumination history
- Cannot achieve zero illumination history in arbitrary locations



Pau *et al.*, *J Modern Optics*, vol. 48 no. 7 p. 1211, 2001.

Printing arbitrary patterns by interference lithography

Single interfering beam pair:

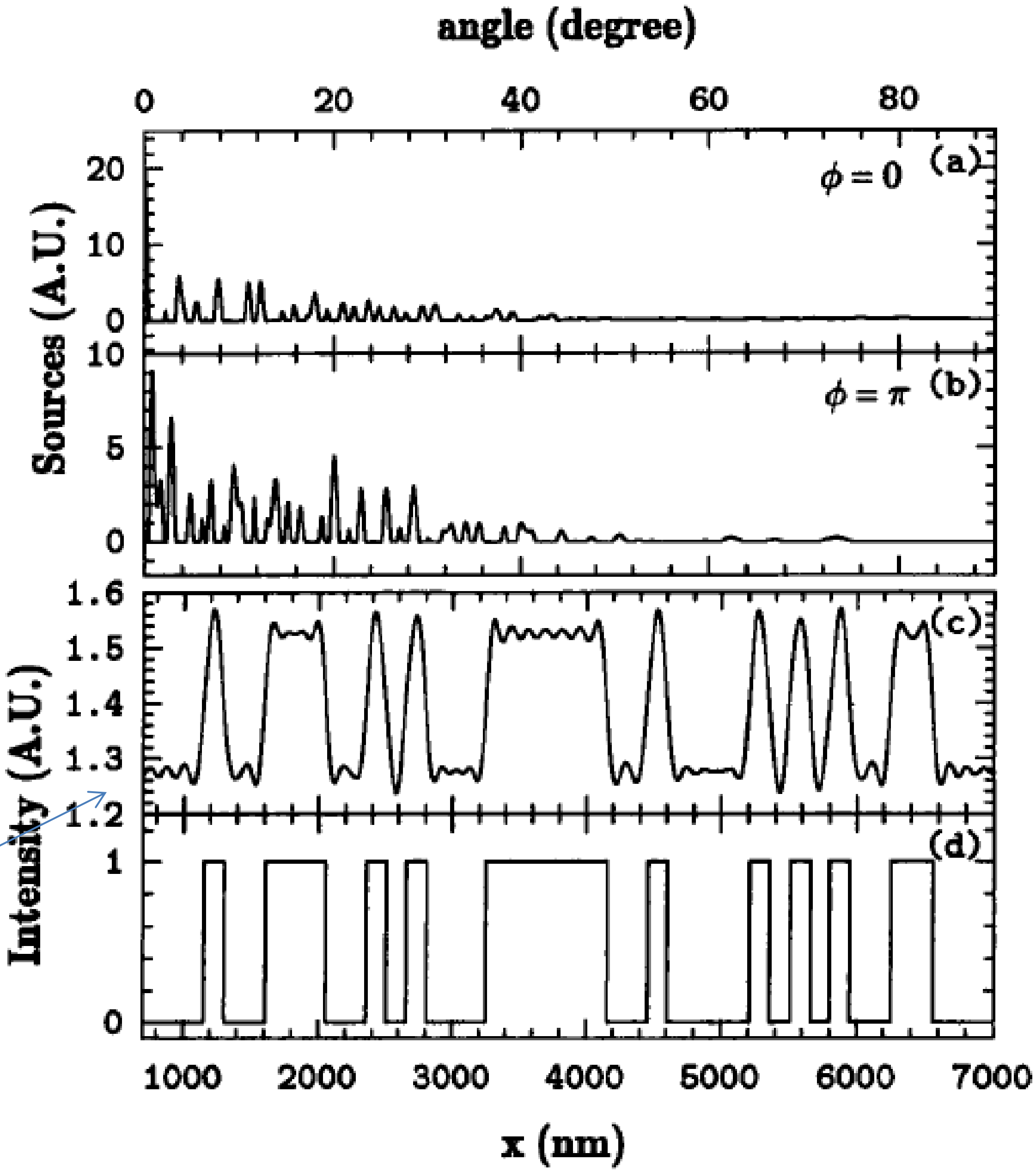
$$I(x,\theta) = \frac{I_{s1}(\theta)}{r_1^2} + \frac{I_{s2}(\theta)}{r_2^2} + \frac{2\sqrt{I_{s1}(\theta)I_{s2}(\theta)}}{r_1 r_2}\cos\left[\frac{2\pi n}{\lambda}(r_1 - r_2) + \phi\right]$$

Swept beam pair with varying intensity:

$$\begin{aligned}
I(x) &= \int_0^{\pi/2} \mathrm{d}\theta\, I(x,\theta) = \int_0^{\pi/2} \mathrm{d}\theta\, I_s(\theta)\left[\frac{1}{r_1^2} + \frac{1}{r_2^2} + \frac{2}{r_1 r_2}\cos\left[\frac{2\pi n}{\lambda}(r_1 - r_2) + \phi\right]\right] \\
&\simeq \int_0^{\pi/2} \mathrm{d}\theta\, \frac{2I_s(\theta)}{R^2}\left[1 + \cos\left[\frac{4\pi n}{\lambda}\sin(\theta)x\right]\right] \\
&= \int_0^{\pi/2} \mathrm{d}\theta\, \frac{2I_s(\theta)}{R^2} + \int_0^{2n/\lambda} \mathrm{d}u\, \frac{2I_s(\theta = \sin^{-1}(\lambda u/2n))}{\sqrt{4n^2\lambda^{-2} - u^2}R^2}\cos[2\pi u x],
\end{aligned}$$

Pau *et al*., *J Modern Optics*, vol. 48 no. 7 p. 1211, 2001.

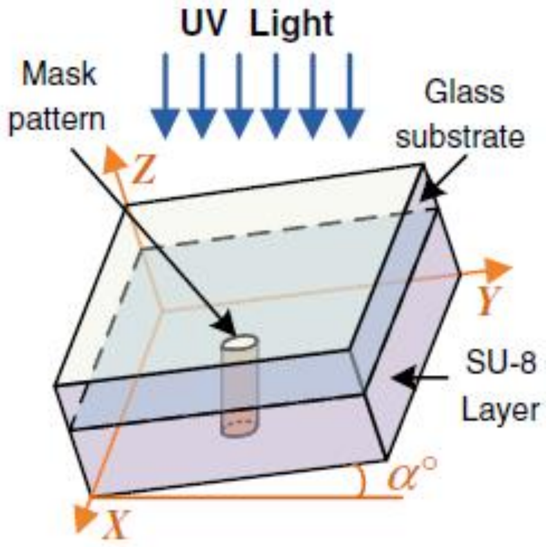
Printing arbitrary patterns by interference lithography



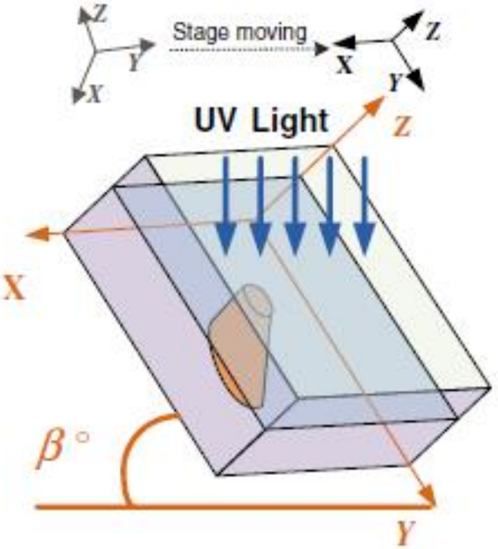
Note background intensity history in simulation

Pau *et al.*, *J Modern Optics*, vol. 48 no. 7 p. 1211, 2001.

3D projection lithography approaches

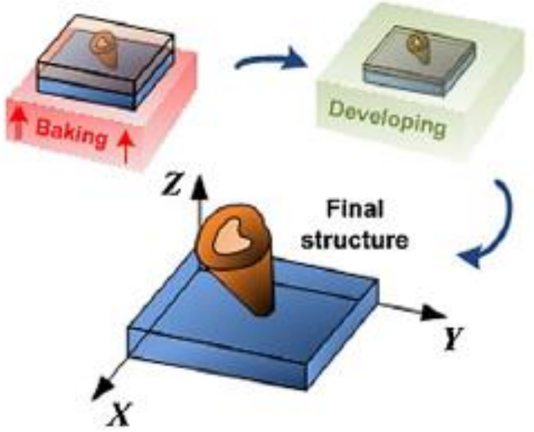


(a)

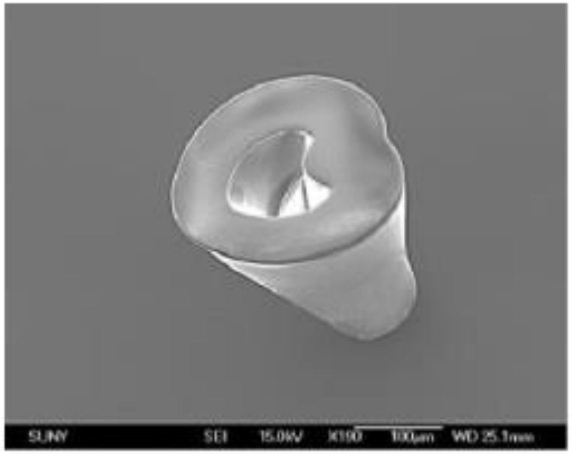


(b)

SU-8 negative resist



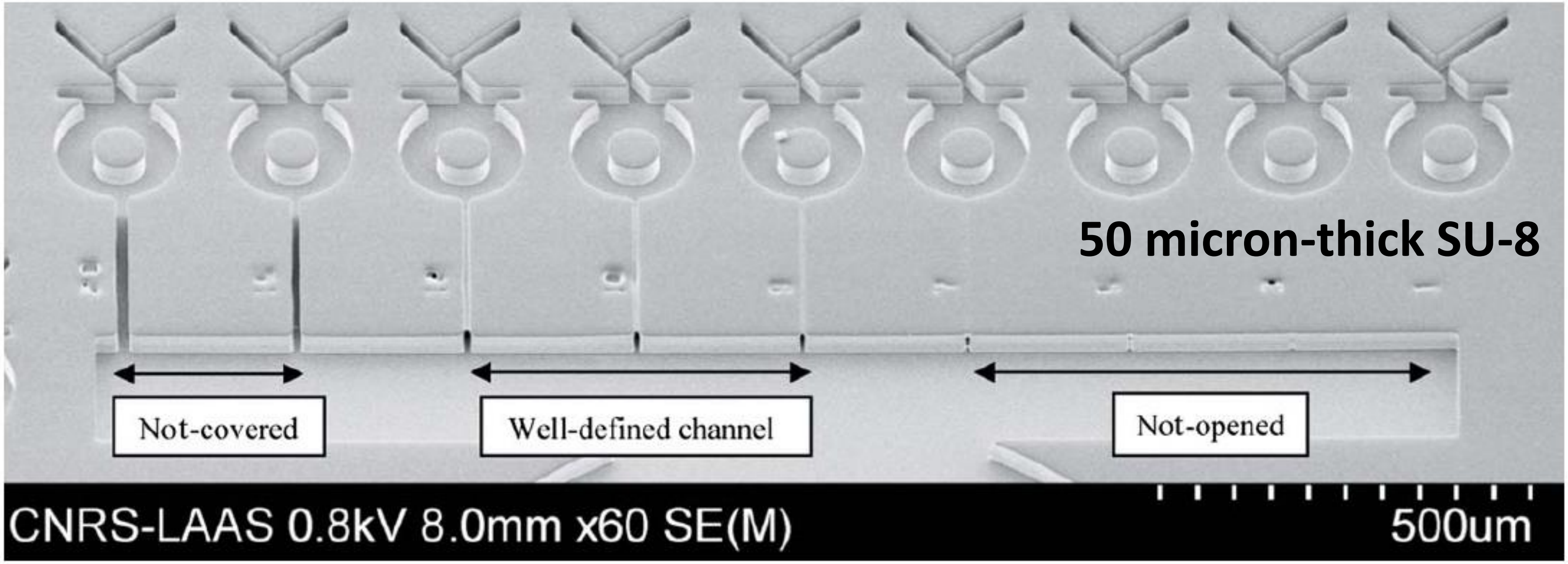
(c)



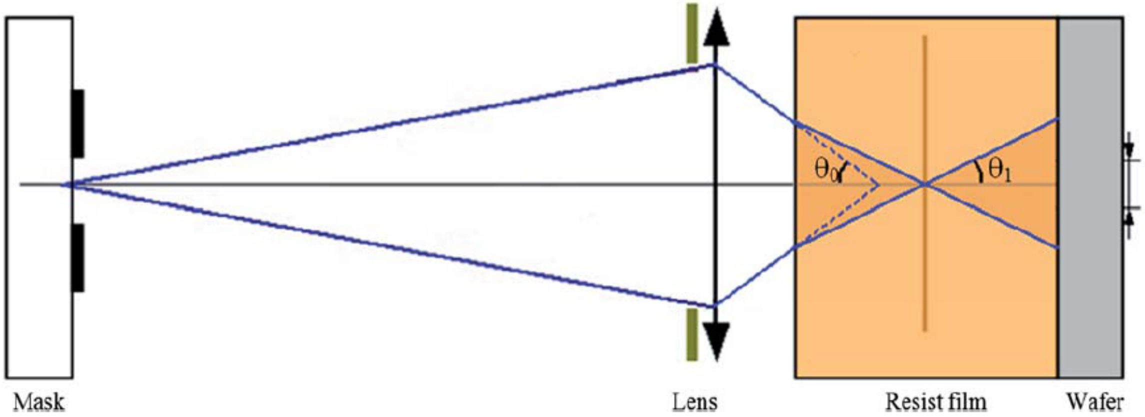
(d)

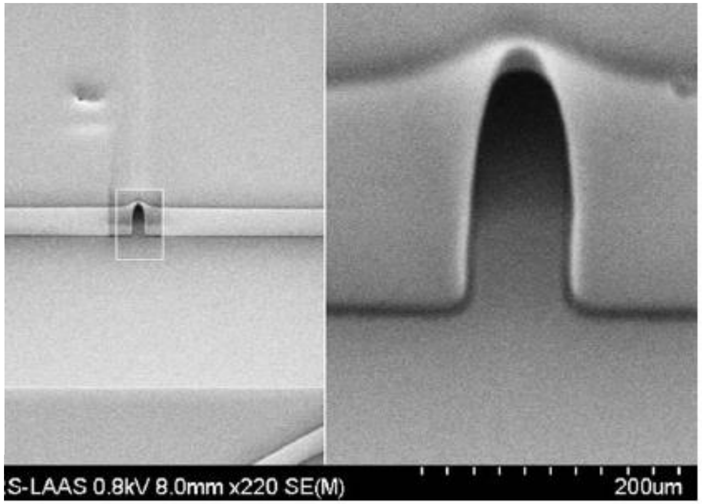
Kim et al., J. Micromech. Microeng. **21** (2011) 035003

Controlling focal point in projection lithography to form enclosed microchannels



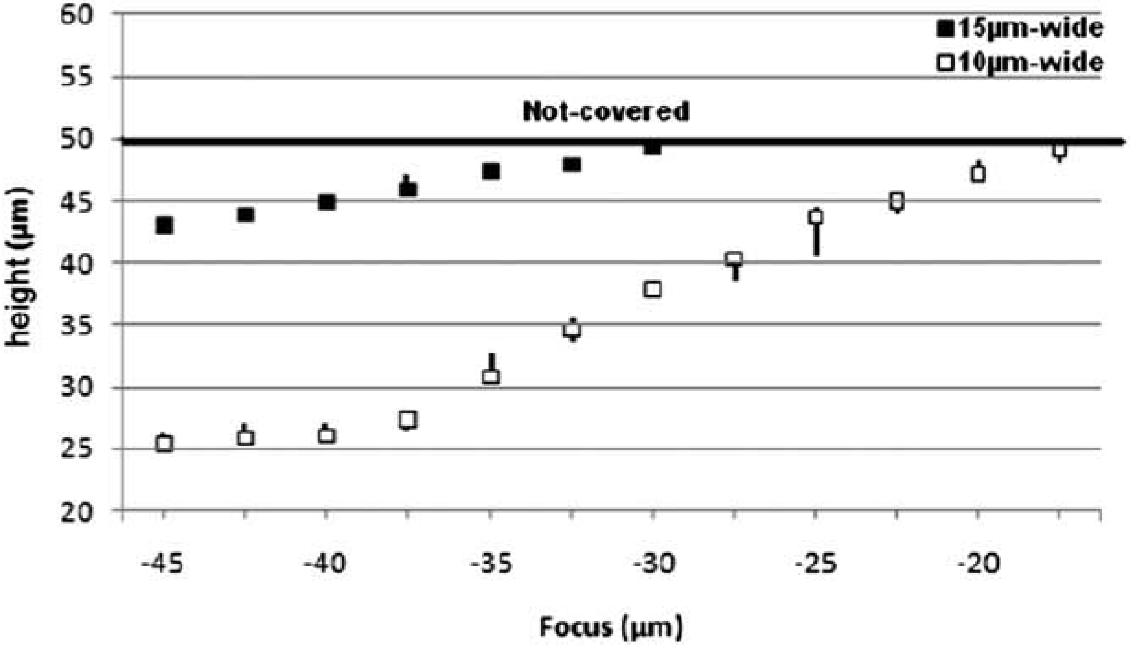
50 micron-thick SU-8

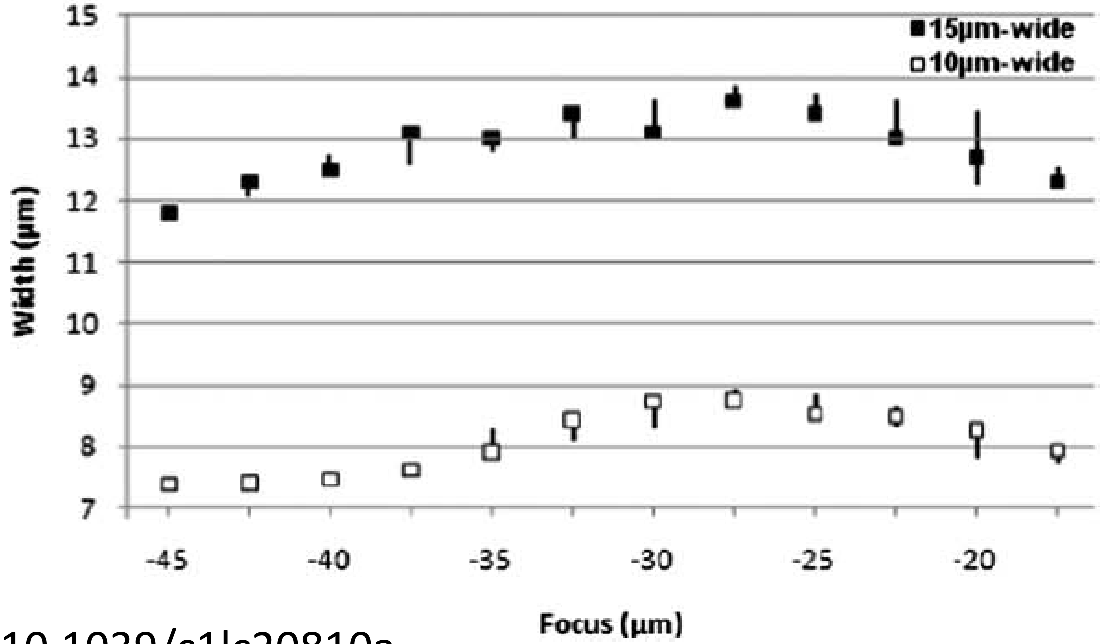




Larramendy *et al.*, *Lab Chip* 2011, DOI: 10.1039/c1lc20810a

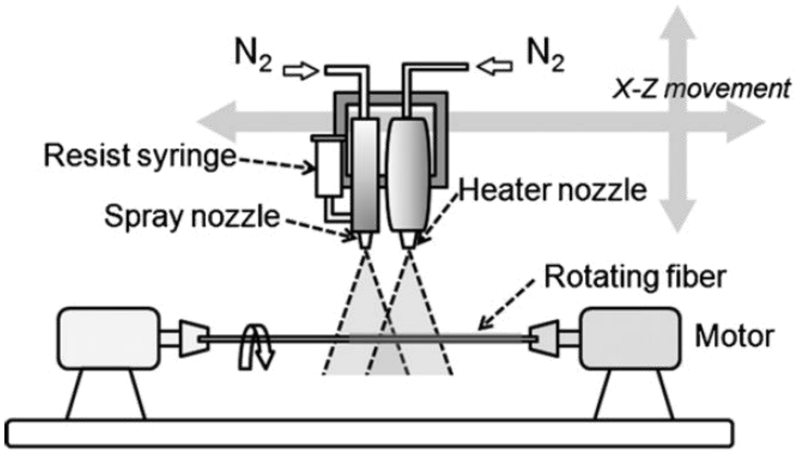
Controlling focal point in projection lithography to form enclosed microchannels



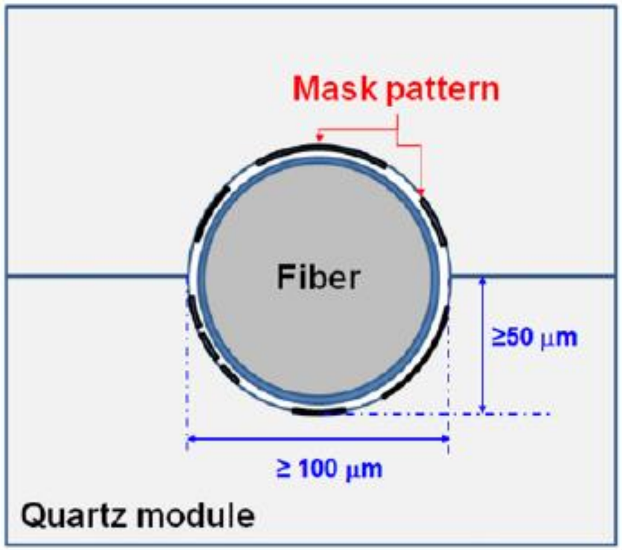


Larramendy *et al.*, *Lab Chip* 2011, DOI: 10.1039/c1lc20810a

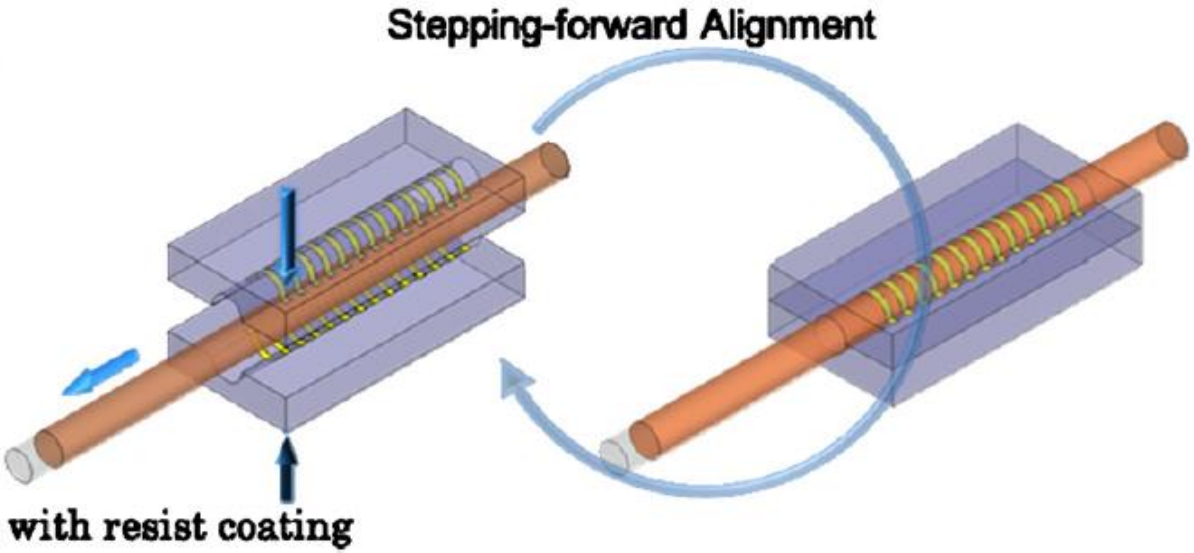
Photolithography on optical fibers



(a)



(b)



Lu *et al.*, *J. Micromech. Microeng.* **20** (2010) 125013