Nanometer Scale Patterning and Processing

Spring 2016

Lecture 3

Lithography Used In Semiconductor Manufacturing

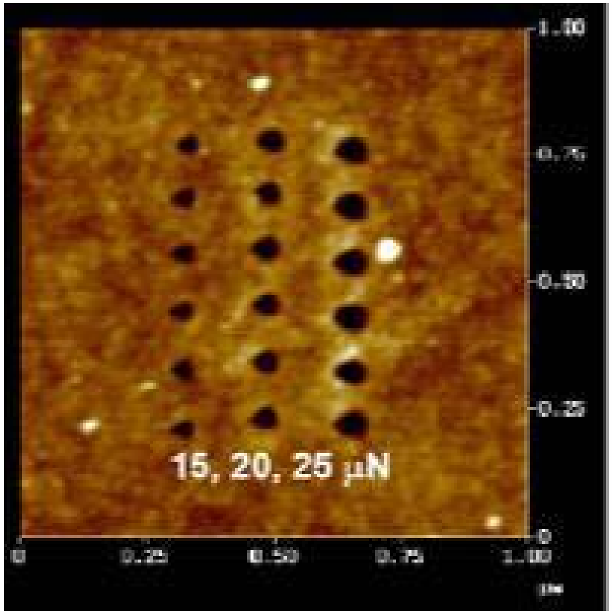
List of Lithography Techniques (I)

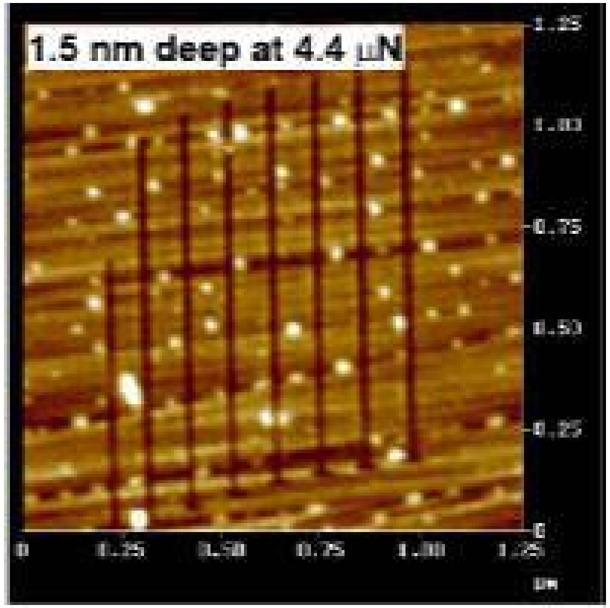
- High resolution photon-based lithography.
  - Deep UV lithography with high NA and/or low k1 factor.
  - Extreme UV lithography, why selected as next generation lithography by industry.
  - X-ray lithography, X-ray optics, mask, LIGA process.
- Electron beam lithography.
  - Electron optics, e-beam sources, instrumentation.
  - Electron-matter interaction, proximity effect, pattern design, alignment.
  - Resists and developers, resolution limits, contrast, sensitivity, etching selectivity.
  - CAD tool, fraction tool (CATS, Cview, etc)
- Nano-patterning by focused ion beam.
  - Ion source, ion optics, instrumentation.
  - Ion-matter interaction, focused ion beam etching and lithography.
  - Focused ion beam induced deposition, mechanism and applications.
  - Focused electron beam induced deposition.
- Nanoimprint lithography (NIL).
  - Thermal NIL, resist, thermoplastic properties of polymers, tools.
  - UV-curable NIL, resist, whole wafer vs. step-and-flash imprint, tools.
  - Alignment, mold fabrication, defects, limits.
  - Reverse NIL, NIL using thermal-set resist, pulsed laser assistant NIL of metals.

Contents courtesy of Prof. Bo Cui

AFM lithography – scratching (simplest, mechanical lithography)

- Material is removed from the substrate leaving deep trenches with the characteristic shape of the tip used.
- The advantages of nano-scratching for lithography
  - Precision of alignment, see using AFM imaging, then pattern wherever wanted.
  - The absence of additional processing steps, such as etching the substrate.
- But it is not a clean process (debris on wafer), and the AFM tip cannot last long.

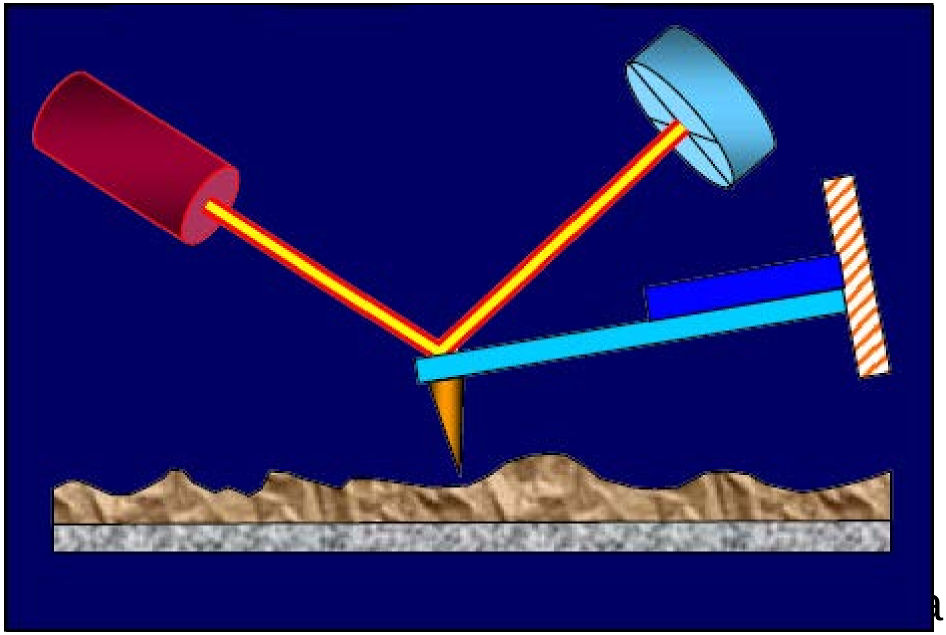


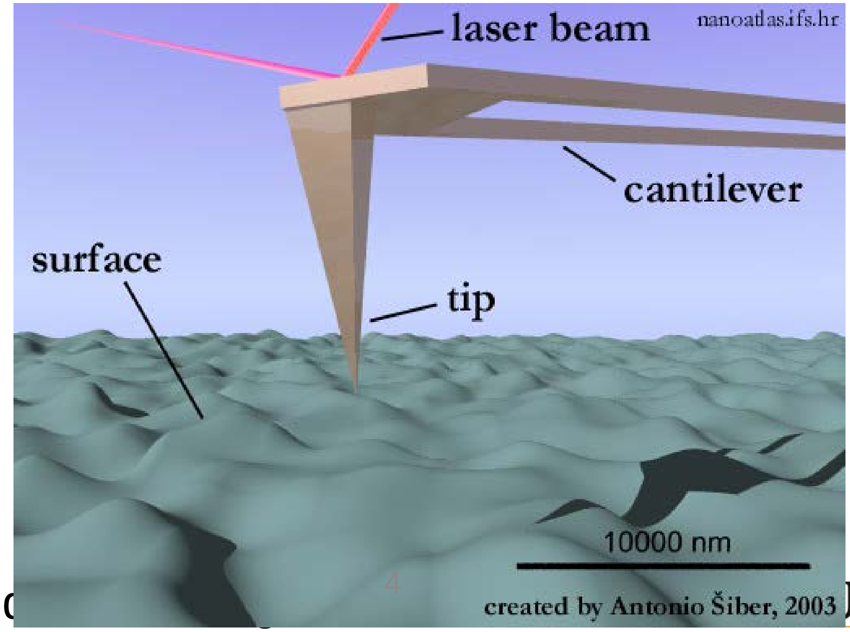


Scanning probe lithography (SPL)

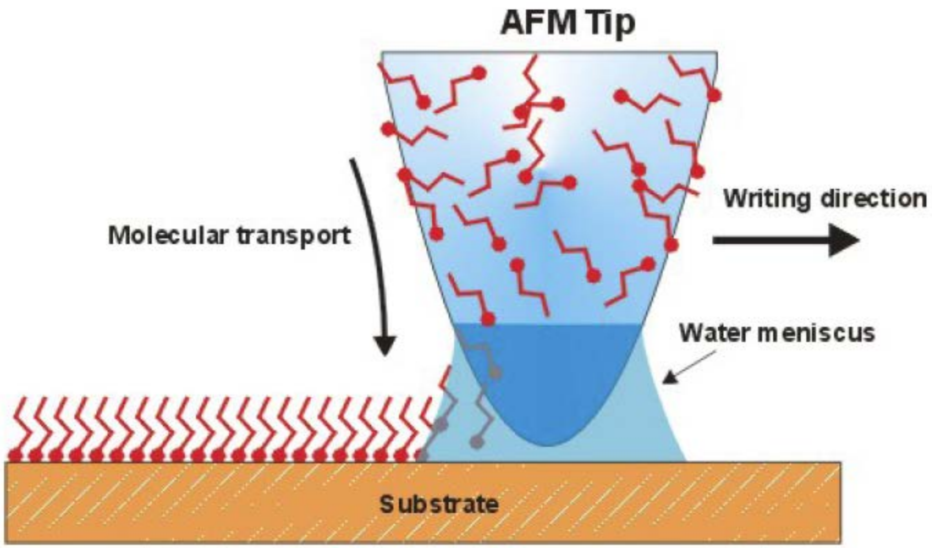
- Mechanical patterning: scratching, nano-indentation
- Chemical and molecular patterning (dip-pen nanolithography, DPN)
- Voltage bias application
    - Field enhanced oxidation (of silicon or metals)
    - Electron exposure of resist materials
- Manipulation of atoms/molecules by STM, or nanostructures by AFM

AFM: atomic force microscopy (X-Y positioning by piezo; Z deflection by optical measurement)

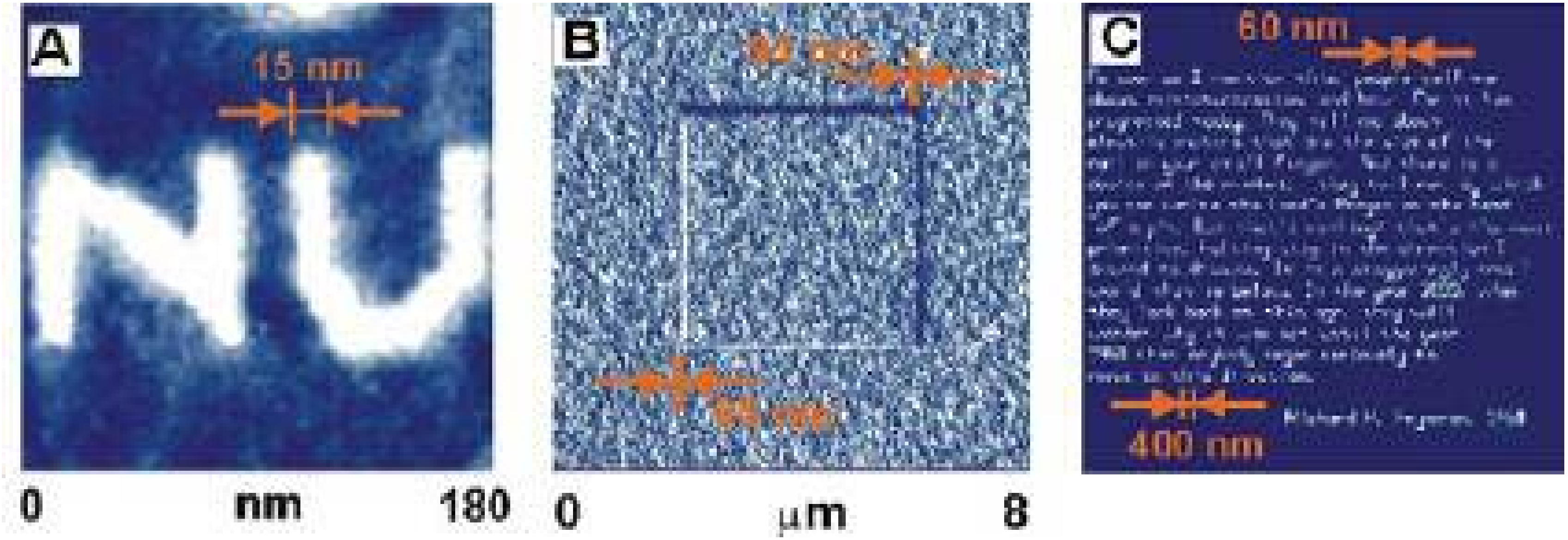




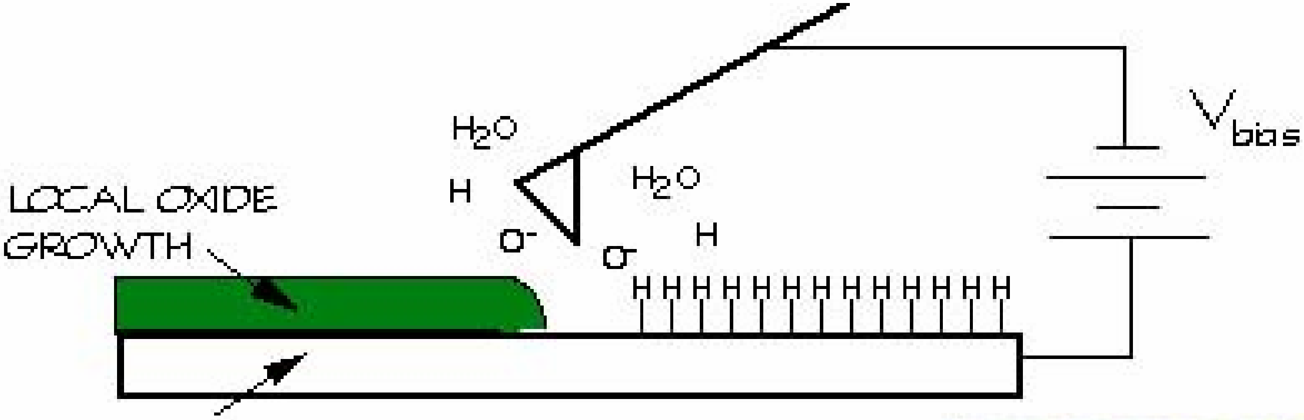
Dip-pen nanolithography (DPN)

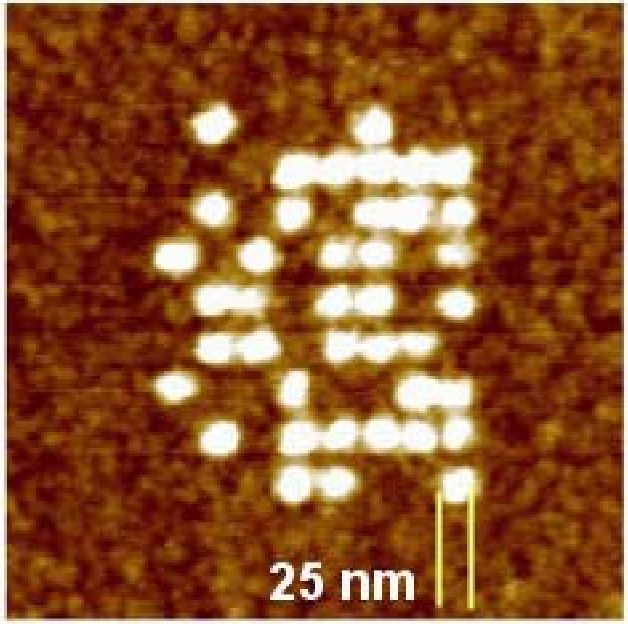


- Similar to micro-contact printing, and writing using a fountain pen.
- AFM tip is “inked” with material to be deposited
- Material is adsorbed on target
- <15nm features
- Multiple DPN tip arrays for higher throughput production



AFM lithography: oxidation (local electrochemical anodization)



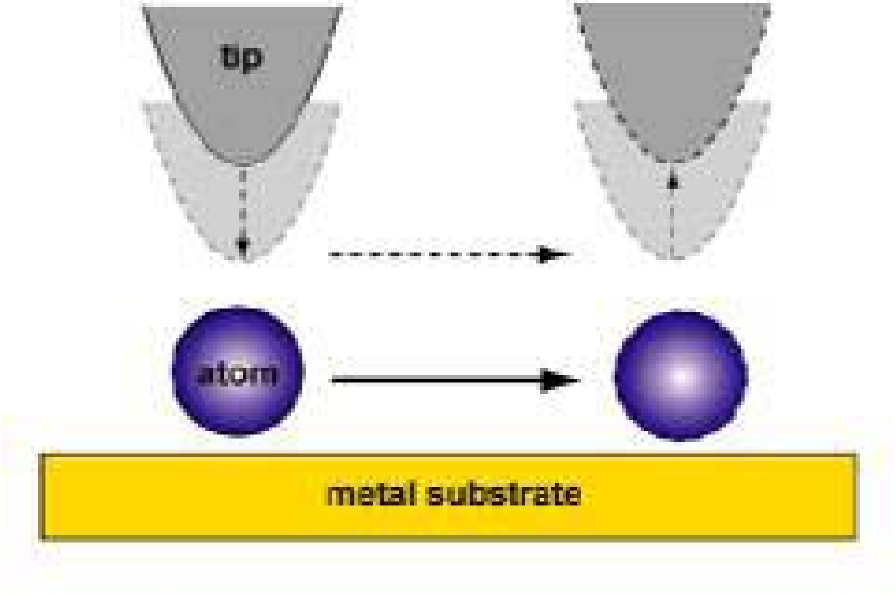


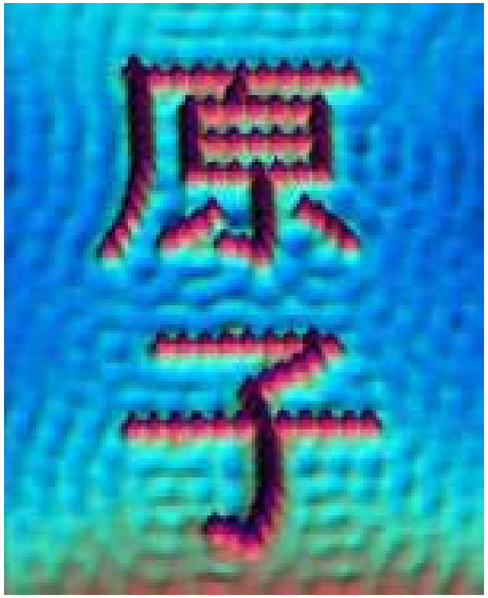
- Resulting oxide affected by experimental parameters
  - Voltage (typically from 5-10V)
  - Tip scan speed (stationary to tens of µm/s)
  - Humidity (20% to 80%)
- Detected current can be used for process control
- Changes in translational velocity influence current flow

STM lithography (STM: scanning tunneling microscopy)

By applying a voltage between tip and substrate it is possible to deposit or remove atoms or molecules.
Van der Waals force used to drag atoms/molecules.

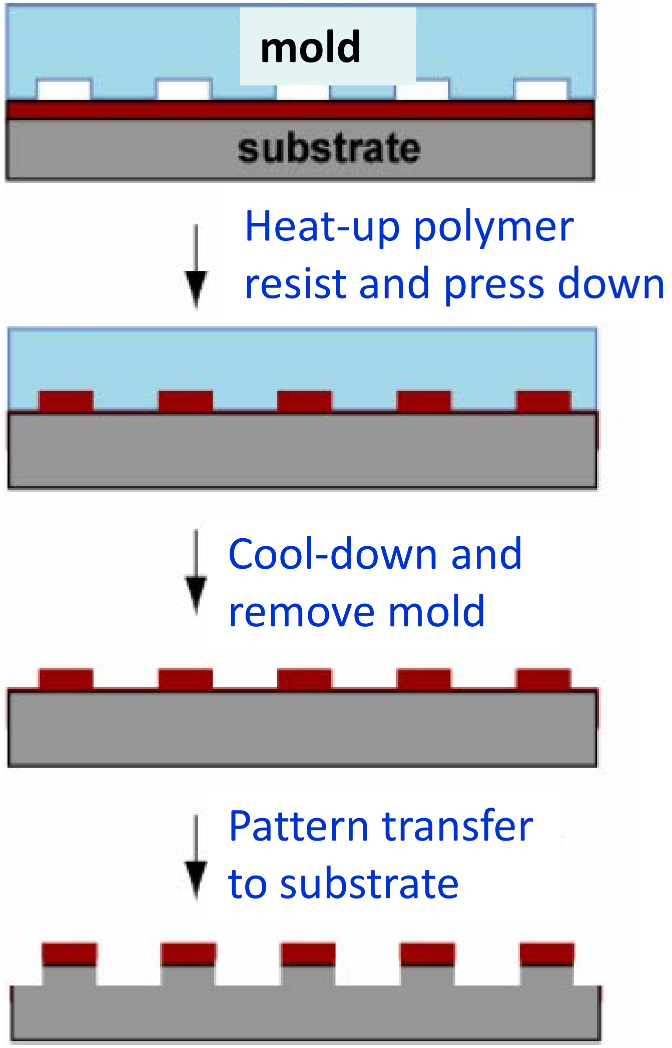
Advantages of STM Lithography
- Information storage devices (one atom per bit, highest storage density).
- Nanometer patterning technique (highest resolution, ~Å).
- Manipulations of big molecules and individual atoms.





Iron on copper (111)

Lithography by molding/material transferring II: nanoimprint lithography (thermal/hot embossing)

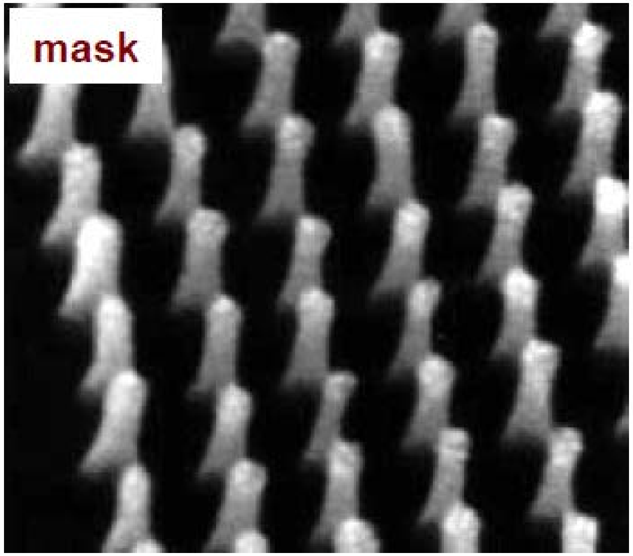


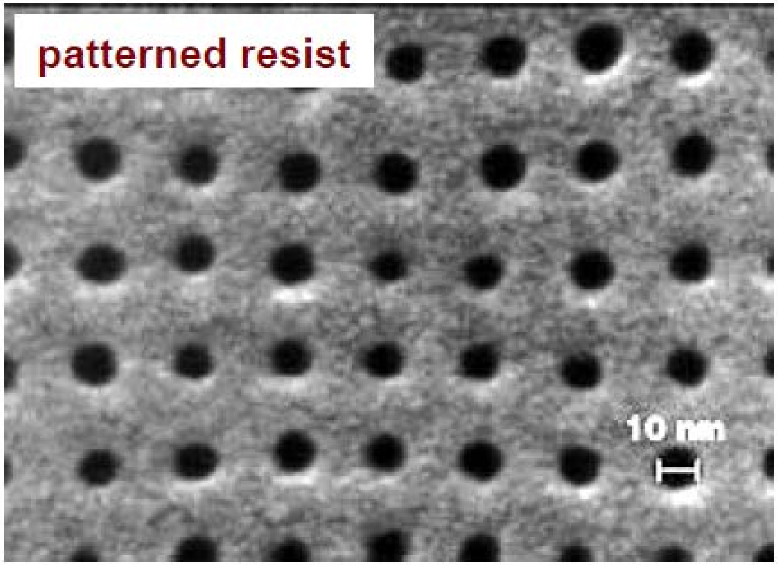
Heat-up polymer resist and press down

Cool-down and remove mold

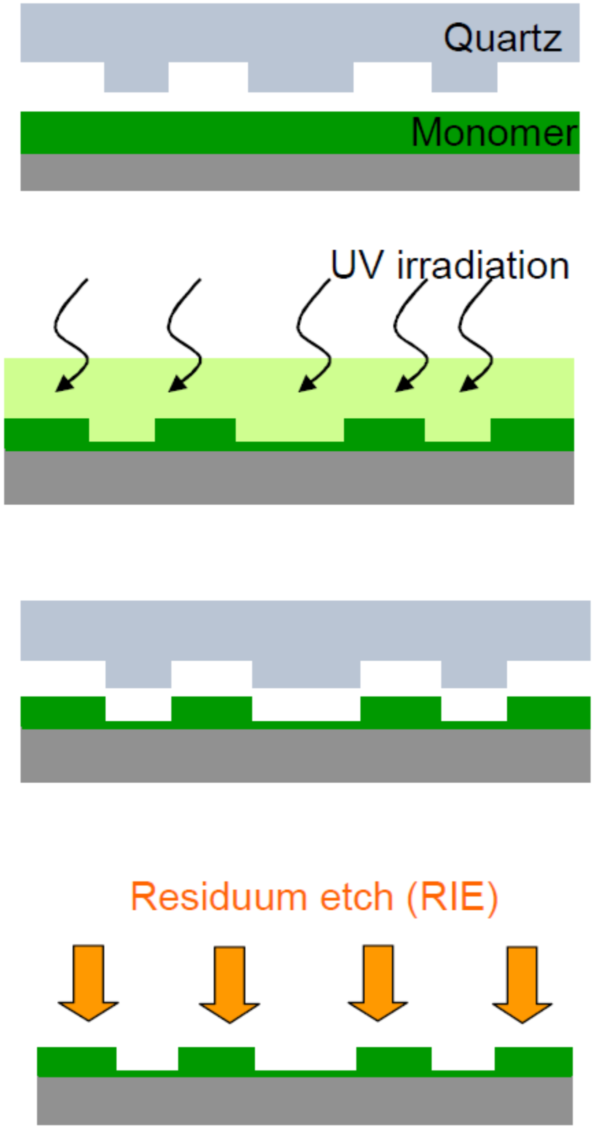
Pattern transfer to substrate

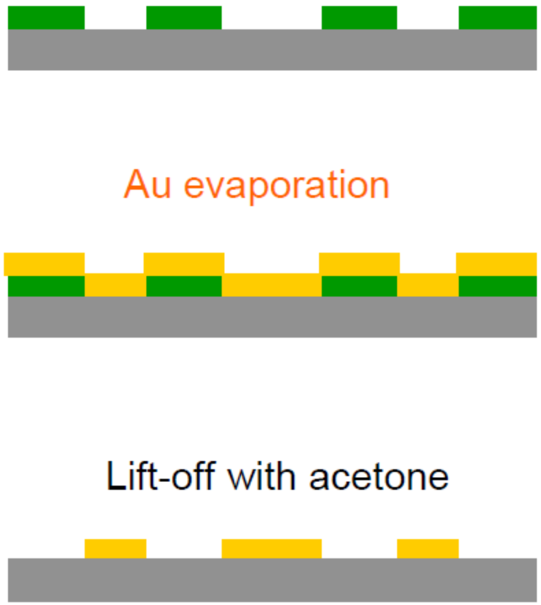
Mold = mask = template = stamp





UV-curable nanoimprint lithography (Au patterning by liftoff as an example)





- Liquid resist, soft and deformable by mold.
- Hardened by UV-curing (polymerization).
- Molds must be transparent (PDMS, Quartz).
- No temperature (thermal cycle) necessary.
- Thus a very gentle process, and thermal expansion mismatch no longer an issue.
- Many UV-curable resists are sensitive to oxygen – exposure under inert conditions.

Lithography by molding/material transferring (II): soft lithography (pattern duplication)

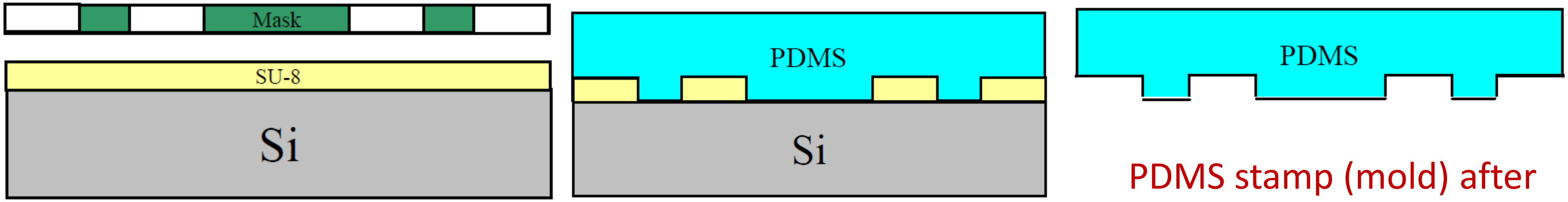
- A master mold is made by lithographic techniques and a stamp is cast from this master.
- Poly di-methyl siloxane (PDMS) is most popular material for stamps.
- Image reversal: fill PDMS stamp with PDMS pre-polymer, then peeled from PDMS stamp.

Stamp (mold) production

PDMS properties:

- Soft and flexible.
- Can be cured to create a robust PDMS stamp.
- Chemically inert, non-hygroscopic, good thermal stability.
- Can be bonded to a glass slide to create micro-fluidic components.

(hygroscopic: readily taking up and retaining moisture)



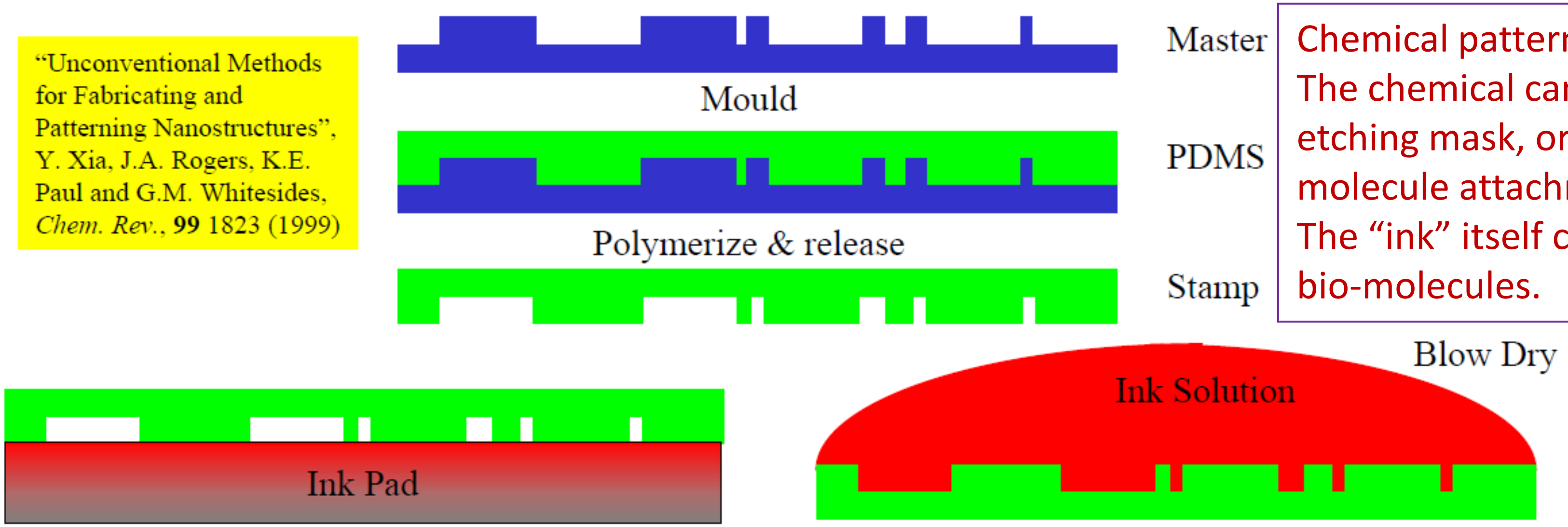
Photolithography pattern SU-8

Cast PDMS pre-polymer and cure

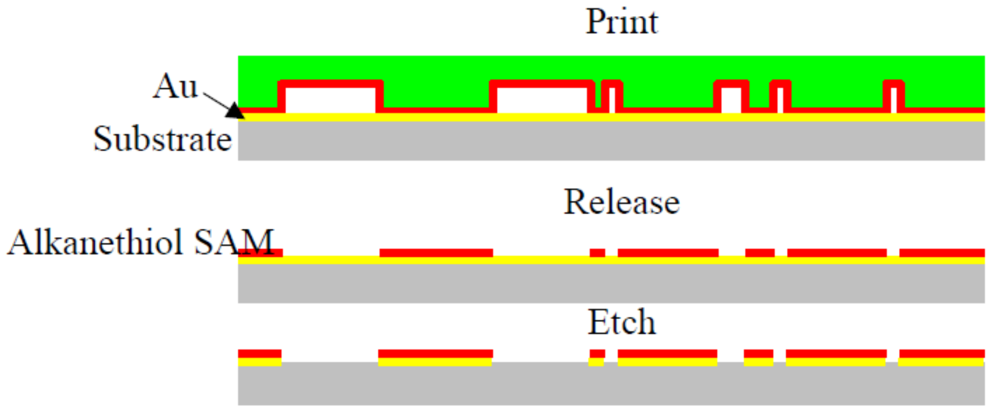
PDMS stamp (mold) after peel off from SU-8 master

Soft-lithography I: micro-contact printing (μCP)

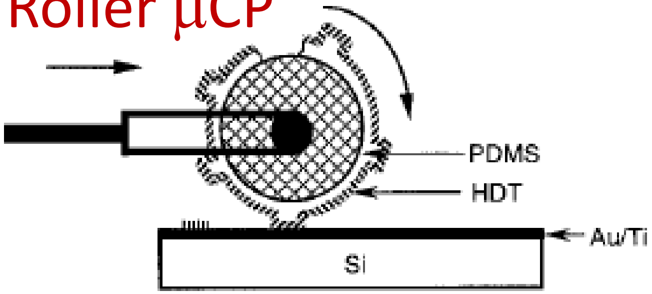
"Unconventional Methods for Fabricating and Patterning Nanostructures", Y. Xia, J.A. Rogers, K.E. Paul and G.M. Whitesides, *Chem. Rev.*, **99** 1823 (1999)



Chemical patterning.
The chemical can be used as etching mask, or for bio-molecule attachment.
The "ink" itself can also be bio-molecules.



Roller μCP

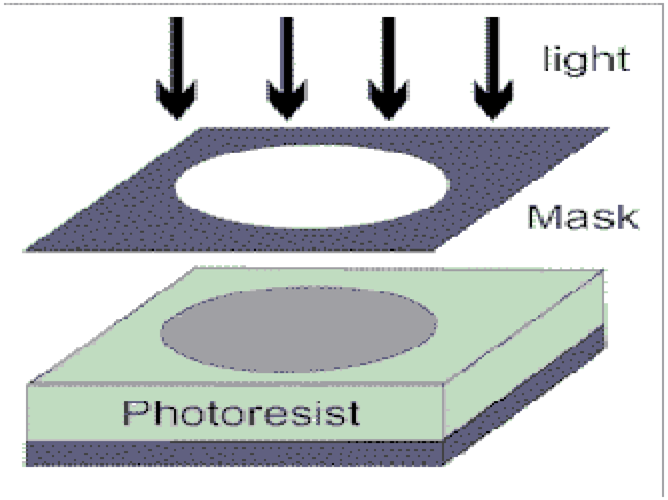


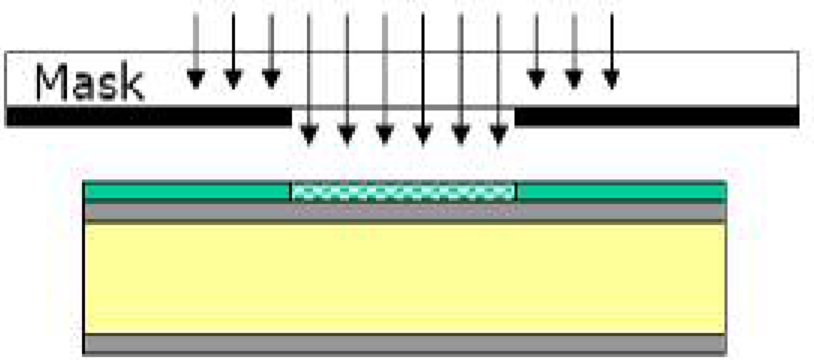
- Minimum resolution affected by diffusion of molecules, can reach sub-50nm.
- PDMS is deformable – can accommodate rough surfaces or spherical substrates.
- Self assembled mono-layers (SAM) are efficient barriers against chemical etches.
- For example, SAM monolayer can be used as etching mask to pattern Au using wet-etch.

Key requirements for lithography in IC Manufacturing

- **High Fidelity, High Throughput and High Cost**
- Life span of the mask/template/mold
  - Defect control to both the mask and wafer
- Critical dimension (CD) control + Line edge roughness
  - Size of features must be controlled within wafer and wafer-to-wafer
  - At small feature sizes, e.g. 22 nm, a roughness of 5 nm may affect the CD
  - Other than designed pattern, no additional patterns can be imaged
- Overlay (alignment between different layers)
  - For correct functionality, alignment must be precisely controlled
  - Placement accuracy in the mask
- Fast throughput
- Manageable cost
  - Tool, resist, mask; fast step-and-repeat
- 30-40% of total semiconductor manufacturing cost is due to lithography (masks, resists, metrology)
- Micro-processors require 39+ mask levels

Optical lithography or photolithography





- Block radiation where it is not wanted i.e. absorb radiation
  Need opaque material at the desired wavelength
- Transmit radiation where it is needed
  Need material with high transmission at the desired wavelength
- For binary optical lithography, mask is quartz glass (transparent) + Cr (opaque)

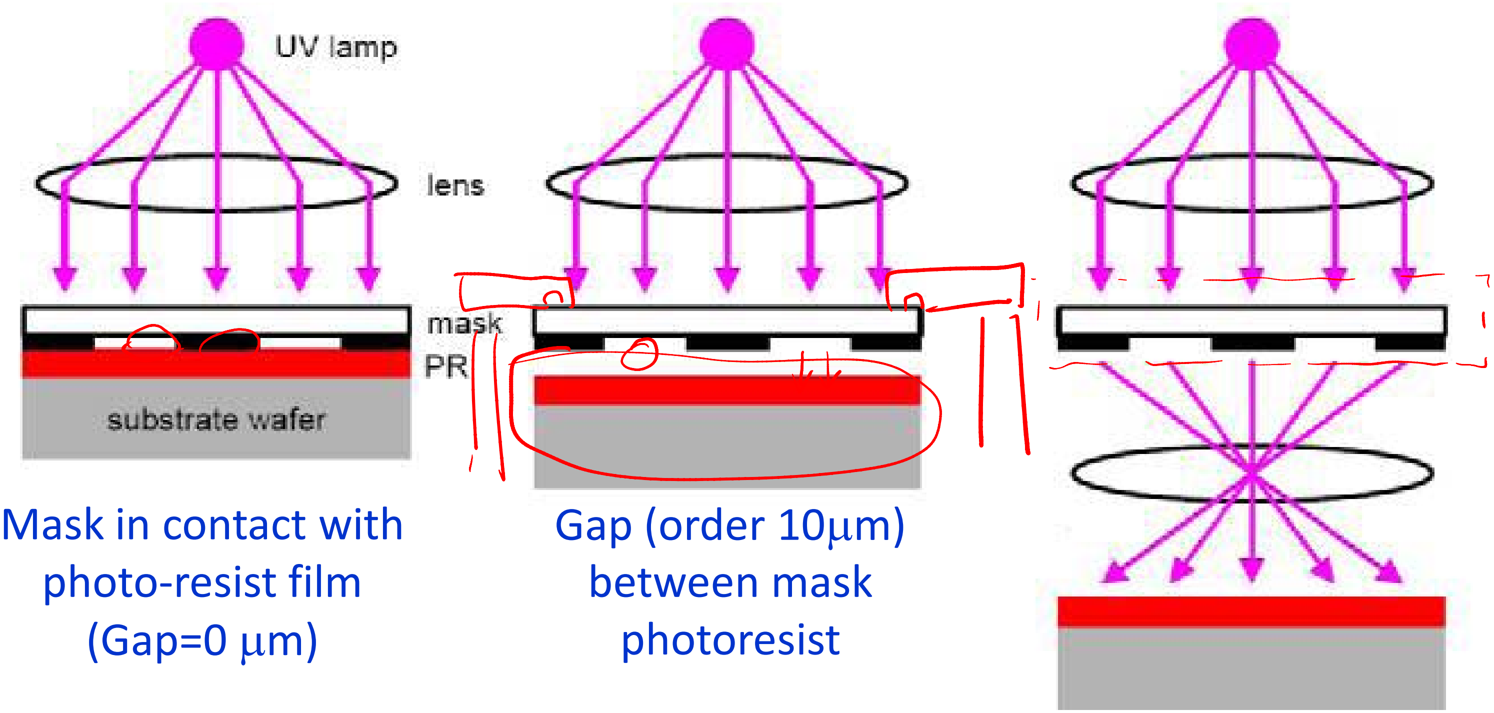
- Formation of images with visible or ultraviolet radiation in a photoresist
- No limitation of substrate (Si, glass, metal, plastic...)
- Work horse of current chip manufacturing processes (14 nm feature size)
- Widely used lithography for R&D (~1μm feature size, *micro*-fabrication)

Three optical lithography Configurations

Contact aligner

Proximity aligner

Projection aligner



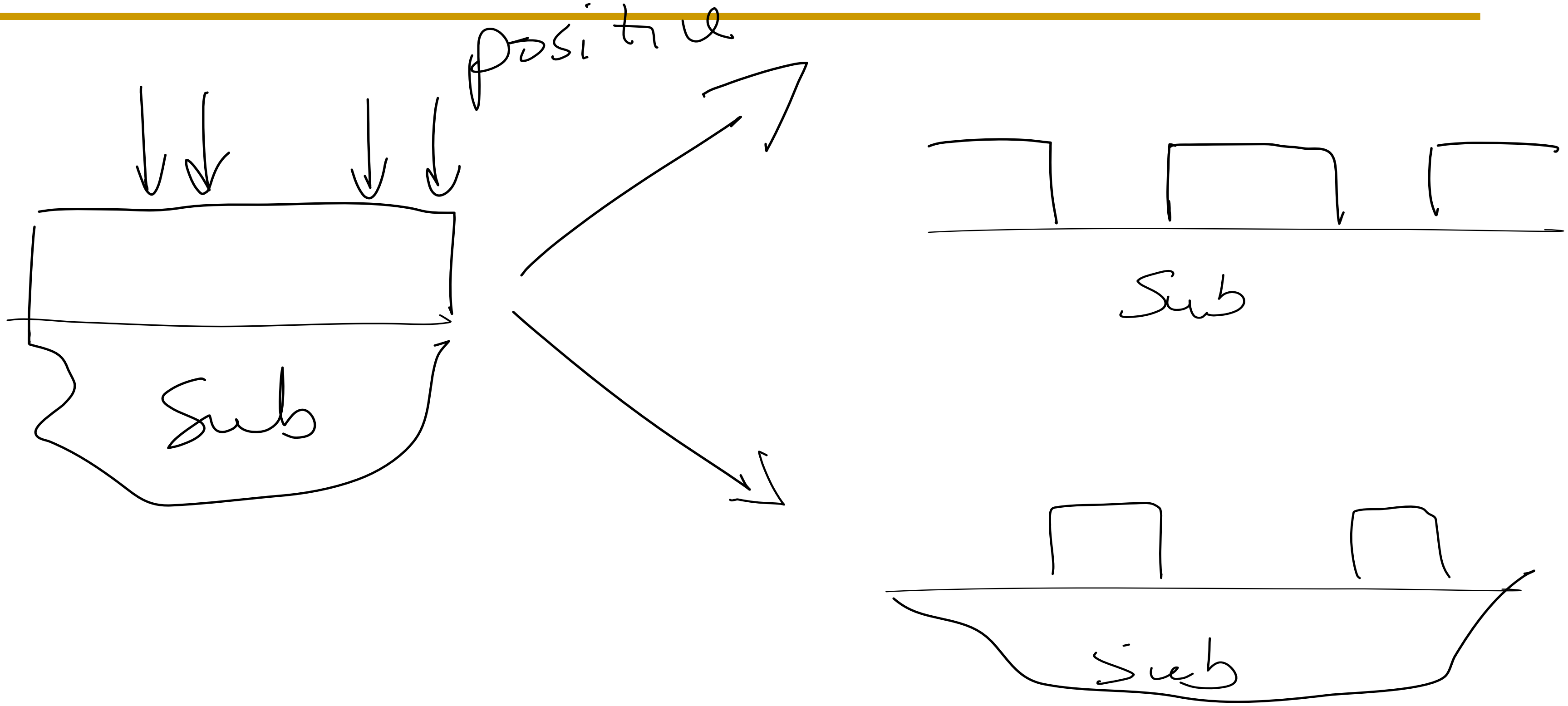
Mask in contact with photo-resist film (Gap=0 µm)

Gap (order 10µm) between mask photoresist

Like photography, imaging

PR = photoresist

Photoresist (PR)



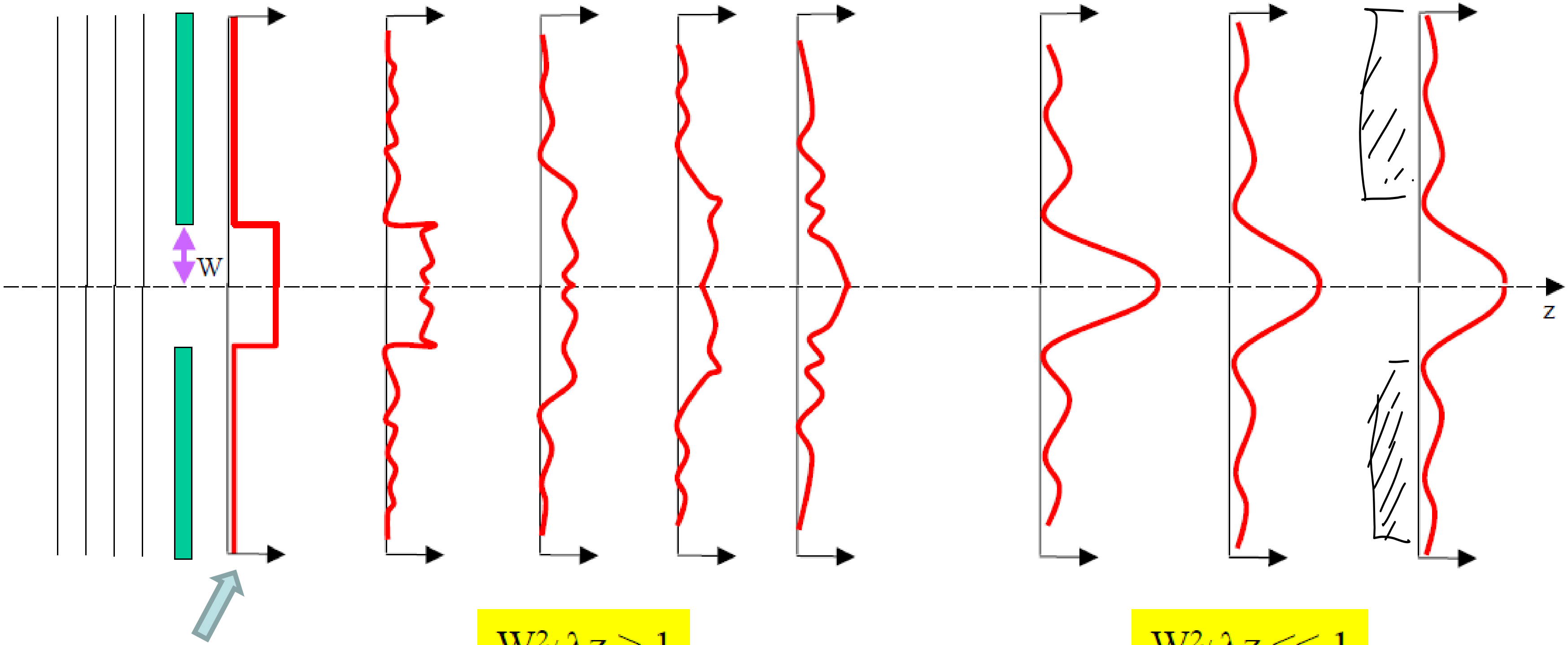
- Photoresist is a light-sensitive material to form a patterned coating on a surface
- Photoresists are classified into two groups: positive and negative resists.
- Positive resists become more soluble on exposure to radiation (e.g. PMMA, S1805).
- Negative resists become less soluble on exposure to radiation (e.g. SU-8).

Limitation of Optical Diffraction

Fresnel & Fraunhofer diffraction (from an aperture)

Near Field (Frensel) Diffraction
λ close to aperture size

Far Field (Fraunhofer) Diffraction
Source and Image at infinity



Light intensity profile

$W^2/\lambda z > 1$

$W^2/\lambda z \ll 1$

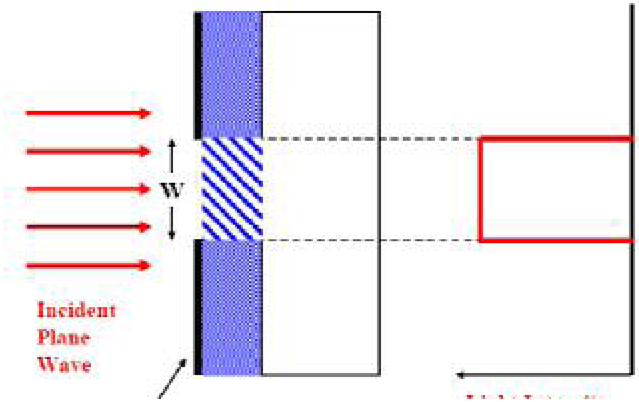
Contact

Proximity

Projection

Contact and proximity photolithography

Contact

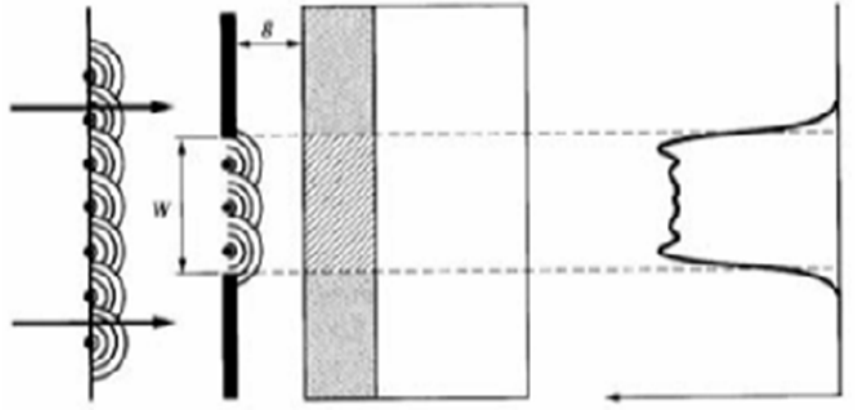


- Mask is brought into physical contact with photoresist
- Mask image : resist image is 1:1
- Not limited by diffraction
  - If resist has 0 thickness
- Damage of mask possible
- Highest resolution: (t is resist thickness)

$$R \approx \frac{3}{2}\sqrt{\frac{\lambda t}{2}} \quad (<\lambda)$$

Proximity

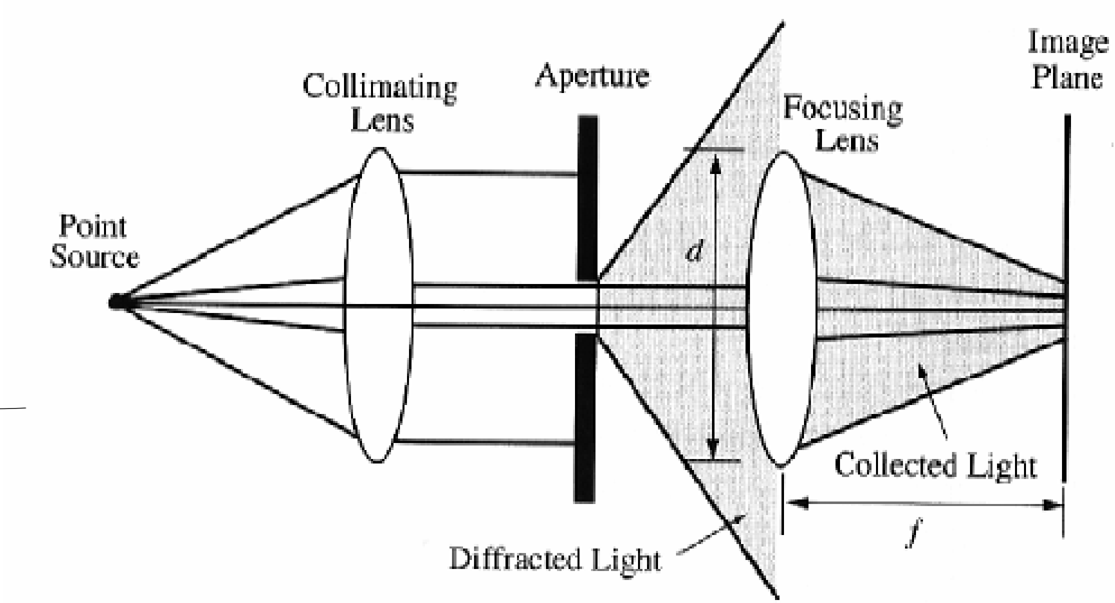
g (=gap between mask and resist top surface)



- Small gap (2-20μm) between mask and photoresist (mask damage eliminated).
- Near-field (Fresnel) diffraction effects.
- Loss of exact mask reproduction for small feature size (i.e. reduced resolution).
- As mask separation g (=gap) increases, quality of image degrades.
- Resolution: (t is resist thickness)

$$R = \frac{3}{2}\sqrt{\lambda\left(g + \frac{t}{2}\right)} \quad (>>\lambda)$$

Optical Projection Lithography



Rayleigh resolution:

$$R = \frac{0.61\lambda}{n\sin\theta}$$

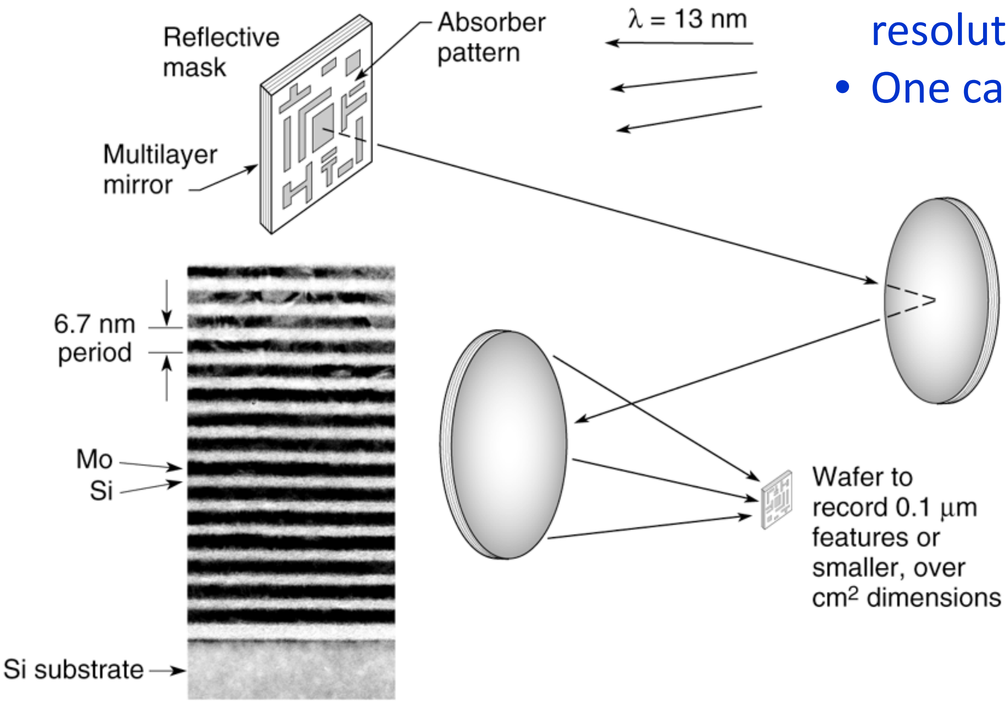
Numerical aperture, NA

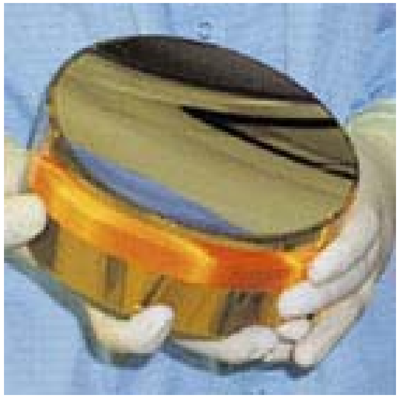
- Similar to photography: image formation on the resist surface
- Resolution is limited by far field diffraction (Fraunhofer), need good lens for high resolution.
- Usually print small area (e.g. ¼ reduction), then step and repeat.
- Very expensive, used mainly by semiconductor industry, unpopular for academic research.
- Currently, IC industry uses λ=193nm deep UV light from ArF excimer laser (10s nano-second incoherent pulse) for exposure, with resolution (**half-pitch** of dense line array) of 32 nm or smaller (with double patterning)

Period=lamda/2*index

Reducing the wavelength: Extreme ultraviolet (EUV) lithography (λ=13.5nm)

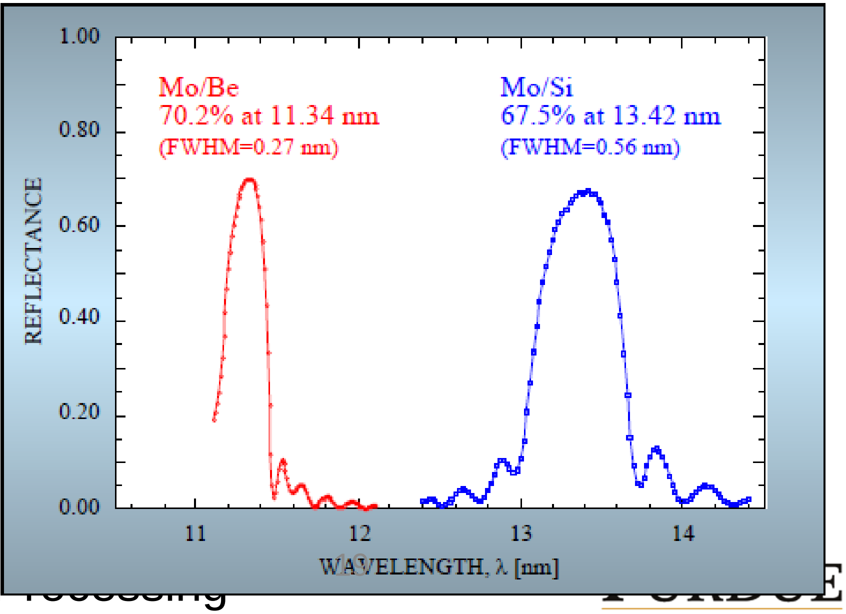
- Short wavelength (13.5 nm) permits high resolution even with small numerical apertures.
- One candidate for next generation lithography





EUV mirror

Lens (transmission) is not possible at EUV. So use reflection lens.
Bragg reflector made of alternating Mo/Si layers that enables high efficiency (68% at normal incidence) reflection of 13.5 nm light.

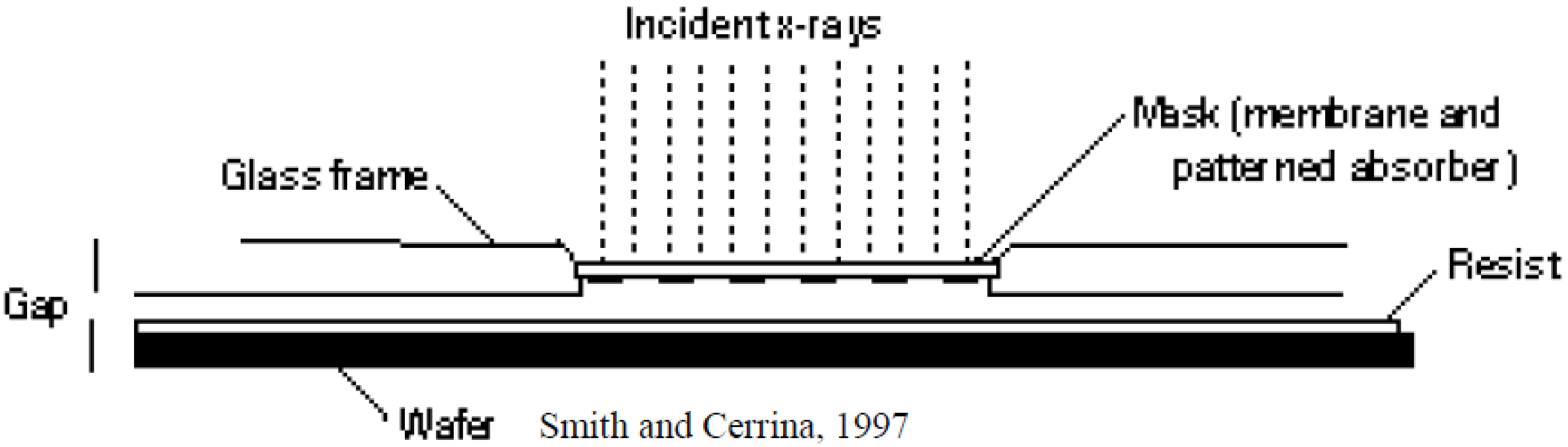


Even smaller wavelength: X-ray lithography (XRL)

- λ ~ 1nm (extremely short wavelength for high resolution).
- X-rays are produced by synchrotron radiation in a high energy electron storage ring.
- Contamination becomes a smaller concern because X-rays will penetrate most dust particles (low atomic number).
- No need for vacuum (little absorption of x-ray by Helium).
- No lens (transmission or reflection), because for X- ray, refractive index n≡1; thus only proximity printing.
- Proximity printing can still achieve high resolution (<30nm) due to small λ (proximity has much longer mask life than contact printing).
- Deep penetrating power of the x-rays into the photoresist and low diffraction (spread of beam), thus good for creating microstructures with great height (high aspect ratio).
- Popular resist (PMMA) has very low sensitivity to X-rays (SU-8 is much more sensitive).

Resolution: $$R = \frac{3}{2}\sqrt{\lambda\left(g + \frac{t}{2}\right)}$$ (>>λ)

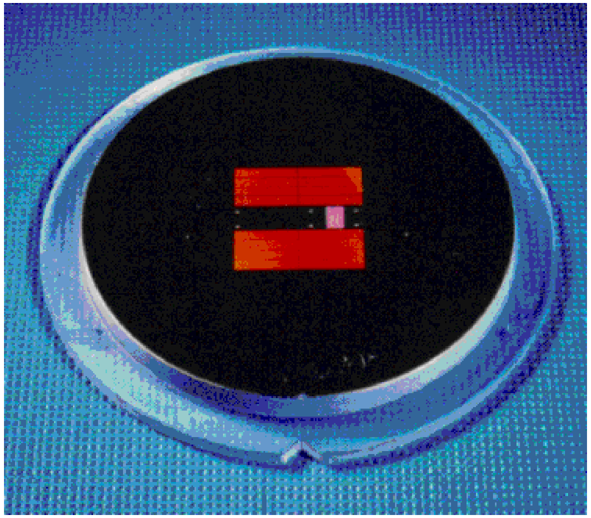
X-ray lithography (XRL) masks



Smith and Cerrina, 1997

- XRL masks are composed of thin membrane substrate/support (Si, Be, or SiC, Si_3N_4 (few µm, very thin!)) and X-ray absorbers (high Z atoms such as Au, W).
- Strain in the thin membrane may warp the patterns.
- Masks degrade due to repeated exposure to X-rays.
- In one word, the high cost of *membrane* mask is the most serious issue that prevents XRL from application for semiconductor industry. (The other issue is bright X-ray source, need synchrotron radiation)

XRL mask



http://www.xraylith.wisc.edu/overview/cxrlibm.html

XRL: advantages and disadvantages

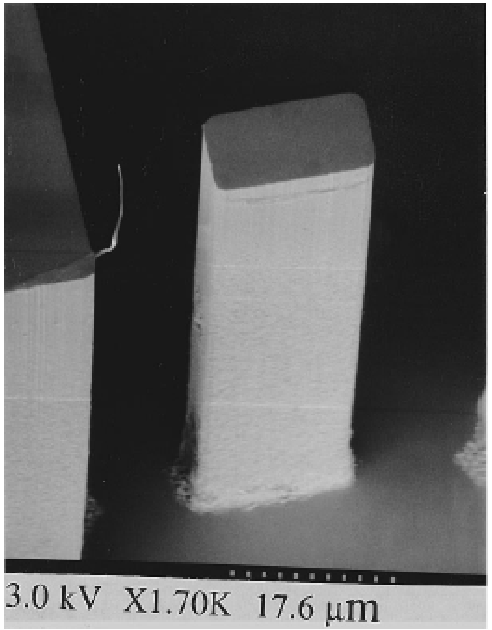
Advantages

- Good resolution (down to 30 nm)
- No interference from dust
- Relatively fast
- Deep penetration to resist, high aspect ratio
- No depth of focus problem

Disadvantages

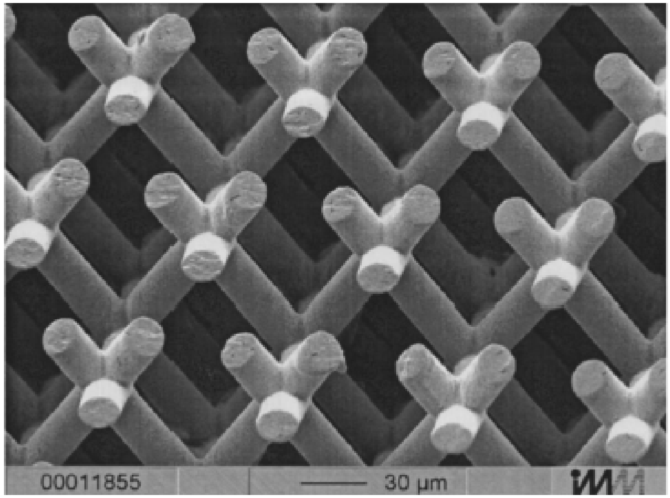
- X-ray masks are very difficult to make
- Conventional lenses cannot focus X-rays
- Expensive (synchrotron radiation source)

High aspect ratio *micro*-structures by XRL



80µm resist structure with aspect ratio > 10.

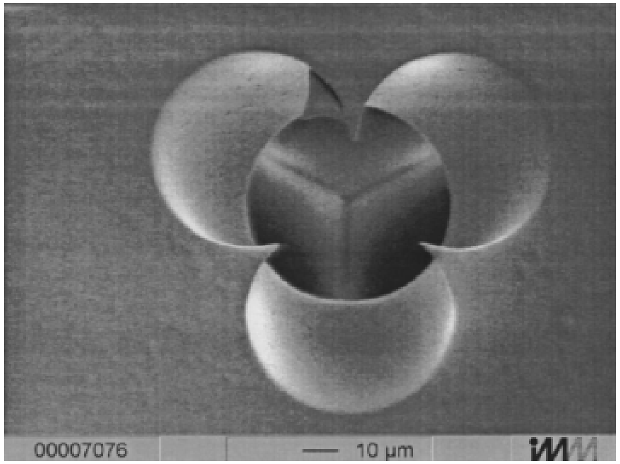
White, APL, 66 (16) 1995.

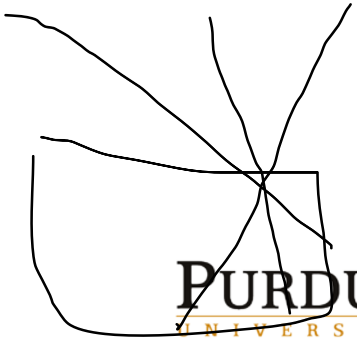


Three-cylinder photonic crystal structure in ceramic. Exposed by repeated exposures at different tilt angles between the mask and synchrotron. Almost like mechanical drilling.

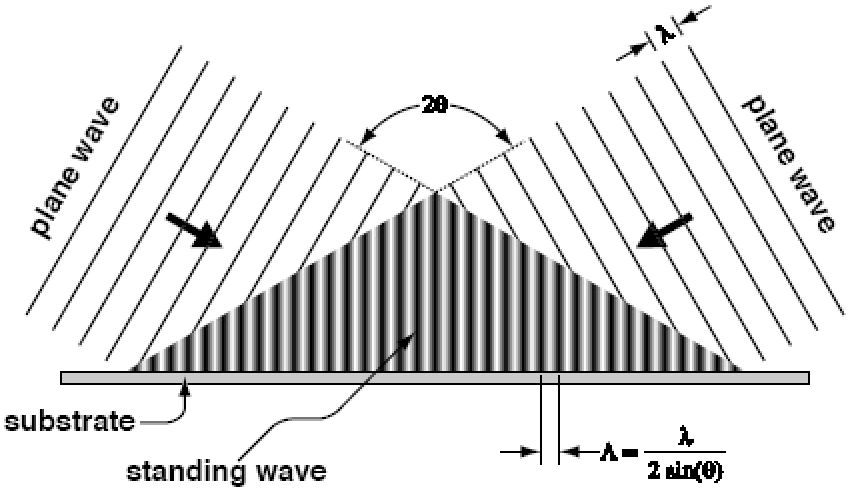
G. Feiertag, APL, 71 (11) 1997.

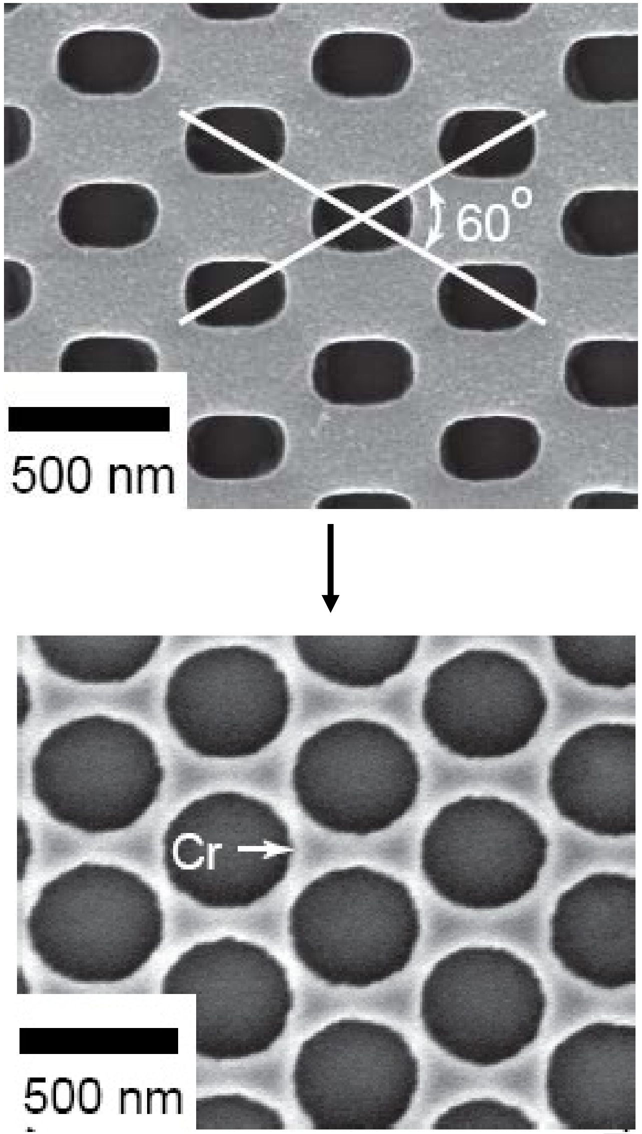
Intersection of the three beams





Interference Lithography





Large area,
Fast,
Low cost
High resolution,
Spatial coherent

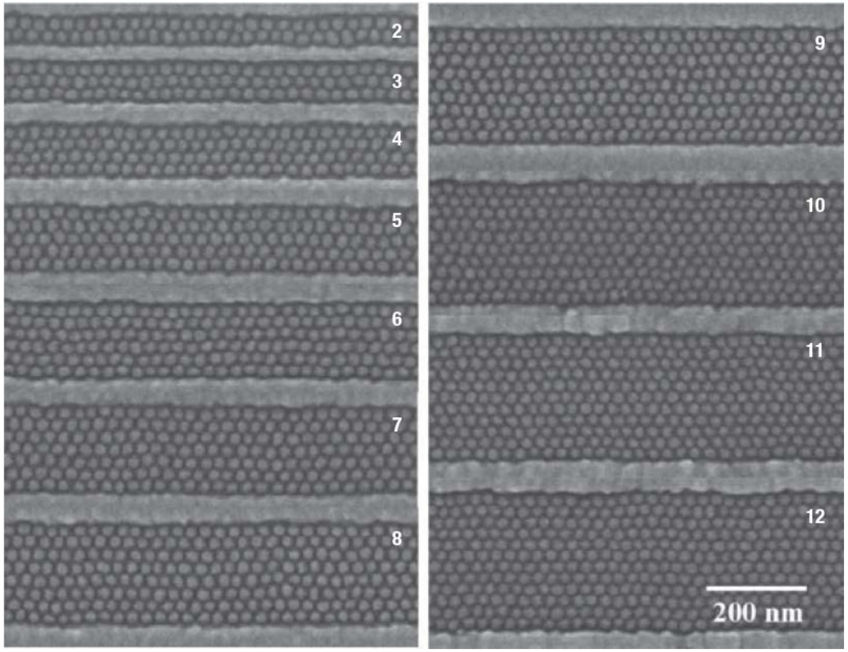
Nanotechnology: What do living systems do?

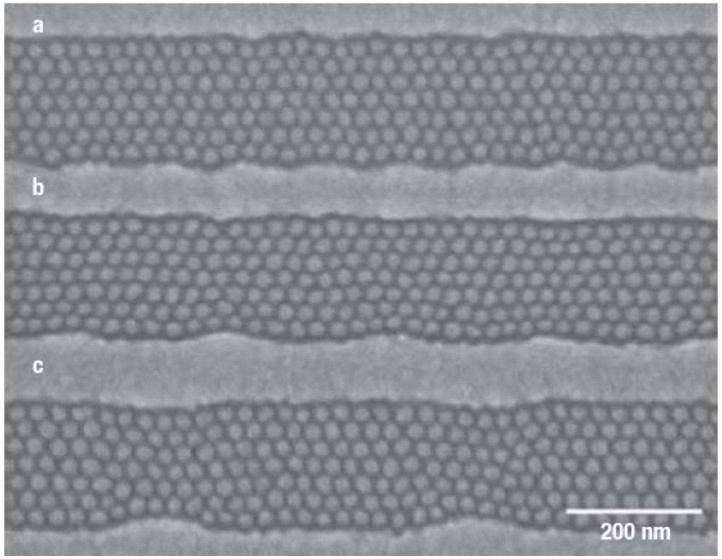
Living	Artificial
Computation	yes, better?
Memory	yes, better?
Material synthesis	yes, not better
Catalysis via enzymes	yes, not better
Energy conversion	yes, not better
EM detection	yes, better
Acoustic detection	yes, better
Chemical sensing	yes, not better
Motion	yes, better?
Water based	no

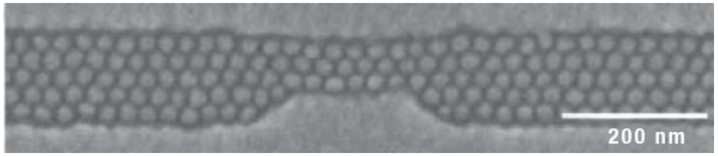
The missing technology

- A bridge between the planar process and the molecular domain
  - How to cope with the complexity (enormous amount of information)
  - Device I/O
- Sub-nanometer accuracy and precision
- Atomic-level perfection (smoothness)
- Probably not a stochastic process
- No damage to sensitive organic molecules

Templated self-assembly





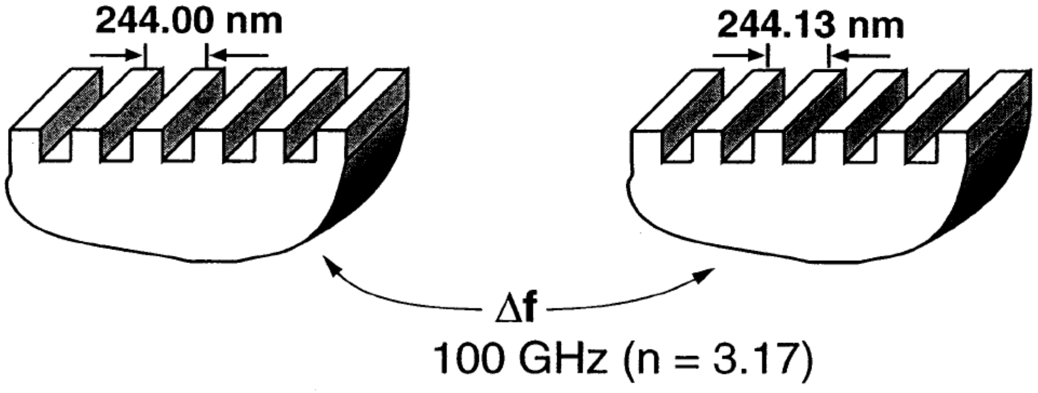


- No grain boundary is observed
- Fewer than 10 defects in 4 μm by 4 μm area
- Same orientation of the block copolymer in adjacent group
- Domains can be modulated with designed template

(figures courtesy of Joy Cheng, MIT, J. Y. Cheng, *et al Nature Materials,* **3**, 823, 2004)

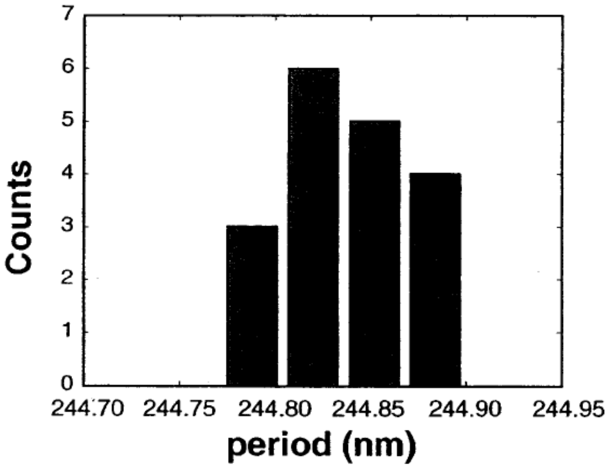
Can we report 244.84 nm ± 0.03 nm?

Why Nanoaccuracy?



Spatial coherence is critical

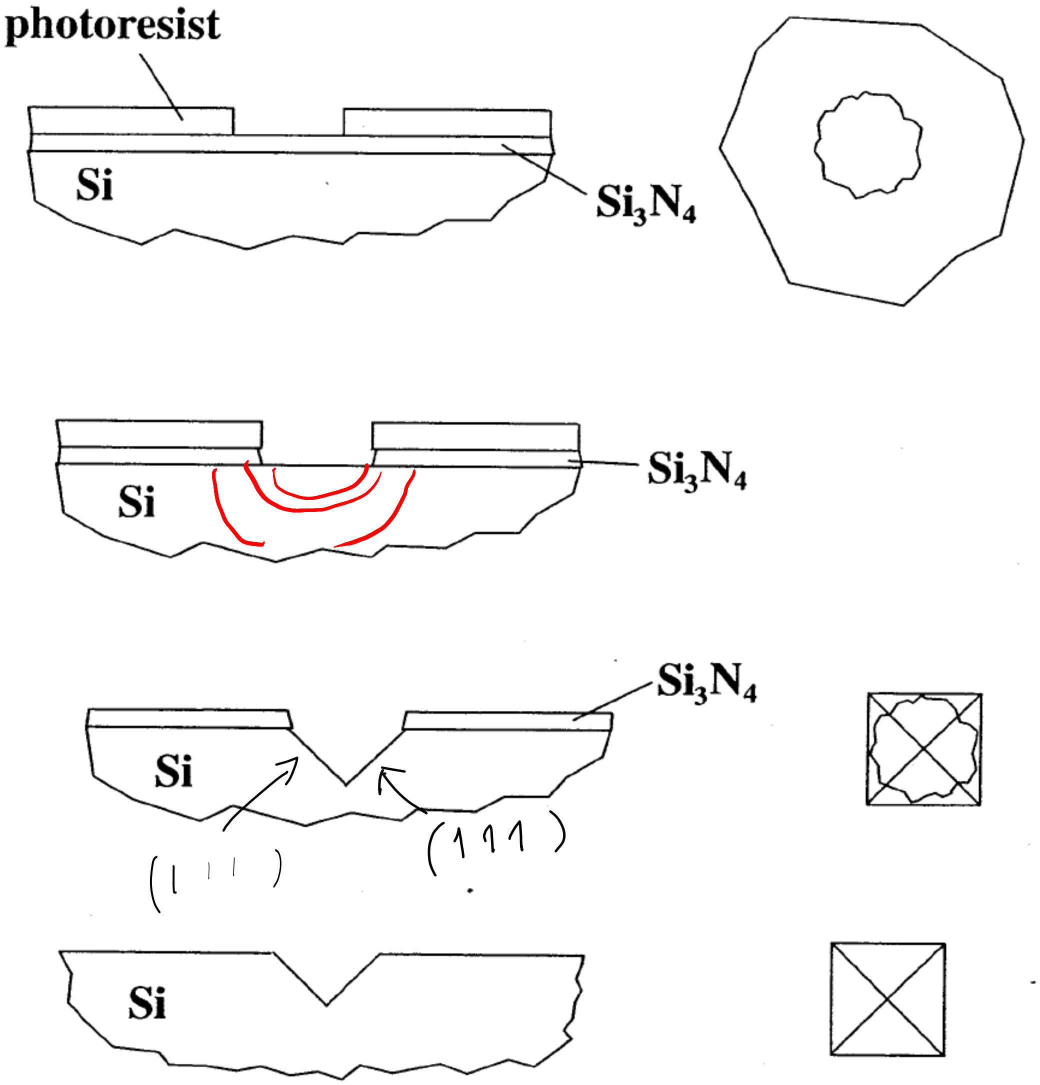
Precision measurement of Bragg period
(laser interferometer + e-beam)



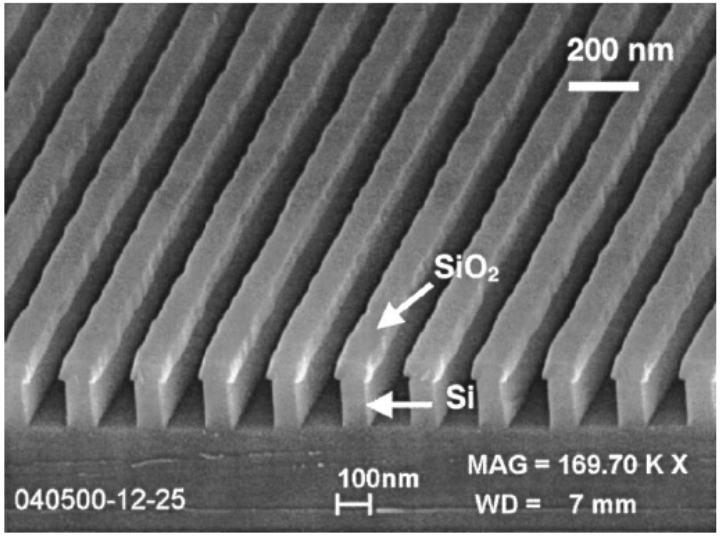
$\overline{p}$ = 244.84 nm
σ_p = 0.03 nm

The radius of a hydrogen atom is 0.053 nm!

Achieving atomic perfection from imperfect lithography



- Ideal, inverted pyramid with atomically smooth facets.



Yu, et al, JVST B, 21, 1071 (2003)

Summary of Top-down approach

- There is plenty of room at the bottom
- We haven’t reached the bottom yet
- There are plenty of challenges at the bottom
- We need a general purpose “nano machine shop”
- Tool cost needs to be reduced.