Lecture 6: Lithography 2

Outline:

Mask engineering
Resolution enhancements technologies (RET)
Model and simulation
Next generation lithography (NGL)
- X-Ray
- e-beam litho
- Imprint Litho

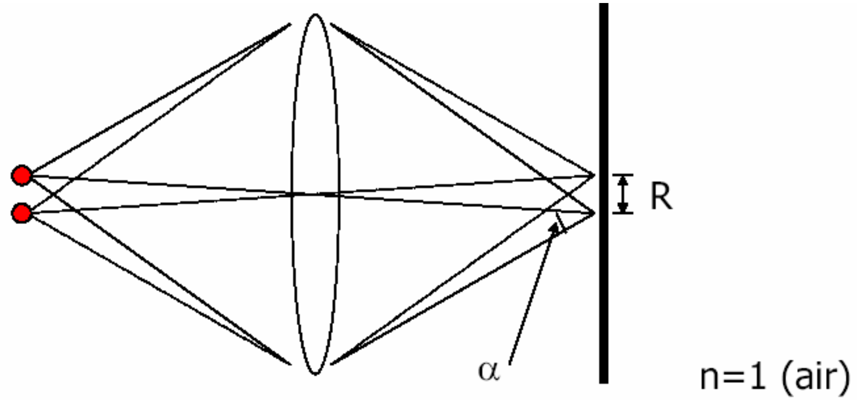
How to Improve Resolution

$$W_{min} = k_1 \bullet \frac{\lambda}{NA}$$

Reduce λ

Reduce k_1

Increase NA

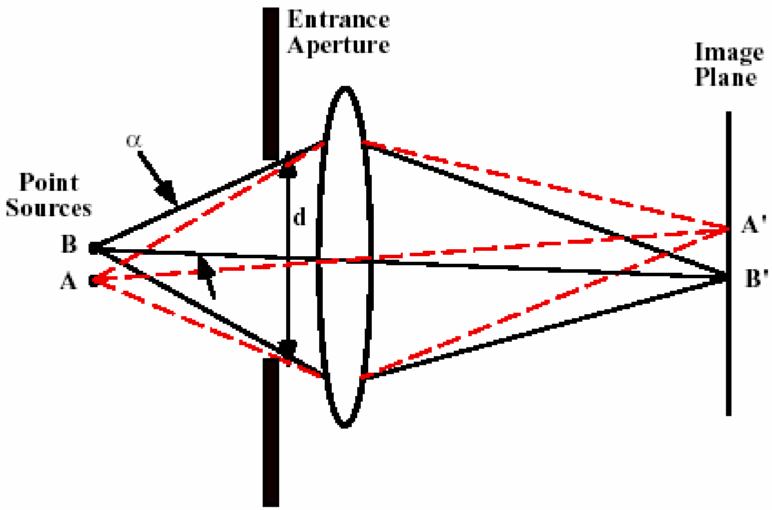


$R = 1.22\lambda f/d = 1.22\lambda f/n(2f\sin\alpha) = 0.61\lambda/n\sin\alpha$

$NA = n\sin\alpha$ (Range from 0.16-0.76)

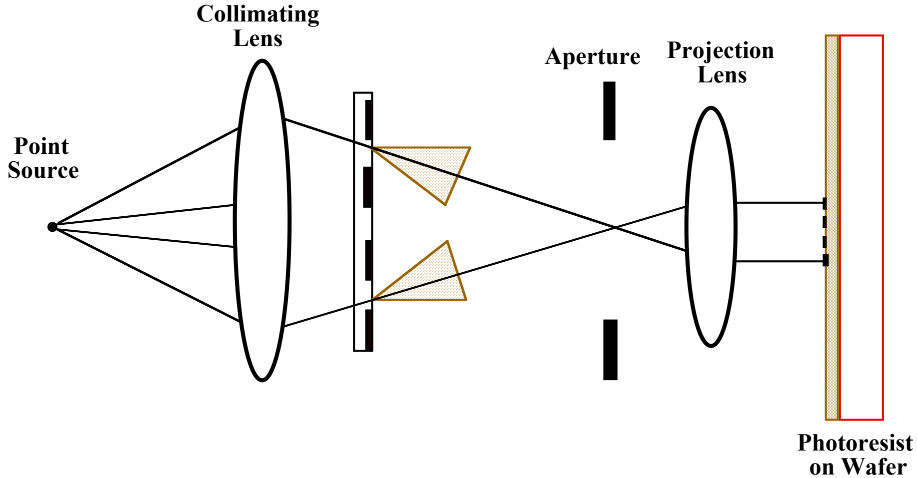
$R = 0.61\lambda/NA = k_1\lambda/NA$

(practical k_1 = 0.6-0.8)

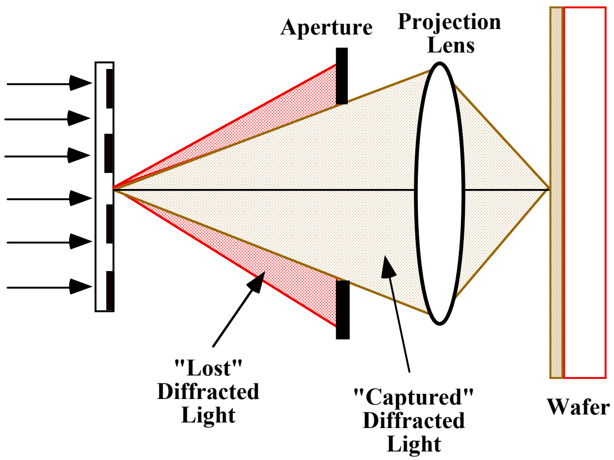


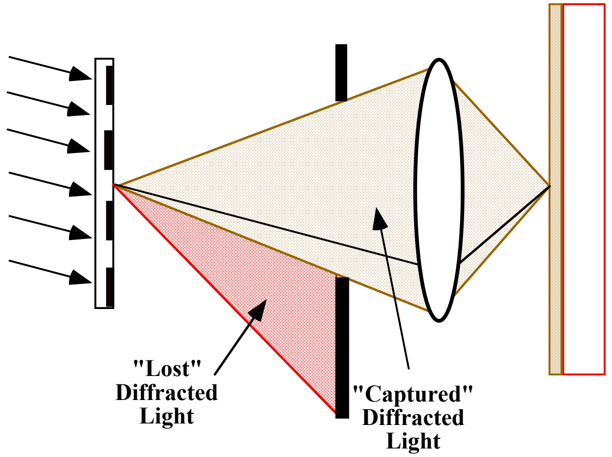
Illumination System Engineering

- Advanced optical systems using Kohler illumination and/or off axis illumination are commonly used today.



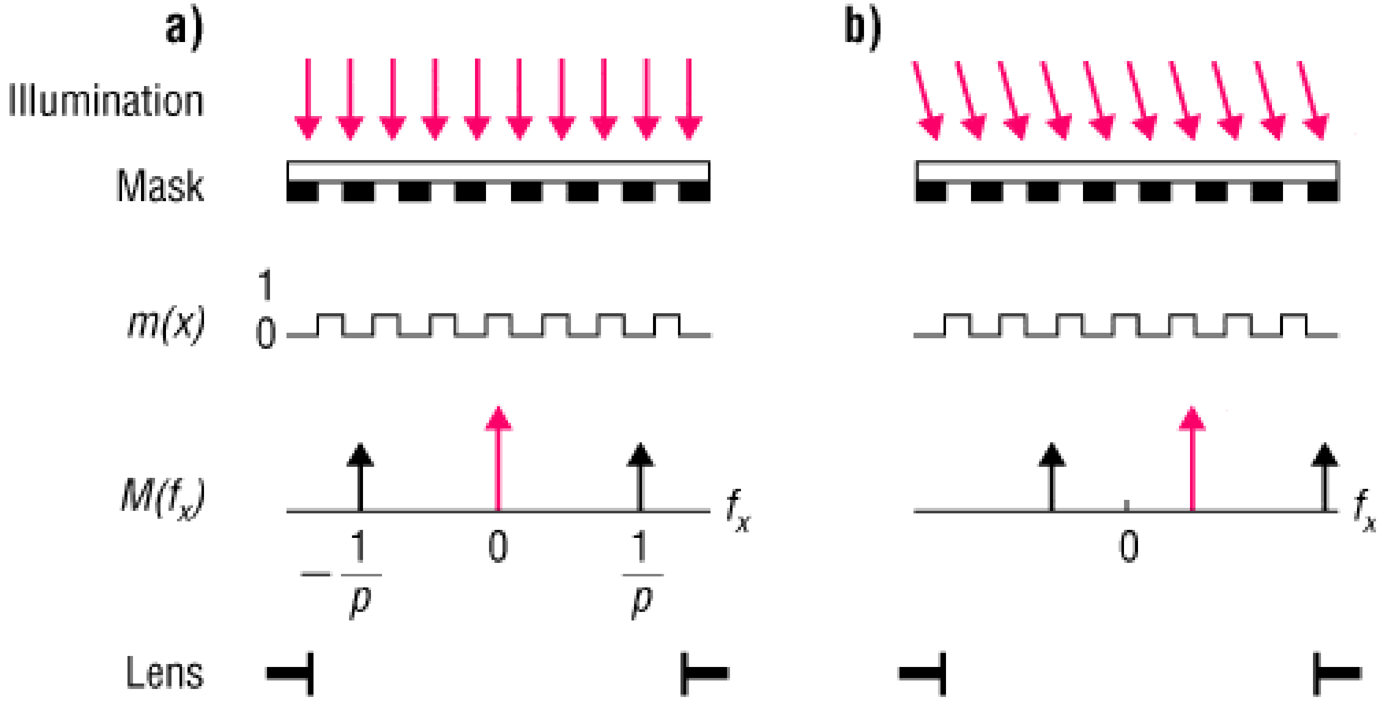
- Kohler illumination systems focus the light at the entrance pupil of the objective lens. This “captures” diffracted light equally well from all positions on the mask.





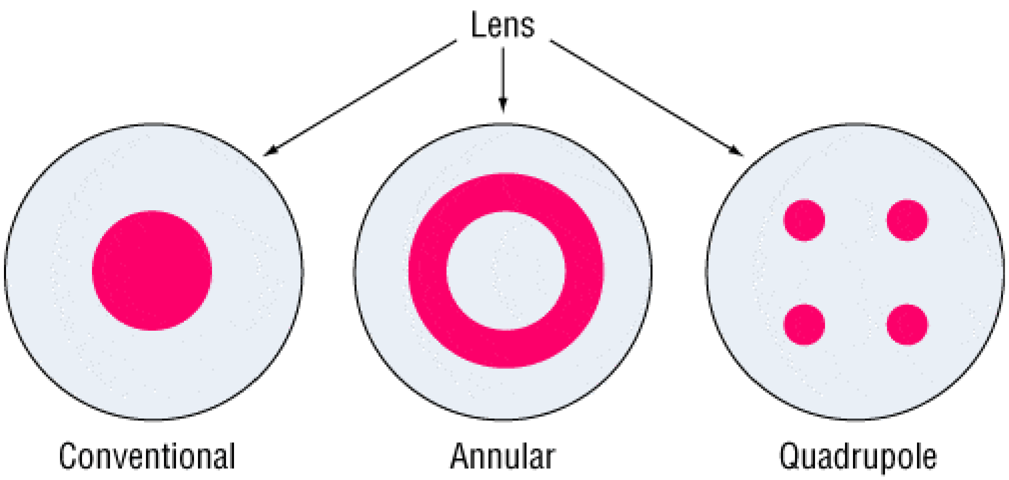
- “Off-axis illumination” also allows some of the higher order diffracted light to be captured and hence can improve resolution.

Off-Axis Illumination



Improve resolution (Allowing smaller pitch)
Improve depth of focus (Centered diffraction orders)

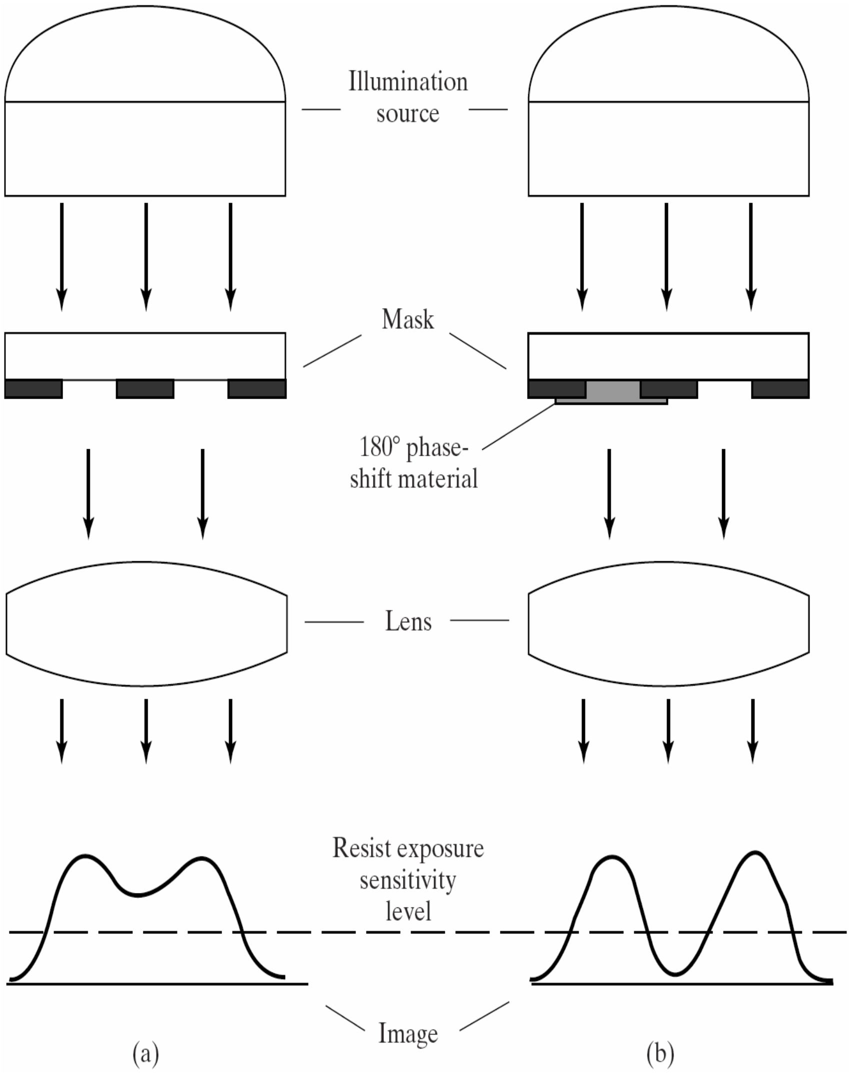
Off-Axis Illumination



Various shapes for conventional and off-axis illumination

Design of illumination relates to pupil distribution of mask patterns

Phase Shifting Masks

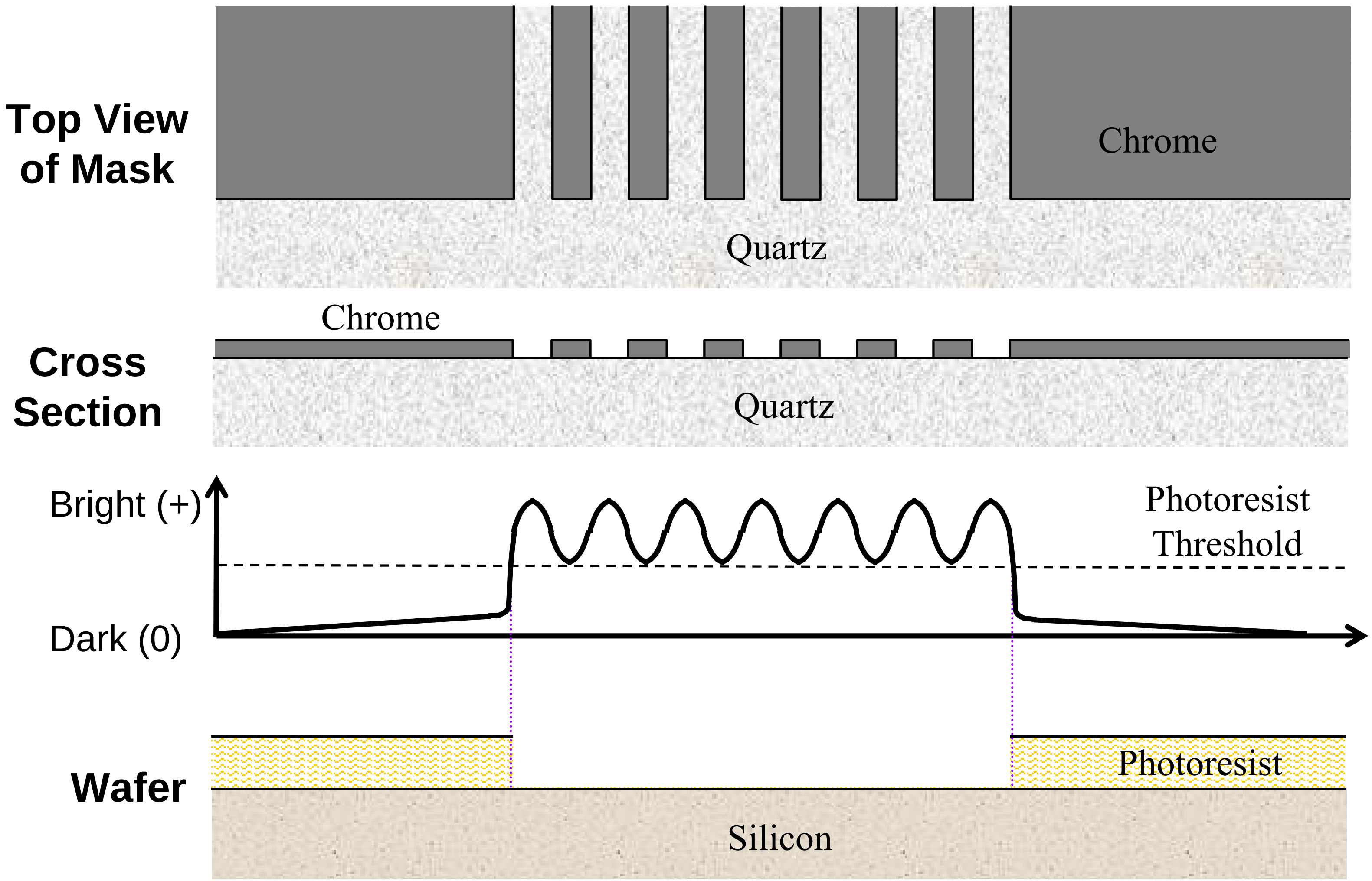


Pattern transfer of two closely spaced lines

(a) Conventional mask technology - lines not resolved

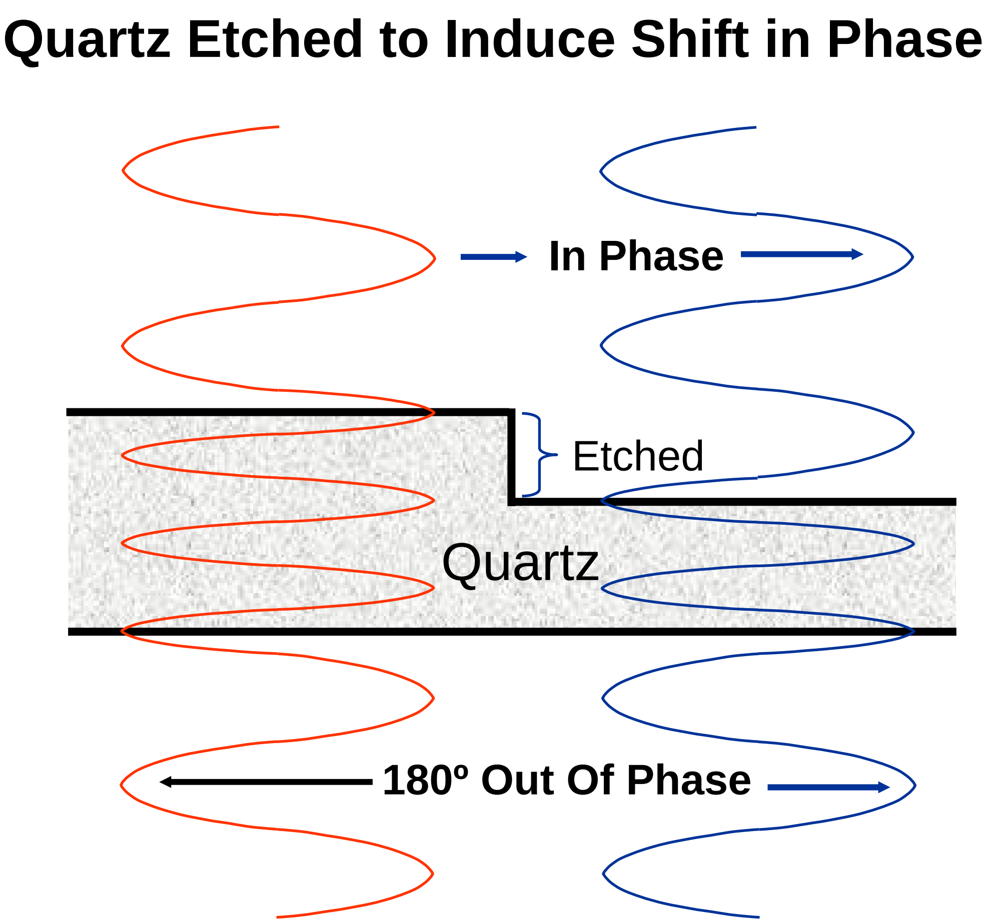
(b) Lines can be resolved with phase-shift technology

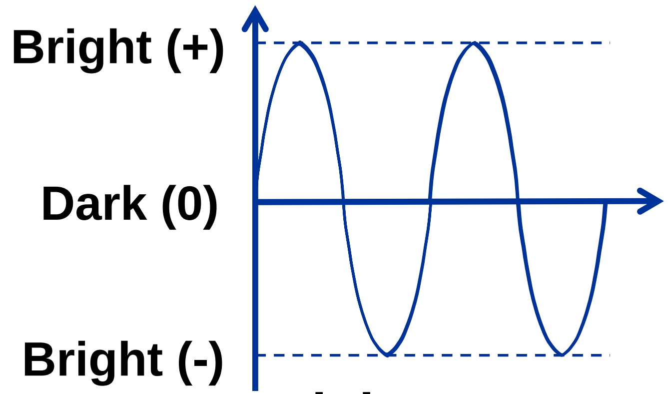
Binary Technology Limits



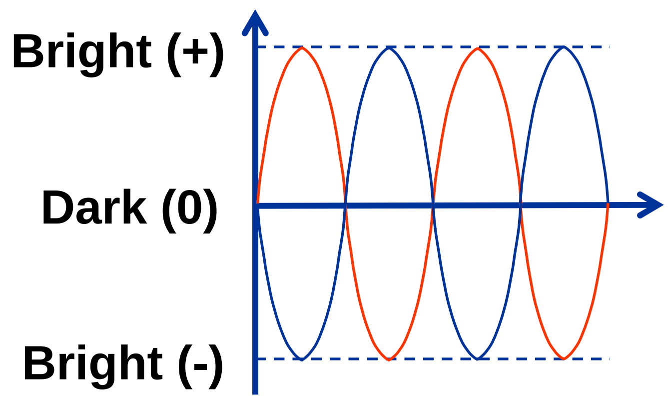
Source: Photronics.com

Phase Shift Mask Basics





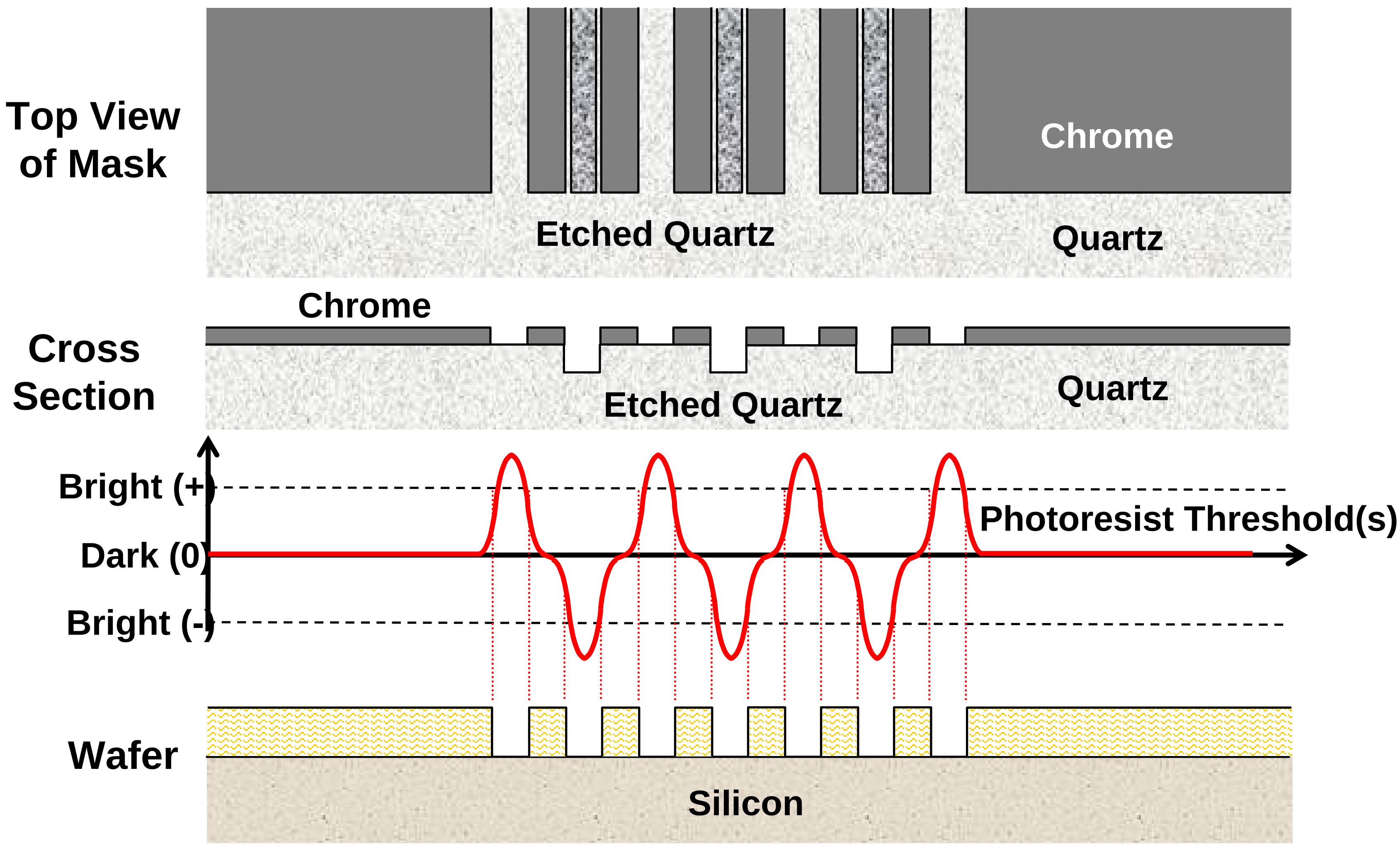
Light Waves
in Phase



Light Waves
Out of Phase

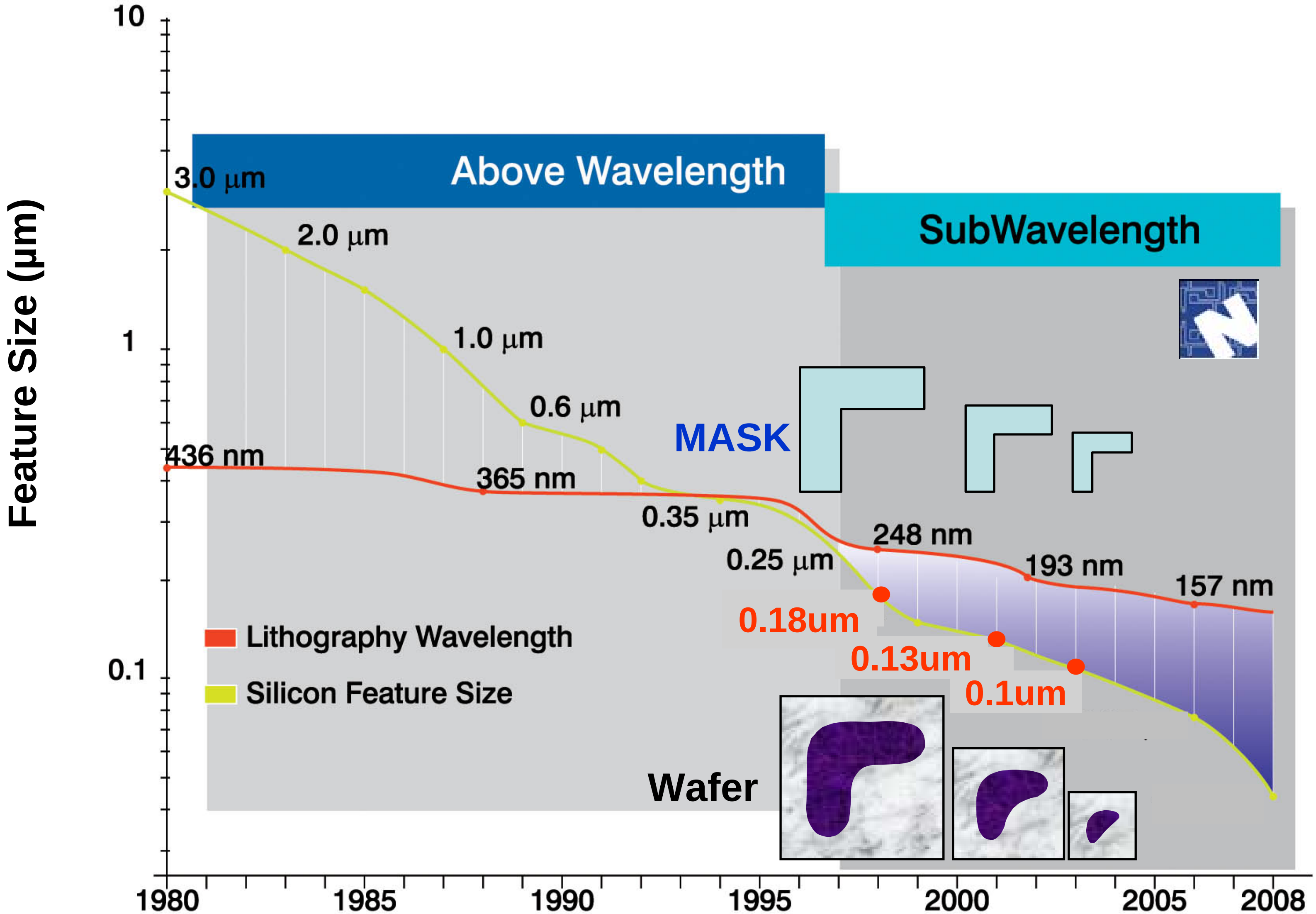
Source: Photronics.com

Alternating Aperture PSM

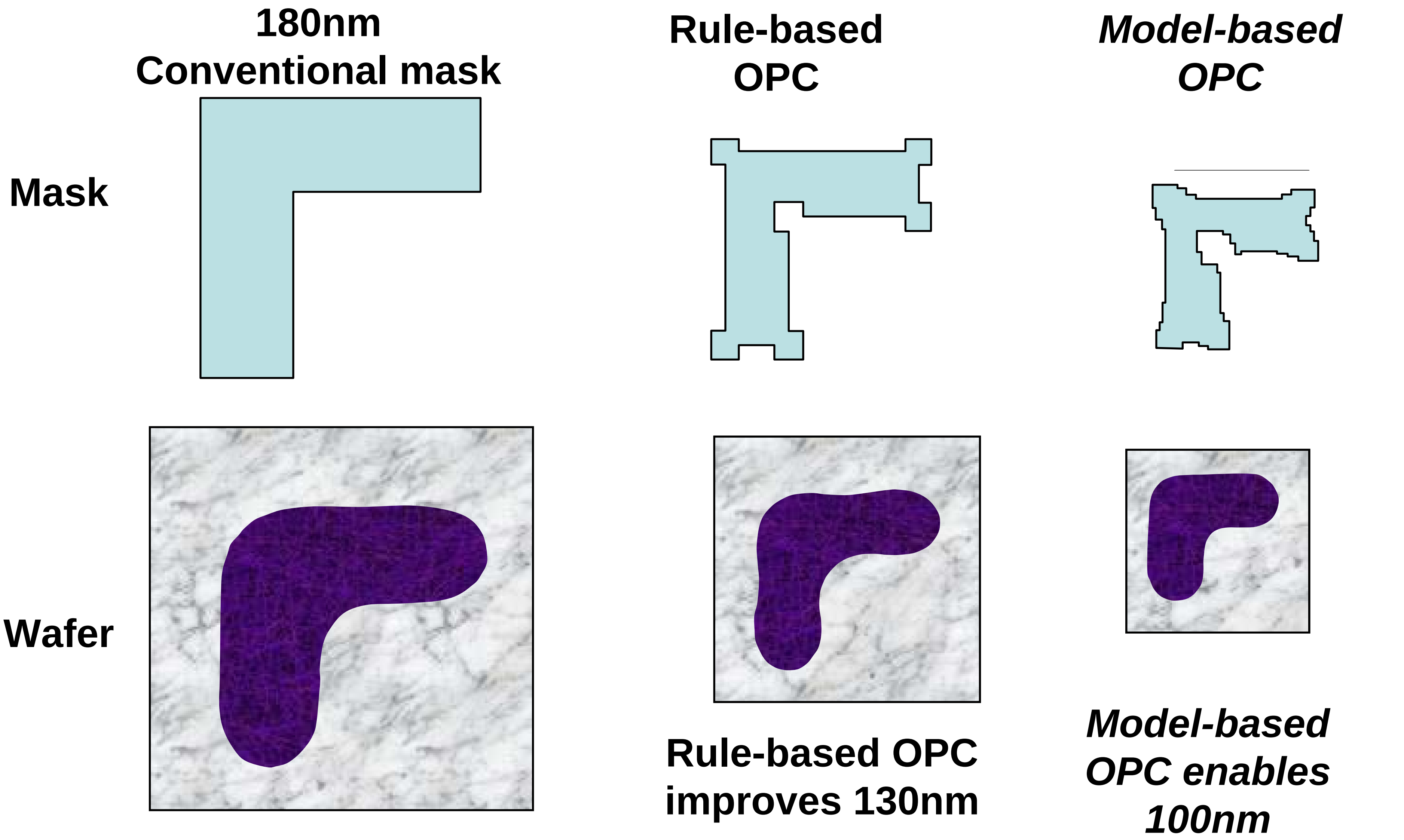


Source: Photronics.com

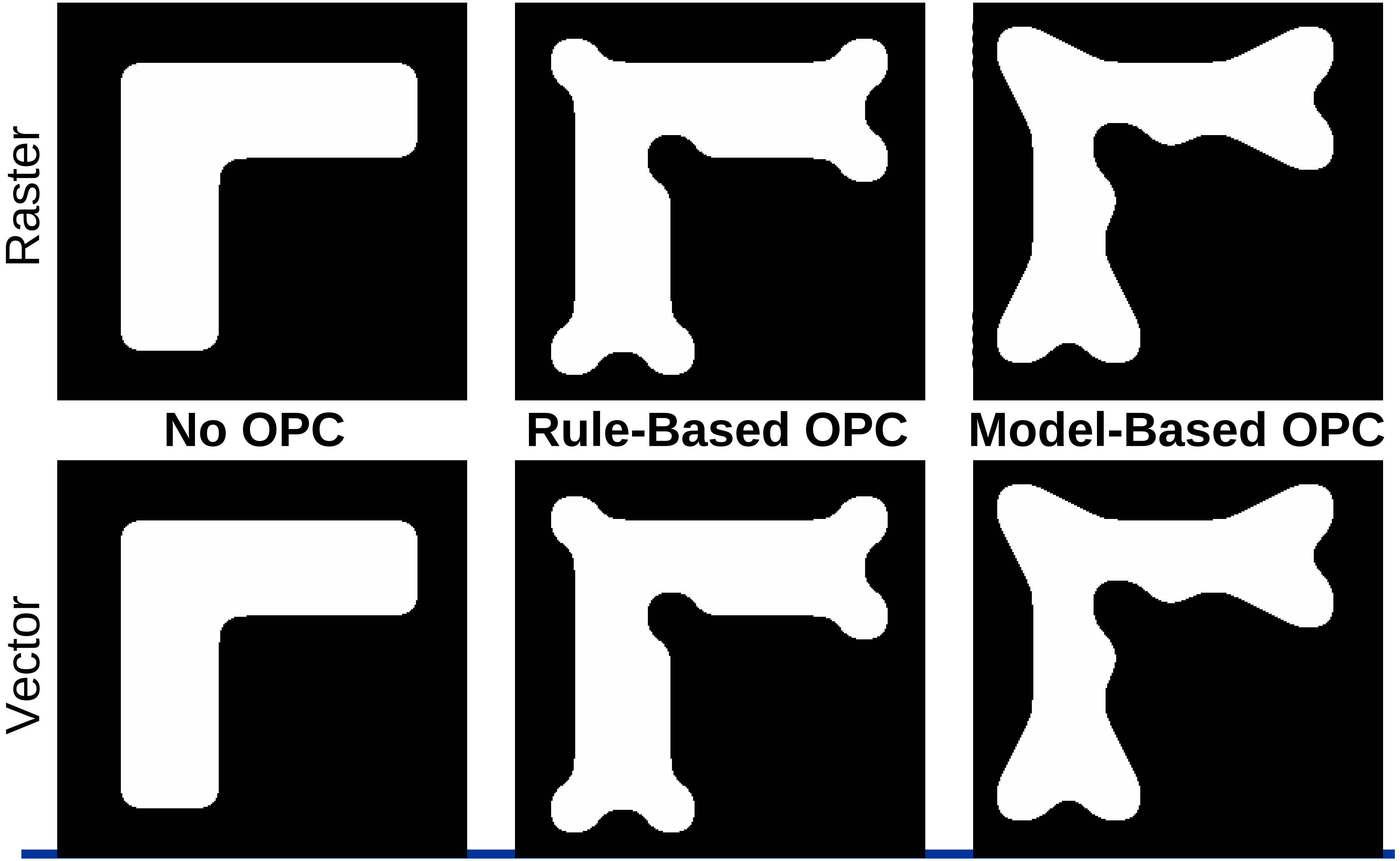
“The SubWavelength Gap”



Optical Proximity Correction (OPC)

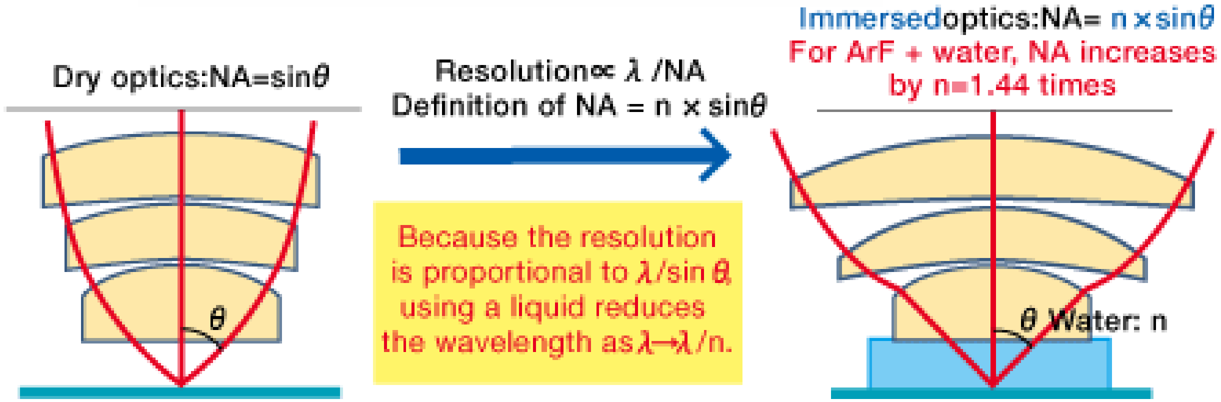


Mask Making: Raster vs. Vector



Immersion Lithography

$$NA = n\sin\alpha = d/(2f) \qquad W = \frac{k_1\lambda}{n\sin\alpha} = \frac{0.25\times 193}{1.47\times 0.93} = 35nm$$



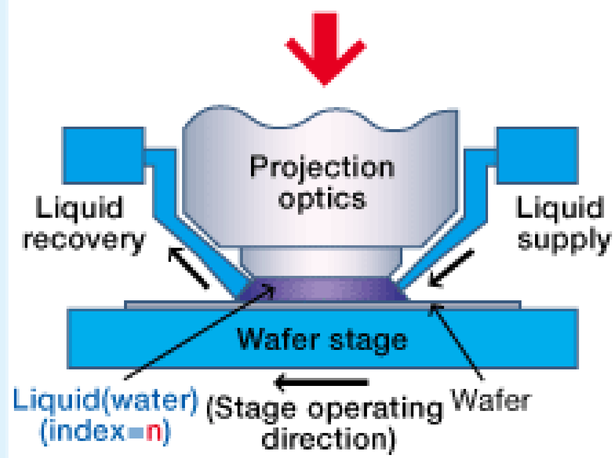
Issues

Liquid
- How liquid is inserted (Local fill)
- Supply and recovery of water
  - Bubbles
  - Temperature control

Optics
- Development of a reduced projection lens with ultra-high NA
- Polarizing effect and polarized illumination
- Focus sensor

Stage mechanism
- Edge shot
- Liquid supply nozzle and stage mechanism

Process
- Resist
- Coater, developer

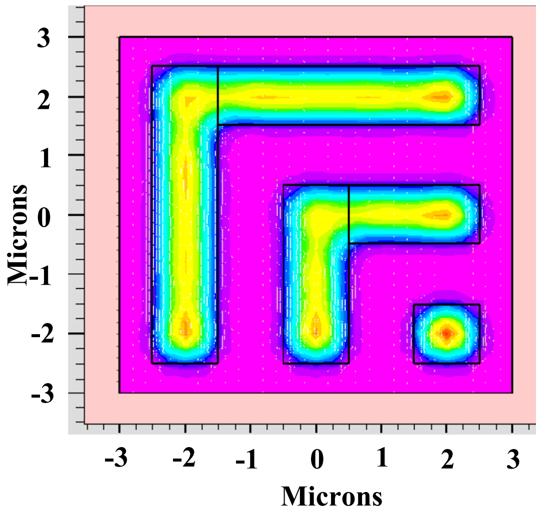


* Diagram supplied by Nikon Corporation

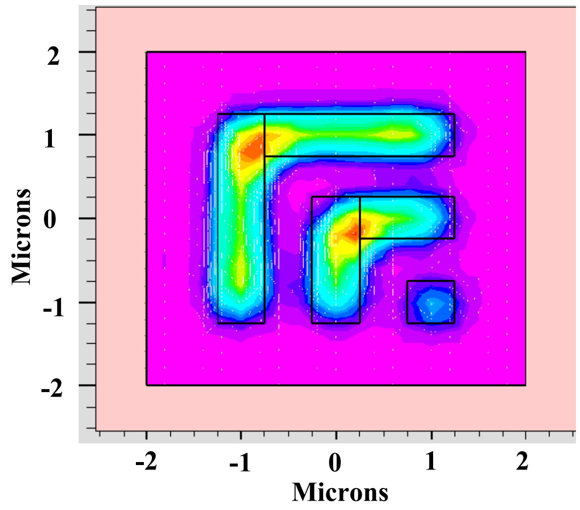
resource.renesas.com

Simulation of Exposure

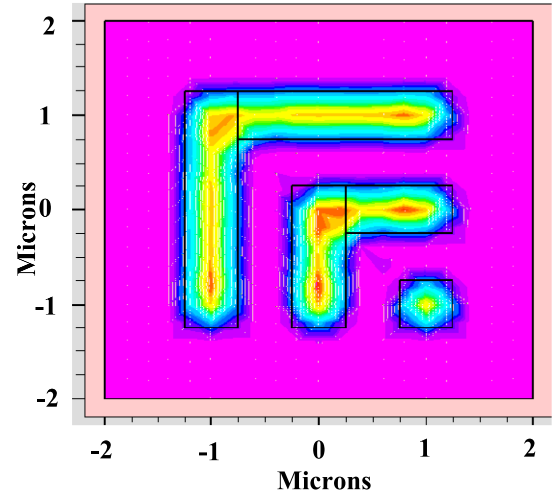
- **ATHENA simulator (Silvaco). Colors correspond to optical intensity in the aerial image.**



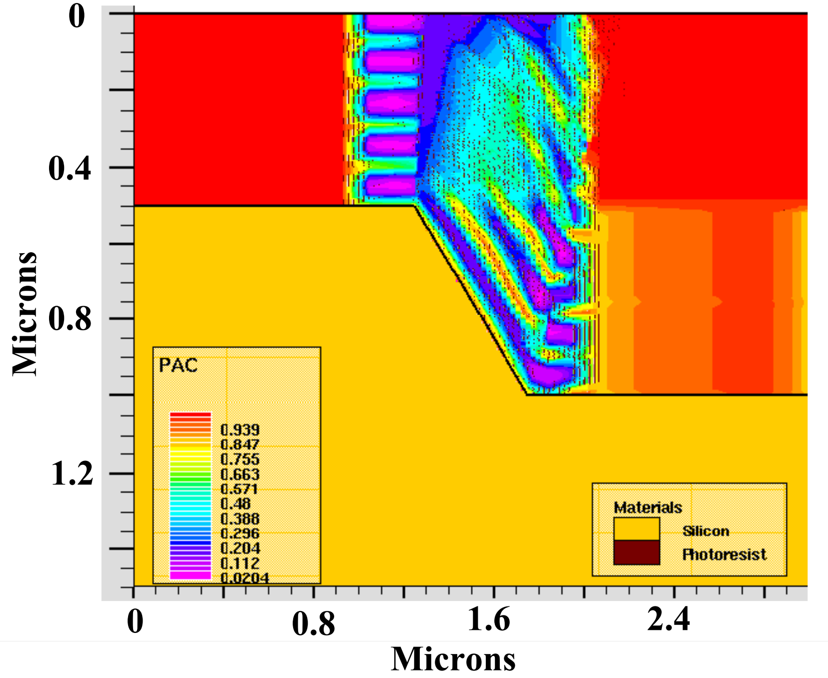
Exposure system: NA = 0.43, partially coherent g-line illumination (λ = 436 nm). No aberrations or defocusing. Minimum feature size is 1 µm.



Same example except that the feature size has been reduced to 0.5 µm. Note the poorer image.



Same example except that the illumination wavelength has now been changed to i-line illumination (λ = 365 nm) and the NA has been increased to 0.5. Note the improved image.



- Example of calculation of light intensity distribution in a photoresist layer during exposure using the ATHENA simulator. A simple structure is defined with a photoresist layer covering a silicon substrate which has two flat regions and a sloped sidewall. The simulation shows the [PAC] calculated concentration after an exposure of 200 mJ cm^{-2}. Lower [PAC] values correspond to more exposure. The color contours thus correspond to the integrated light intensity from the exposure.

Photoresist Exposure

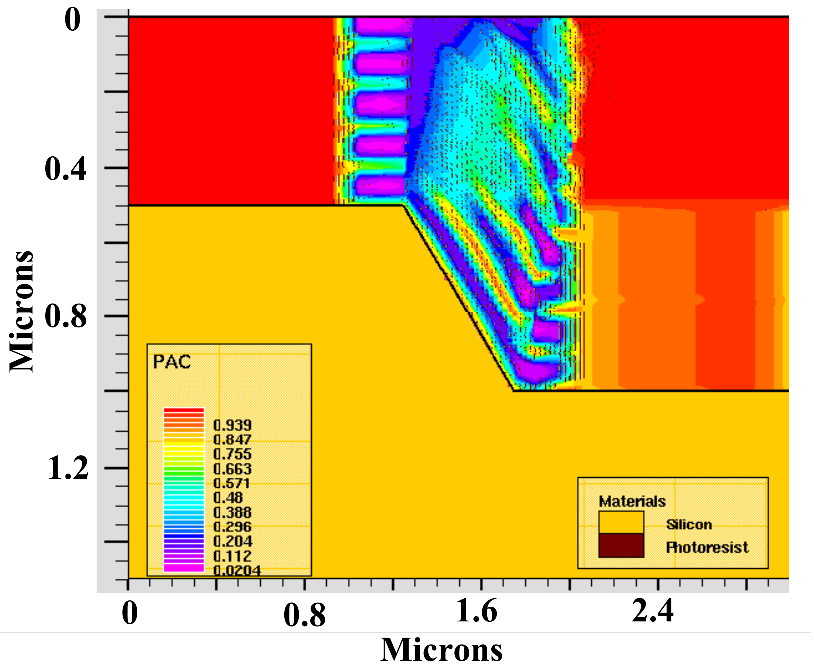
- Neglecting standing wave effects (for the moment), the light intensity in the resist falls off as

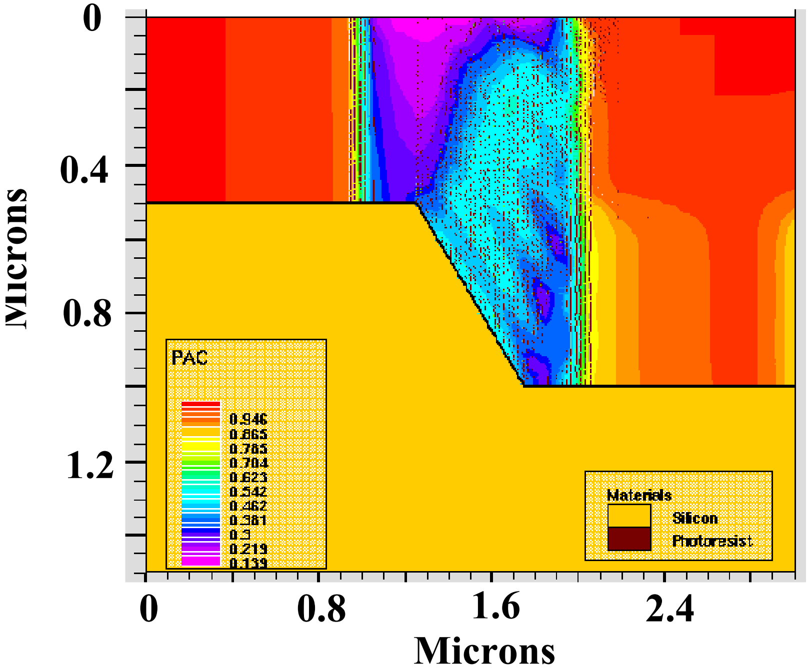
$$\frac{dI}{dz} = -\alpha I \qquad (23$$

(The probability of absorption is proportional to the light intensity and the absorption coefficient.)

Simulation of Photoresist Baking

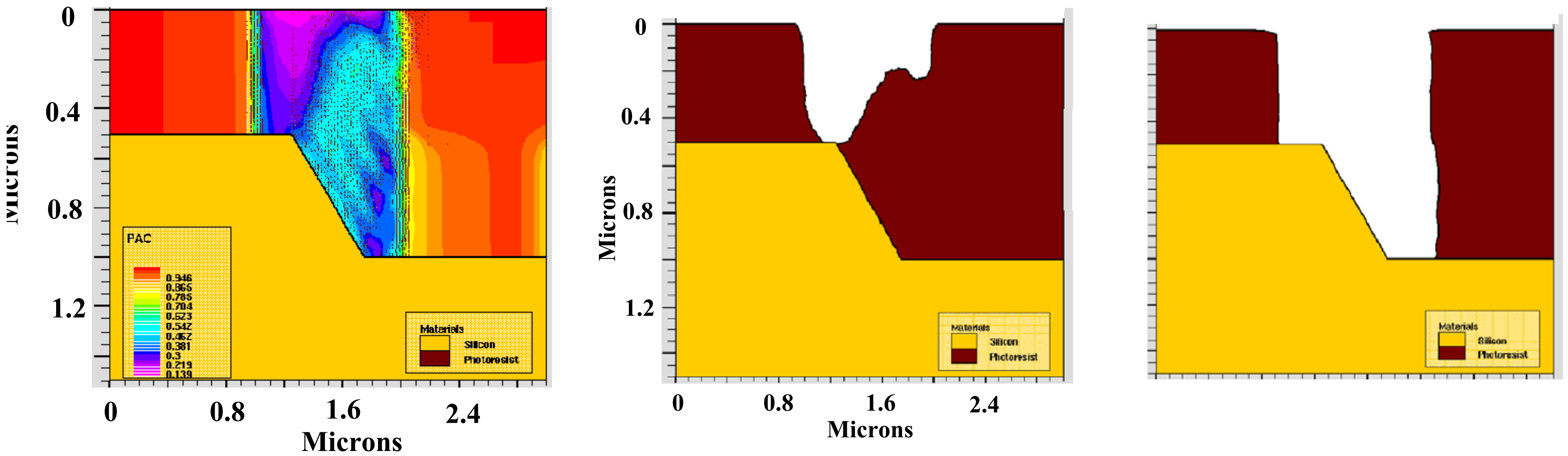
- A post exposure bake is sometimes used prior to developing the resist pattern.
- This allows limited diffusion of the exposed PAC and smoothes out standing wave patterns.
- Generally this is modeled as a simple diffusion process (see text).





- Simulation on right after a post exposure bake of 45 minutes at 115 °C. The color contours again correspond to the [PAC] after exposure. Note that the standing wave effects apparent earlier have been “smeared out” by this bake, producing a more uniform [PAC] distribution.

Simulation of Resist Development



- Example of the calculation of a developed photoresist layer using the ATHENA simulator. The resist was exposed with a dose of 200 mJ cm^{-2}, a post exposure bake of 45 min at 115 °C was used and the pattern was developed for a time of 60 seconds, all normal parameters. The Dill development model was used. Center - part way through development. Right - complete development.

Next Generation Lithography

- Immersion 193 with RETs
  - Double exposures
  - Multiple Lithography (ML2)
  - Advanced mask technology…
- Extreme UV (EUV) or Soft X-ray Lithography, 2015-2020.
- Nanoimprint, 2008?
  - Step and Flash Imprint Lithography (S-FIL)

X-Ray Lithography

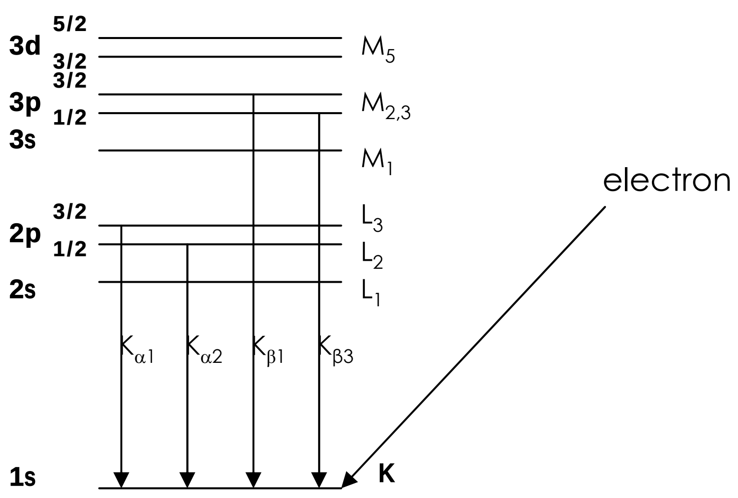
- General Characteristics
- Energy Sources
- Masks
- Exposure Systems / Aligners
- Resists
- Interaction of X-rays with substrate

General Characteristics

- Eliminates the diffraction limitations of optical lithography
- Issues
  - Brightness of sources
  - Optical components (lens, reflectors, etc.)
  - Masks
  - Resists

X-Ray Generation

X-rays
- electromagnetic radiation of high energy
  - Characteristic X-rays of a specific element
  - Continuum of X-rays due to Bremmstralhung
  - Produced by
    - » High energy electrons (10's of keV) impinging on a material
    - » Higher energy photons (X-rays or gamma rays) impinging on a material



Electromagnetic radiation

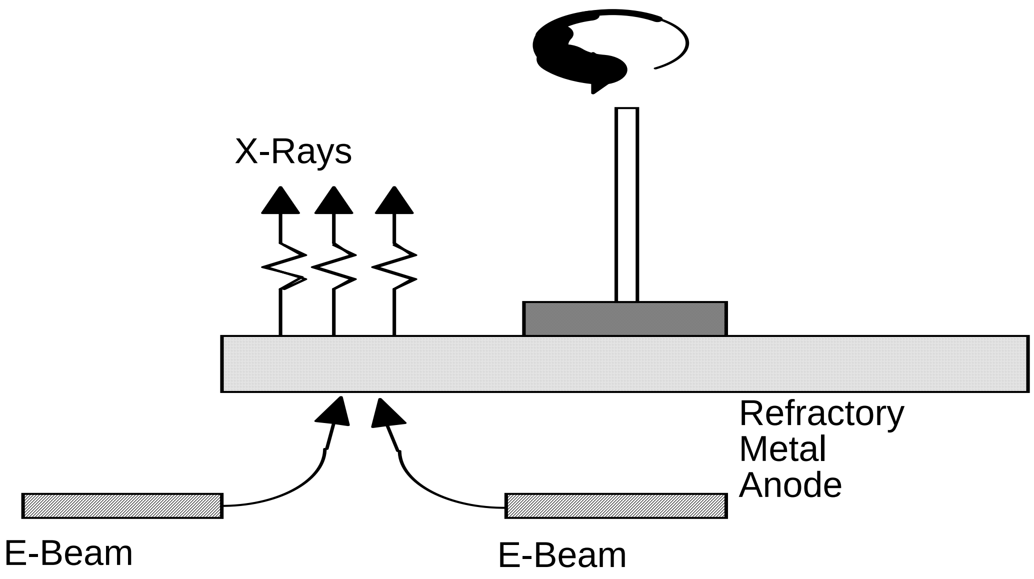
- $\lambda\nu = c$
- $E = h\nu$
- $\nu = c / \lambda$
- $E = h\, c / \lambda$

X-Ray Energy Sources

- **Electron Impact X-ray source**
- **Plasma heated X-ray source**
  - **Laser heated**
  - **E-beam heated**
- **Synchrotron X-ray source**

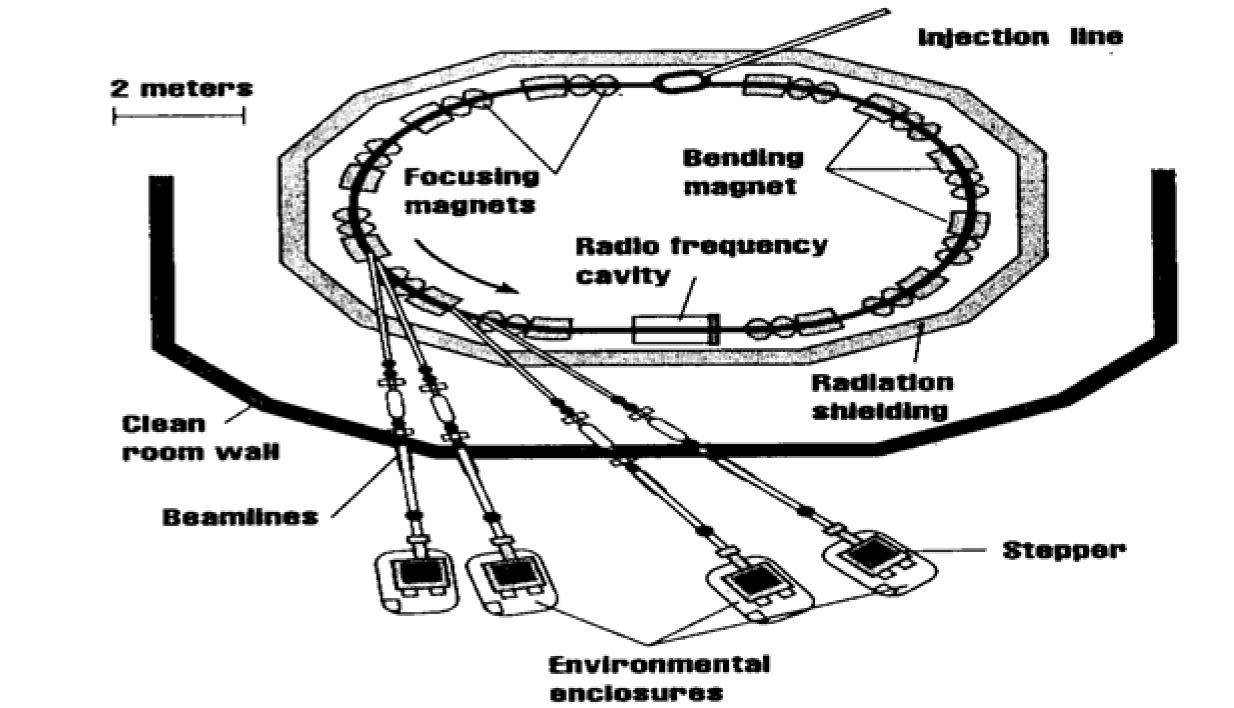
Electron Impact X-ray Sources

- E-beam accelerated at high energy to a rotating refractory anode
- Core electrons in refractory anode excited and x-rays emitted when they fall back to the core levels
- Water cooled to prevent evaporation



X-Ray Energy Sources

Synchrotron X-ray Sources

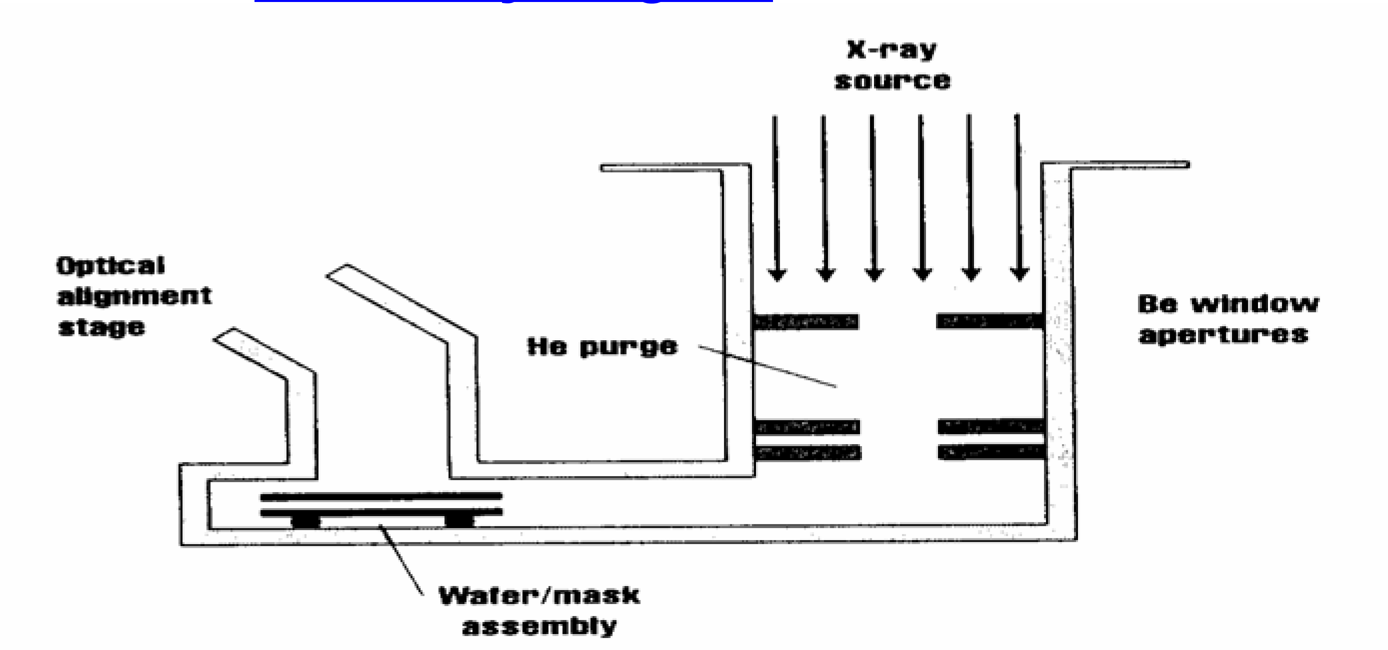


- Brightest X-ray source
- Requires electron storage ring
- X-rays emitted when electrons are bent by magnet
- Size is an issue

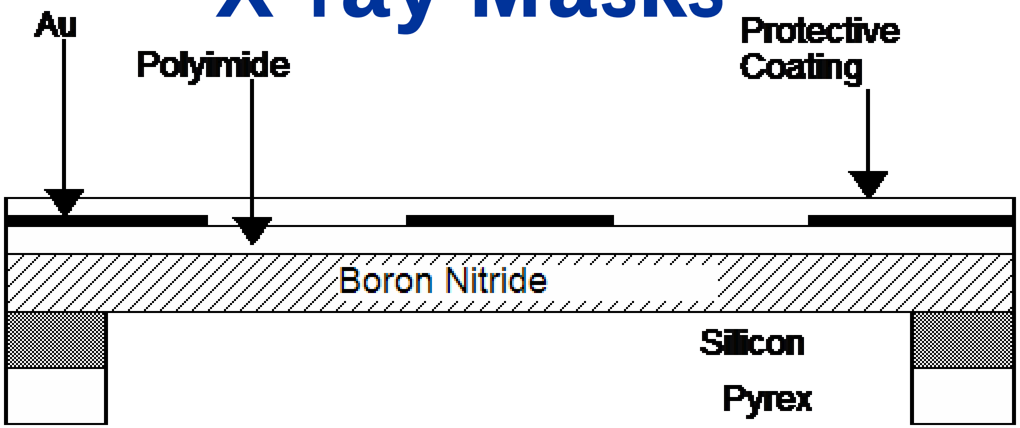
X-ray Exposure Systems

- Optics extremely difficult
  - No good lenses
- Proximity Printing
  - Penumbral blur limits resolution
- Projection Printing
  - Reflectors

Proximity Aligner

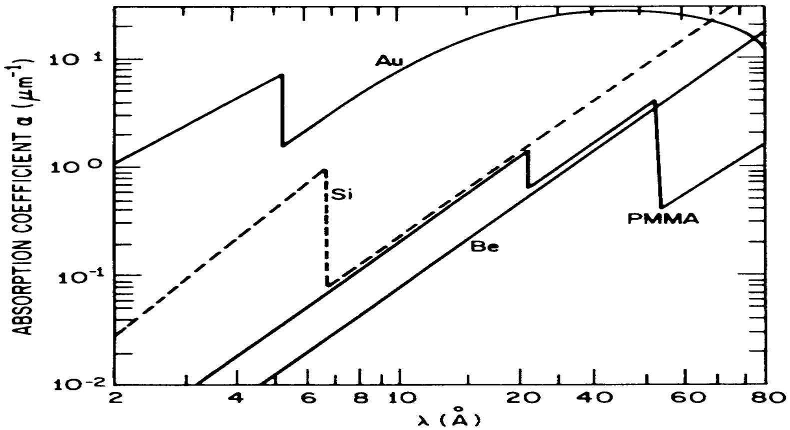


X-ray Masks

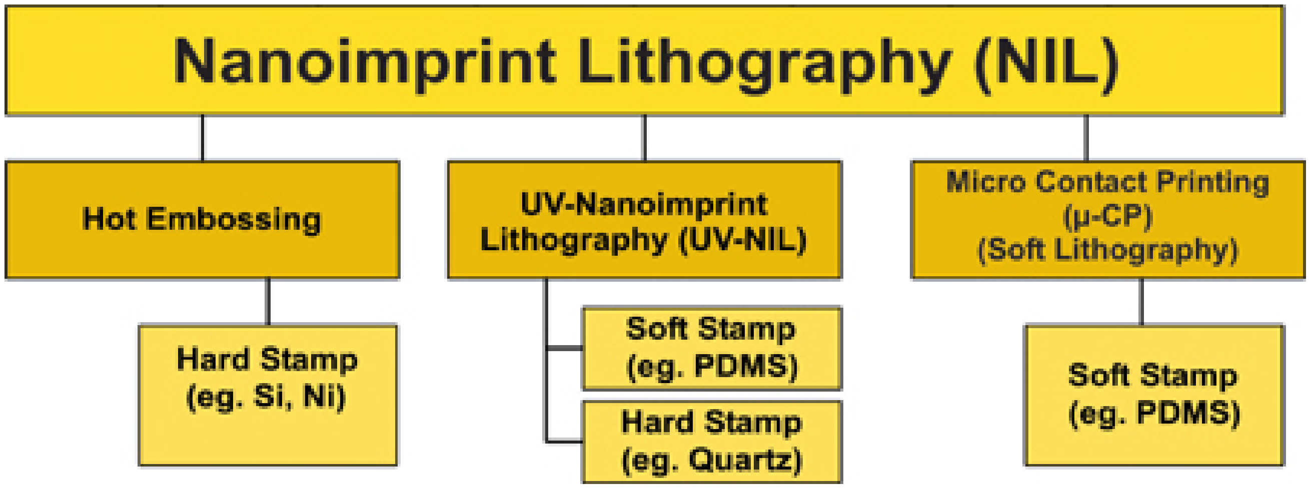


- Need combination of materials that are opaque(heavy element, e.g. Au) and transparent(low atomic mass membrane, e.g. BN or S_3N_4) to x-rays
- Mask written by e-beam
- Diffraction is not an issue (shadowing is)
- Masks difficult to make due to need to manage stress
- Dust less of a problem because they are transparent to X-rays

Absorption Coefficient of Common Materials



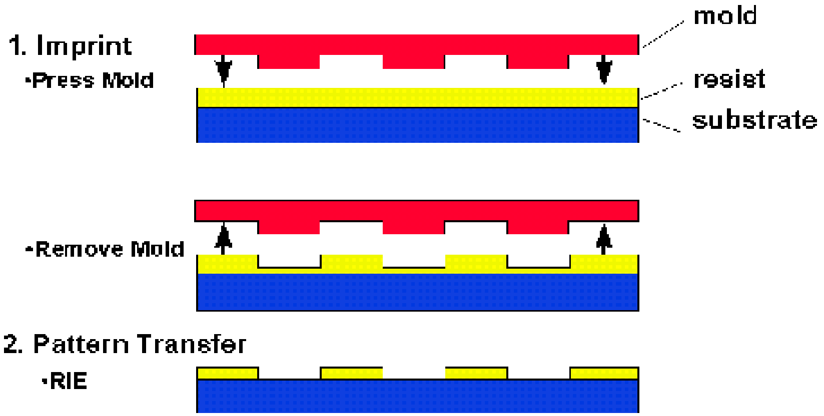
Overview of Imprint Technology

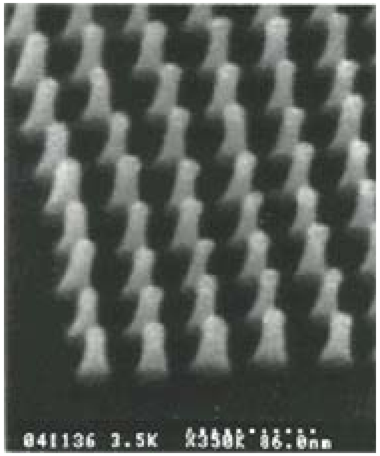


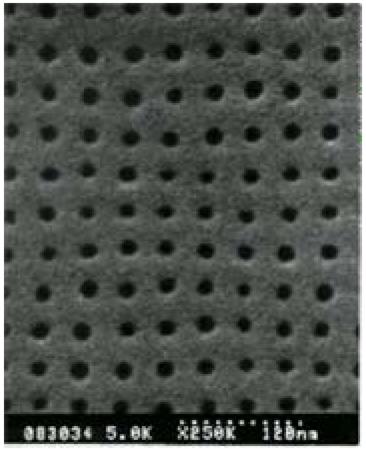
Soft litho, micro contact printing; direct imprint metal; NanoTransfer printing; reversal NIL, reversal UV NIL; Duo-Mold NIL; Laser-NIL; Low-P NIL; S-NIL, nano-second NIL; Roll-to-roll imprint, etc.

Nanoimprint Lithography (NIL)

Thermal Imprint, hot embossing

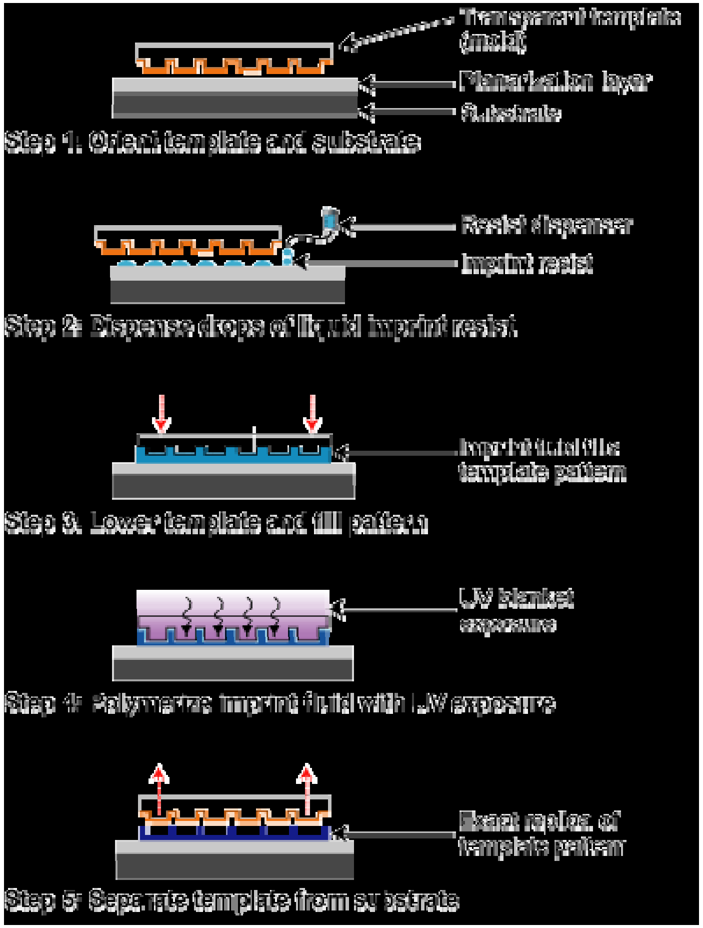






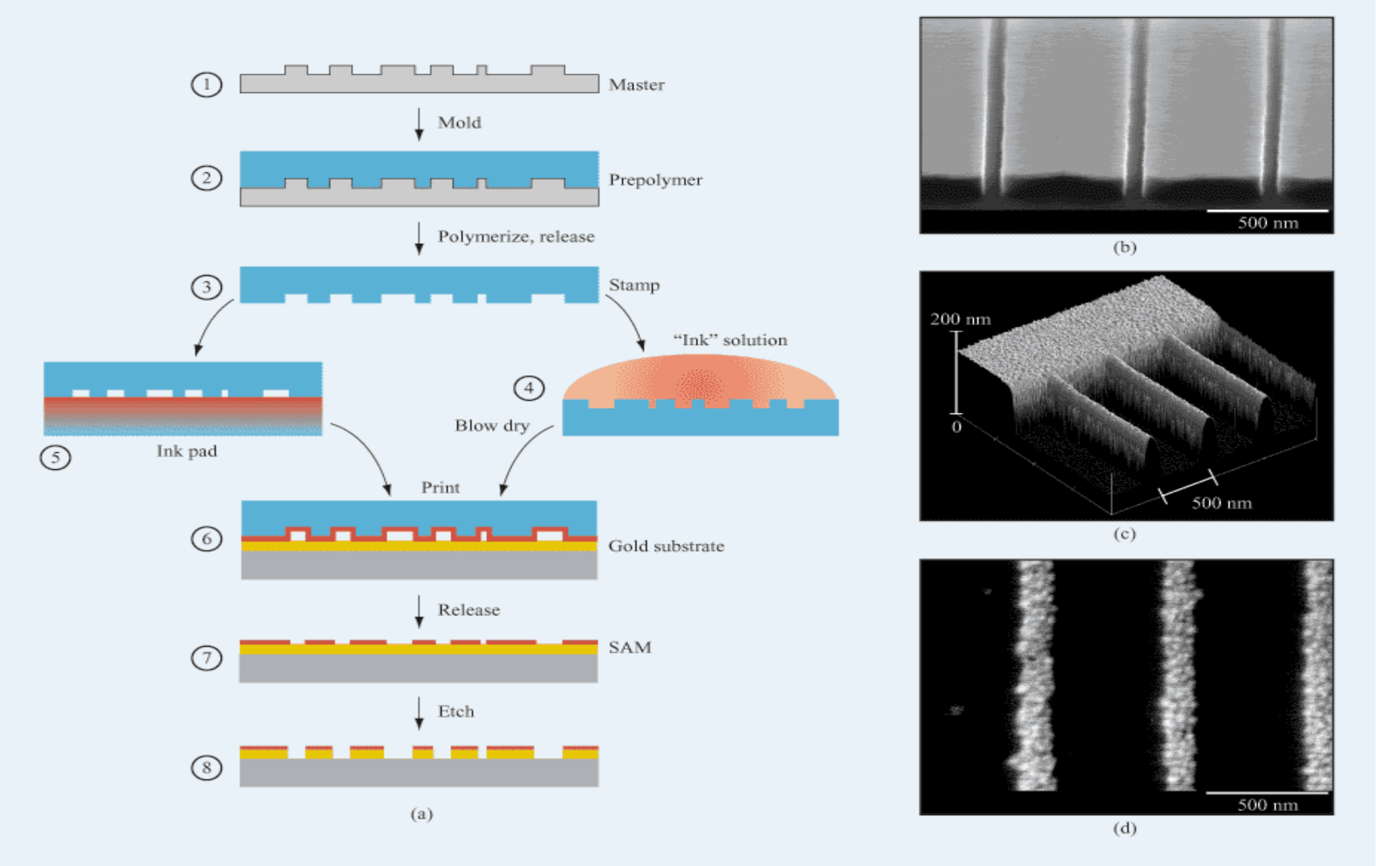
Stephen Chou, Princeton
Nanonex Inc.

Step-Flash Imprint Lithography (SFIL)



Grant Willson, UT Austin
Molecular Imprint Inc.

Soft Lithography



George Whitesides
Younan Xia
(Harvard)

Figure 3

Soft-lithography components. (a) Diagram of process: A prepolymer (2) covering the master (1) is cured by heat or light, and demolded to form an elastomeric stamp (3). The stamp is inked by immersion (4) or contacted with an ink pad (5), and printed onto the substrate (6), forming a self-assembled monolayer (SAM). The ink pattern (7) is then transferred into the substrate by a selective etch (8). (b) Scanning electron microscopy (SEM) micrographs of the master, (c) image of the stamp, and (d) SEM micrograph of a printed and etched pattern.

Pictures
From IBM

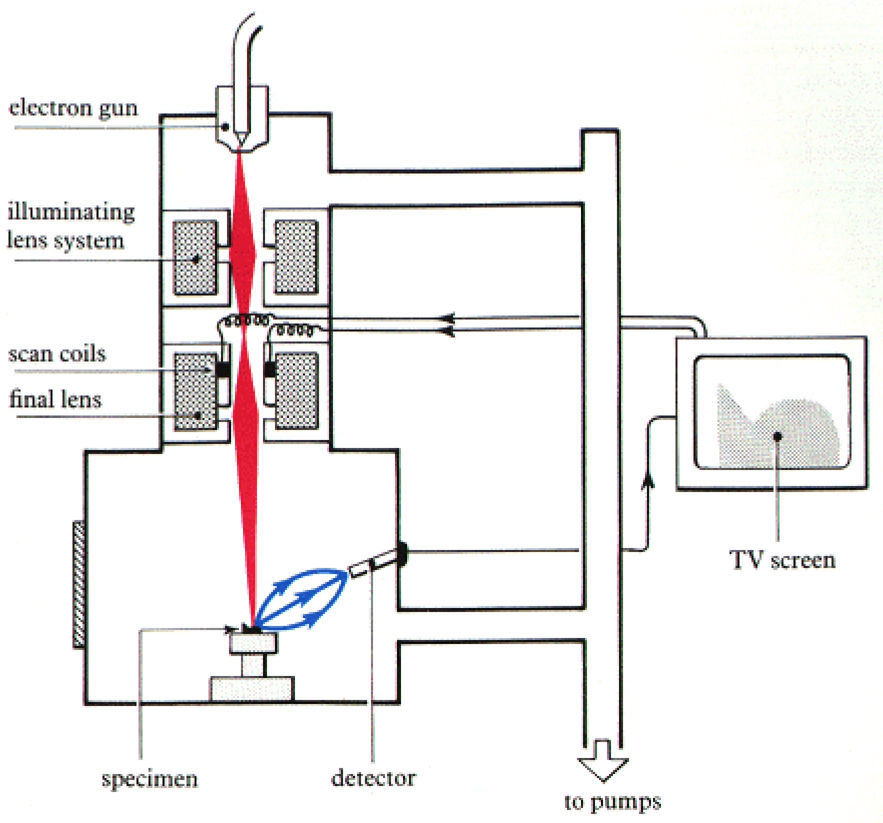
E-Beam Litho Systems

Leica VB6 UHR EWF

- High resolution Gaussian Beam system
- 50 to 100KeV Thermal Field Emission Gun
- 50MHz Intelligent Pattern Generator with 20bit main field resolution
- Large field size operation (1.2mm) with nano-lithography performance.
- Sub-20nm Resolution guaranteed with <10nm routinely demonstrated

E-beam litho SEM

EBL/SEM Systems

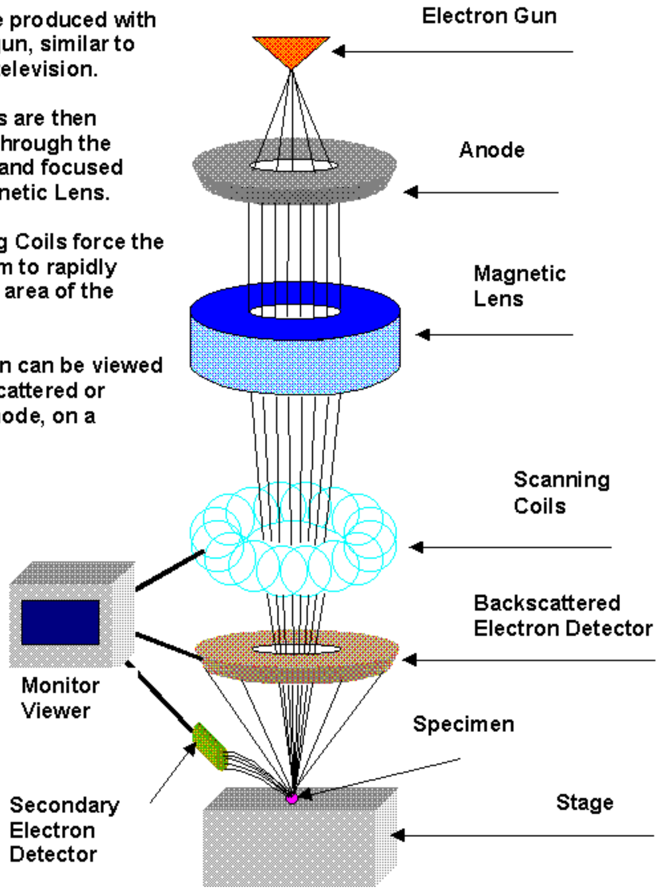


Electrons are produced with an electron gun, similar to the one in a television.

The electrons are then accelerated through the Anode plate and focused with the Magnetic Lens.

The Scanning Coils force the electron beam to rapidly scan over an area of the specimen.

The specimen can be viewed in the Backscattered or Secondary mode, on a monitor.



Electron Beam Sources

- **Thermionic emitters**
  - Electrons "boiled" off the surface by giving them thermal energy to overcome the barrier (work function)
  - Current given by Richardson-Dushman Equation
- **Field Emitters**
  - Takes advantage of the quantum mechanical properties of electrons.
  - Electrons tunnel out when the surface barrier becomes very narrow
  - Current given by Fowler-Nordheim equation
- **Photo Emitters**
  - Energy given to electrons by incident radiation (photons)
  - Only photo-electrons generated close to the surface are able to escape

- Electrons extracted, collimated or focused and accelerated to 20 kV
- Spot diameters of ≈50 Å can be achieved
- Similar to ion-implantation

E-beam Lithography Resolution

Why can't we write 100 Å lines when the beam width is 100 Å?

- **Interaction of e- and substrates + resist leads to beam spreading**
  - Elastic and in-elastic scattering in the resist
  - Back-scattering from substrate and generation of secondary e-
  - 100 Å e-beam become 0.2 µm line