520/530/580.495
Microfabrication Laboratory
and
520.773
Advanced Topics in
Fabrication and Microengineering

Lecture 5

Photolithography (II)

Conventional Photoresists

Typically consist of 3 components:

-resin or base material

- **a binder that provides mechanical properties (adhesion, chemical resistance, etc)**

-photoactive compound (PAC)

-solvent

- **control the mechanical properties, such as the viscosity of the base, keeping it in liquid state.**

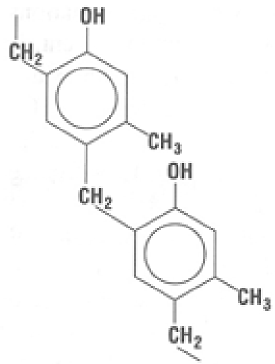
Positive Photoresist (I)

•Two-component DQN resists:

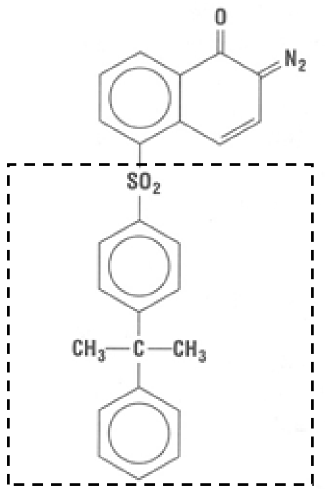
Currently the most popular positive resists are referred to as DQN, corresponding to the photo-active compound, diazoquinone (DQ) and resin, novolac (N), respectively.

- •Dominant for G-line and I- line exposure, however, these resists cannot be used for very-short-wavelength exposures.

- •Novolac (N):
  - a polymer whose monomer is an aromatic ring with two methyl groups and an OH group.
  - it dissolves in an aqueous solution easily.
  - solvent added to adjust viscosity, however, most solvent is evaporated from the PR before exposure and so plays little part in photochemistry

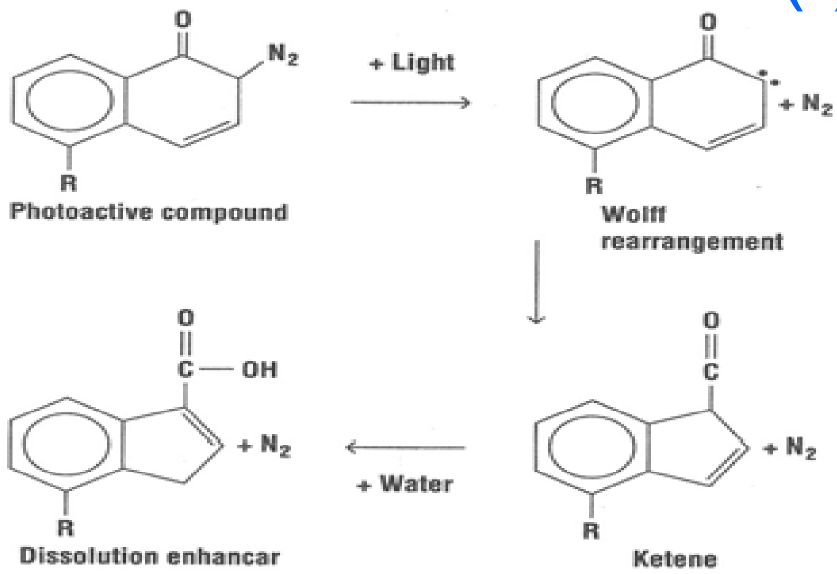


- •Diazoquinone(DQ)
  - 20-50 % weight
  - photosensitive
  - an inhibitor that reduces the dissolution rate by > 10 folds.
  - DQ $\xrightarrow{UV}$ Carboxylic acid (dissolution enhancer)



R

Positive Photoresist (I)



-Photoactive compound (DQ) is insolvable in base solution.
-Carboxylic acid readily reacts with and dissolve in a base solution
 -resin/carboxylic acid mixture will rapidly takes up water
 (the nitrogen released in the reaction also foams the resist, further assisting the dissolution)
 -The chemical reaction during the dissolution is the breakdown of the carboxylic acid into water-soluble amines such aniline and slat of K (or Na depending on the developer).
 -Typical developer KOH or NaOH diluted with water

Advantages of DQN photoresists:

- the unexposed areas are essentially unchanged by the presence of the developer. Thus, line width and shape of a pattern is precisely retained.
- novolac is a long-chain aromatic ring polymer that is fairly resistant chemical attack. The PR therefore is a good mask for the subsequent plasma etching.

Pattern Transfer

- The PR patterns defined by photolithography are not permanent elements of the final device, but only replicas of the IC or MEMS features. To produce such features these PR patterns must be transferred once more into underlying layers comprising the device.
- The remaining image after pattern transfer can be used as a mask for subsequent process such as etching, ion implantation, and deposition

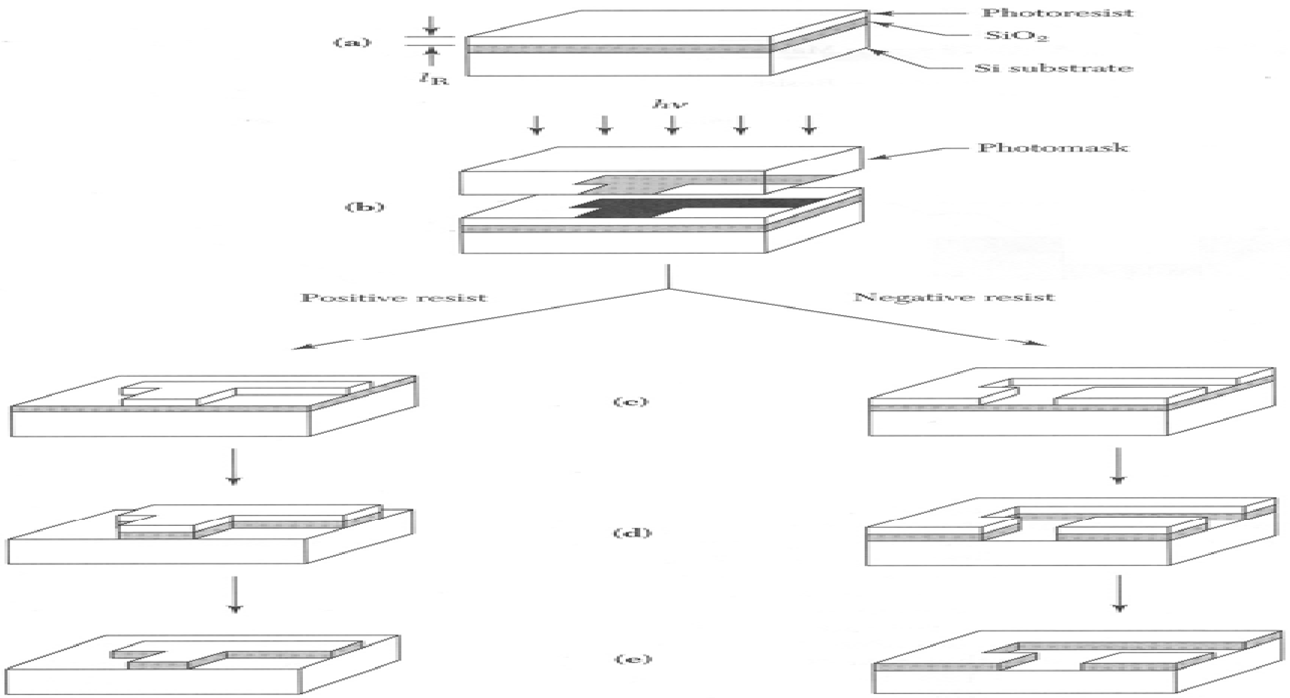
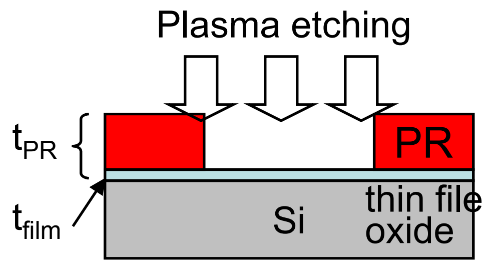


Figure 4.10 Details of the optical lithographic pattern transfer process.[5]

Positive Photoresist (II)

- PMMA (Ploymethyl methacrylate)

  - short-wavelength lithography: deep UV, extreme UV, electron-beam lithography
  - resin itself is photosensitive (Slow)
  - (pro's) high resolution
  - (con's)
    - Plasma etch tolerance of the resist is very low.
      it needs to have thick PMMA to protect the thin film,
      otherwise the PMMA will disappear before the thin film does



resist feature with aspect ratio higher than 4 is not considered to mechanical stable.

    - dissociation of PMMA changes the chemistry of the plasma etch and often leads to polymeric deposits on the surface of the substrate.

  - Low sensitivity
    it needs to add PACs or to elevate exposure temperature
    to increase the speed (the elevation of temperature can also increase the contrast).

Negative Photoresist

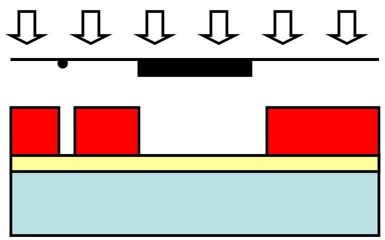
•Based on azide-sensitized rubber such as cyclized polyisoprene

•Advantages

- •Negative photoresists have very high photospeeds
- •Adhere to substrate without pretreatment

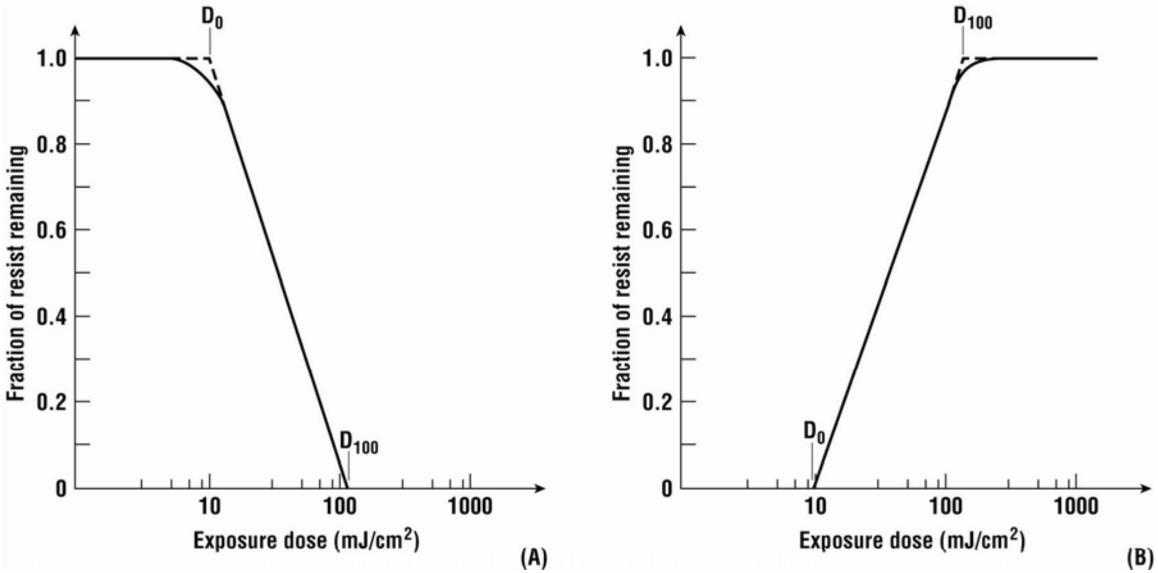
•Disadvantages

- ▪Swelling of photoresists during the development.
  - an after develop bake will make the lies to return to their original dimension, but this swelling and shrinking process can cause the lines to be distorted. The minimum feature size of negative PR is limited to 2 μm



- ▪Dirt on mask causes pinhole
- ▪Developer is usually organic solvent
  - less ecological

Photoresist Contrast Ratio



Sensitivity ≡ the threshold energy (D_{100})

Contrast ratio :

$$\gamma \equiv \frac{1}{\left[\log_{10}\left(\frac{D_{100}}{D_0}\right)\right]}$$

- a more directly metric to character PR performance
- the ability of a PR to distinguish between light and dark portions of the mask
- sensitive to develop process, the soft bake and post exposure bake processes, and wavelength of exposure

Photoresist Profile

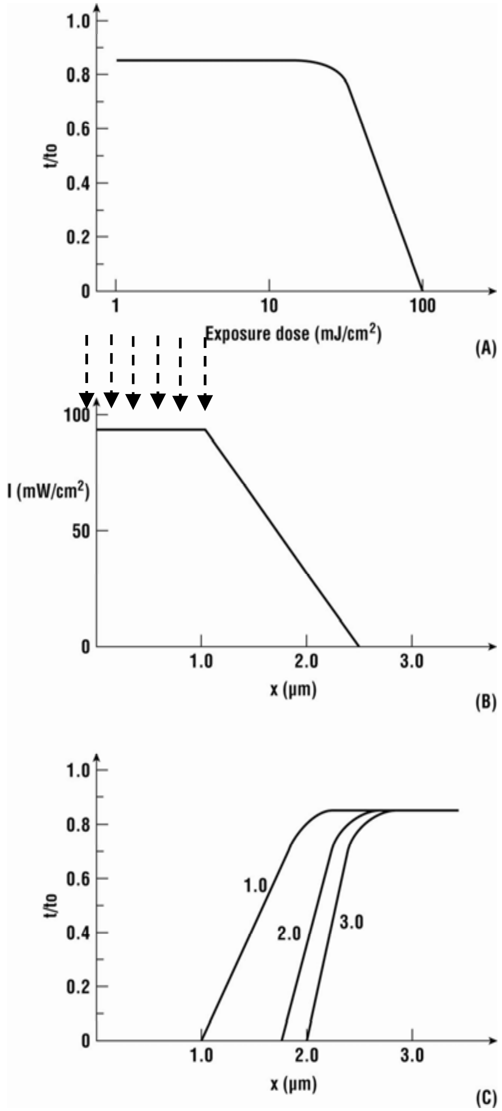
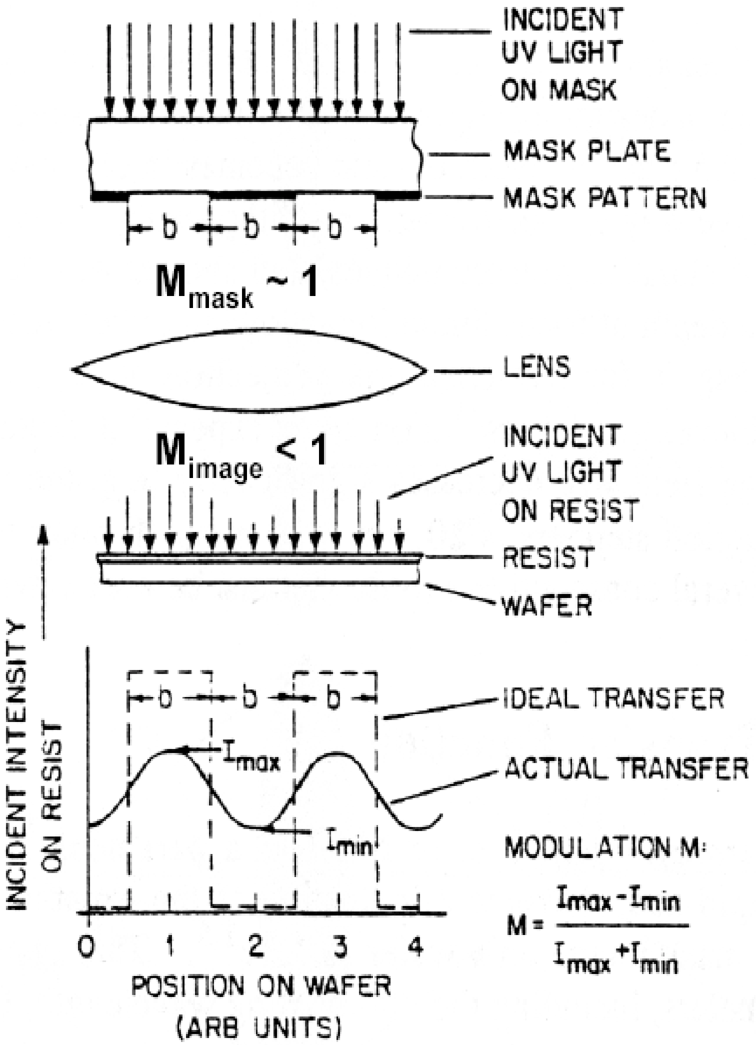


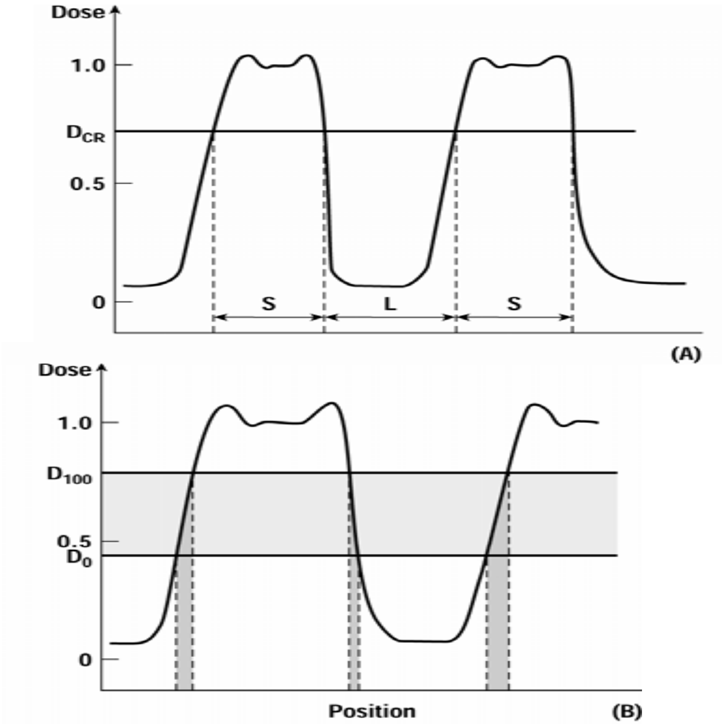
Figure 8.8 (A) Measured contrast curve for a commercial DQN resist. (B) Simple areal image. (C) Approximate profiles for 1-, 2-, and 3-sec exposures.

Sharper image v.s. higher throughput

PR : Critical Modulation Transfer Function (CMTF)



M: Modulation Transfer Function (MTF) of a optical system



Critical Modulation Transfer Function

$$\mathrm{CMTF} = \frac{D_{100} - D_0}{D_{100} + D_0} = \frac{10^{\frac{1}{\gamma}} - 1}{10^{\frac{1}{\gamma}} + 1}$$

General rule:
In order to resolve the image,

$MTF_{optics} \geq CMTF_{resist}$

Resolution Enhancement Techniques (I)
Phase-shifting mask (PSM)

Optical Intensity and Exposure Energy

•Light is an Electromagnetic Wave

-Electrical field (ε)

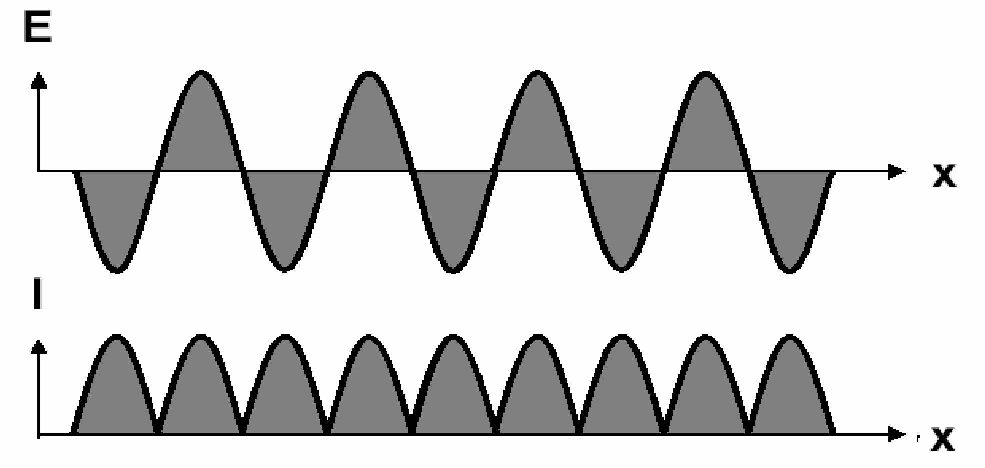
$$\varepsilon(\vec{r},\nu) = \varepsilon_0(\vec{r})e^{j\phi(\vec{r},\nu)}$$

-Intensity I

$$I = \varepsilon \cdot \varepsilon^* = \phi_0 e^{j\phi} \cdot \varepsilon_0 e^{-j\phi} = \varepsilon_0^2$$

-Energy E

$$E = \int I \cdot dt \approx I \cdot t$$



Resolution Enhancement Techniques (I)

Phase-shifting mask (PSM)

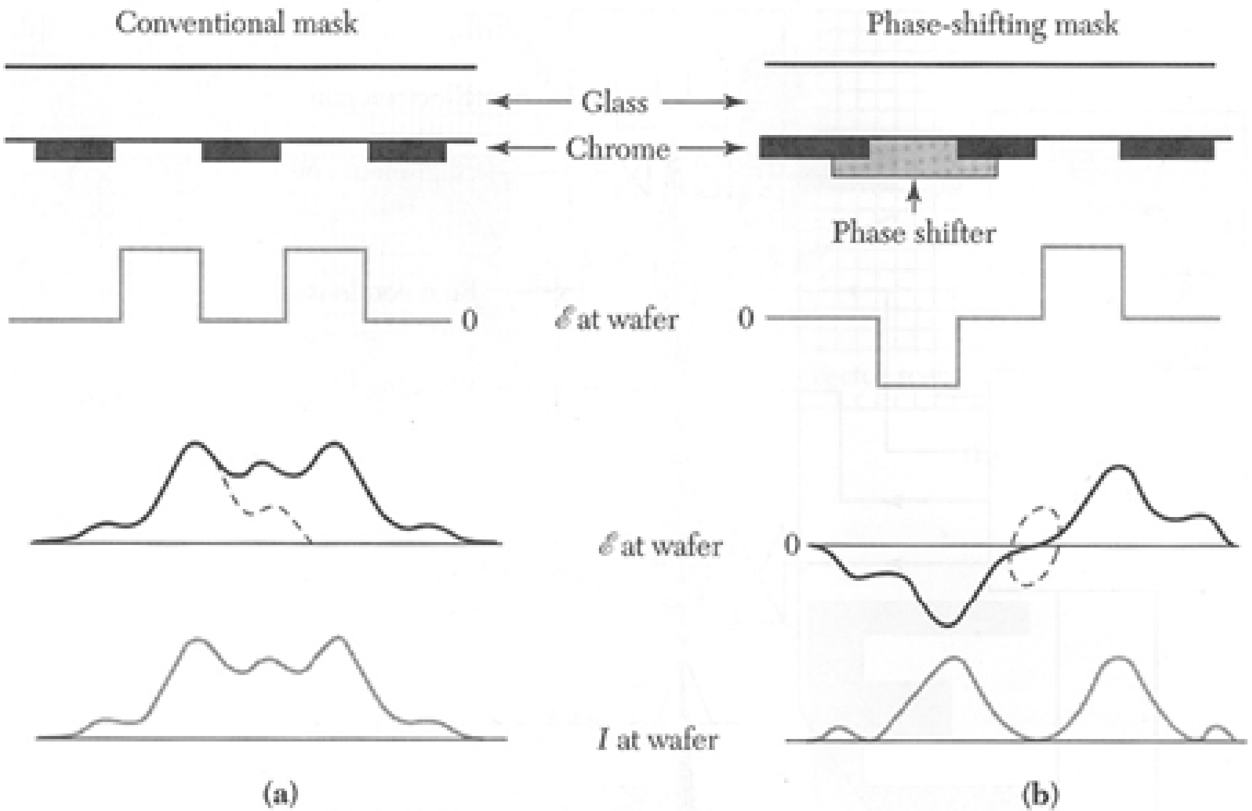


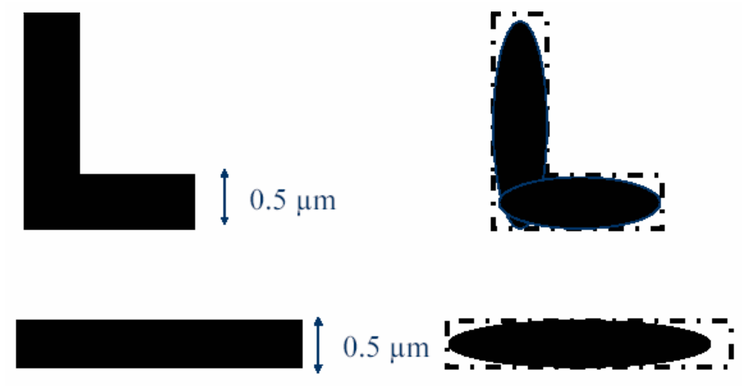
Figure 4.12 The principle of phase-shift technology. (*a*) Conventional technology. (*b*) Phase-shift technology.[9]

Resolution Enhancement Techniques (I)

Optical proximity correction (OPC)

OPC uses modified shapes of adjacent subresolution geometry to improve imaging capability

Figure on the mask **Pattern on the wafer**

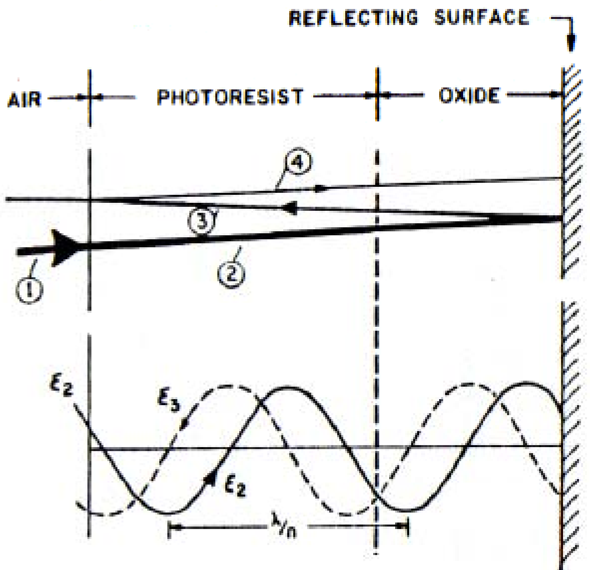


When the feature size is smaller than the resolution, the pattern will be distorted in several ways:

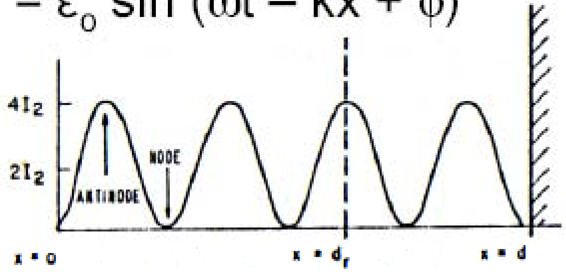
- **Line width variation**
- **Corner rounding**
- **Line shortening**

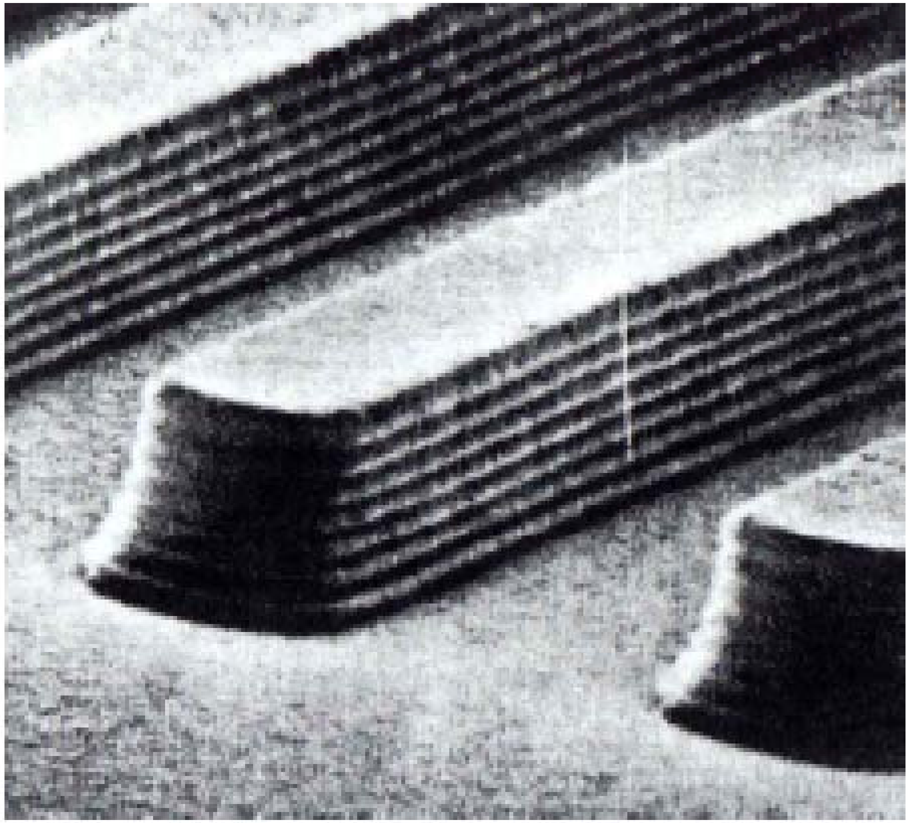
Modify the Mask based on rules or model

Reflections and Standing Waves



$$\varepsilon(x,t) = \varepsilon_o \sin(\omega t - kx + \phi)$$





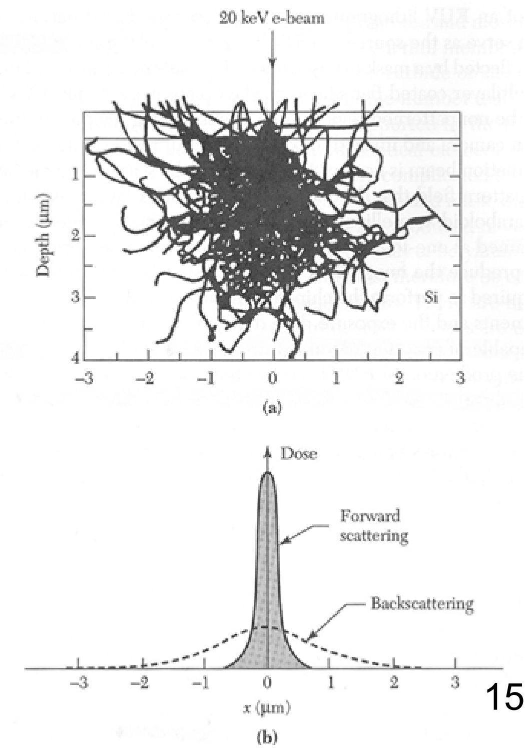
•Reduce the effect with post-exposure bake (PEB)
- thermal re-distribution of exposure products

Next Generation Lithographic Methods (I)

- Electron Beam (E-Beam) Lithography
  - Electron-beam is used for direct writing
  - E-beam lithography is primarily used to produce photomasks
  - Electron resist : PMMA

  - **Advantages:**
    - Sub-micro resolution (even 20nm resolution can be achieved)
    - Direct patterning without a mask
    - Greater depth of focus
    - Highly automated and precise control

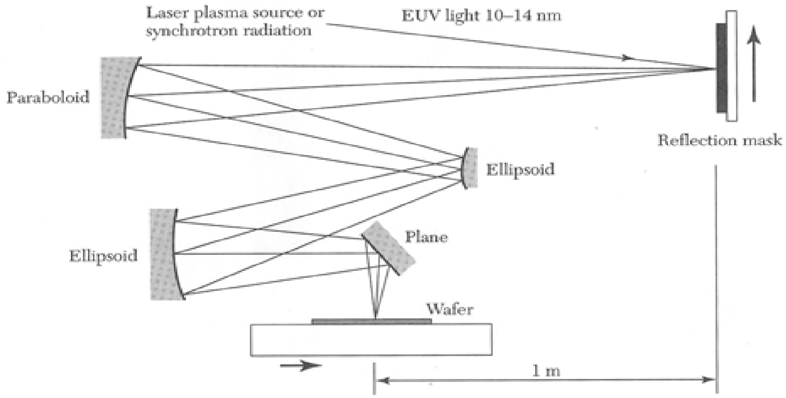
  - **Disadvantages:**
    - Proximity effect due to electron scattering
    - Very low throughput (10 wafers per hour)
    - Very expensive



Next Generation Lithographic Methods (II)

- Extreme Ultraviolet Lithography
  - A laser-produced plasma or synchrotron radiation serves as the source of EVU (10 to 14nm)
  - A mask is produced by patterning an absorber materials deposited on a multilayer coated silicon or glass mask blank.
  - Electron resist : PMMA

  Advantages:
    - Extending minimum linewidth to 30 nm without throughput loss
  - **Disadvantages:**
    - EUV is strongly absorbed in all materials, therefore the lithography process must be performed in vacuum
    - Mask blank fabrication difficulty



Next Generation Lithographic Methods (III)

- X-ray Lithography (XLR)
  - X-ray (1nm) generated by a synchrotron storage ring is used as the energy source
  - As most materials have low transparency at λ ~ 1nm, the mask substrate must be a thin membrane (1-2μm thick). The pattern itself is defined in a thin (~0.5 μm), relative high-atomic-number materials such as tungsen and gold.

Advantages:

- High resolution (100 nm or better) and high depth of focus
- No reflection from the substrate to create standing wave

Disadvantages:

- Complex and expensive XRL system
- Complex mask fabrication

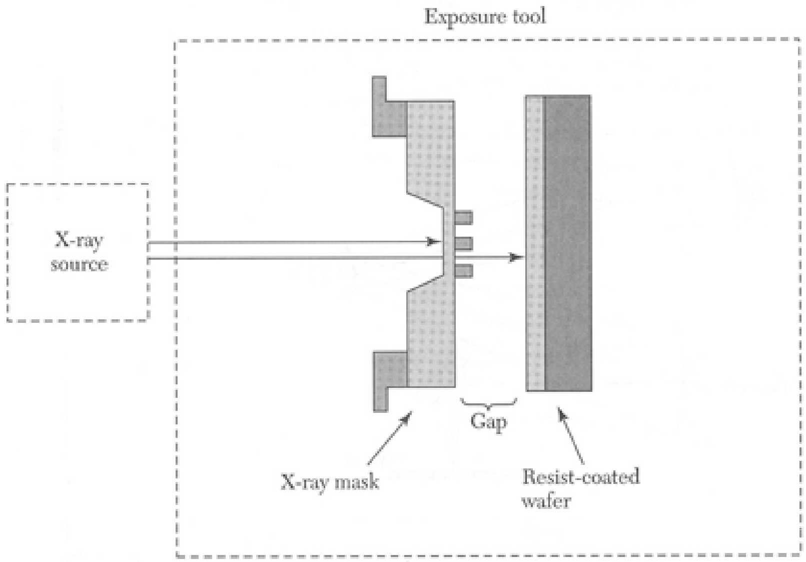


Figure 4.18 Schematic representation of a proximity x-ray lithography system.[17]

Next Generation Lithographic Methods (IV)

- Ion Beam Lithography
  - High energy ion beam is used for writing
  - PR : PMMA

  - **Advantages:**
  - Higher resolution than optical, x-ray or e-beam lithography because Ions have a higher mass and therefore scatter less than electrons
  - **Disadvantages:**

  Ion beam lithography may suffer from random space-charge effects, causing broadening of ion beam

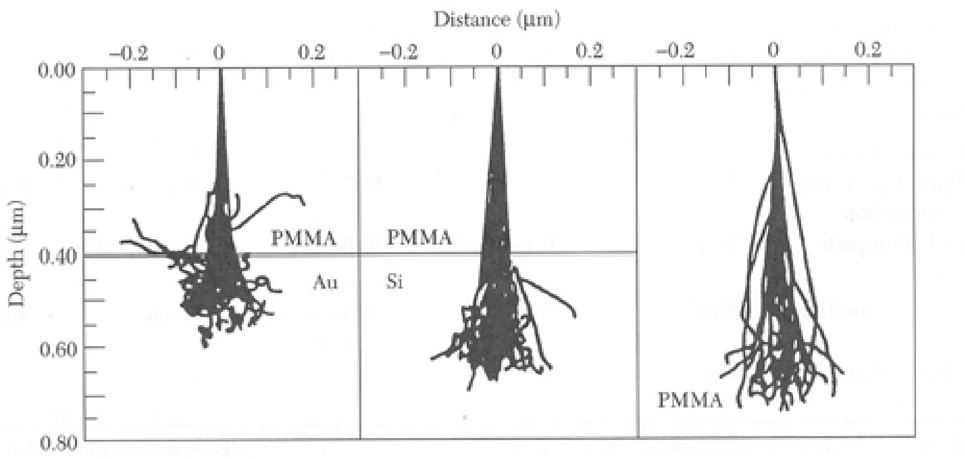


Figure 4.19 Trajectories of 60-keV H^+ ions traveling through PMMA into Au, Si, and PMMA.[17]