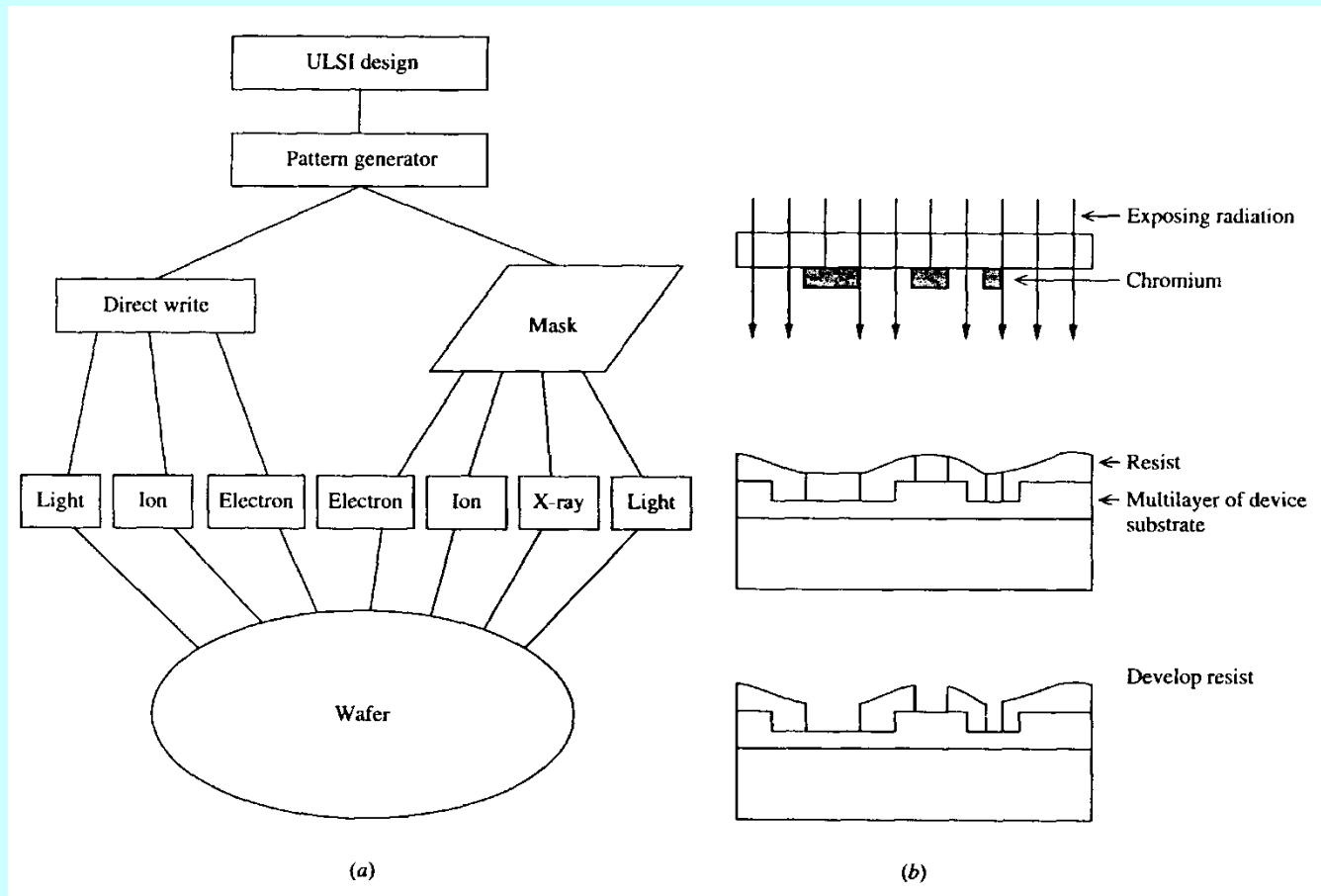# Chapter 5

Lithography

Professor Paul K. Chu

(a) (b)

Lithography is the process of transferring patterns of geometric shapes in a mask to a thin layer of radiation-sensitive materials (called resist) covering the surface of a semiconductor wafer

Resolution is defined to be the minimum feature dimension that can be transferred with high fidelity to a resist film on a semiconductor wafer

Registration is a measure of how accurately patterns on successive masks can be aligned or overlaid with respect to previously defined patterns on the same wafer

Throughput is the number of wafers that can be exposed per hour for a given mask level and is thus a measure of the efficiency of the lithographic process

An IC fabrication facility requires a clean room, particularly in lithography areas. Airborne particles settling on semiconductor wafers and lithographic masks behave as opaque patterns that can be subsequently transferred to the wafers.
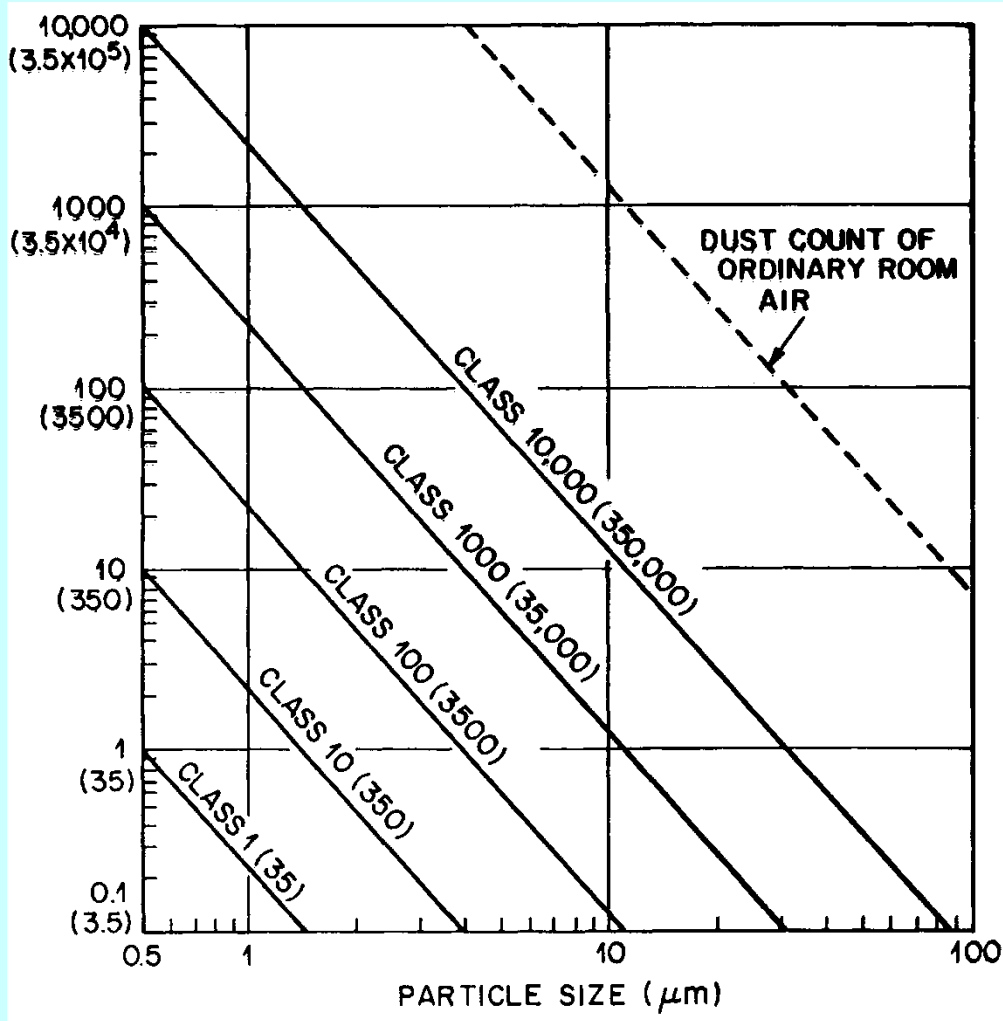
Particle 1 may result in the formation of a pinhole in the underlying layer
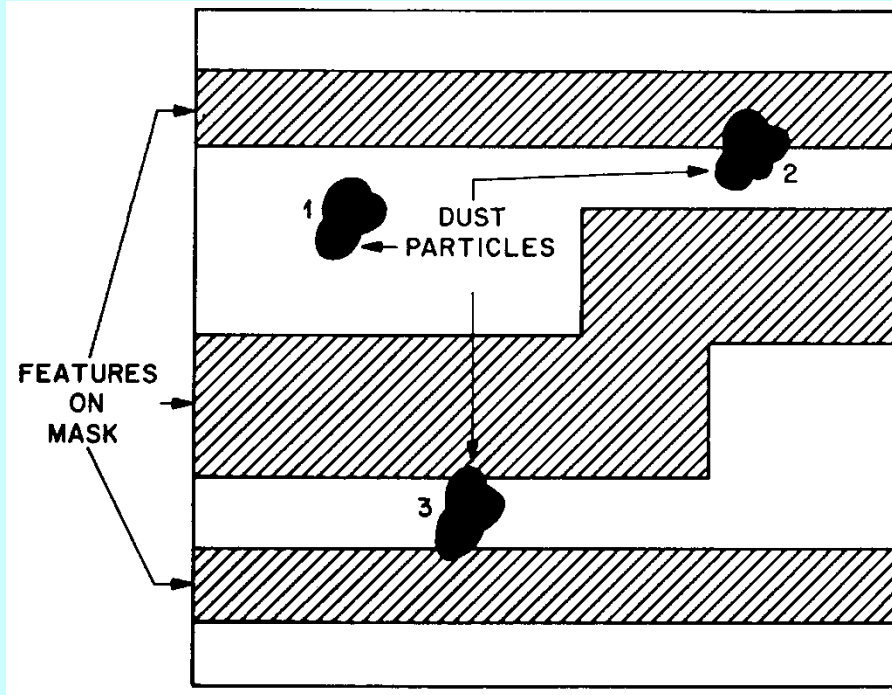
Particle 2 may cause constriction of current flow in the metal runner

DUST PARTICLES

FEATURES ON MASK

1

2

3

Particle 3 may lead to a short circuit between the two conducting regions and render the circuit useless

Clean Room

In a clean room, the total number of dust particles per unit volume must be tightly controlled along with other parameters such as temperature, humidity, pressure, and so on.

A class *X* clean room is usually defined to be one that has a dust count of *X* particles (diameters of 0.5 μm or larger) per cubic foot.

For modern lithographic processes, a class 10 or better clean room is required

Optical Lithography – Shadow Printing
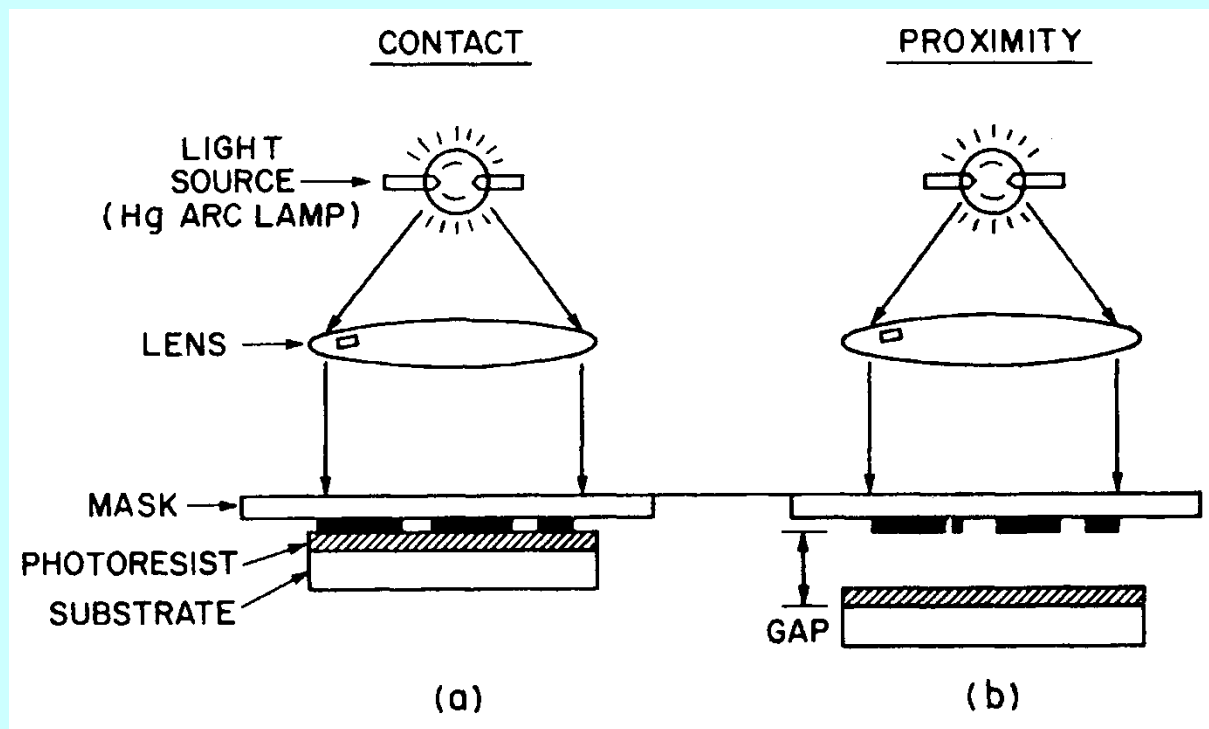
Contact printing yields very high resolution (~ 1 µm), but suffers from major drawback caused by dust particles or silicon specks accidentally embedded into the mask.

Proximity printing is not as prone to particle damage. However, the small gap between the mask and wafer (typically 10 m to 50 µm) introduces optical diffraction at the feature edges on the photomasks and the resolution is degraded.

Shadow Printing

The minimum linewidth that can be printed, l_m, in shadow printing is roughly given by

$$l_m = (\lambda g)^{1/2}$$

where λ is the wavelength of the exposure radiation and g is the gap between the mask and the wafer and includes the thickness of the resist. For typical values of λ (~ 0.4 µm) and g (~ 50 µm), l_m is on the order of 4.5 µm. The above equation imparts that the minimum linewidth can be improved by reducing the wavelength λ (that is, going to deep UV spectral region) or the gap g.

Projection Printing

In order to circumvent problems associated with shadow printing, projection printing exposure tools have been developed to project an image of the mask patterns onto a resist-coated wafer many centimeters away from the mask. The small image area is scanned or stepped over the wafer to cover the entire surface.

1:1 WAFER-SCAN
(a)

1:1 RASTER-SCAN
(b)

M:1 STEP-AND-REPEAT
(c)

1:1 STEP-AND-REPEAT
(d)
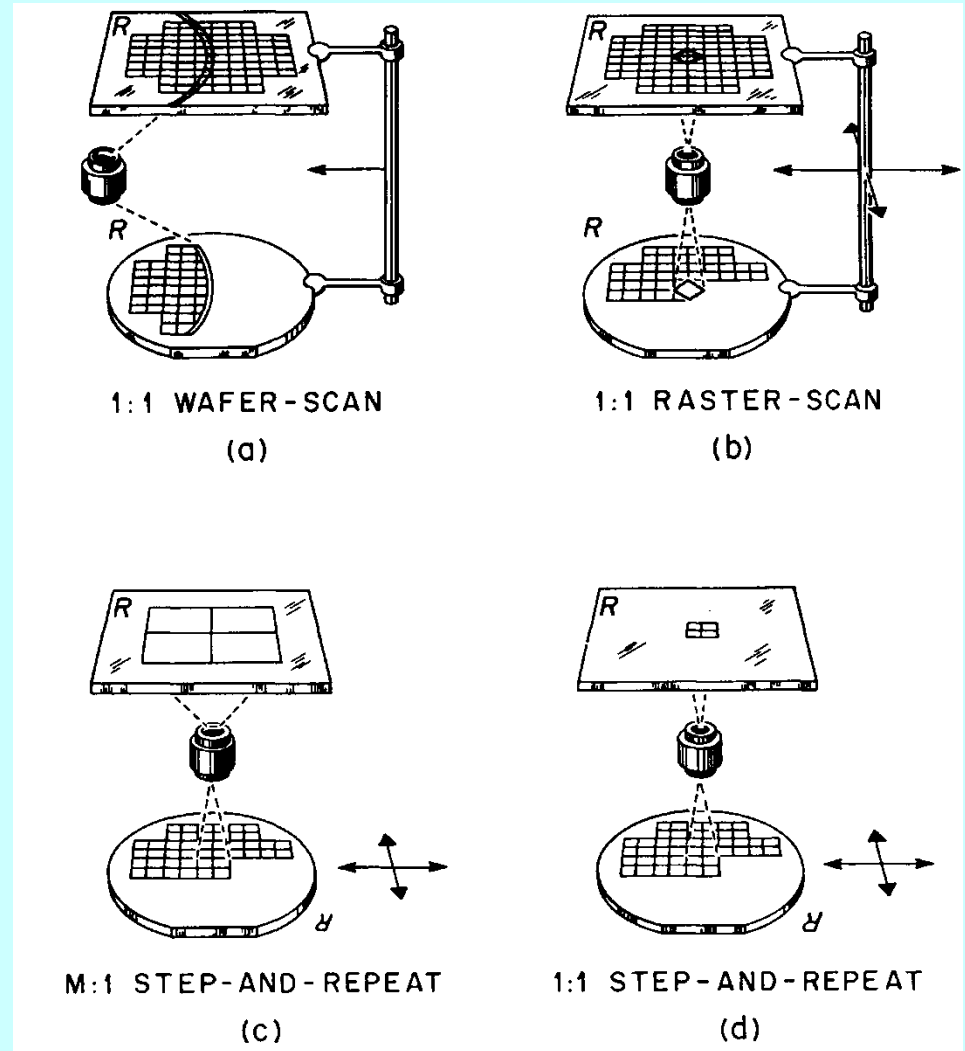
The **resolution** of a projection system is given by

$$l_m = \lambda / NA$$

where λ is the wavelength of the exposure radiation and NA is the numerical aperture given by
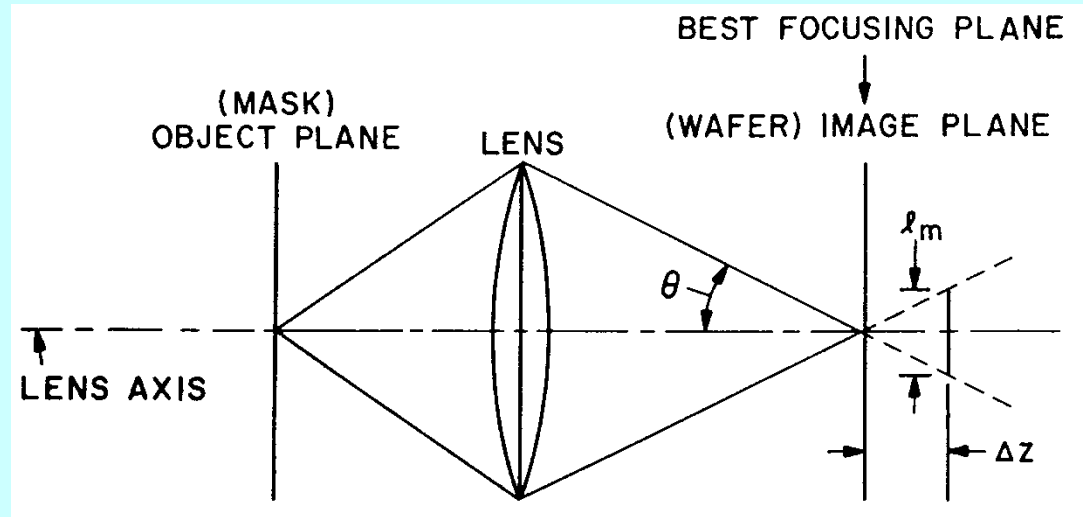
$$NA = \bar{n} \sin \theta$$

where $\bar{n}$ denotes the refraction index of the imaging medium (= 1 in air) and θ is the half angle of the cone of light converging to a point image at the wafer.

The depth of focus, Δz, can be expressed as

$$\Delta_z = \pm l_m / 2 \tan \theta \cong \pm l_m / 2 \sin \theta = \pm \bar{n} \lambda / [2 (NA)^2]$$

Resolution can be enhanced by reducing λ. This explains the trend towards shorter wavelength in optical lithography.
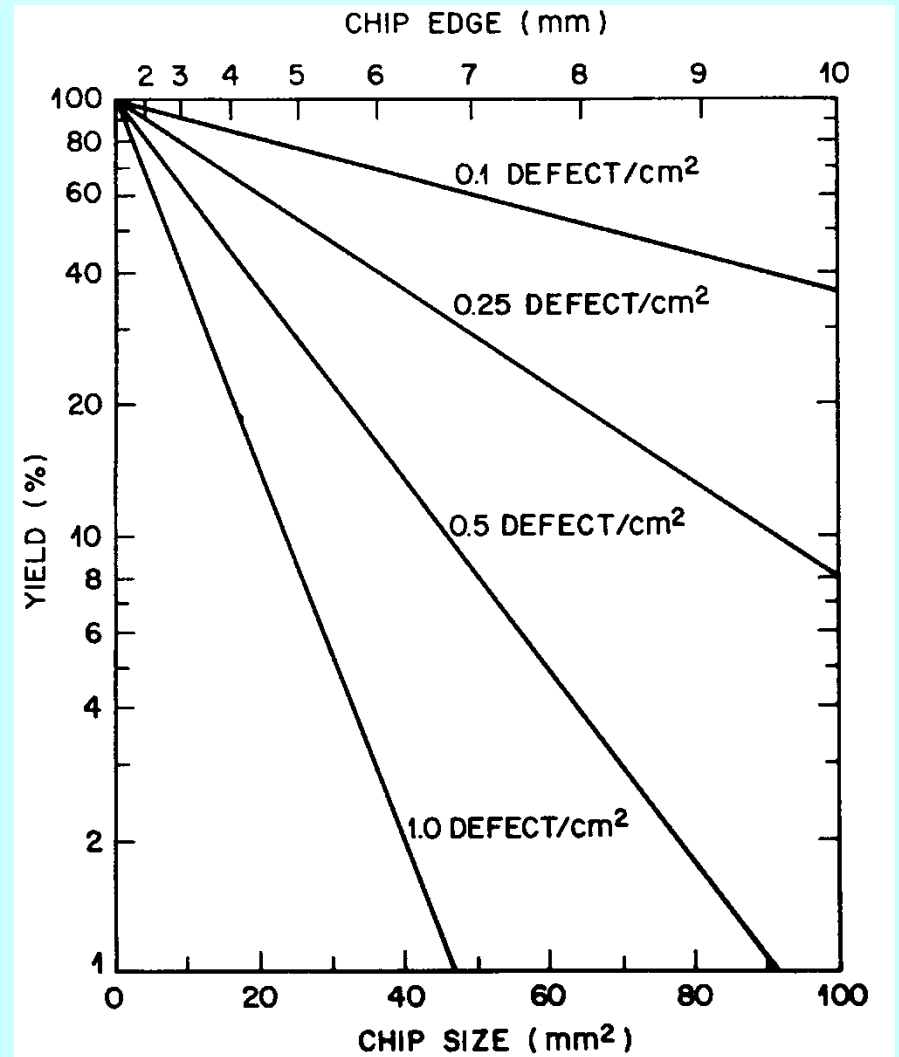
Mask Defects

The number of mask defects has a profound effect on the final IC yield, which is defined as the ratio of good chips per wafer to the total number of chips per wafer. As a first-order approximation,
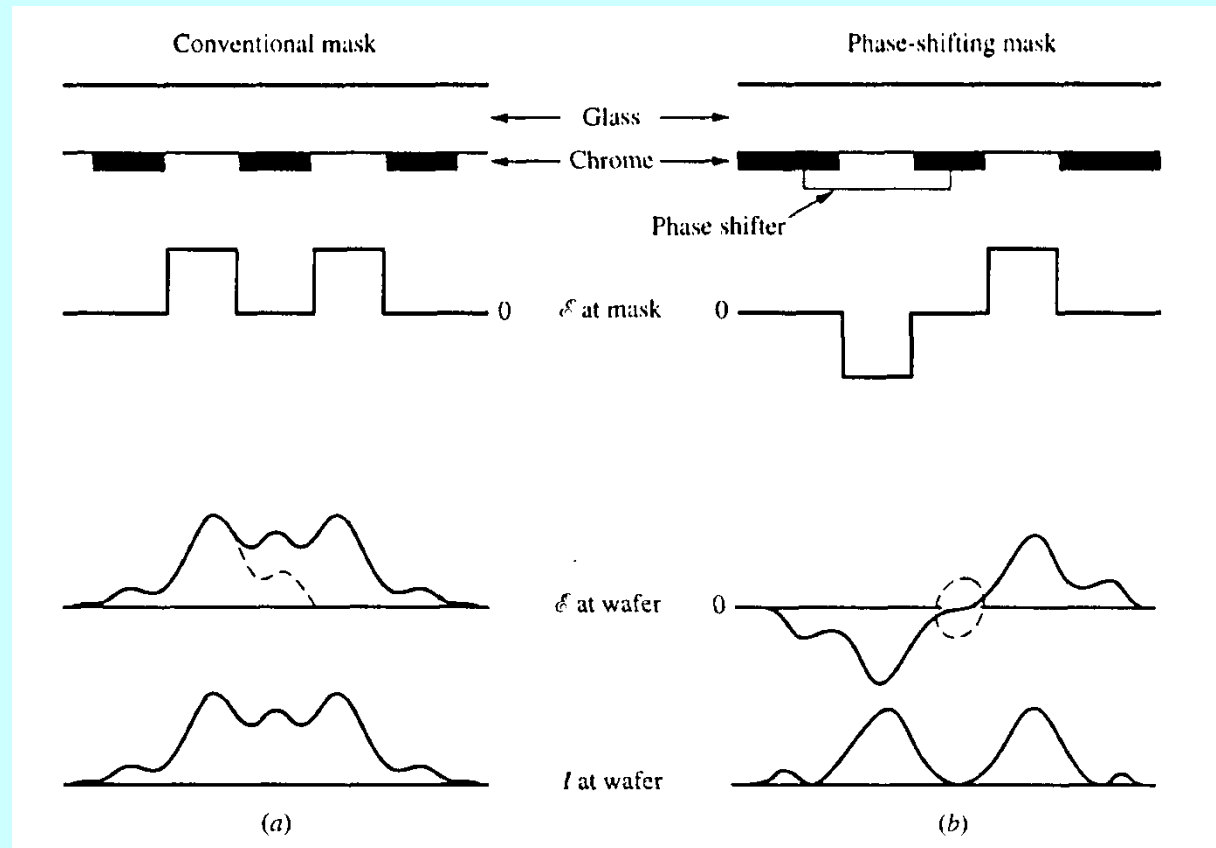
$$Y \cong \exp\{-DA\}$$

where Y is the yield, D is the average number of "fatal" defects per unit area, and A is the area of an IC chip. If D remains the same for all mask levels, N, then

$$Y \cong \exp\{-NDA\}$$

Phase Shift Mask

The phase-shifting layer that covers adjacent apertures reverses the sign of the electric field. Although the absolute intensity at the mask is unchanged, the electric field of these images at the wafer, shown by the dotted line, can be canceled (right figure). Consequently, images that are projected close to one another can be separated completely. A 180° phase change occurs when a transparent layer of thickness $d = \lambda / 2 (n - 1)$, where n is the refraction index and λ is the wavelength, covers one aperture as shown in the figure.
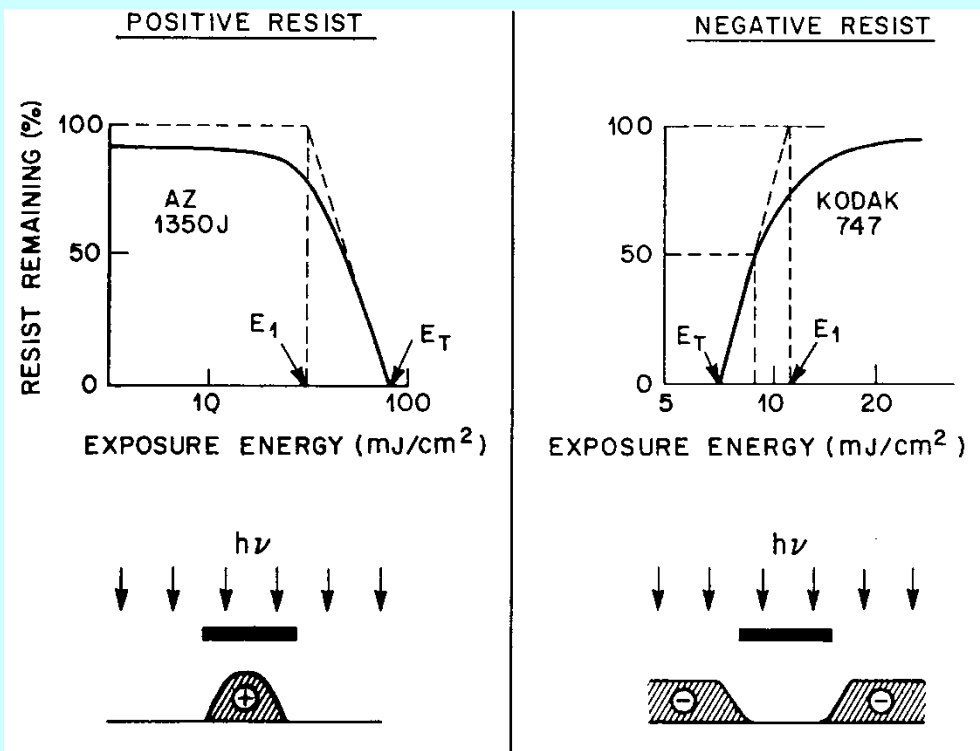
Photoresists

- A photoresist is a radiation-sensitive compound. For positive resists, the exposed region becomes more soluble and thus more readily removed in the developing process. The net result is that the patterns formed in the positive resist are the same as those on the mask. For negative resists, the exposed regions become less soluble, and the patterns engraved are the reverse of the mask patterns

- A positive photoresist consists of three constituents: **photosensitive compound, base resin,** and **organic solvent**. Prior to exposure, the photosensitive compound is insoluble in the developer solution. After irradiation, the photosensitive compound in the exposed pattern areas absorbs energy, changes its chemical structure, and transforms into a more soluble species. Upon developing, the exposed areas are expunged

- Negative photoresists are polymers combined with a photosensitive compound. Following exposure, the photosensitive compound absorbs the radiation energy and converts it into chemical energy to initiate a chain reaction, thereby causing cross-linking of the polymer molecules. The cross-linked polymer has a higher molecular weight and becomes insoluble in the developer solution. After development, the unexposed portions are removed

- One major drawback of a negative photoresist is that the resist absorbs developer solvent and swells, thus limiting the resolution of a negative photoresist

The left figure depicts a typical exposure response curve for a positive resist. The resist has a finite solubility in the developer solution even prior to exposure. At a threshold energy, E_T, the resist becomes completely soluble. E_T therefore corresponds to the sensitivity of the photoresist. Another parameter, γ, is the contrast ratio and is given by:

$$\gamma = \left[\ln \frac{E_T}{E_1} \right]^{-1}$$

A larger γ implies a more rapid dissolution of the resist with an incremental increase of exposure energy and results in a sharper image. The edges of the resist image are generally blurred due to diffraction.

The right figure shows the response curve for a negative photoresist. The sensitivity of a negative photoresist is defined as the energy required to retain 50% of the original resist film thickness in the exposed region.

Pattern Transfer

The wafer is placed in a clean room that typically is illuminated with yellow light as photoresists are not sensitive to wavelengths greater than 0.5 µm. The wafer is held on a vacuum spindle, and approximately 1 cm^3 of liquid resist is applied to the center of the wafer. The wafer is than spun for about 30 seconds. The thickness of the resulting resist film, l_R, is directly proportional to its viscosity as well as the percent solid content indigenous to the resist, and varies inversely with the spin speed. For spin speeds in the range of 1000 to 10000 rpm, film thicknesses on the order of 0.5 to 1 µm can be obtained.
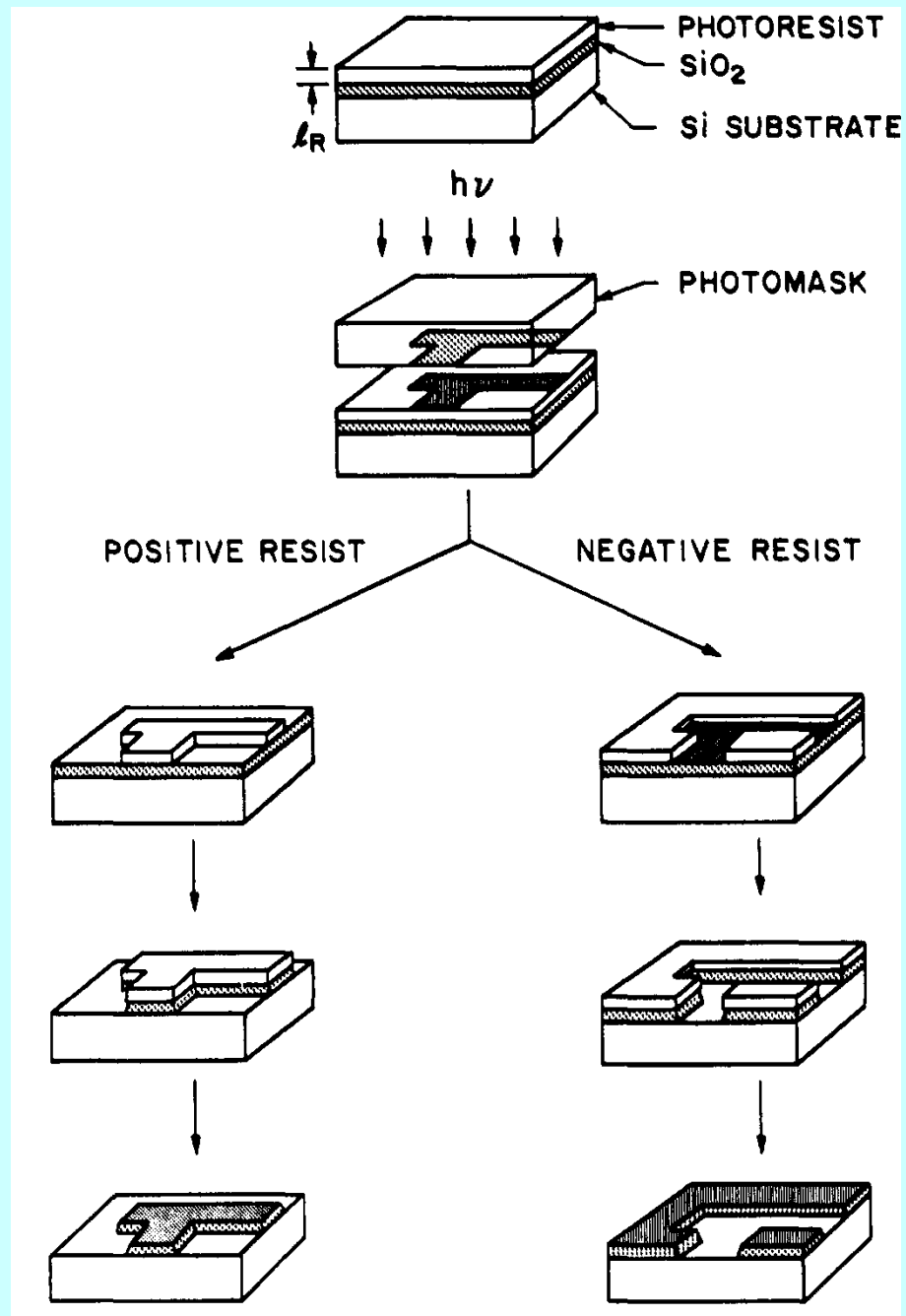
The wafer is then given a pre-exposure bake (80^oC to 100^oC) to remove solvent and improve adhesion. The wafer is aligned with respect to the mask in an optical lithographic system prior to exposure to UV or deep UV light. For a positive photoresist, the exposed portions are dissolved in the developer solution. The wafer is then rinsed, dried, and then put in an ambient that etches the exposed insulating layer but does not attack the resist. Finally, the resist is stripped, leaving behind an insulator image (or pattern) that is the same as the opaque image on the mask. For a negative photoresist, the exposed area becomes insoluble, and the final insulator pattern is the reverse of the opaque image on the mask.
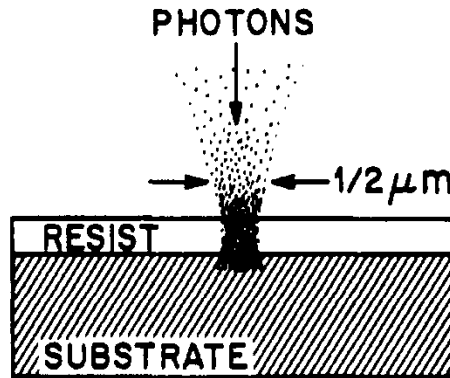
The insulator image can be employed as a mask for subsequent processing. For instance, ion implantation can be performed to dope the exposed regions selectively.
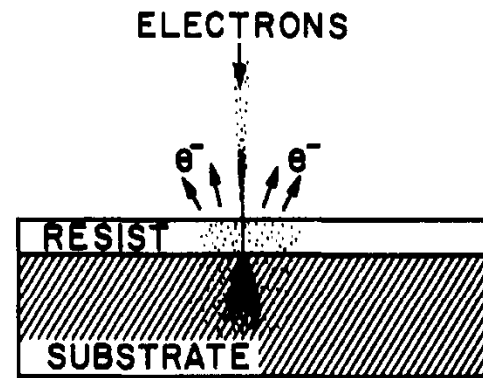
Lift-Off Technique
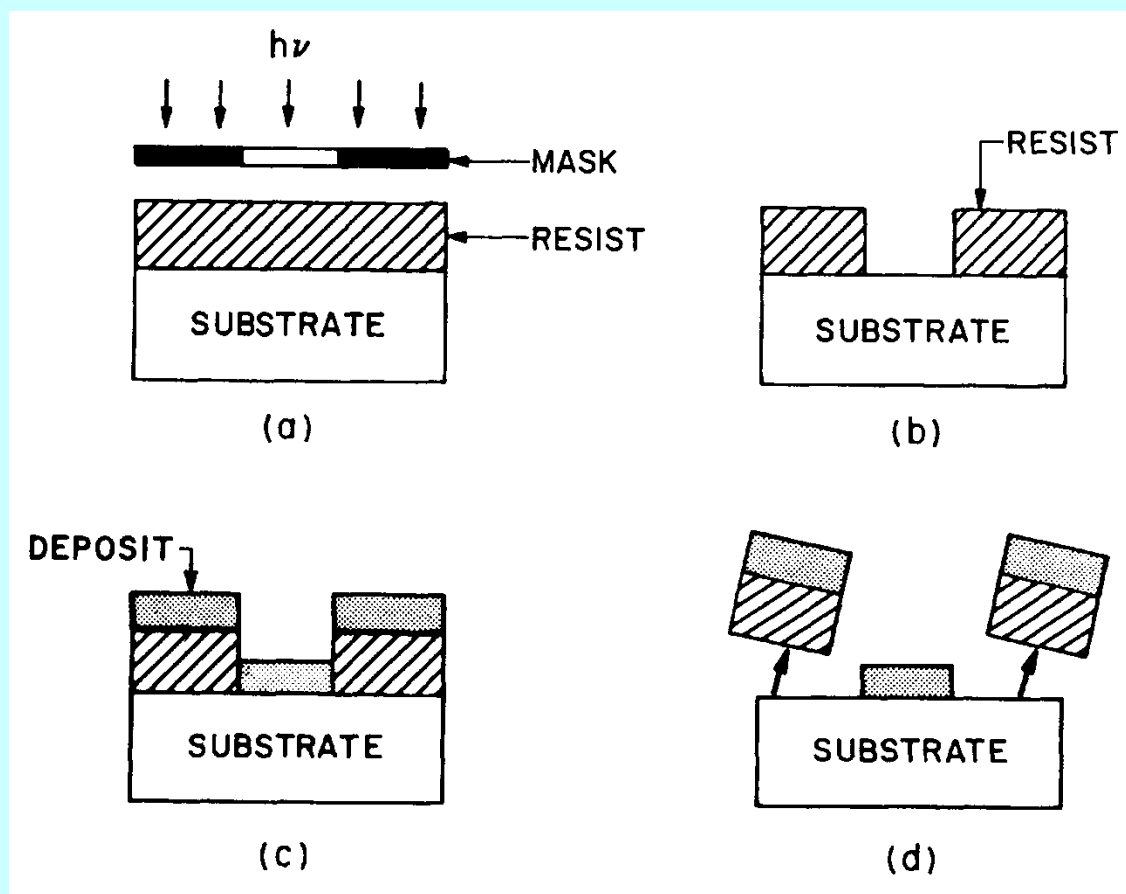
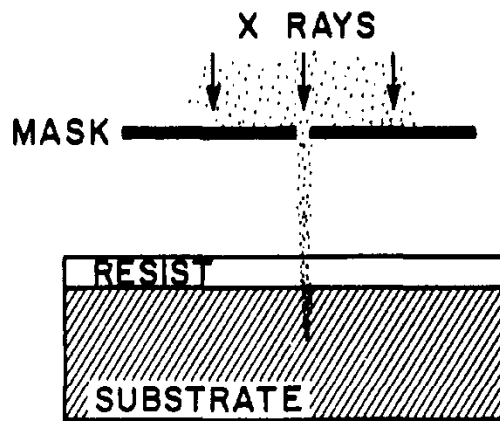This method works if the film thickness is smaller than that of the photoresist
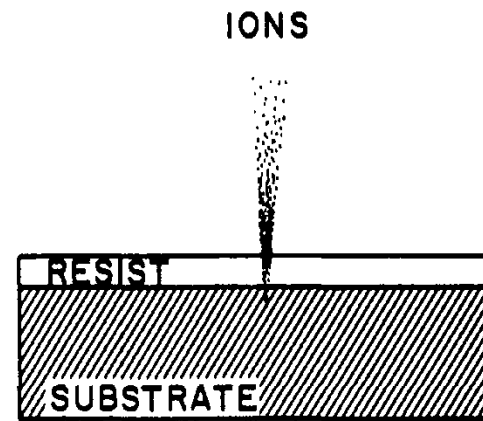
Lithographic Techniques

Electron lithography offers high resolution because of the small wavelength of electrons ($\leq$ 0.1 nm for 10-50 keV electrons). The resolution is not limited by diffraction, but by electron scattering in the resist and the various aberrations of the electron optics. Electron lithography has the following advantages:

- **Generation of micron and submicron resist geometries**
- **Highly automated and precisely controlled operation**
- **Greater depth of focus**
- **Direct patterning without a mask**

The biggest disadvantage of electron lithography is its low throughput (approximately 5 wafers / hour at less than 0.1 μm resolution). Therefore, electron lithography is primarily used in the production of photomasks and in situations that require small number of custom circuits.

Electron Resists

POSITIVE RESIST

CHAIN SCISSION

NEGATIVE RESIST

CROSS-LINK
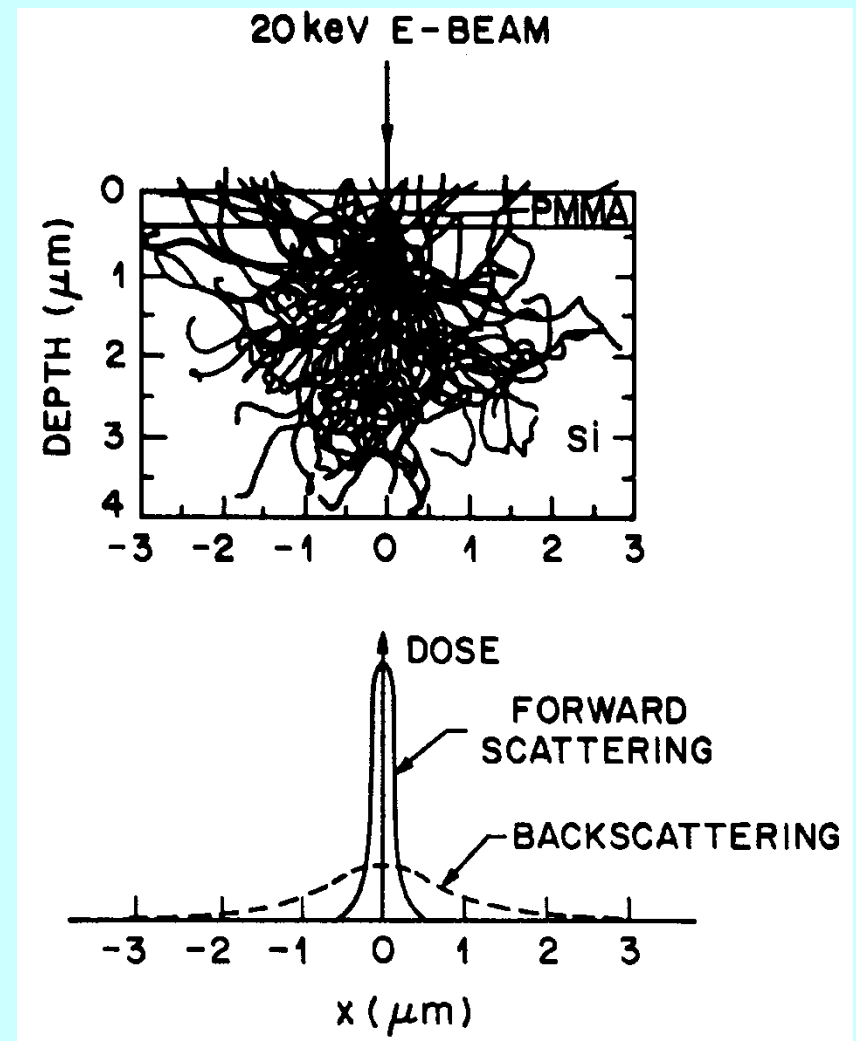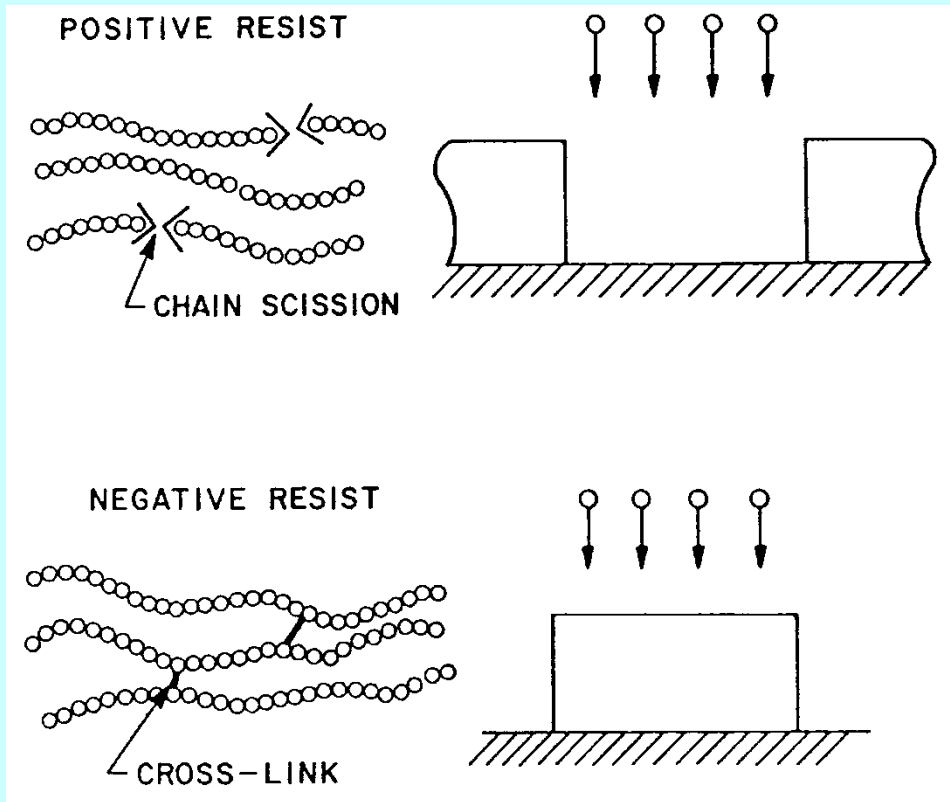
For a positive electron resist, the polymer - electron interaction causes chain scission, that is, broken chemical bonds. The irradiated areas can be dissolved in a developer solution that attacks low – molecular - weight material. Common positive electron resists are poly (methyl methacrylate), abbreviated PMMA, and poly (butene-1 sulfone), abbreviated PBS. Positive electron resists typically have resolution of $0.1\mu m$ or better.

When electrons impact a negative electron resist, polymer linking is induced. Poly (glycidyl methacrylate-co-ethyl-acrylate), abbreviated COP, is a common negative electron resist. Like a negative photoresist, COP swells during developing, and resolution is limited to about $1\mu m$.

X-Ray Lithography
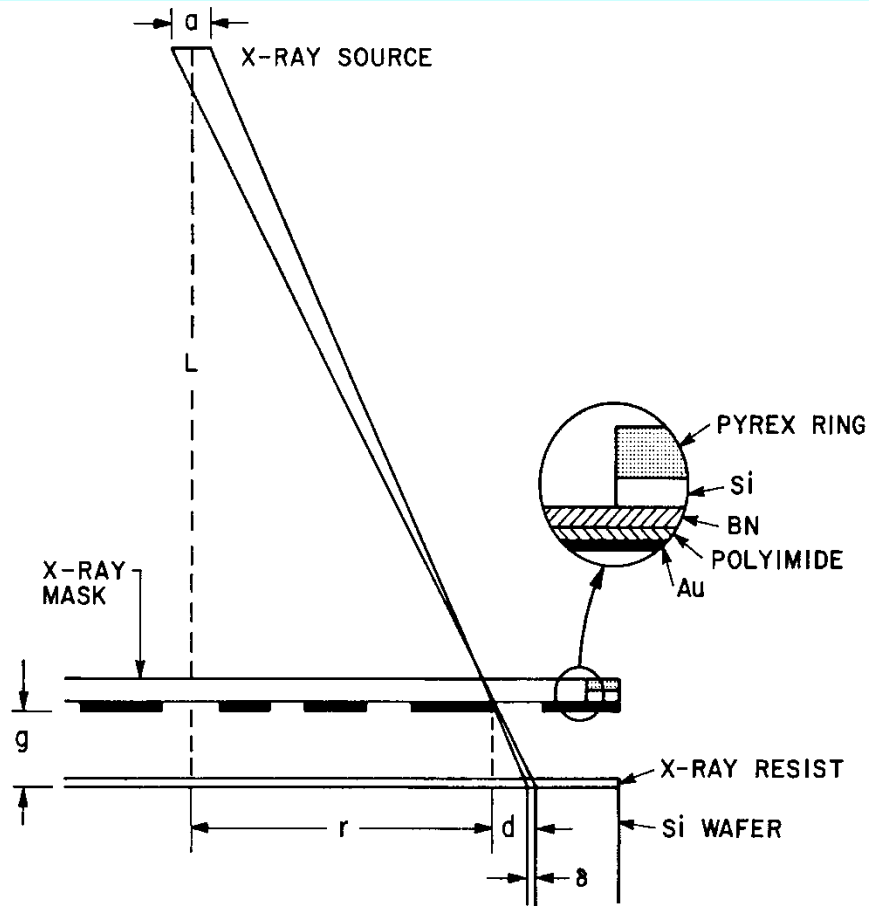
X-ray lithography employs a shadow printing method similar to optical proximity printing. The x-ray wavelength (0.4 to 5 nm) is much shorter than that of UV light (200 to 400 nm). Hence, diffraction effects are reduced and higher resolution can be attained. For instance, for an x-ray wavelength of 0.5 nm and a gap of 40 µm, l_m is equal to 0.2 µm. X-ray lithography has a higher throughput when compared to e-beam lithography because parallel exposure can be adopted. However, on account of the finite size of the x-ray source and the finite mask-to-wafer gap, a penumbral effect results which degrades the resolution at the edge of a feature.

The penumbral blur, δ, on the edge of the resist image is given by

$$\delta = ag / L$$

where a is the diameter of the x-ray source, g is the gap spacing, and L is the distance from the source to the x-ray mask. If a = 3 mm, g = 40 µm, and L = 50 cm, δ is on the order of 0.2 µm.

An additional geometric effect is the lateral magnification error due to the finite mask-to-wafer gap and the non-vertical incidence of the x-ray beam. The projected images of the mask are shifted laterally by an amount d, called runout given by

$$d = rg / L$$

where r denotes the radial distance from the center of the wafer. For a 125-mm wafer, the runout error can be as large as 5 µm for g = 40 µm and L = 50 cm. It is compensated for during the mask making process.
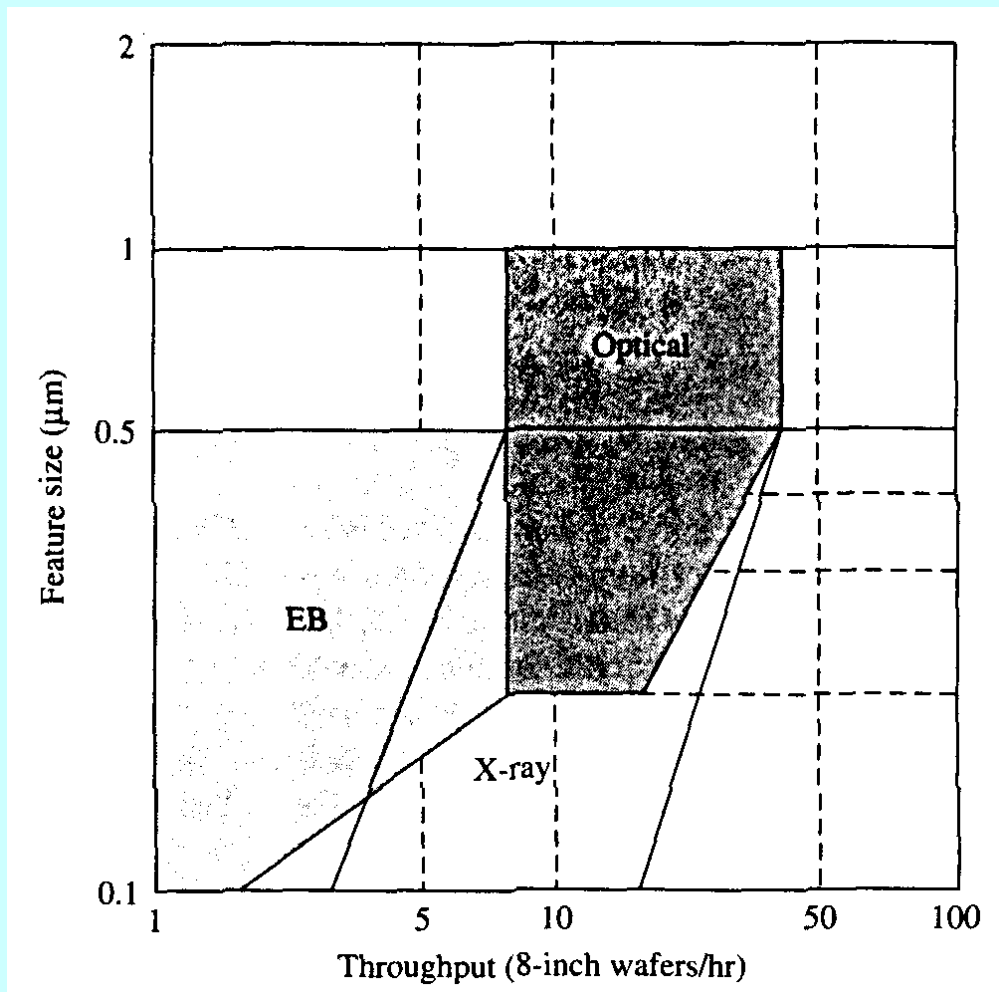
Ion Lithography
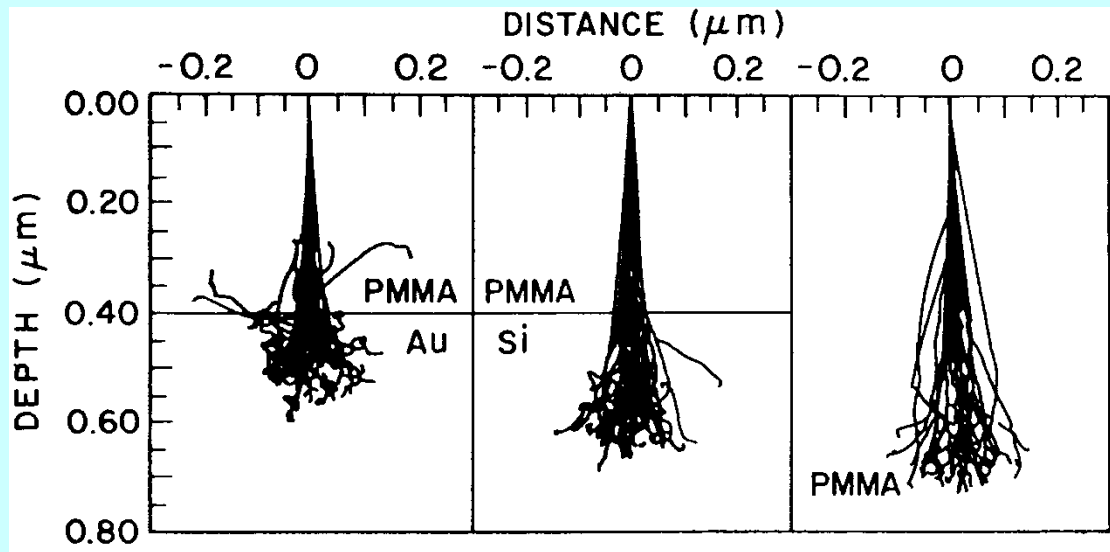
The figure depicts the computer trajectory of 50 H^+ ions implanted at 60 keV. The spread of the ion beam at a depth of 0.4 µm is only 0.1 µm.

Ion lithography may achieve higher resolution than optical, x-ray, or electron lithographic techniques because ions undergo no diffraction and scatter much less than electrons. In addition, resists are more sensitive to ions than to electrons and there is the possibility of a resistless wafer process. However, ion beams are larger than electron beams. Due to the slow throughput, the most important application of ion lithography is the repair of masks for optical or x-ray lithography.

Optical lithography is the main stream technology and some commercial resists can resolve down to 0.1 μm or lower

Conventional optical lithography is considered difficult for a design rule of much less than 0.1 μm due to its resolution limit. For deep sub-micrometer structures, the two remaining options are electron beam direct writing or x-ray lithography. Perfect x-ray masks are difficult to make and the throughput of electron lithography is slow (the throughput varies as the reciprocal of the square of the minimum feature length). For mass production, the cost and footprint (required floor area) of the machine must also be minimized.