# EE 212 FALL 1999-00

## LITHOGRAPHY- Chapter 5 in the Text

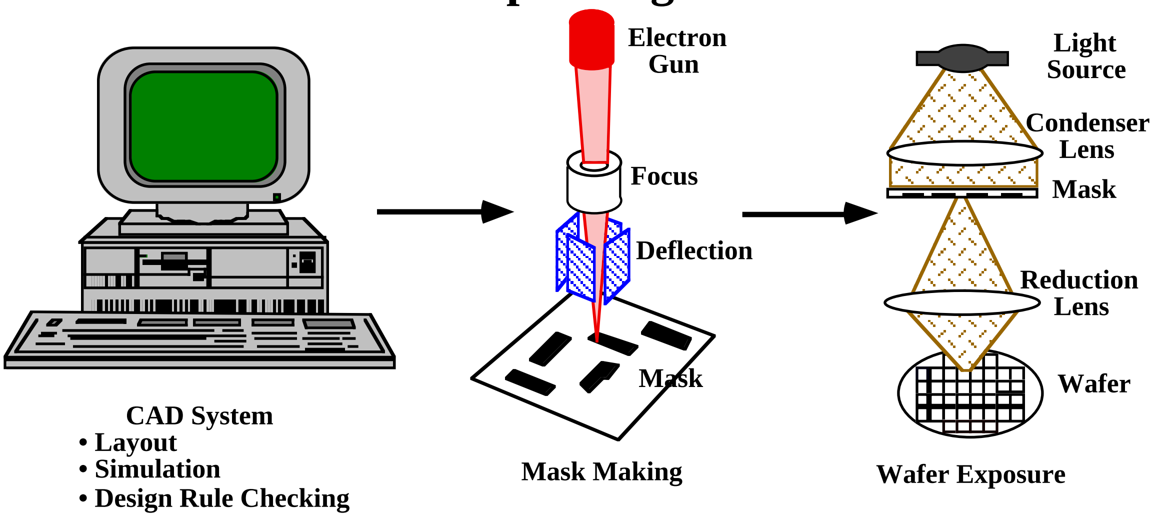
- Lithography is arguably the single most important technology in IC manufacturing.
- The SIA NTRS is driven by the desire to continue scaling device feature sizes.

| Year of 1st DRAM Shipment | 1997 | 1999 | 2003 | 2006 | 2009 | 2012 |
|---|---|---|---|---|---|---|
| DRAM Bits/Chip | 256M | 1G | 4G | 16G | 64G | 256G |
| Minimum Feature Size nm<br>Isolated Lines (MPU)<br>Dense Lines (DRAM)<br>Contacts | <br>200<br>250<br>280 | <br>140<br>180<br>200 | <br>100<br>130<br>140 | <br>70<br>100<br>110 | <br>50<br>70<br>80 | <br>35<br>50<br>60 |
| Gate CD Control 3σ (nm) | 20 | 14 | 10 | 7 | 5 | 4 |
| Alignment (mean + 3σ) (nm) | 85 | 65 | 45 | 35 | 25 | 20 |
| Depth of Focus (μm) | 0.8 | 0.7 | 0.6 | 0.5 | 0.5 | 0.5 |
| Defect Density (per layer/$m^2$)<br>@ Defect Size (nm) | 100<br>@ 80 | 80<br>@ 60 | 60<br>@ 40 | 50<br>@ 30 | 40<br>@ 20 | 30<br>@ 15 |
| DRAM Chip Size ($mm^2$) | 280 | 400 | 560 | 790 | 1120 | 1580 |
| MPU Chip Size ($mm^2$) | 300 | 360 | 430 | 520 | 620 | 750 |
| Field Size (mm) | 22x22 | 25x32 | 25x36 | 25x40 | 25x44 | 25x52 |
| Exposure Technology | 248nm DUV | 248nm DUV | 248nm or 193nm DUV | 193nm DUV or ??? | 193nm DUV or ??? | ??? |
| Minimum Mask Count | 22 | 22/24 | 24 | 24/26 | 26/28 | 28 |

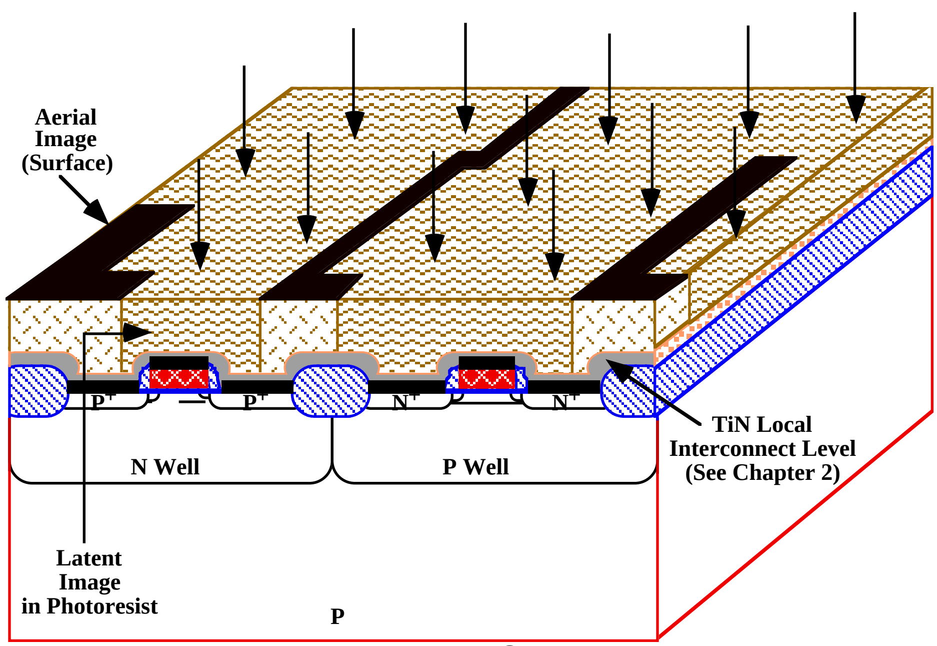
- 0.7X in linear dimension every 3 years.
- Placement accuracy ≈ 1/3 of feature size.
- ≈ 35% of total wafer manufacturing costs for lithography.
- Note the ???. This represents the single biggest uncertainty about the future of the roadmap.

# Historical Development and Basic Concepts

- **Patterning process consists of mask design, mask fabrication and wafer printing.**




- **It is convenient to divide the wafer printing process into three parts A. Light source.**
  **B. Wafer exposure system.**
  **C. Resist.**




- **Aerial image is the pattern of optical radiation striking the top of the resist.**
- **Latent image is the 3D replica produced by chemical processes in the resist.**

## A. Light Sources

- Decreasing feature sizes require the use of shorter $\lambda$.
- Traditionally Hg vapor lamps have been used which generate many spectral lines from a high intensity plasma inside a glass lamp.
- (Electrons are excited to higher energy levels by collisions in the plasma. Photons are emitted when the energy is released.)
    - g line - $\lambda = 436$ nm
    - i line - $\lambda = 365$ nm (used for 0.5 $\mu$m, 0.35 $\mu$m)
- Brightest sources in deep UV are excimer lasers

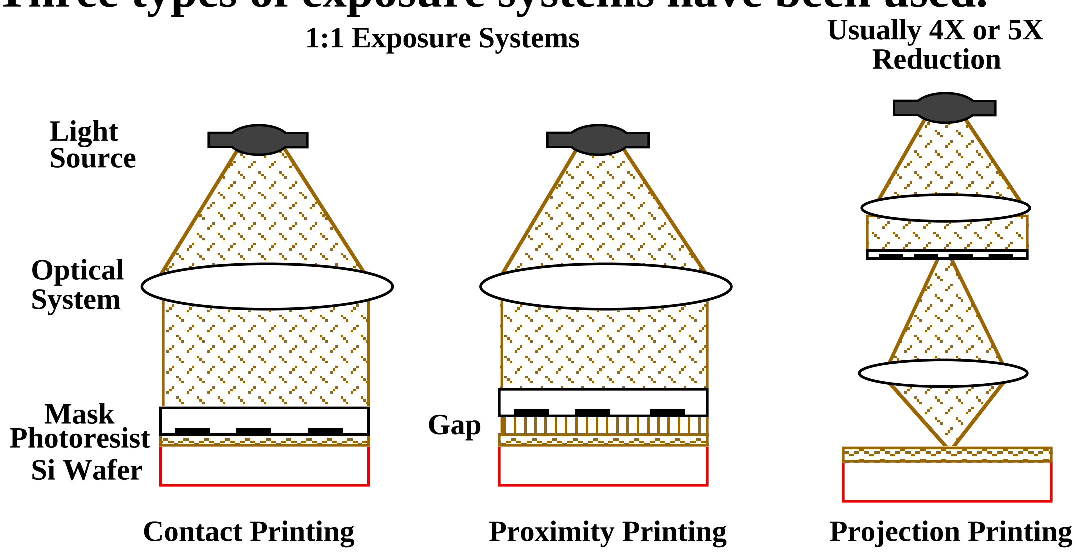
$$Kr + NF_3 \xrightarrow[\text{energy}]{} KrF \rightarrow \text{photon emission} \quad (1)$$

- KrF - $\lambda = 248$ nm (used for 0.25 $\mu$m)
- ArF - $\lambda = 193$ nm

- Issues include finding suitable resists and transparent optical components at these wavelengths.

## B. Wafer Exposure Systems

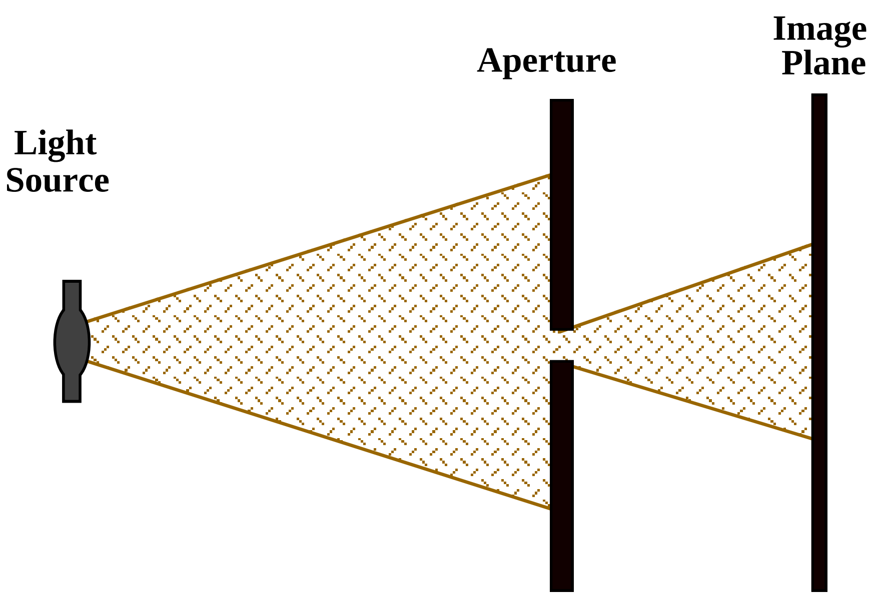
- Three types of exposure systems have been used.



- **Contact printing is capable of high resolution but has unacceptable defect densities.**
- **Proximity printing cannot easily print features below a few µm (except for x-ray systems).**
- **Projection printing provides high resolution and low defect densities and ∴ dominates today.**
- **Typical projection systems use reduction optics (2X - 5X), step and repeat or step and scan mechanical systems, print ≈ 50 wafers/hour and cost $5 - 10M.**

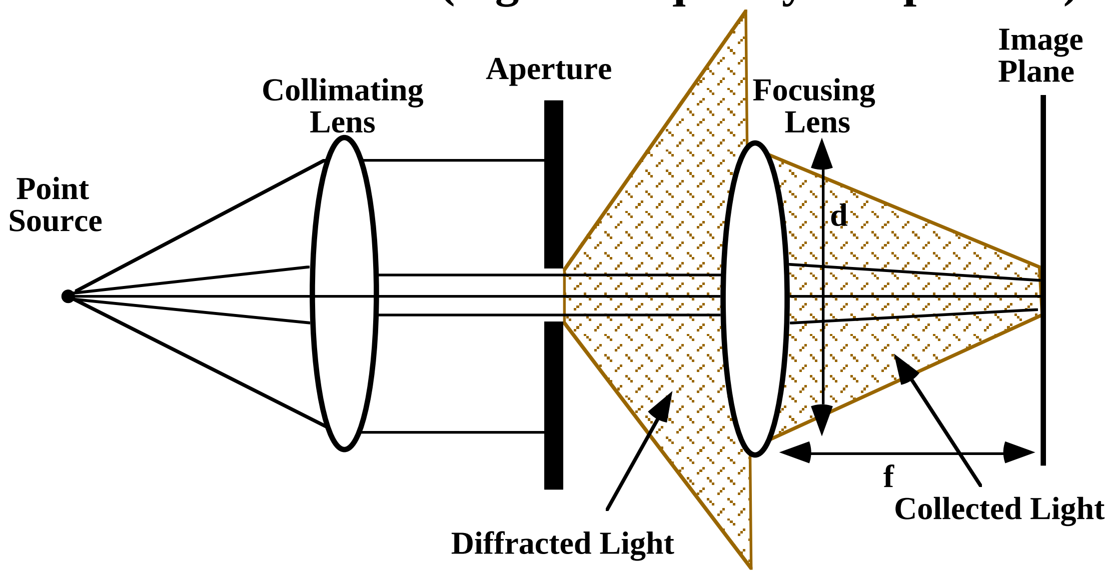
## B1. Optics - Basics and Diffraction

- **Ray tracing (assuming light travels in straight lines) works well as long as the dimensions are large compared to λ.**
- **At smaller dimensions, diffraction effects dominate.**

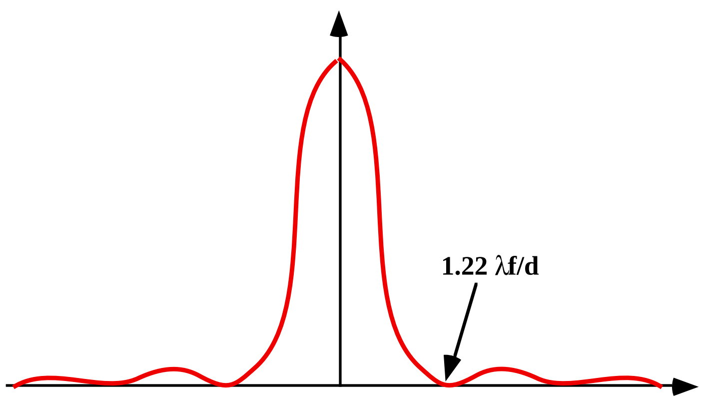


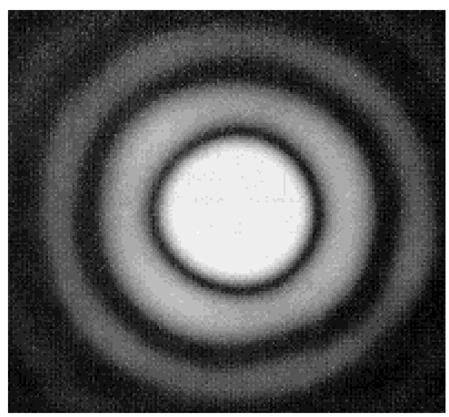

- **If the aperture is on the order of λ, the light spreads out after passing through the aperture. (The smaller the aperture, the more it spreads out.)**

- If we want to image the aperture on an image plane (resist), we can collect the light using a lens and focus it on the image plane.
- But the finite diameter of the lens means some information is lost (higher frequency components).




- A simple example is the image formed by a small circular aperture (Airy disk).



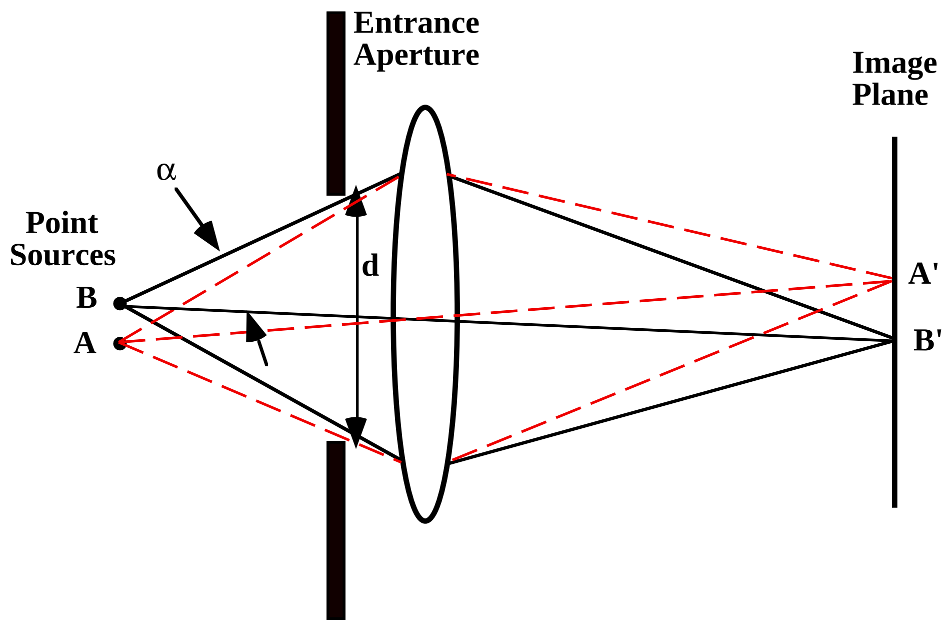



- Note that a point image is formed only if $\lambda \rightarrow 0$, $f \rightarrow 0$ or $d \rightarrow \infty$.
- Diffraction is usually described in terms of two limiting cases
  - Fresnel diffraction - near field.
  - Fraunhofer diffraction - far field.

## B2. Projection Systems (Fraunhofer Diffraction)

- **These are the dominant systems in use today.**
- **Performance is usually described in terms of**
  - **resolution**
  - **depth of focus**
  - **field of view**
  - **modulation transfer function**
  - **alignment accuracy**
  - **throughput**

- **Consider the basic optical projection system below.**




- **Rayleigh suggested that a reasonable criterion for resolution was that the central maximum of each point source lie at the first minimum of the Airy pattern.**
- **With this definition,**

$$R = \frac{0.61\,\lambda}{n\ \sin\alpha} \qquad (2)$$

**• The numerical aperture of the lens is by definition,**

$$\mathbf{NA \equiv n\ \sin\alpha} \qquad \mathbf{(3)}$$

**• NA represents the ability of the lens to collect diffracted light.**

$$\therefore \mathbf{R = \frac{0.61\ \lambda}{NA} = k_1 \frac{\lambda}{NA}} \qquad \mathbf{(4)}$$

**• $k_1$ is an experimental parameter which depends on the lithography system and resist properties and is ≈ 0.6 - 0.8.**

**• Obviously resolution can be increased by**
   - **decreasing λ**
   - **increasing NA (bigger lenses)**

**• However, higher NA lenses also decrease the depth of focus. (See text for derivation.)**

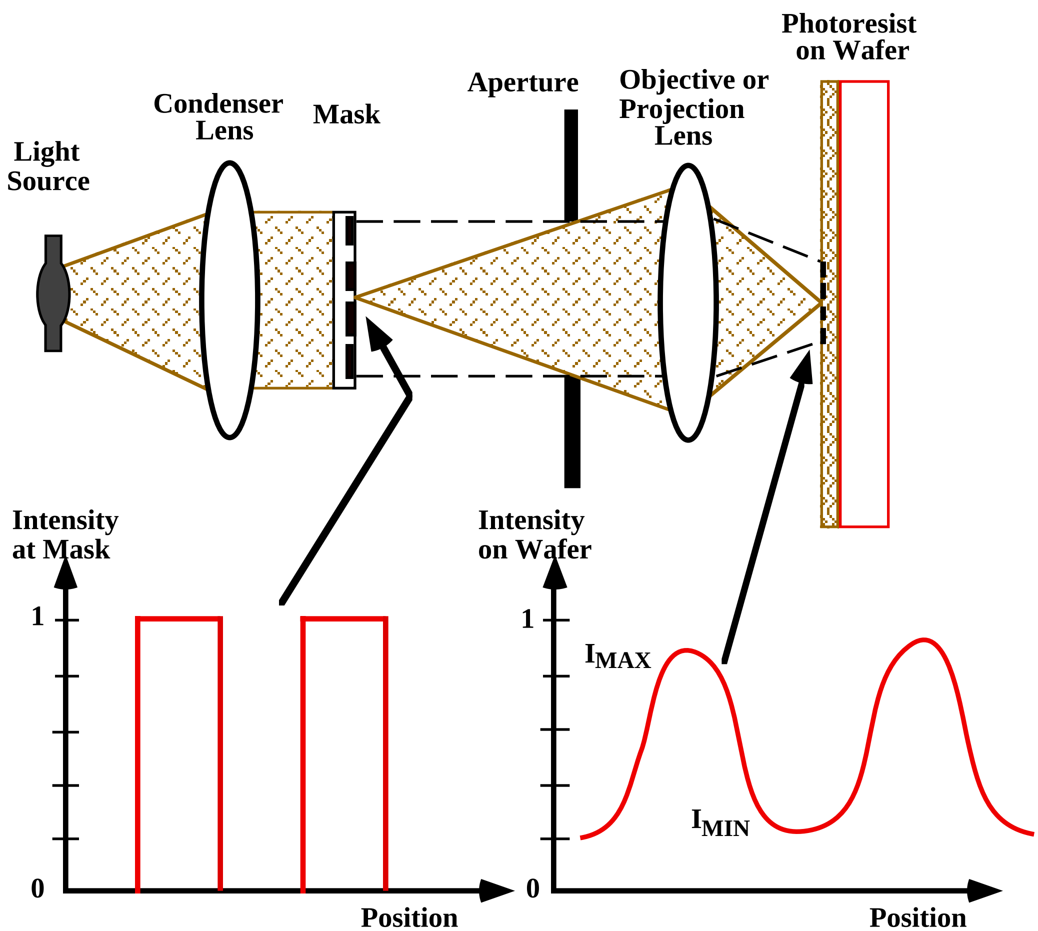
$$\mathbf{DOF = \pm \frac{\lambda}{2(NA)^2} = \pm\ k_2 \frac{\lambda}{(NA)^2}} \qquad \mathbf{(5)}$$

**• $k_2$ is usually experimentally determined.**

**• Thus a 248nm (KrF) exposure system with a NA = 0.6 would have a resolution of ≈ 0.3 µm ($k_1$ = 0.75) and a DOF of ≈ ± 0.35 µm ($k_2$ = 0.5).**

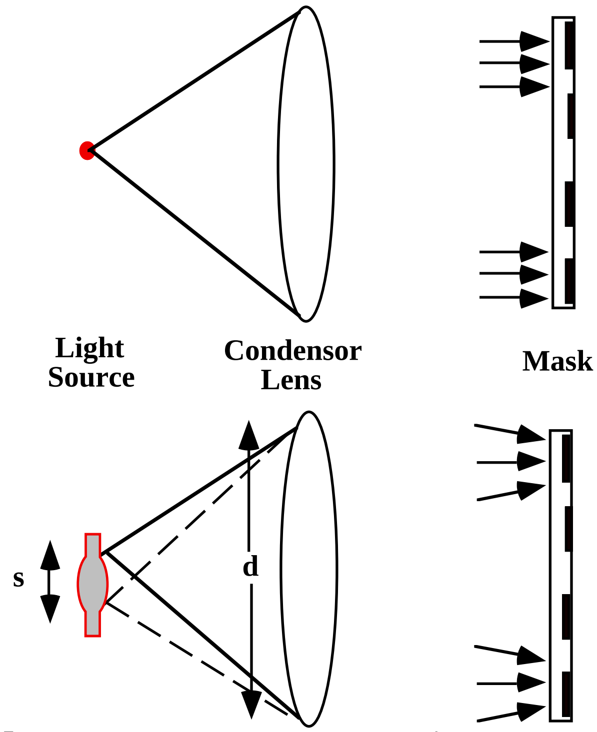
**• Another useful concept is the modulation transfer function or MTF, defined as shown below.**

$$\text{MTF} = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}} \qquad (6)$$




- **Note that MTF will be a function of feature size (see text).**

- **Finally, another basic concept is the spatial coherence of the light source.**




• Practical light sources are not point sources.
• ∴ the light striking the mask will not be plane waves.
• The spatial coherence of the system is defined as

$$S = \frac{\text{light source diameter}}{\text{condenser lens diameter}} = \frac{s}{d} \qquad (7)$$

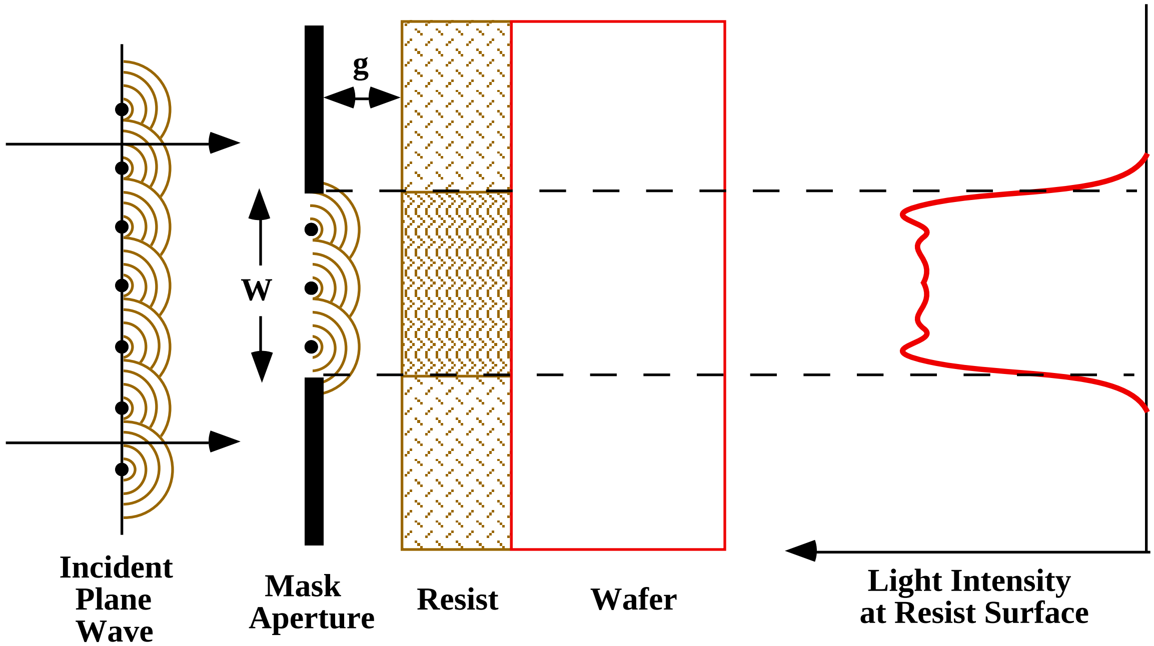
or often as

$$S = \frac{NA_{\text{condenser}}}{NA_{\text{projection optics}}} \qquad (8)$$

• Typically, S ≈ 0.5 to 0.7 in modern systems.

## B3. Contact and Proximity Systems (Fresnel Diffraction)

• Contact printing systems operate in the near field or Fresnel diffraction regime.
• There is always some gap g between the mask and resist.




- The aerial image can be constructed by imagining point sources within the aperture, each radiating spherical waves (Huygens wavelets).
- Interference effects and diffraction result in "ringing" and spreading outside the aperture.
- Fresnel diffraction applies when

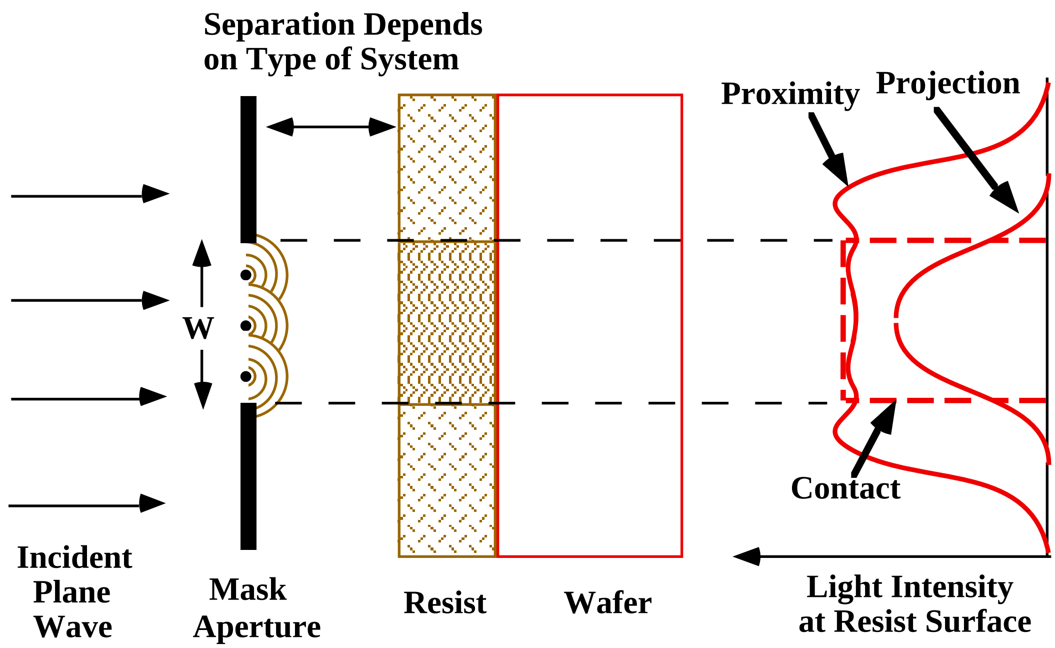
$$\lambda < g < \frac{W^2}{\lambda} \tag{9}$$

- Within this range, the minimum resolvable feature size is

$$W_{min} \approx \sqrt{\lambda g} \tag{10}$$

- Thus if g = 10 μm and an i-line light source is used, $W_{min} \approx 2$ μm.

- Summary of wafer printing systems:




## C. Photoresists

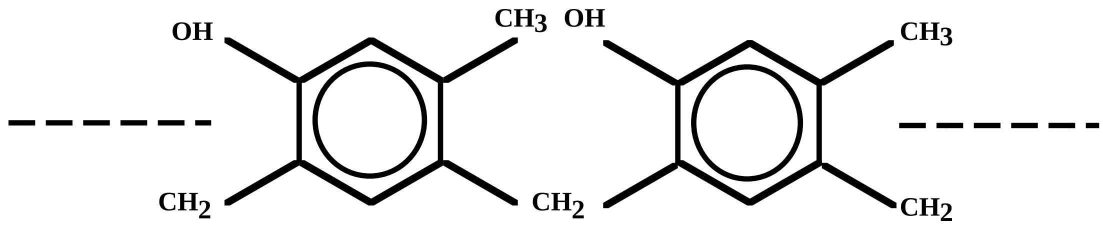
• Resists are organic polymers that are spun onto wafers and prebaked to produce a film ≈ 0.5 - 1 µm thick.

## g-Line and i-Line Resists

• Generally consist of 3 components:
  - Inactive resin
  - Photoactive compound (PAC)
  - Solvent - used to adjust viscosity

• After spinning and baking resists are ≈ 1:1 PAC and resin.

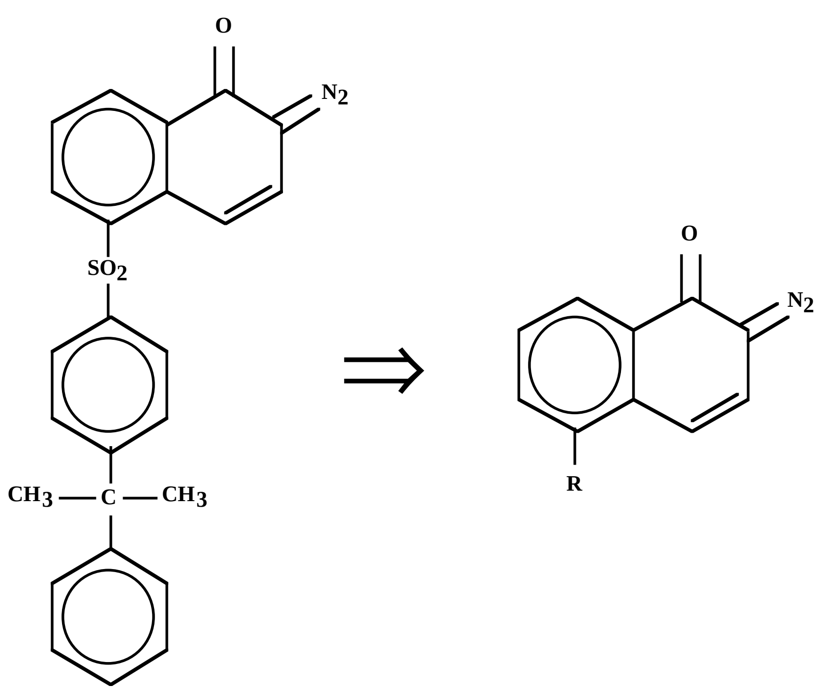
• Diazonaphthoquinone or DNQ resists are commonly used today for g-line and i-line resists.



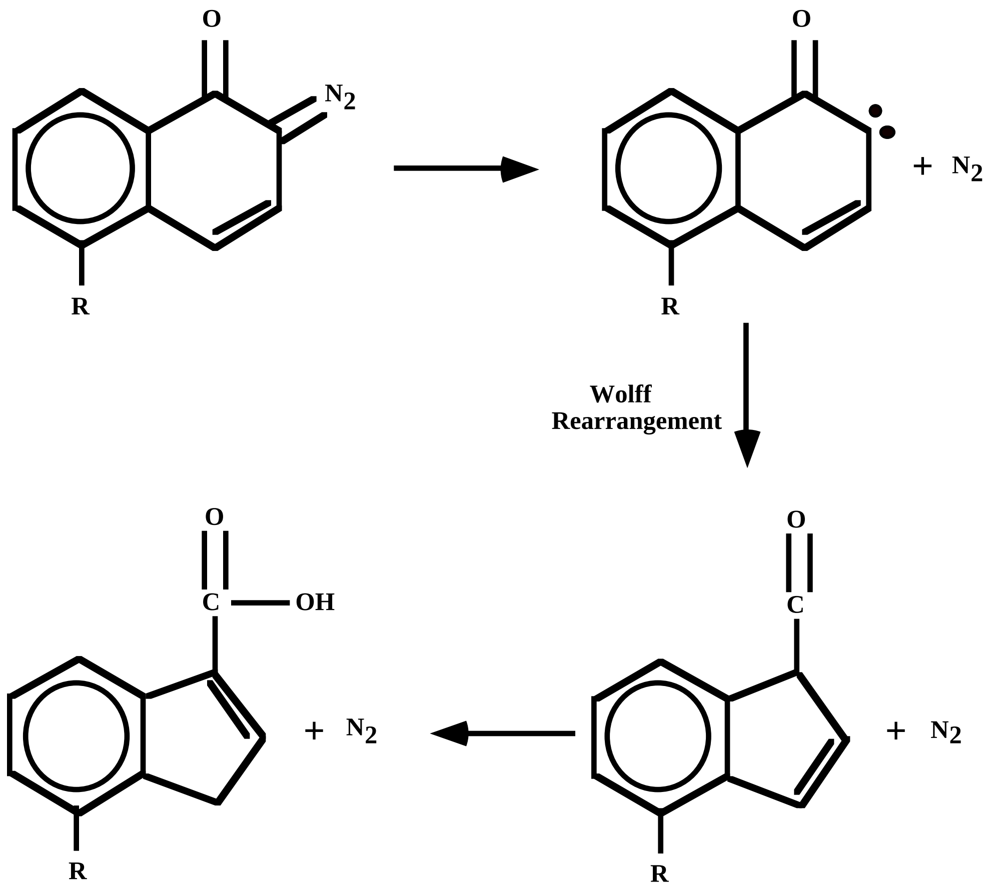

- **The base resin is novolac a long chain polymer consisting of hydrocarbon rings with 2 methyl groups and 1 OH group attached.**

- **The PACs in DNQ resists are often diazoquinones. The photoactive portion is above the $SO_2$.**

- **Diazoquinones are insoluble in typical developers and reduce the dissolution rate of unexposed resists to ≈ 10 - 20 Å $sec^{-1}$.**

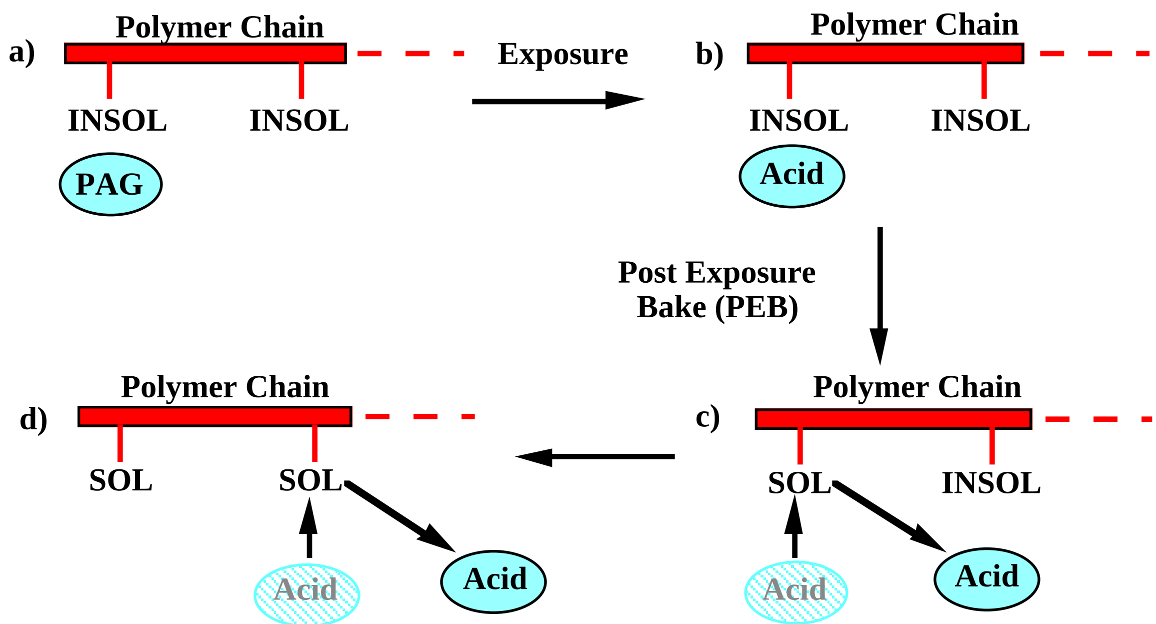



- **After exposure to light, the PAC component in DNQ resists undergoes a transformation into carboxylic acid which is soluble in the developer (basic solution).**



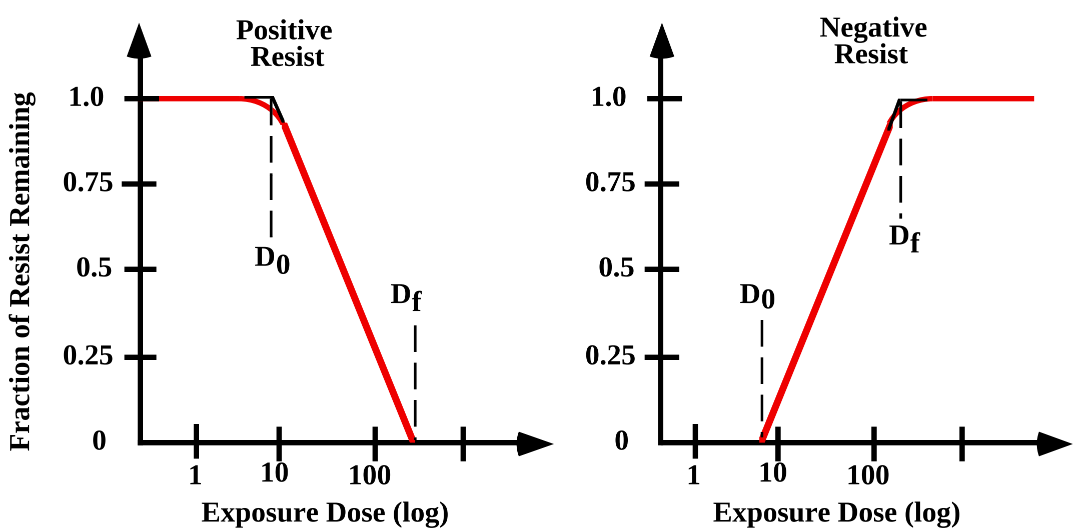

## DUV Resists

- **g-line and i-line resists have maximum quantum efficiencies < 1 and are typically ≈ 0.3.**
- **Chemical amplification can improve this substantially.**
- **DUV resists all use this principle. A catalyst is used.**
- **Photo-acid generator (PAG) is converted to an acid by photon exposure. Later, in a post exposure bake, the acid molecule reacts with a "blocking" molecule on a polymer chain, making it soluble in developer AND REGENERATING THE ACID MOLECULE.**
- **∴ catalytic action and sensitivity is enhanced.**




## Basic Properties of Resists

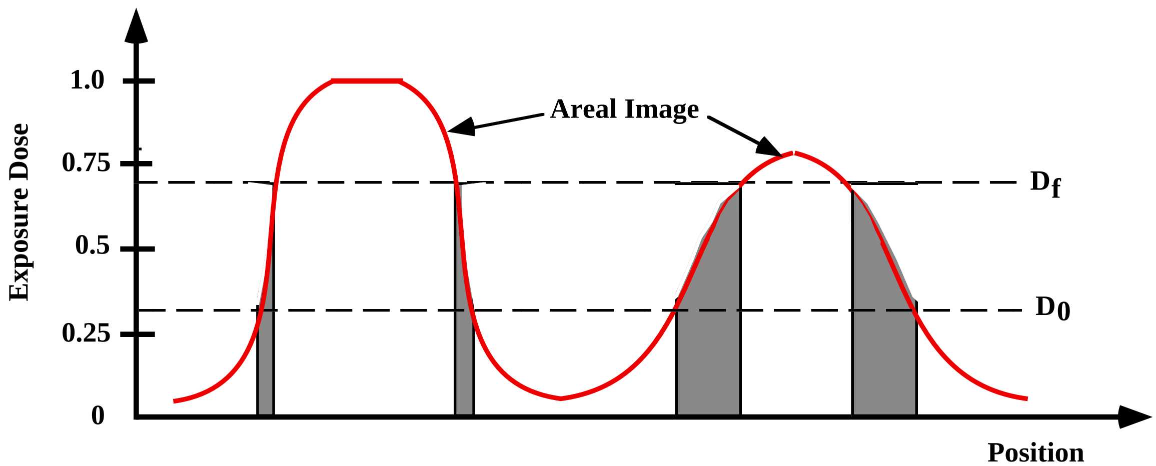
- **Two basic parameters are used to describe resist properties, contrast and the critical modulation transfer function or CMTF.**




- **Contrast is defined as**

$$\gamma = \frac{1}{\log_{10} \frac{D_f}{D_0}} \qquad (11)$$

- Typical g-line and i-line resists achieve $\gamma$ values of 2 - 3 and $D_f$ values of about 100 mJ $cm^{-2}$. DUV resists have much higher $\gamma$ values (5 - 10) and $D_f$ values of about 20 - 40 mJ $cm^{-2}$.



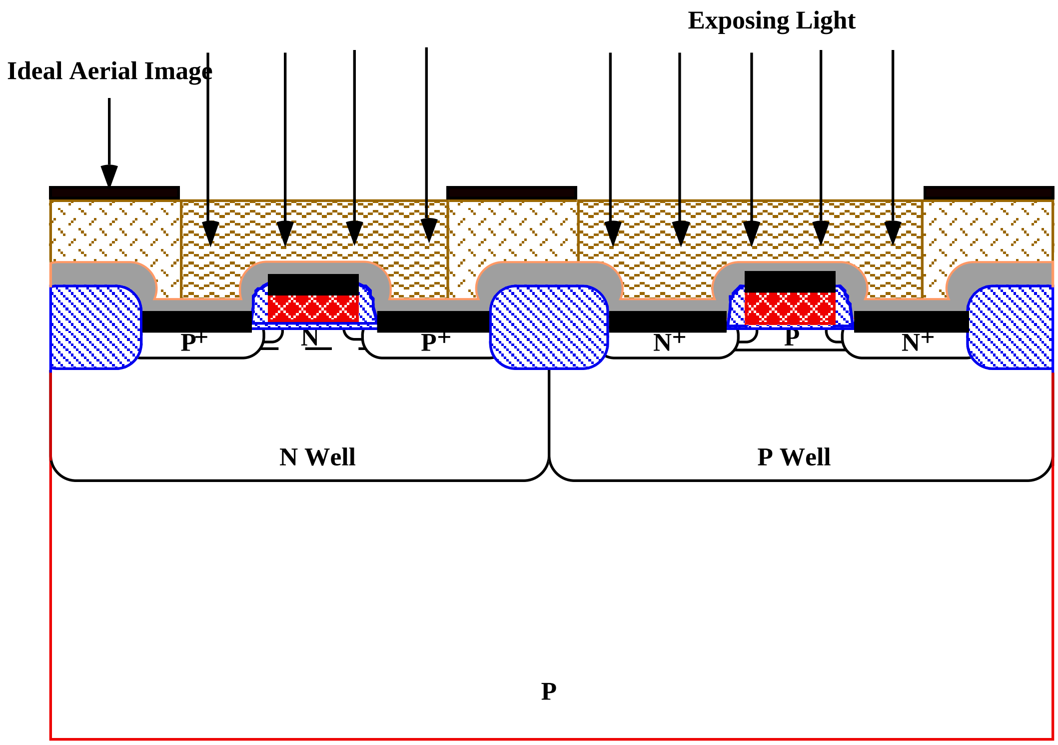

- The aerial image and the resist contrast in combination, result in the quality of the latent image produced. (Gray area is "partially exposed" area which determines the resist edge sharpness.)

- By analogy to the MTF defined earlier for optical systems, the CMTF for resists is defined as

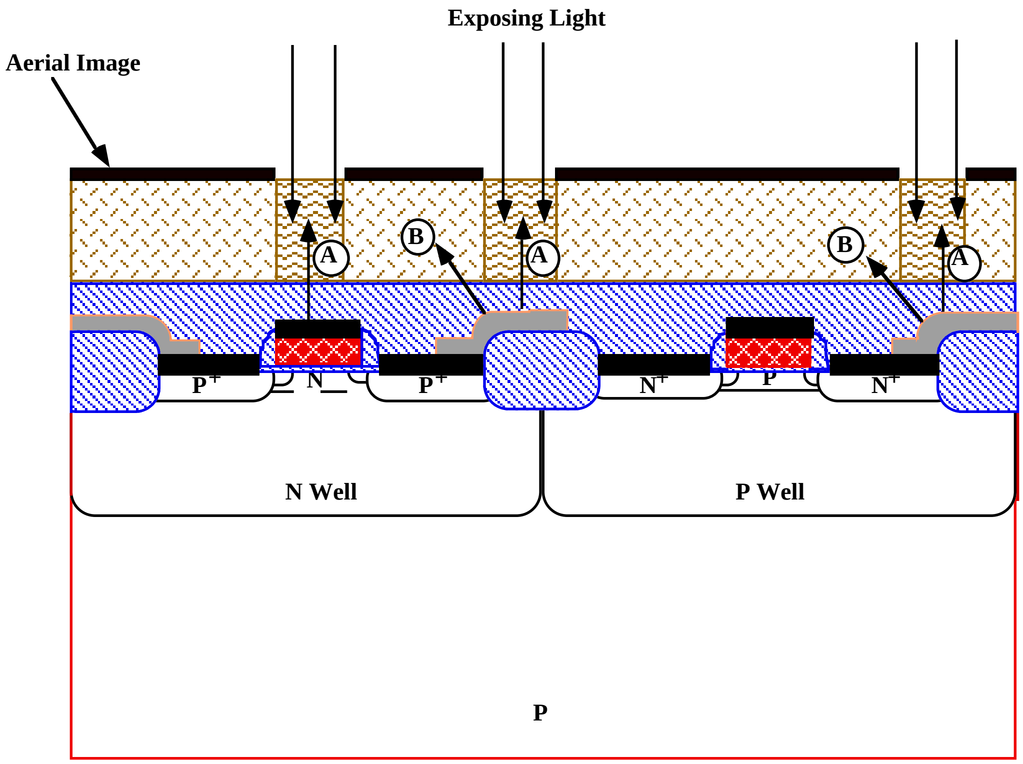
$$CMTF_{resist} = \frac{D_f - D_0}{D_f + D_0} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1} \qquad (12)$$

- In general CMTF < MTF is required for the resist to resolve the aerial image.

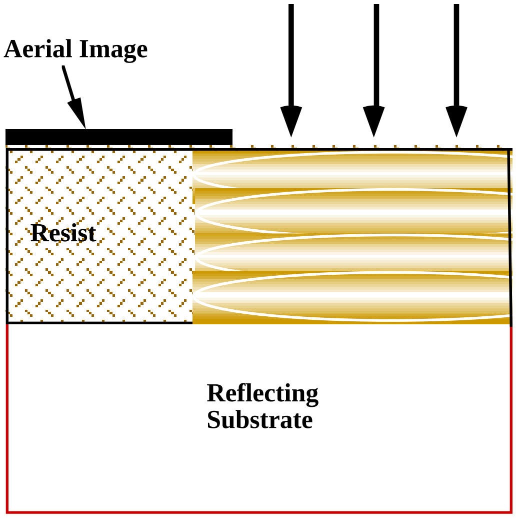
- There are often a number of additional issues that arise in exposing resist.

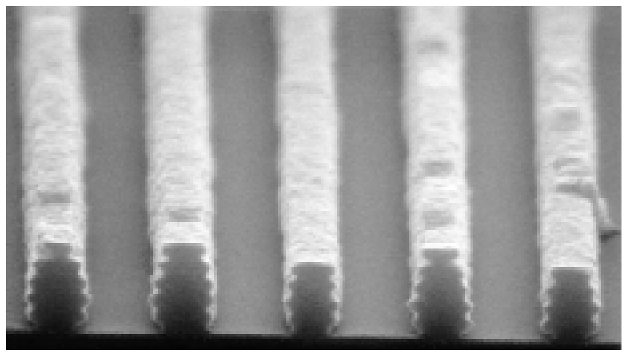



• **Resist thickness may vary across the wafer. This can lead to under or over exposure in some regions and hence linewidth variations.**



• **Reflective surfaces below the resist can set up reflections and standing waves and degrade resolution.**



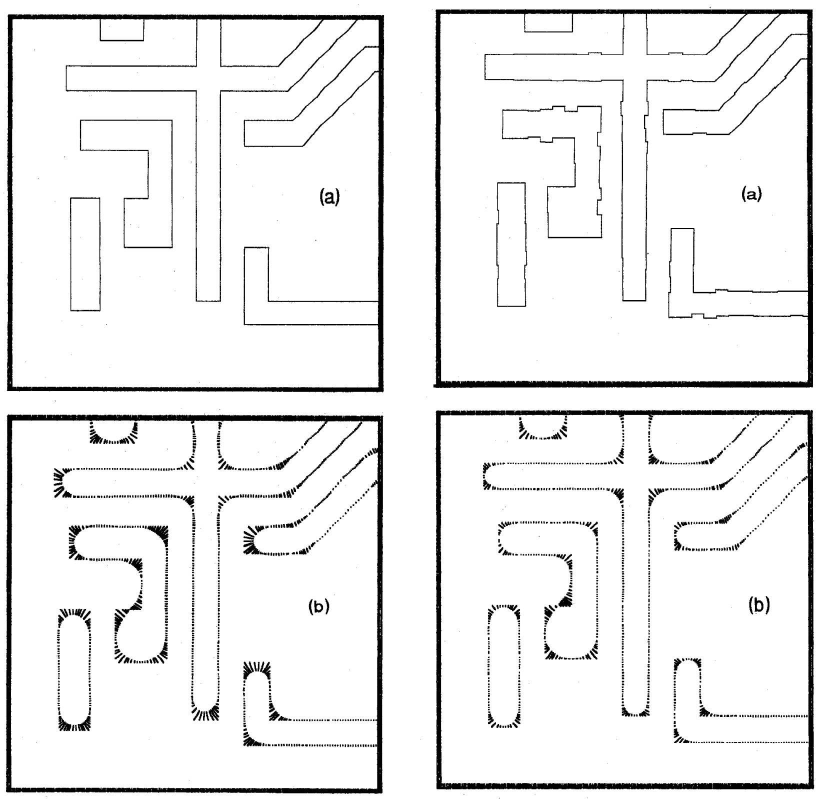



• **In some cases an antireflective coating (ARC) can help to minimize these effects. Baking the resist after exposure, but before development can also help.**

## D. Mask Engineering - OPC and Phase Shifting

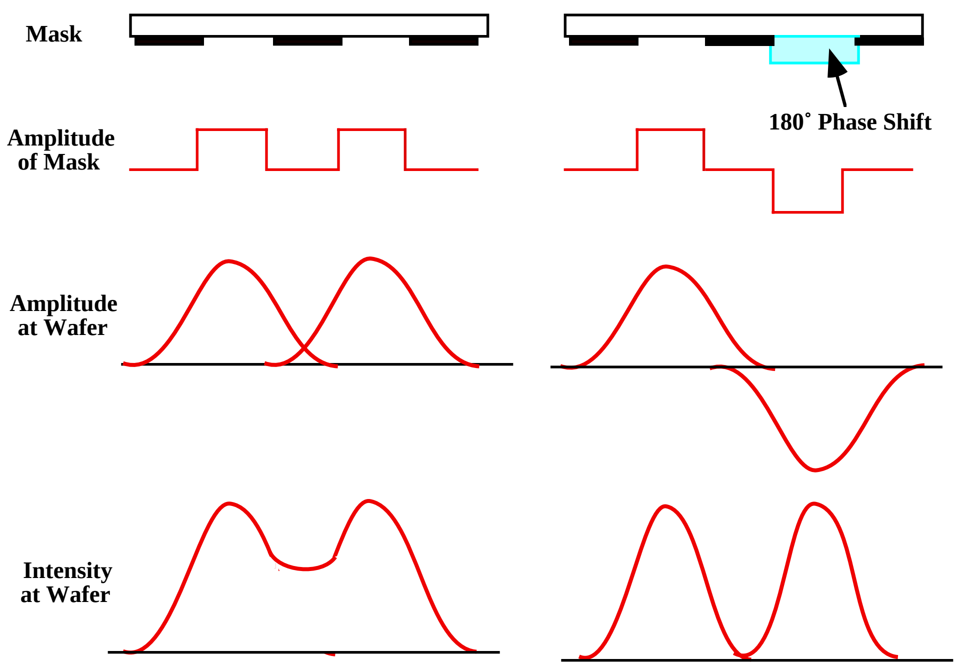
• **Optical Proximity Correction (OPC) can be used to compensate somewhat for diffraction effects.**

• **Sharp features are lost because higher frequencies are lost due to diffraction. These effects are calculable and can be compensated for.**




**Top - mask with and without OPC. Bottom, calculated printed images.**

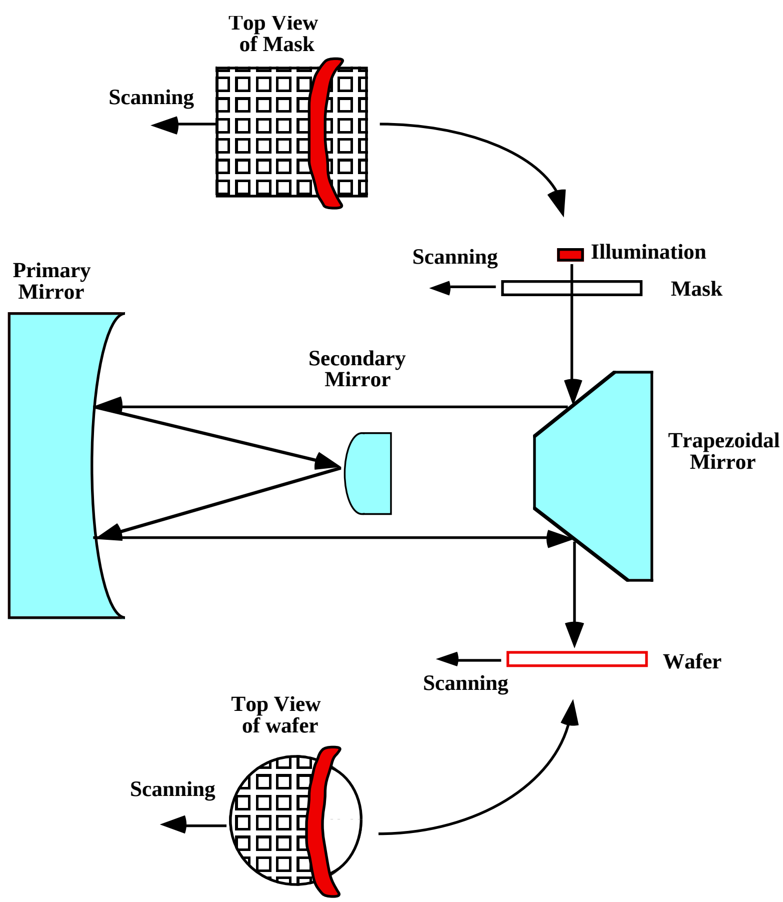
- **Another approach uses phase shifting to "sharpen" printed images.**



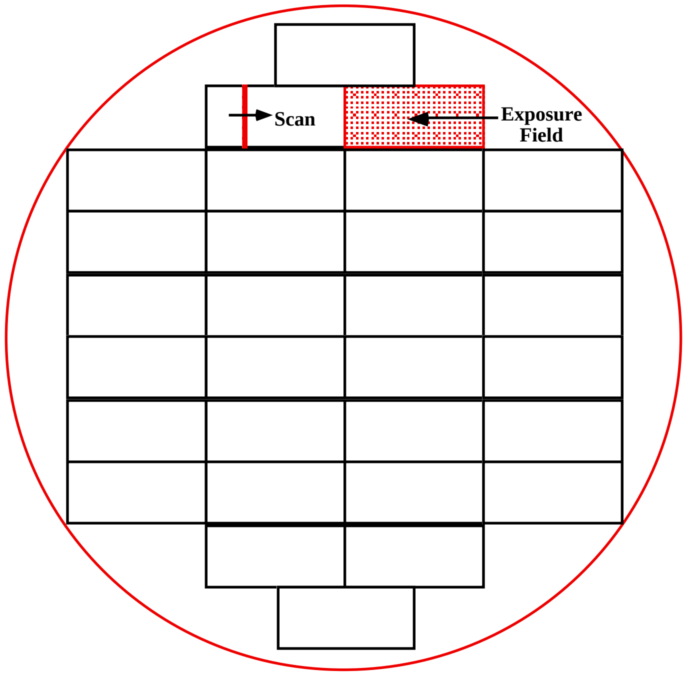
• These techniques can allow existing exposure tools to be used in manufacturing at least one more technology generation.

## Manufacturing Methods and Equipment

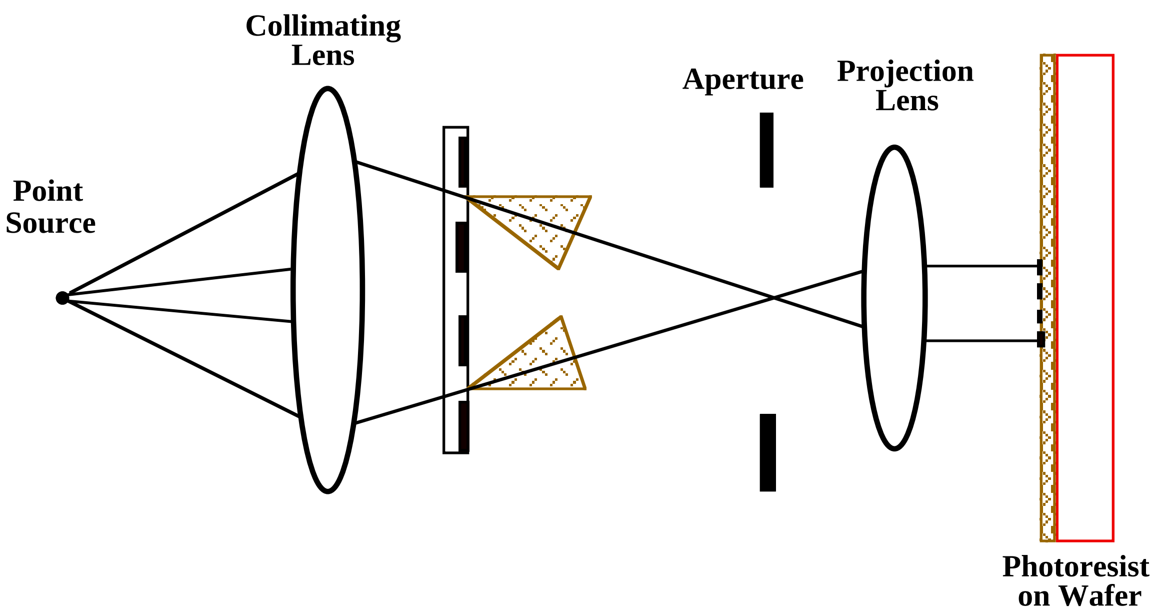
• The first projection printing systems were 1:1 systems introduced by Perkin-Elmer ≈ 20 years ago.
• These systems require full wafer 1X masks which become more difficult to manufacture as wafers get larger and device dimensions smaller.
• Today's steppers are almost all reducing machines - 2X to 5X.
• This makes the masks a lot easier to make and the optics are required to be "perfect" over a smaller area.



• **The most recent "steppers" are step and scan systems.**

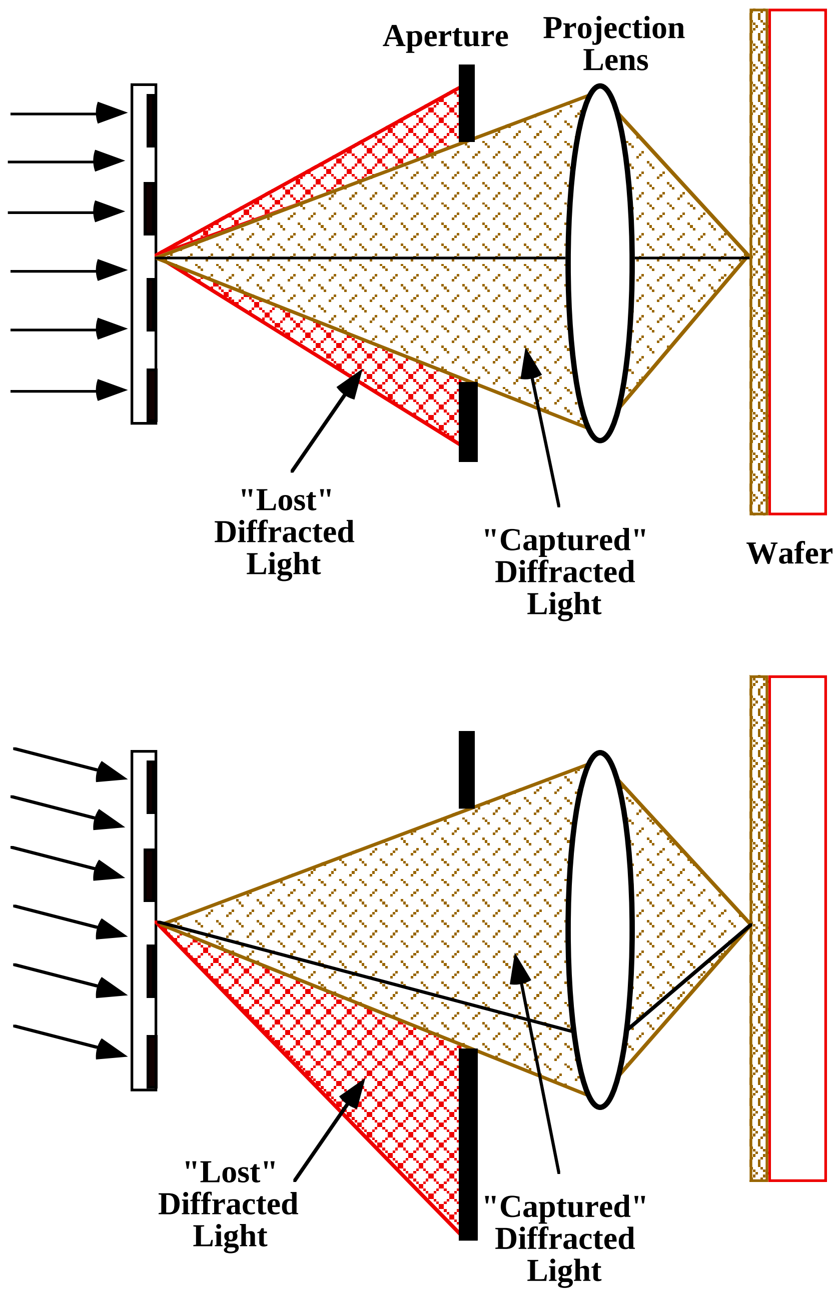



• **This further decreases the optical "window" and therefore makes it possible to build higher performance optical systems over a smaller area.**
• **In addition, advanced optical systems are employed using Kohler illumination and/or off axis illumination.**

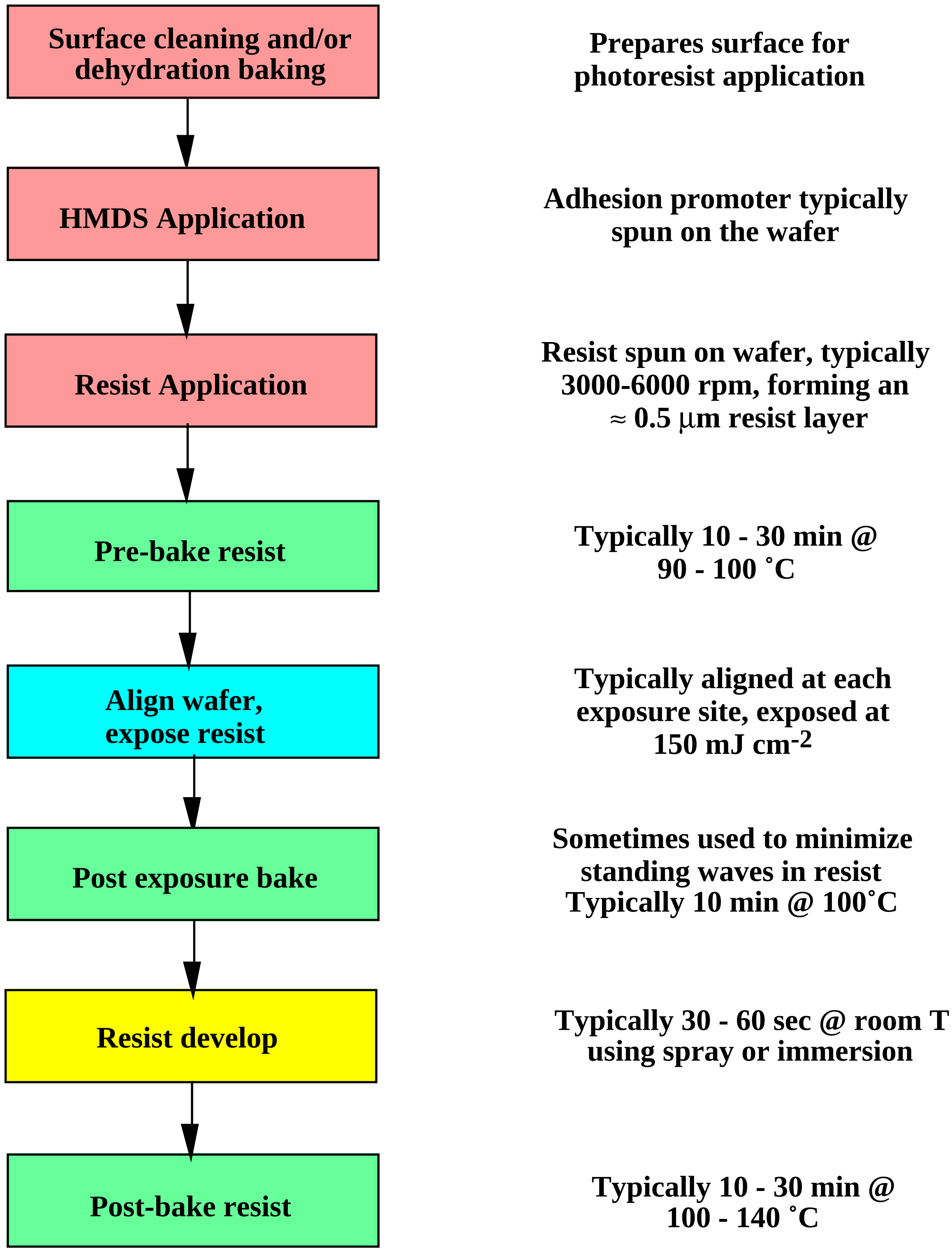


- Kohler illumination systems focus the light at the entrance pupil of the objective lens. This "captures" diffracted light equally well from all positions on the mask.

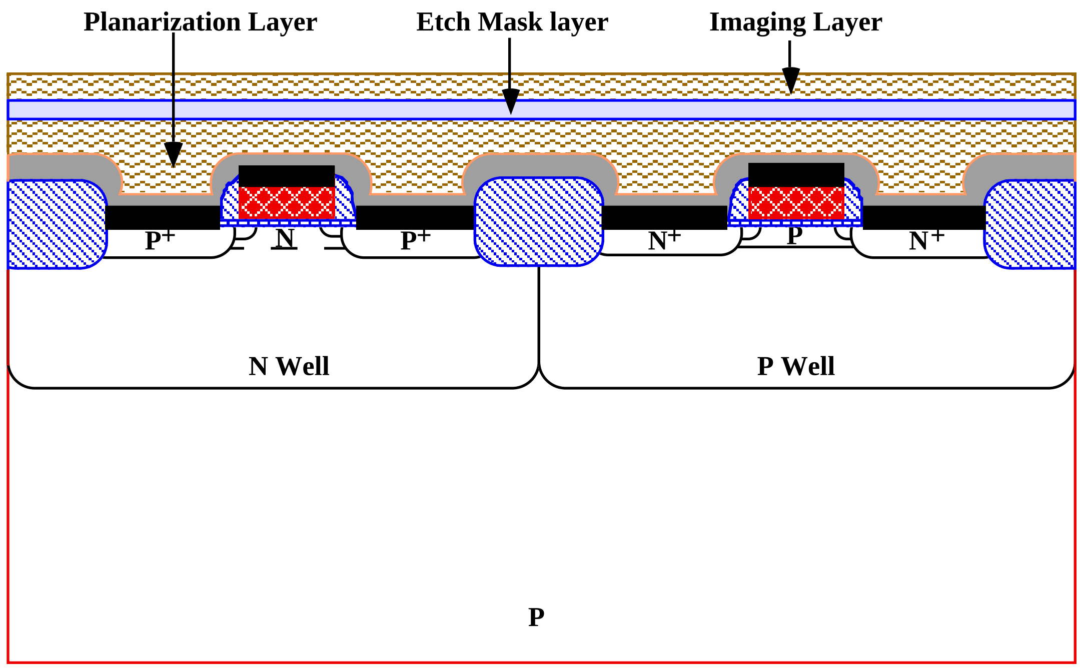
- "Off-axis illumination" also allows some of the higher order diffracted light to be captured and hence can improve resolution.



## • Typical resist process:



• Practical resist processes are also much more complicated than the “simple” chemistry described earlier.




• Multi-layer resists are used to produce a thin, uniform imaging layer in which the aerial image is transformed into a latent image.
• Etching is then used to transfer the latent image down through the planarization layer.

## Models and Simulation

• Lithography simulation relies on models from two fields of science:

  • Optics to model the formation of the aerial image.

  • Chemistry to model the formation of the latent image in the resist.

# A. Wafer Exposure System Models

- There are several commercially available simulation tools that calculate the aerial image - PROLITH, DEPICT, ATHENA.
- All use similar physical models.
- We will consider only projection systems.

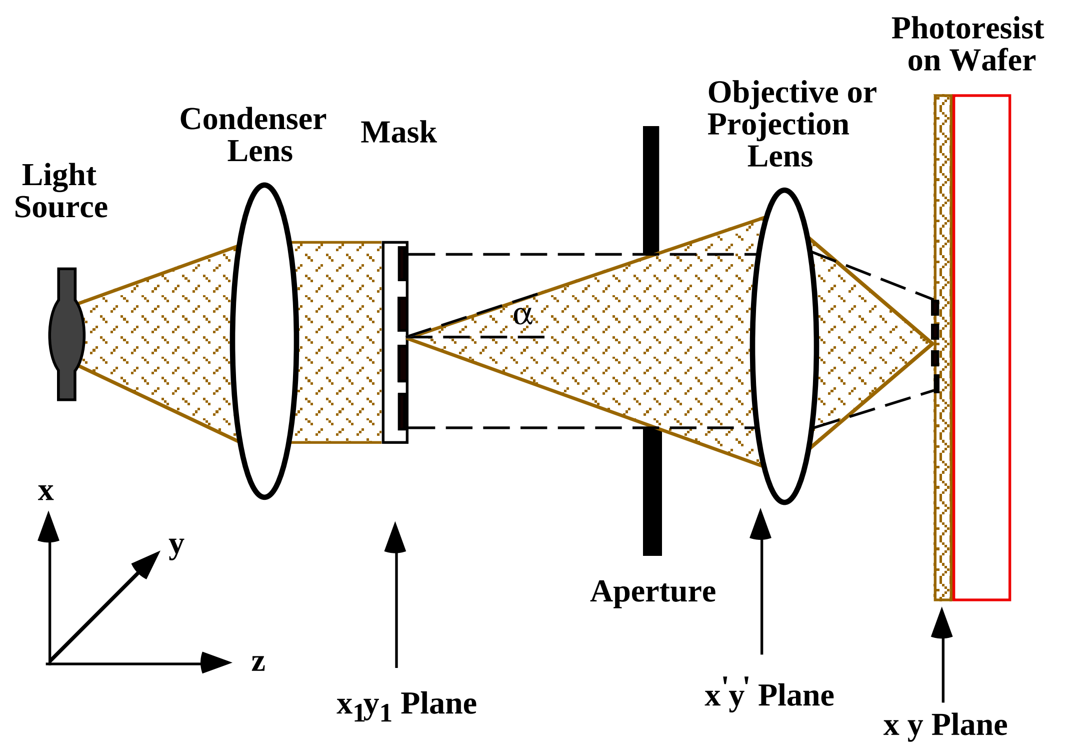
- Light travels as an electromagnetic wave.

$$\mathcal{E}(P,t) = C(P)\cos(\omega t + \phi(t)) \qquad (13)$$

or, in complex exponential notation,

$$\mathcal{E}(P,t) = \mathrm{Re}\left\{U(P)e^{-j\omega t}\right\} \text{ where } U(P) = C(P)e^{-j\phi(P)} \quad (14)$$

- Consider a generic projection system:



• **The mask is considered to have a digital transmission function**

$$t(x_1, y_1) = \begin{cases} 1 \text{ in clear areas} \\ 0 \text{ in opaque areas} \end{cases} \qquad (15)$$

• **After the light is diffracted, it is described by the Fraunhofer diffraction integral**

$$\mathcal{E}(x', y') = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} t(x_1, y_1) e^{-2\pi j (f_x x + f_y y)} dxdy \qquad (16)$$

**where $f_x$ and $f_y$ are the spatial frequencies of the diffraction pattern, defined as**

$$f_x = \frac{x'}{z\lambda} \quad \text{and} \quad f_y = \frac{y'}{z\lambda}.$$

• **$\mathcal{E}(x', y')$ is the Fourier transform of the mask pattern.**

$$\mathcal{E}(f_x, f_y) = F\{t(x_1, y_1)\} \qquad (17)$$

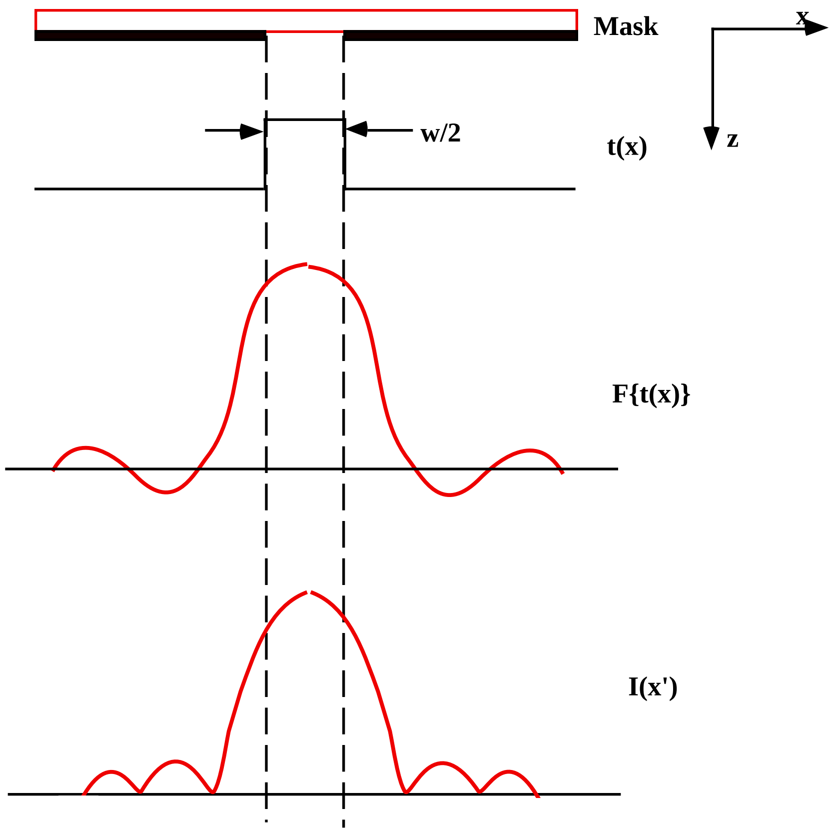
• **The light intensity is simply the square of the magnitude of the $\mathcal{E}$ field, so that**

$$I(f_x, f_y) = \left|\mathcal{E}(f_x, f_y)\right|^2 = \left|F\{t(x_1, y_1)\}\right|^2 \qquad (18)$$

• **Example - consider a long rectangular slit:**

- The Fourier transform of t(x) is in standard texts and is the sin(x)/x function.

- After passing through the mask, the light is collected by the objective lens (x’, y’ plane).




- But only a portion of the light is collected.
- This is characterized by a pupil function:

$$P(f_x, f_y) = \begin{cases} 1 \text{ if } \sqrt{f_x^2 + f_y^2} < \dfrac{NA}{\lambda} \\ 0 \text{ if } \sqrt{f_x^2 + f_y^2} > \dfrac{NA}{\lambda} \end{cases} \qquad (19)$$

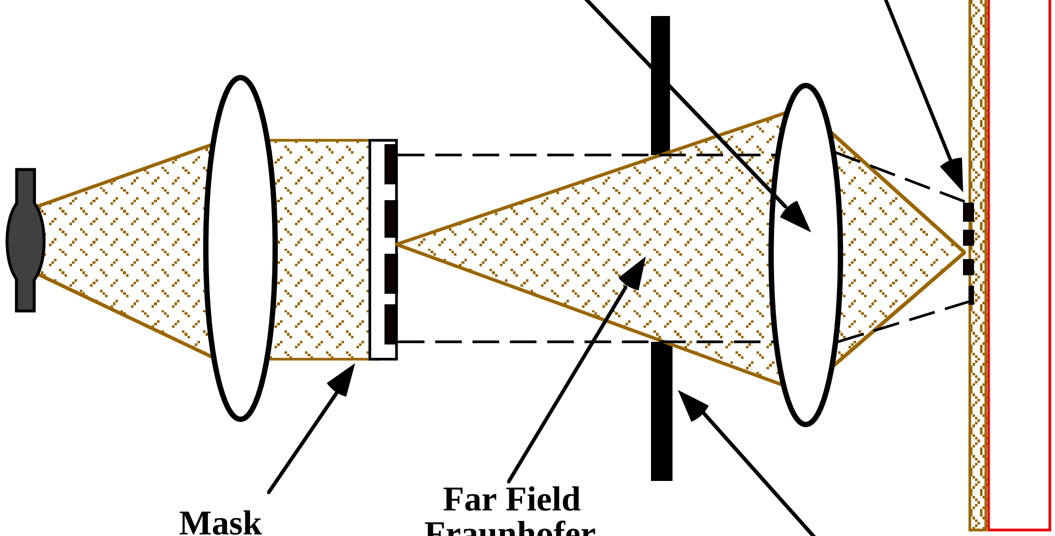
- The objective lens now performs the inverse Fourier transform.

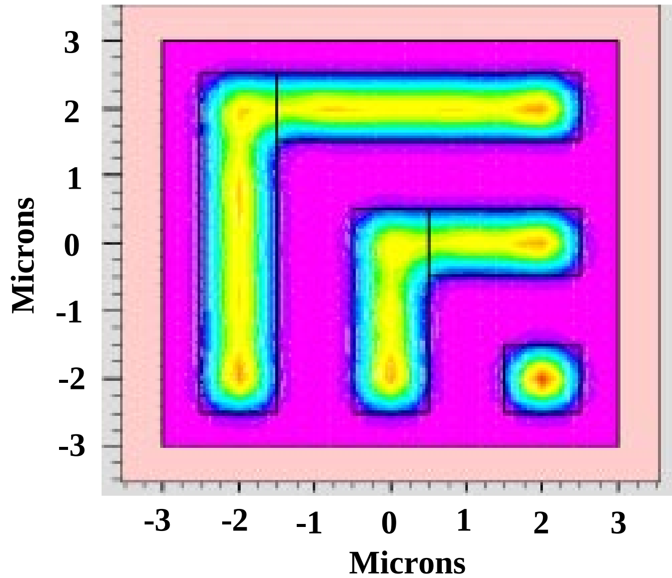
$$\mathcal{E}(x,y) = F^{-1}\left\{\mathcal{E}\left(f_x,f_y\right)P\left(f_x,f_y\right)\right\} = F^{-1}\left\{F\left\{t\left(x_1,y_1\right)\right\}P\left(f_x,f_y\right)\right\} \quad (20)$$

**resulting in a light intensity at the resist surface (aerial image) given by**

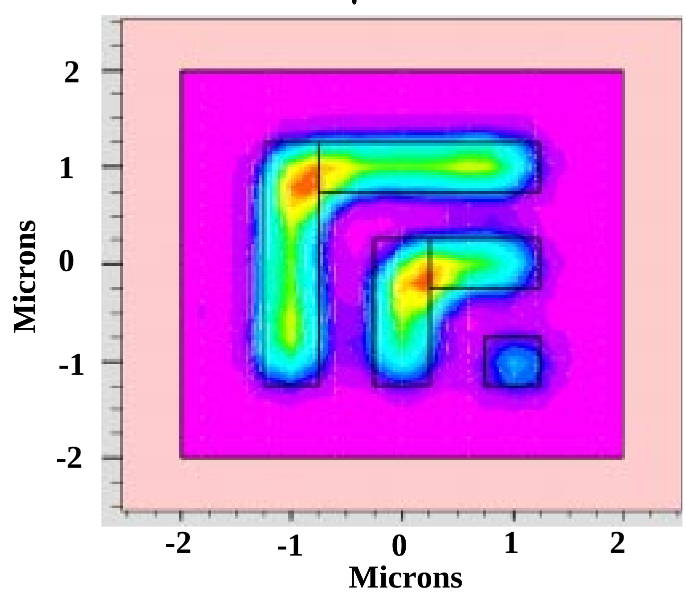
$$I_i(x,y) = \left|\mathcal{E}(x,y)\right|^2 \quad (21)$$

**Summary: Lithography simulators basically perform these calculations, given a mask design and the characteristics of an optical system.**

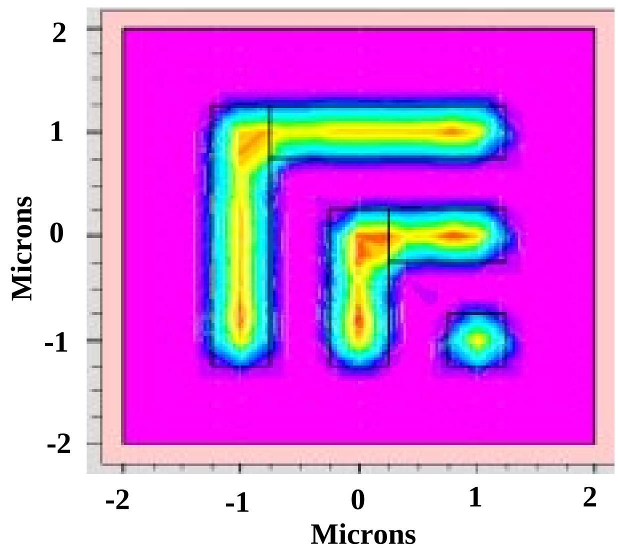





- Simulation using the ATHENA simulator by Silvaco. The colors correspond to optical intensity in the aerial image. The exposure system simulated had a NA = 0.43, partially coherent g-line illumination ($\lambda$ = 436 nm) and no other aberrations or defocusing. The minimum feature size is 1 $\mu$m.




- Same example as above except that the feature size has been reduced to 0.5 $\mu$m. Note the poorer image.

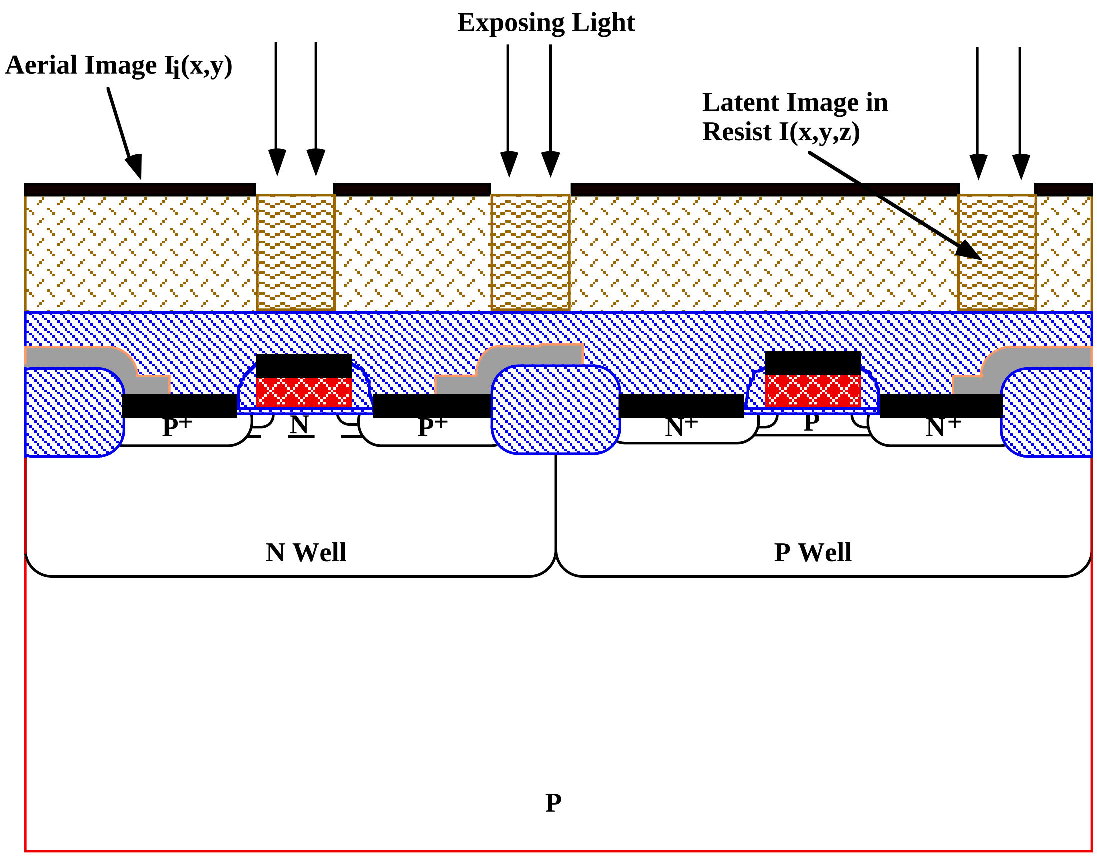



• Same example as above except that the illumination wavelength has now been changed to i-line illumination ($\lambda$ = 365 nm) and the NA has been increased to 0.5. Note the improved in image.

• In practice, additional effects such as spatial coherence, aberrations, depth of focus etc., are also modeled (see text).

## B. Optical Intensity Pattern in the Resist (Latent Image)

• The second step in lithography simulation is the calculation of the latent image in the resist.

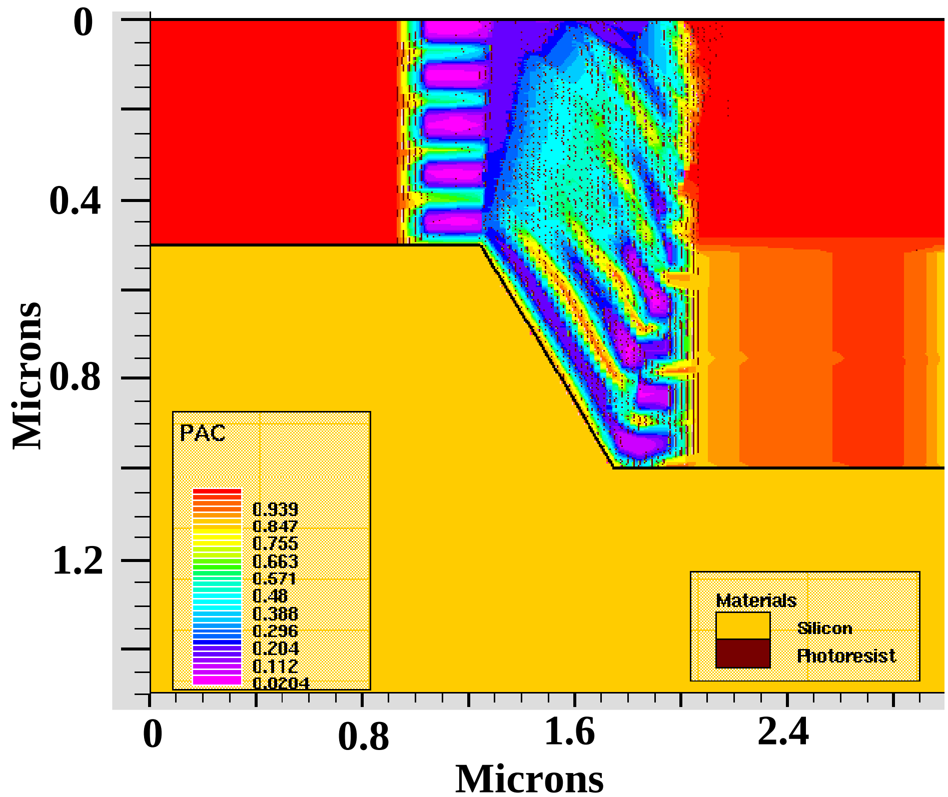



- The light intensity during exposure in the resist is a function of time and position because of
  - Light absorption and bleaching.
  - Defocusing.
  - Standing waves.

- These are generally accounted for by modifying Eqn. (21) as follows:

$$I(x, y, z) = I_i(x, y) I_r(x, y, z) \qquad (22)$$

where $I_r(x,y,z)$ is a correction factor which models these effects (see text).




- **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.**

## C. 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.)**

- **The absorption coefficient $\alpha$ depends on the resist properties and on the [PAC] (see text).**

$$\alpha_{resist} = Am + B \qquad (24)$$

**where A and B are resist parameters (first two Dill parameters) and**

$$m = \frac{[PAC]}{[PAC]_0} \qquad (25)$$

- **m is a function of time and is given by**

$$\frac{dm}{dt} = -C\,Im \qquad (26)$$

- **Substituting (24) into (23), we have:**

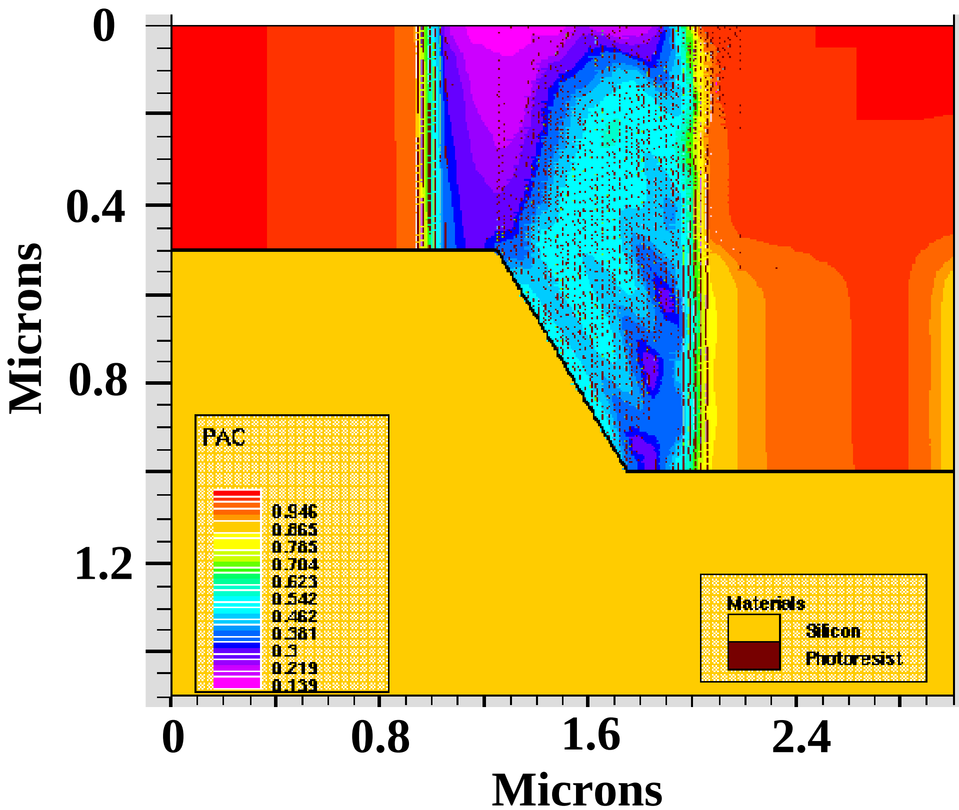
$$\frac{dI}{dt} = -(Am + B)I \qquad (27)$$

- **Eqns. (26) and (27) are coupled equations which are solved simultaneously by resist simulators.**

- **The Dill resist parameters (A, B and C) can be experimentally measured for a resist (see text).**

## D. 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).**




- **Same simulation example as above except that a post exposure bake of 45 minutes at 115 ˚C has now been included. 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.**

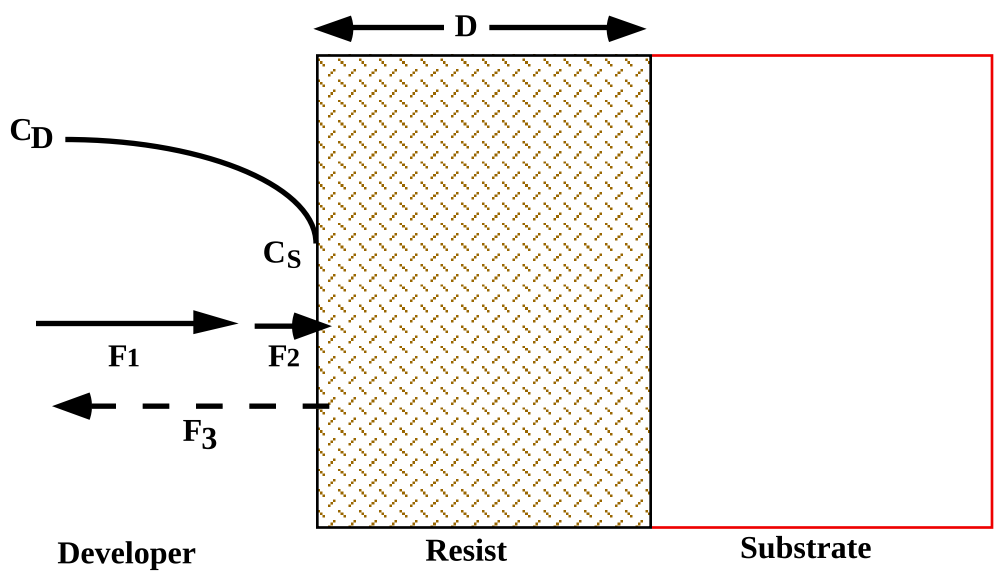
# E. Photoresist Developing

- A number of models for resist developing have been proposed and implemented in lithography simulators.
- The simplest of these is purely empirical and is due to Dill and coworkers.

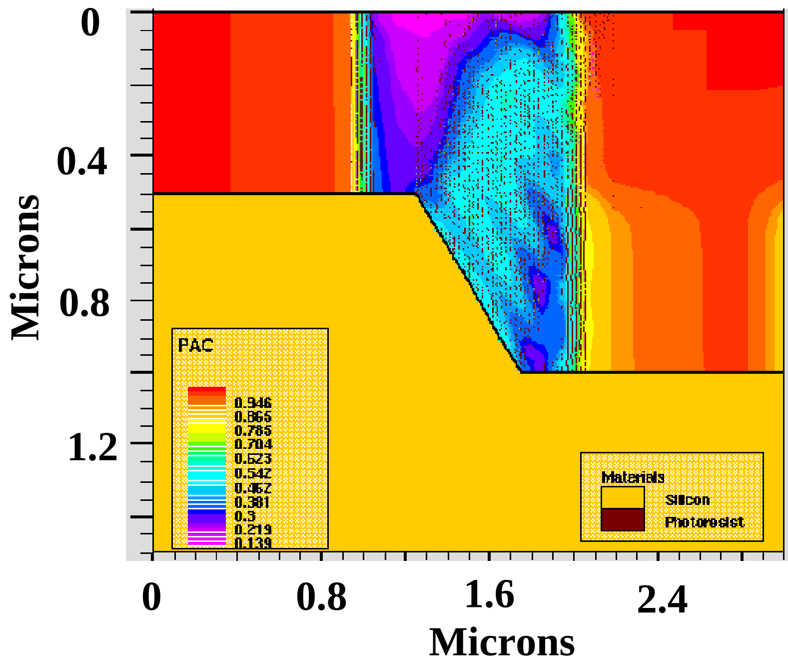
$$R(x,y,z) = \begin{cases} 0.006\exp\left(E_1 + E_2 m + E_3 m^2\right) & \text{if } m > -0.5\dfrac{E_2}{E_3} \\ 0.006\exp\left(E_1 + \dfrac{E_2}{E_3}(E_2 - 1)\right) & \text{otherwise} \end{cases} \quad (28)$$

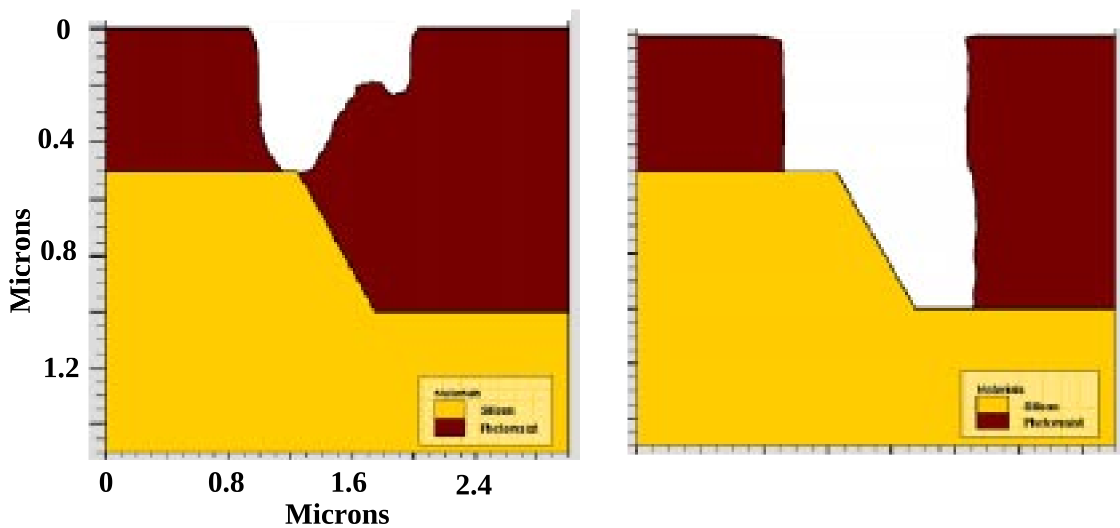
where R is the local developing rate and m is the local [PAC] after exposure. $E_1$, $E_2$ and $E_3$ are empirical constants.

- A more physically based model has been developed by Mack which models developer diffusion and reaction (much like the deposition models discussed in Chpt. 8.)




- See the text for details on this development model.




• **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.**

# Future Trends (See Text)

- **Optical lithography will likely be extendible to the 0.10 μm generation (maybe further).**
- **Beyond that, there is no general agreement on which approach will work in manufacturing.**
- **Possibilities include e-beam, e-beam projection (SCALPEL), x-ray and EUV.**
- **New resists will also likely be required for these systems.**