Lecture 7

Lithography and Pattern Transfer

Reading:

Chapter 7

Lithography and Photoresists

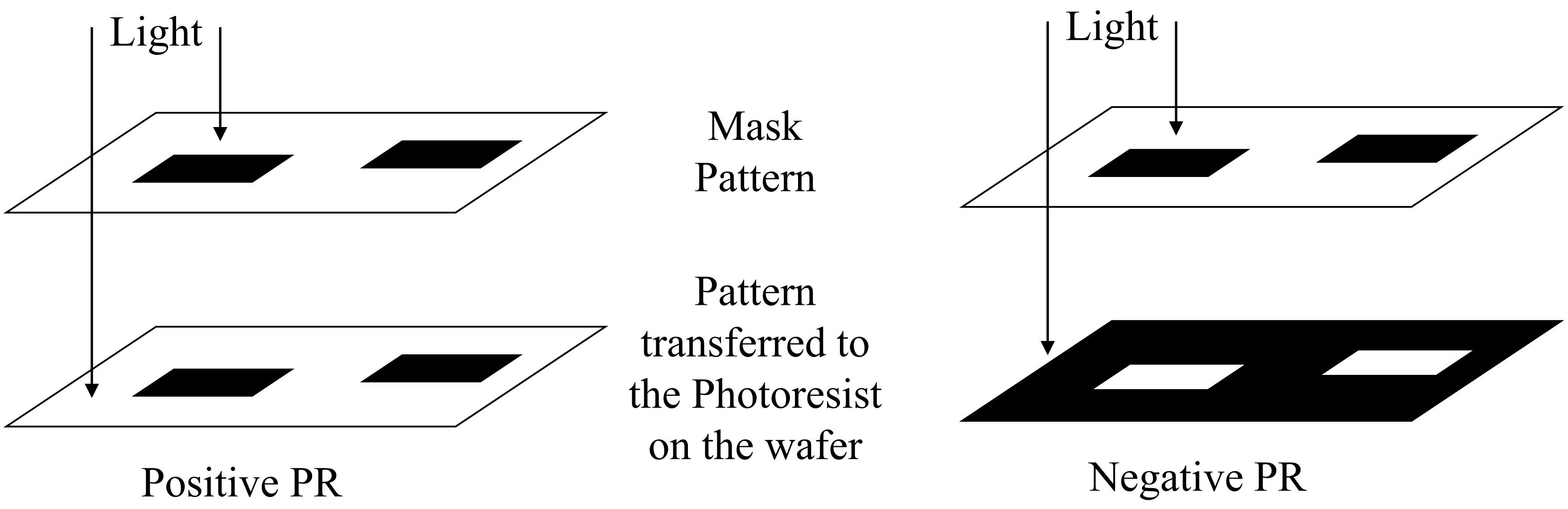
Used for transfer patterns into oxides, metals, semiconductors.

3 types of Photoresists (PR):

1.) Positive: PR pattern is same as mask. On exposure to light, light degrades the polymers (described in more detail later) resulting in the photoresist being more soluble in developers. The PR can be removed in inexpensive solvents such as acetone.

2.) Negative: PR pattern is the inverse of the mask. On exposure to light, light polymerizes the rubbers in the photoresist to strengthen it's resistance to dissolution in the developer. The resist has to be removed in special stripping chemicals. These resists tend to be extremely moisture sensitive.

3.) Combination: Same photoresist can be used for both negative and positive pattern transfer. Can be removed in inexpensive solvents.



Lithography and Photoresists

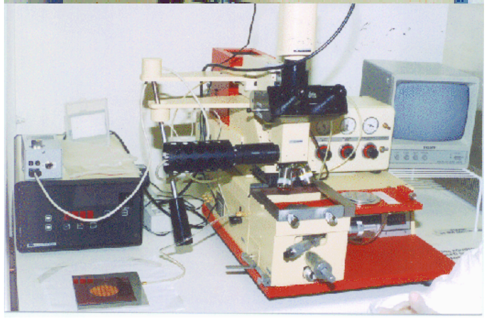
Photoresists are used in a process typical of this process: Dehydration Bake, Apply Adhesion Promoter, Apply Resist, Soft bake, Exposure with Mask, Post Exposure Bake, Develop, Optional Processing. For example:

1.) Dehydration in an oven at ~120 degrees C for as long as 30 minutes

2.) Spin coat (verbally explain) adhesion promoter such as hexamethyldisilane (HMDS)

3.) Spin coat resist

4.) Soft bake to partially solidify PR (85-95 degrees C for 1 to 30 minutes depending on the resist)



5.) Expose to few hundred mJoules/cm^2 of high energy light

6.) (Optional) Hard bake, removes more solvent (~110-150 C)

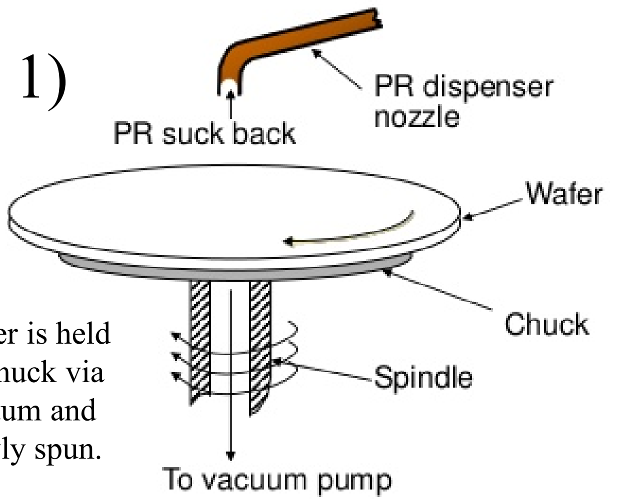
7.) Develop: weak regions of PR dissolved

8.) Additional Hard bake or chemical treatment to harden PR for aggressive processes such as Ion implantation or Plasma etching

More details at the Gt microelectronics teaching lab web page: http://www.ece.gatech.edu/research/labs/vc/

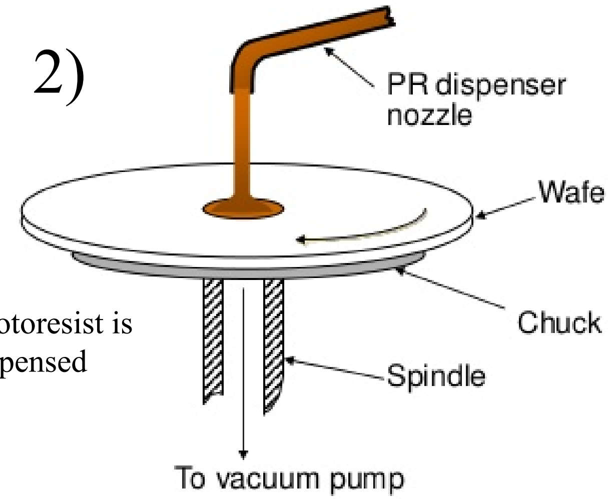
Applying Photoresists and Related Compounds

1)



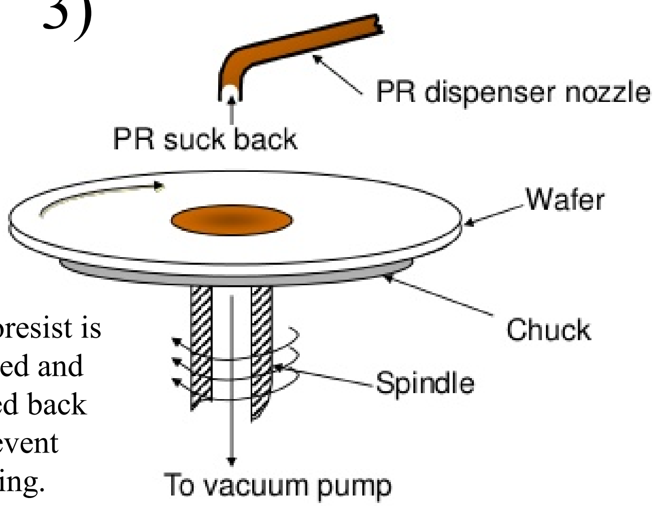
Wafer is held on chuck via vacuum and slowly spun.

2)



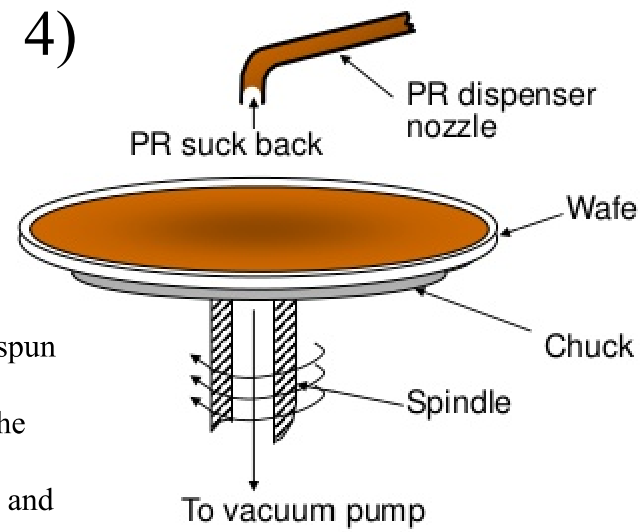
Photoresist is dispensed

3)



Photoresist is stopped and sucked back to prevent dripping.

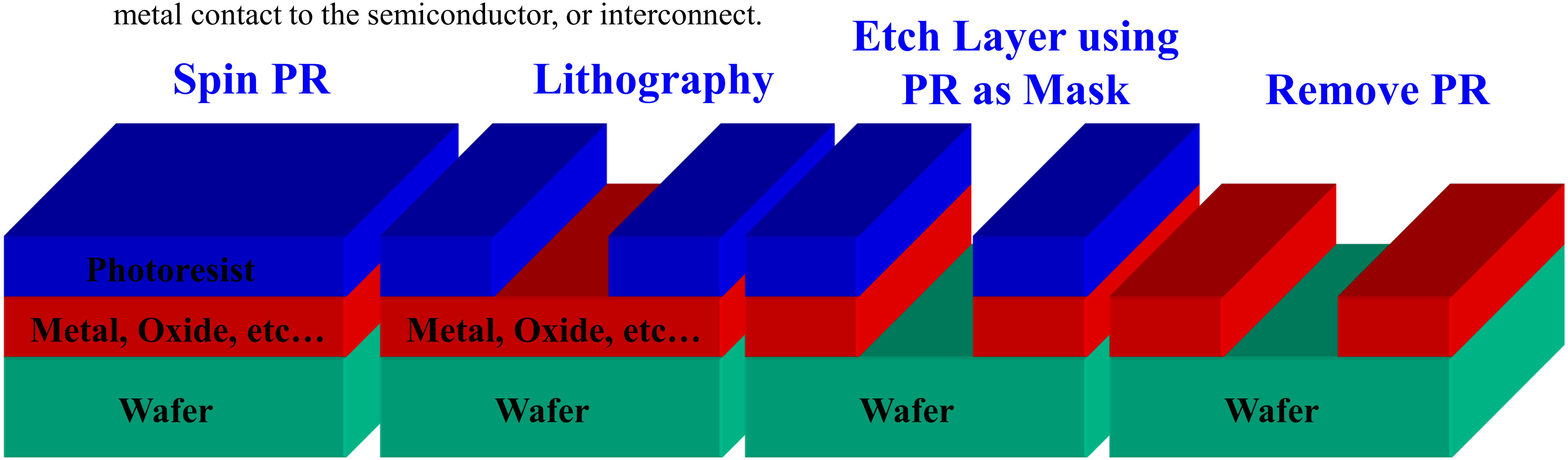
4)



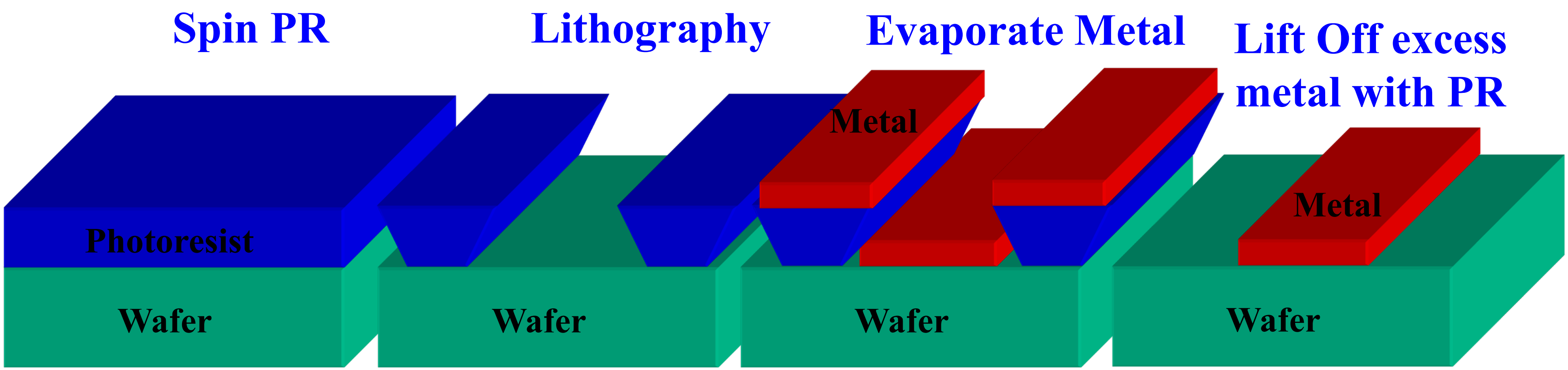
Wafer is spun faster to achieve the desired thickness and uniformity.

Uses of Lithography:

1.) Etching Processes: open windows in oxides for diffusion, masks for ion implantation, etching, metal contact to the semiconductor, or interconnect.



2.) Lift off Processes: Metalization (more common in III-V).



Issues with Photolithography

1.) Resolution: How small of features can you make. (Current production state of the art is ~**0.007** um)

2.) Registration: Can you repeatability align one layer to another. (~1/3 of resolution)

3.) Throughput: Can these be done in a cost-effective time. 50-1000 wafers an hour (~200-300 is state of the art), down to 1 chip per hour for prototype or military chips.

Photolithography Systems

1.) Contact: Resist is in contact with the mask: 1:1 magnification
Advantages: Inexpensive equipment ($~50,000-150,000), moderately high resolution (~0.5 um or better but limited by resist thickness- 0.1 um demonstrated)
Disadvantages: Contact with the mask degrades the mask (pinholes and scratches are created on the metal-oxide layers of the mask, particles or dirt are directly imaged in the wafer, Wafer bowing or local loss of planarization results in non-uniform resolution due to mask-wafer gap variations, and no magnification

2.) Proximity: Resist is almost, but not in contact with the mask: 1:1 magnification
Advantages: Inexpensive equipment, low resolution (~1-2 um or slightly better)
Disadvantages: Diffraction effects limit accuracy of pattern transfer. Less repeatable than contact methods, no magnification

3.) Projection: Mask image is projected a distance from the mask and de-magnified to a smaller image: 1:4 -1:10 magnification
Advantages: Can be very high resolution (~0.007 um or slightly better), No mask contact results in almost no mask wear (high production compatible), mask defects or particles on mask are reduced in size on the wafer.
Disadvantages: Extremely expensive and complicated equipment, diffraction effects limit accuracy of pattern transfer.

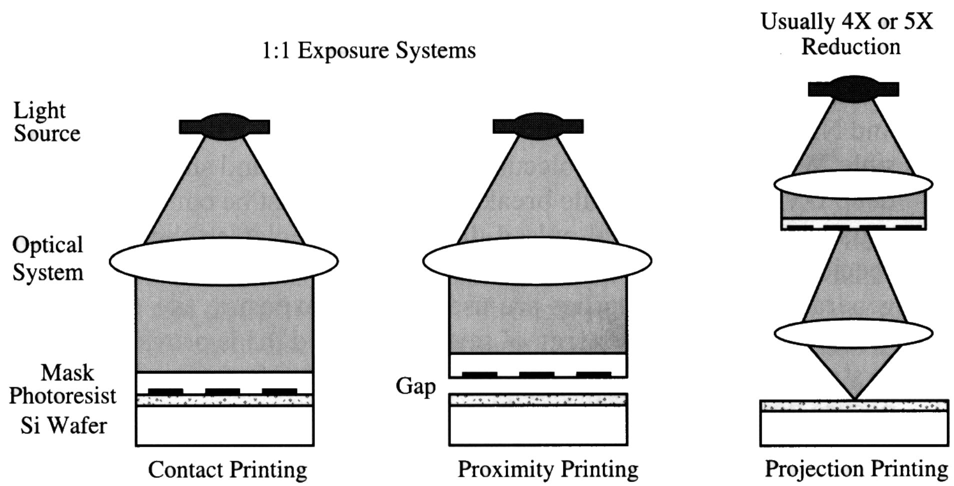


Figure 5–3 Three basic methods of wafer exposure.

Issues with Photolithography

1.) Resolution:

Resolution is "diffraction limited". As patterns approach the same order of magnitude as the wavelength of light, one must be concerned with the wavelike nature of light.

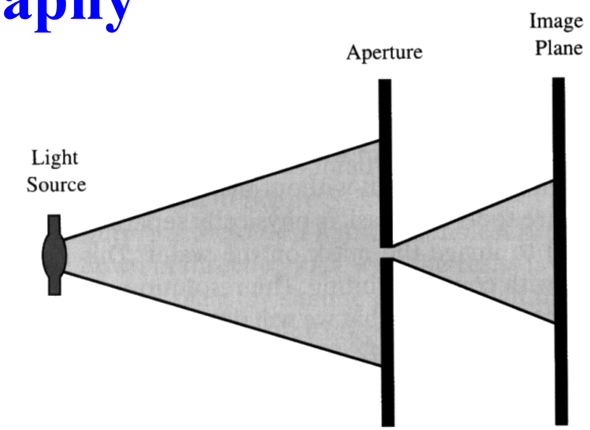
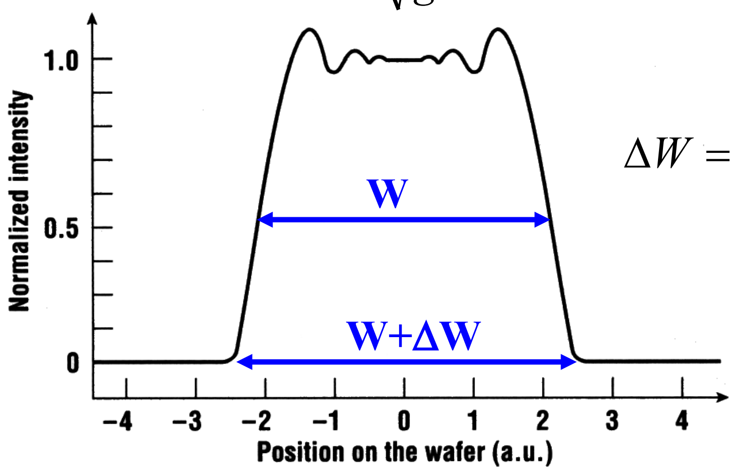


Figure 5–4 Simple example of diffraction effects. Light passes through a narrow aperture. The image formed covers a much larger area than can be explained based on simple straight line ray tracing.

Case 1: Square Mask in the Near Field (Mask close to Wafer)

The mask can be placed in close proximity or directly in contact with the wafer (contact or proximity printing). We define this case, known as the near field or Fresnel diffraction limit, by the expression:

$$W^2 >> \lambda\sqrt{g^2 + r^2}$$



$$\Delta W = W\frac{g}{D}$$

Figure 7.6 Typical near field (Fresnel) diffraction pattern.

Definitions used for Resolution Equations

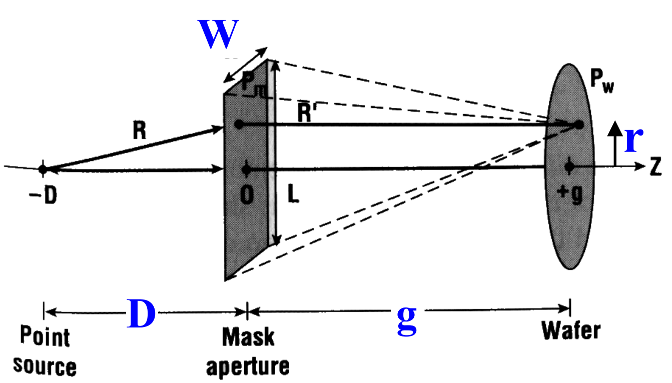


Figure 7.5 Huygen's principle applied to the optical system shown in Figure 7.4. A point source is used to expose an aperture in a dark field mask.

(Contd…) Square Mask in the Near Field (Mask close to Wafer)

Effect of increasing mask-wafer gap spacing

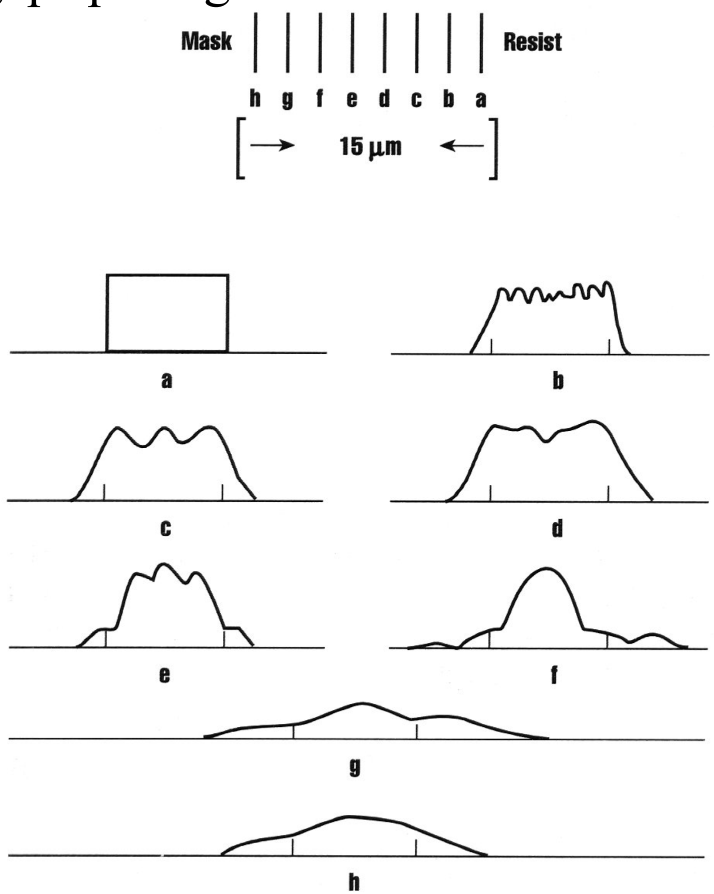


Figure 7-16 Intensity as a function of position on the wafer for a proximity printing system where the gap increases linearly from $g = 0$ to $g = 15$ µm *(after Geikas and Ables)*.

Assuming:

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

Then the minimum feature size that can be resolved is:

$$W_{\min} \approx \sqrt{k\lambda\, g}$$

where k is a constant, normally close to 1, that depends on the photoresist and the development procedures

Example: For a k=1, and λ=0.365 (I-line)

W_{min}	g (gap)
2.7 um	20 um
1.9 um	10 um
1.35 um	5 um
0.6 um	1 um

Case 2: Square Mask in the Far Field (Mask far away from the wafer)

The mask can be placed far away from the wafer (projection printing used in stepping and scanning systems). We define this case, known as the far field or Fraunhofer diffraction limit, by the expression:

$$W^2 << \lambda\sqrt{g^2 + r^2}$$

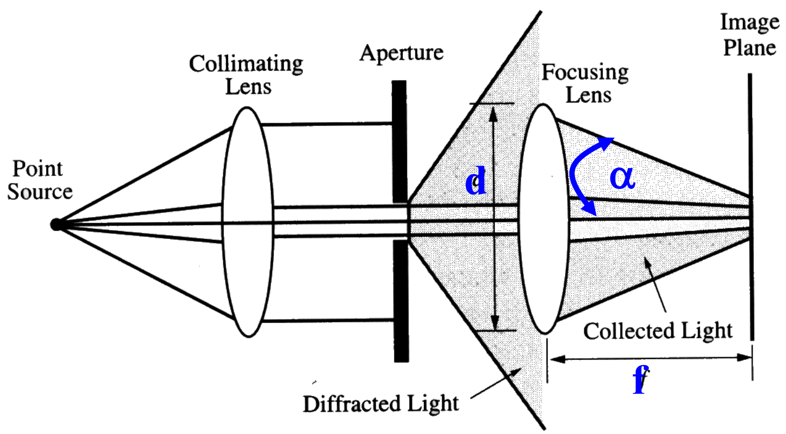


Figure 5–6 Qualitative example of a small aperture being imaged.

d = Diameter of focusing optics
f = Focal length of focusing optics
From geometry,

d= 2[n(f sin(α)] where n is the index of refraction (normally 1 for air but now n>1 is used in "immersion" lithography), and α is the angle to the edge of the focusing optics

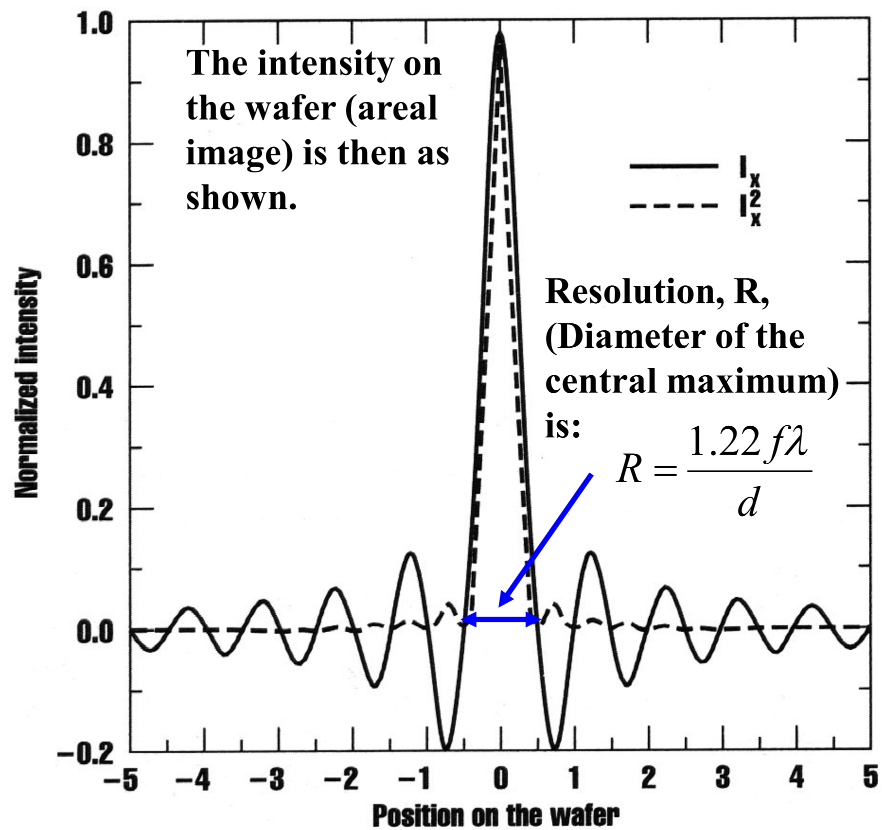


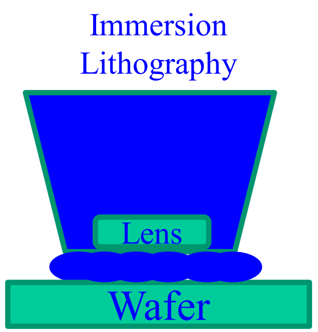
Figure 7-7 Typical far field (Fraunhofer) image.

How Quickly the side lobes die off determines the printable pitch

(cont'd…) Square Mask in the Far Field (Mask far away from the wafer)

$$R = \frac{1.22 f\lambda}{d} = \frac{1.22 f\lambda}{n(2f\sin(\alpha))} = \frac{0.61\lambda}{n\sin(\alpha)} = \frac{0.61\lambda}{NA}$$

Immersion Lithography



Where NA is the numerical aperture of the focusing optics. The Numerical Aperture describes the focusing strength of the projection system:

However, all our derivation is based on a "point source" which is not ever possible, thus, we can generalize using a constant k (normally ~0.75) the result as:

$$W_{\min} \approx k\frac{\lambda}{NA}$$

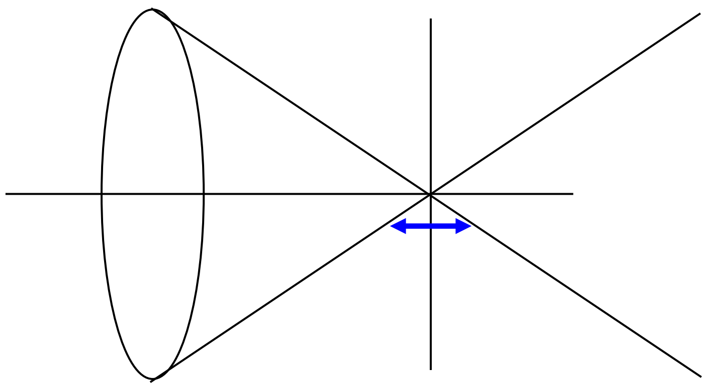
Briefly discuss immersion lithography.

Depth of Focus:

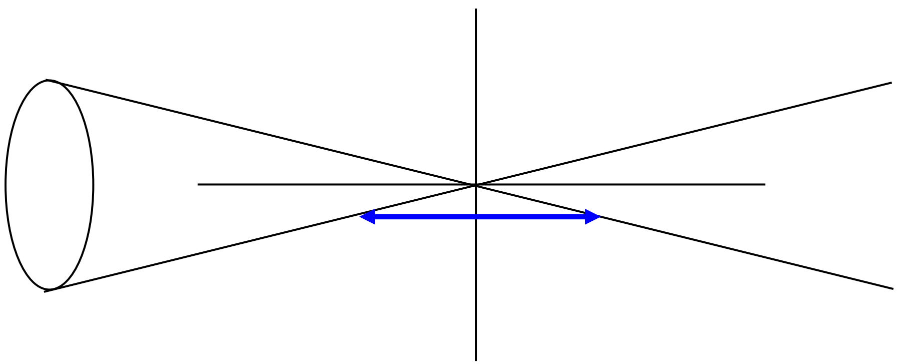
Depth of Focus: While increasing the NA will result in smaller patterns, it also effects the depth of focus (range of lengths for which the image is in focus on the wafer).

$$Depth\ of\ \ focus = \sigma = \frac{\lambda}{NA^2}$$

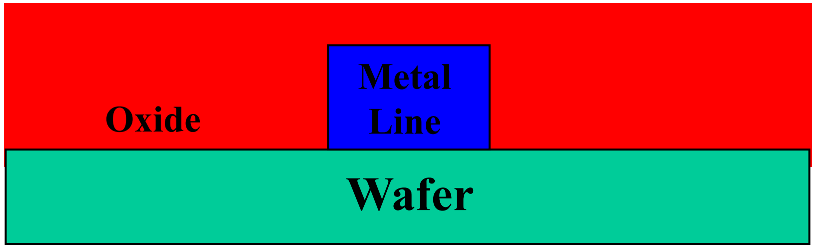
Large NA results in small Depth of Focus



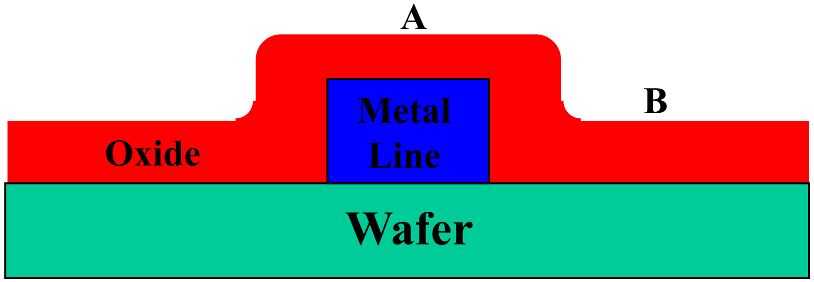
Small NA results in large Depth of Focus



Variations in surface heights of a processed wafer must be less than the optical Depth of Focus. Thus, for high resolution lithography the surface must be planar (flat).



High resolution (small depth of field) lithography can focus on point A or B but not A and B simultaneously



Comparison of Areal Images of the Three types of Photolithography Systems

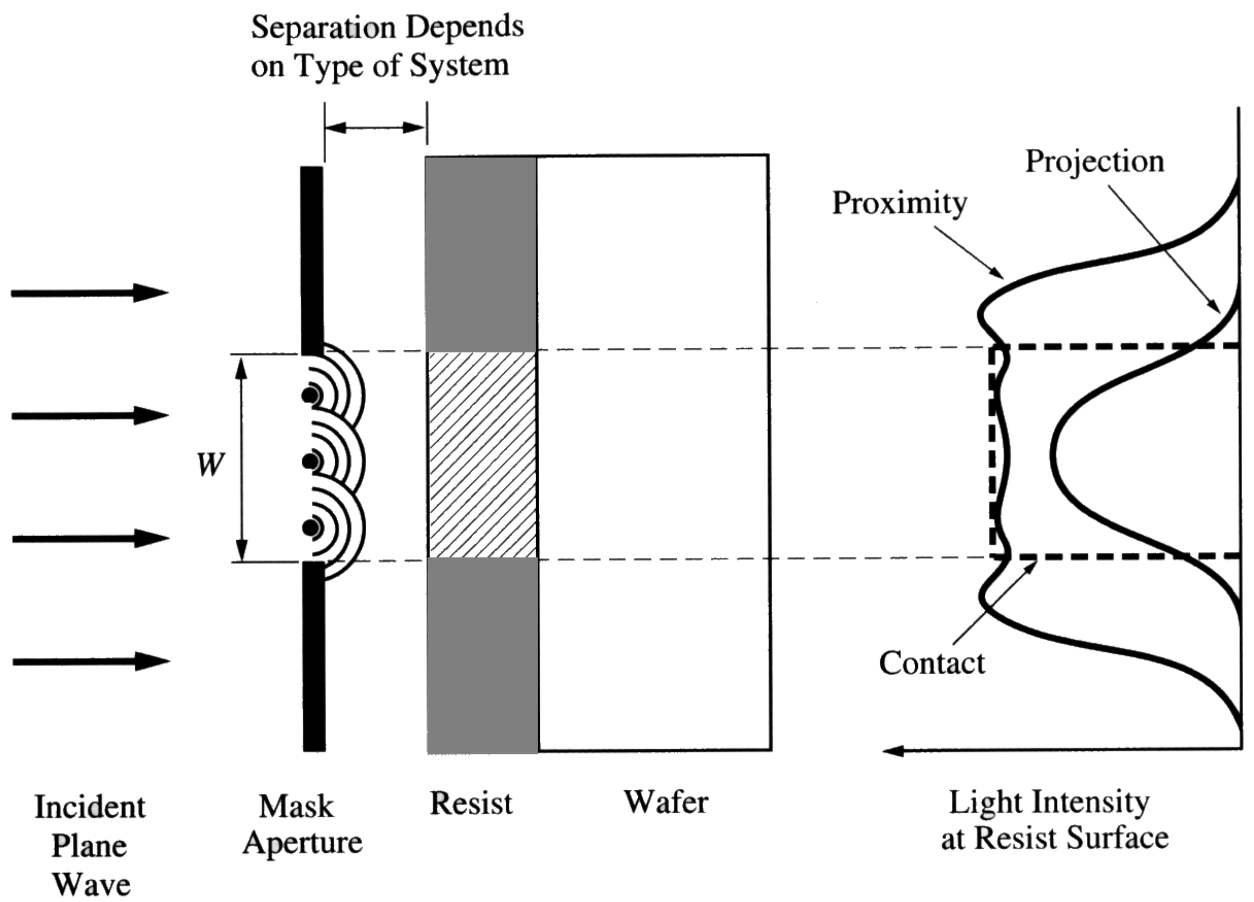
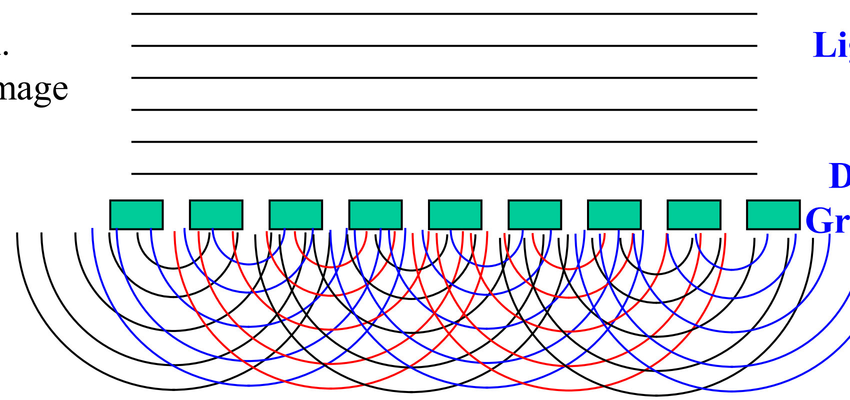


Figure 5–15 Aerial images produced by the three types of optical lithography tools. The mask and wafer would be in hard contact in a contact aligner, separated by a gap *g* in a proximity aligner, and far apart with an intervening focusing lens in a projection system.

Diffraction Gratings

Consider a diffraction grating instead of a single square aperture, the Fraunhofer limited (far field) intensity pattern (non-normalized intensity in W/cm^2) is shown. We can define a measure of the contrast in the areal image (image on the wafer) by the **Modulation Transfer Function**,

$$MTF = \left[\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}\right]$$



MTF is a measure of an exposure tool's ability to modulate the intensity of light at the wafer surface and decreases with decreasing diffraction grating period (more destructive interference).

Imin does not have to be zero! Thus, it is possible for a bad tool or a good tool stretched to its limits to expose the photoresist everywhere, thus not transferring the pattern.

In the next section we will describe the development of photoresists that are sensitive enough to be exposed where we want them but not so sensitive we expose the resist everywhere.

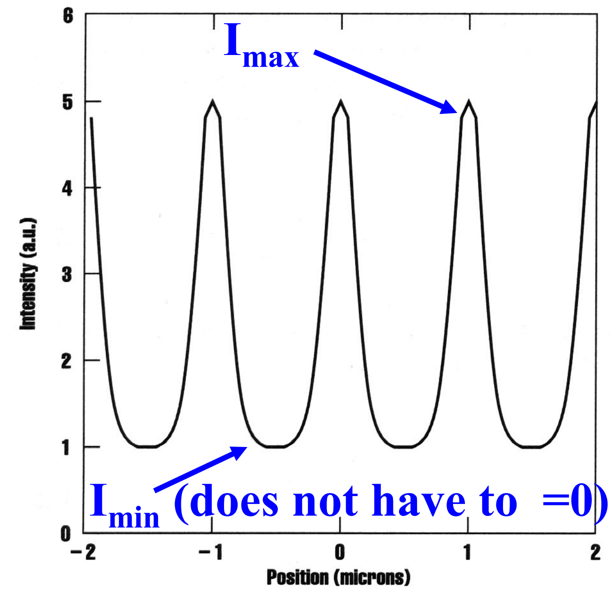


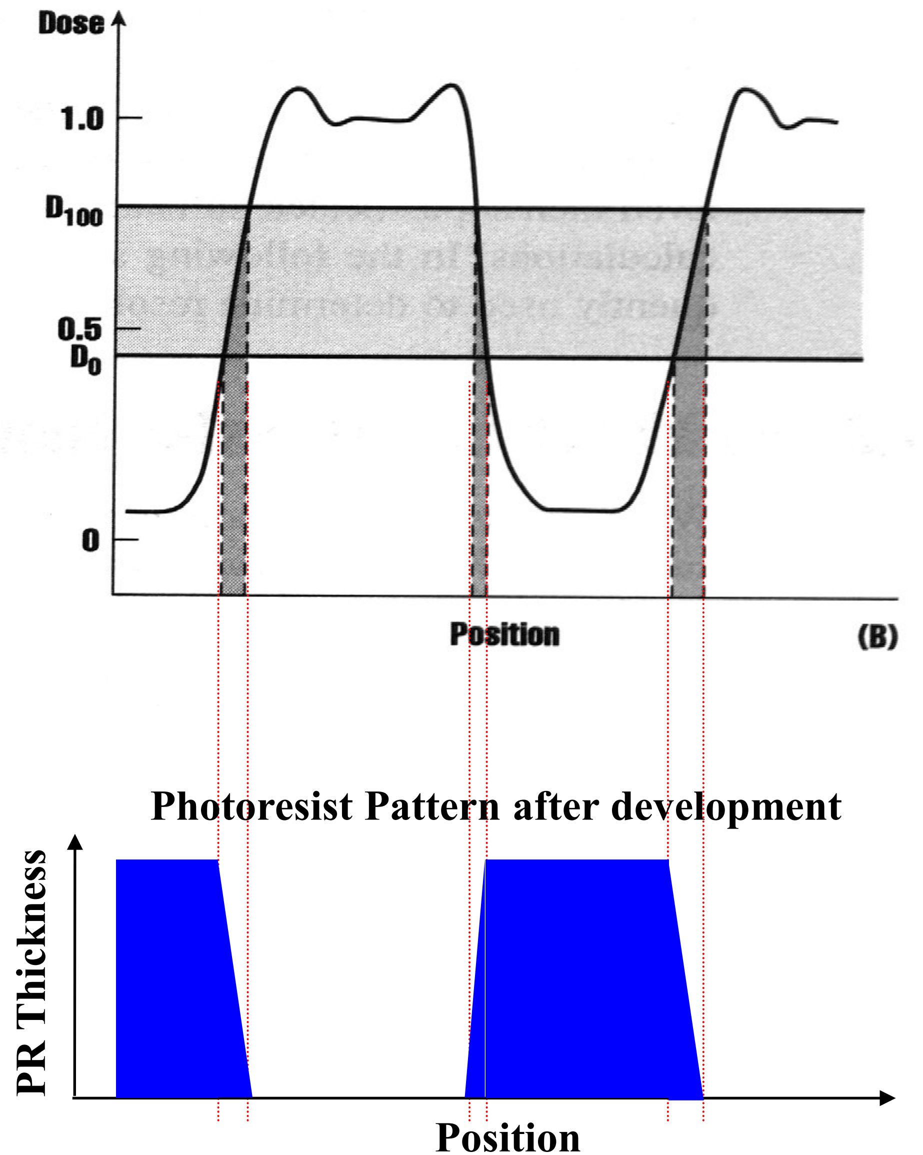
Figure 7-8 Far field image for a diffraction grating.

Optical Dose Supplied to PR

The MTF uses the power density (W/cm^2 or (J/sec)/cm^2). The resist responds to the total amount of energy absorbed. Thus, we need to ***define the Dose, with units of energy density (mJ/cm^2), as the Intensity (or power density) times the exposure time.***

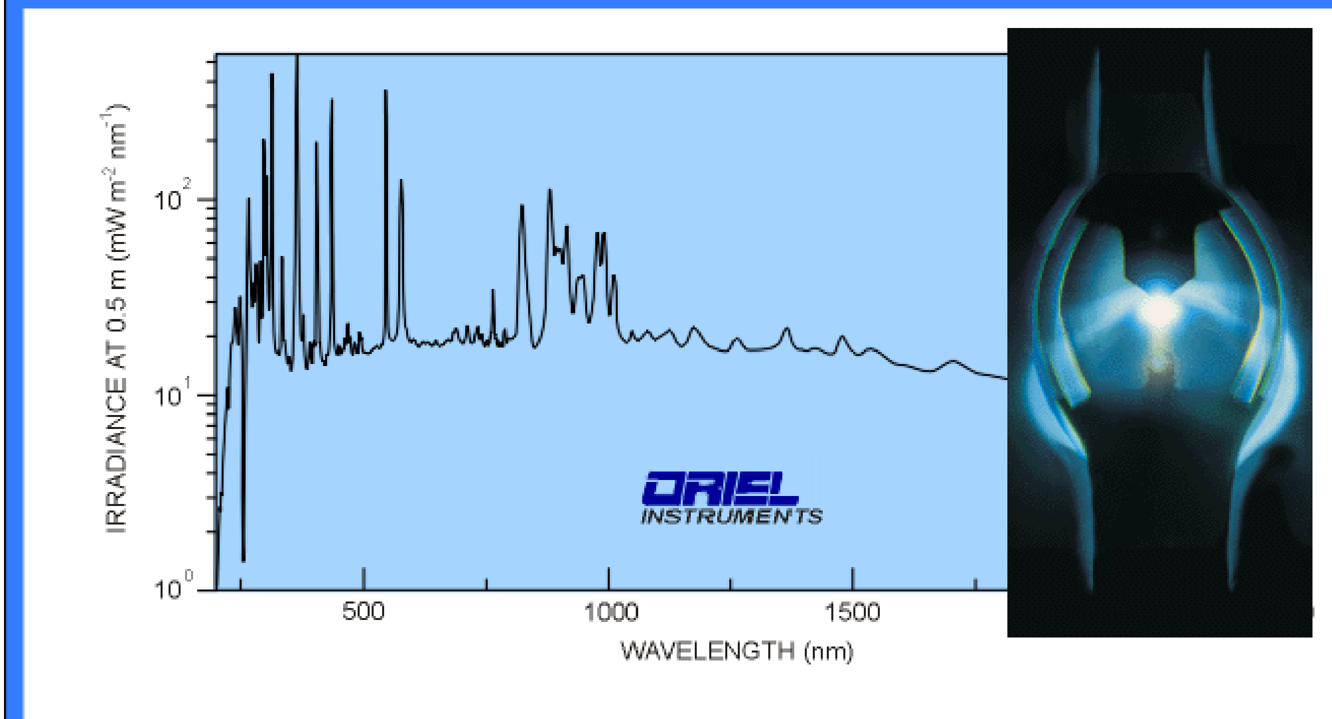
- We can also define ***D_{100}= the minimum dose for which the photoresist will completely dissolve when developed***.
- We define ***D_0 as the maximum energy density for which the photoresist will not dissolve at all when developed***.
- Between these values, the photoresist will partially dissolve.

In many cases, we want very high contrast, producing sharp lines. In very few cases, improving step coverage for deposited layers, or even in an image reversal process such as AZ 5214 resist, one may desire moderately low contrast.



Light Source and Exposure Equipment

Typically mercury (Hg)- Xenon (Xe) vapor bulbs are used as a light source in visible (>420 nm) and ultraviolet (>250-300 nm and <420 nm) lithography equipment.
Commonly used molecular transition lines in Hg-Xe bulbs are 436 nm (g-line), 365 (i-line), 290, 280, 265 and 248 nm. All other wavelengths are filtered out.



Lasers are used to increase resolution (near infinite source to mask spacing), and decrease the optical complexity for deep ultraviolet (DUV) lithography systems. Excited dimer (Excimer or Exiplex) pulsed lasers are typically used. These are powerful, extremely expensive to purchase and maintain, optically noisy lasers.

Final Points

Steppers and Scanners can have a reduction built in. Thus, a 5X reduction means to produce 0.5 um lines, the mask must have 2.5 um features. Also, dirt or particles on the mask are much smaller on the wafer. Most importantly, defects are consistent from exposure to exposure. Steppers can easily incorporate lasers instead of Hg-vapor bulbs, increasing resolution dramatically.

Where are we ~~today~~:
Pentium II was a 0.25 um technology and was produced exclusively with excimer steppers.
Current and future generations of microprocessors will be 0.18, 0.15 and 0.13 um technology.
See Predictions from Solid State Technology Table I.

Update: 2017 node is actually 0.007 um

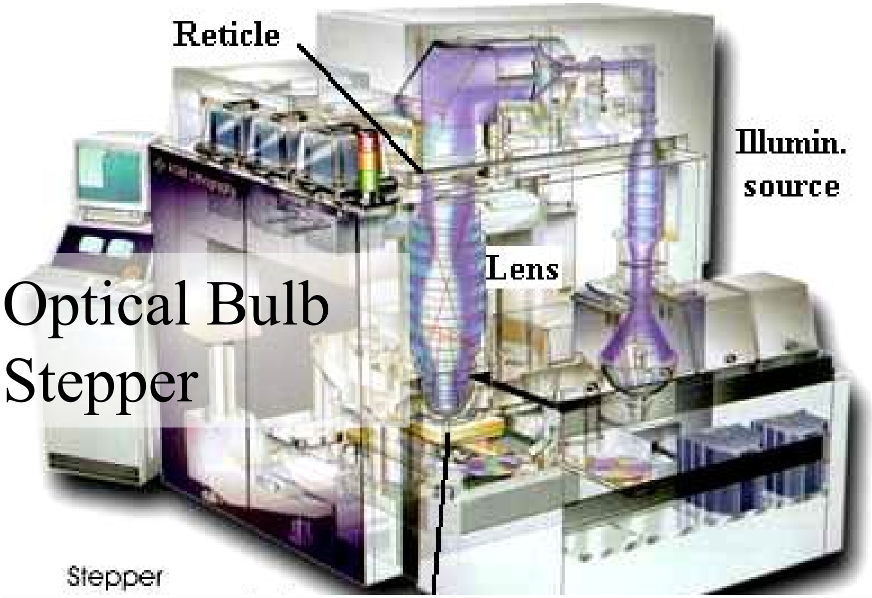
Read sections 7.7, 7.8, 7.9 in your text.

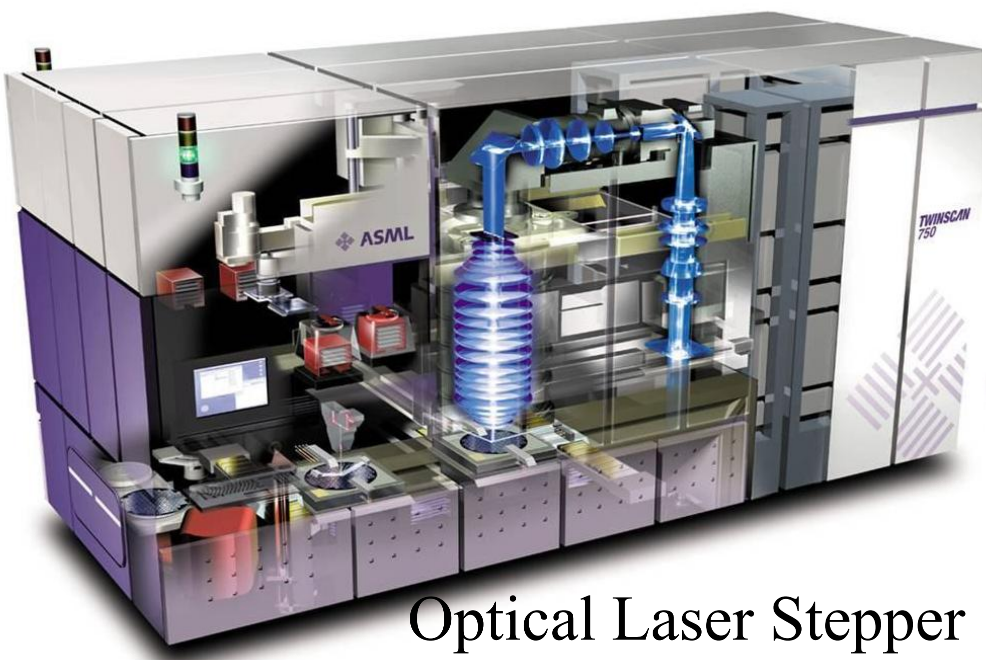
Table 1. Trends in optical lithography system parameters

	1990	1995	1999	2002	2005	2008
NA	0.5	0.6	0.7	0.7	0.75	0.8
k_1	0.7	0.6	0.5	0.45	0.4	0.35
Wavelength (nm)	365	248	248	248/193	248/193	193/157
Critical dimension (nm)	500	250	180	150/130	130/100	80/70
Field size (mm × mm)	20×20	22×22	26×34*	26×34*	26×34**	26x34**
Depth of focus (µm)	1.5	1.0	0.6	0.5	0.4	0.3

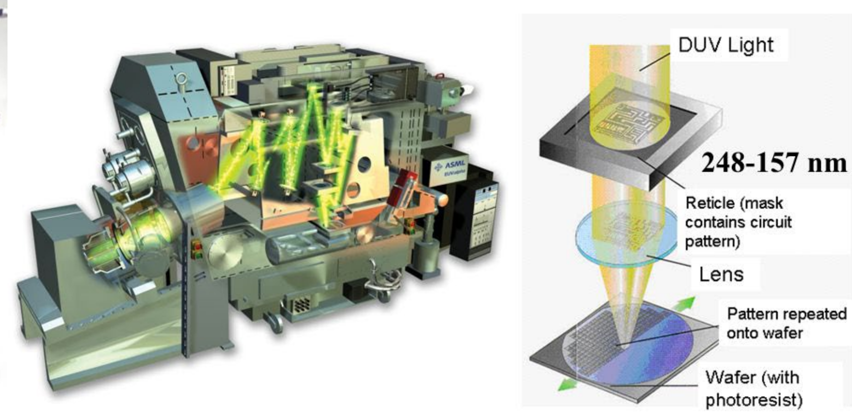
System parameters indicated for the years 2002–2008 are predictions based on current observed trends and anticipated capabilities.
(* = 1D scanning, ** = 2D scanning)

Updated Status: Lithography





Excimer Laser Stepper



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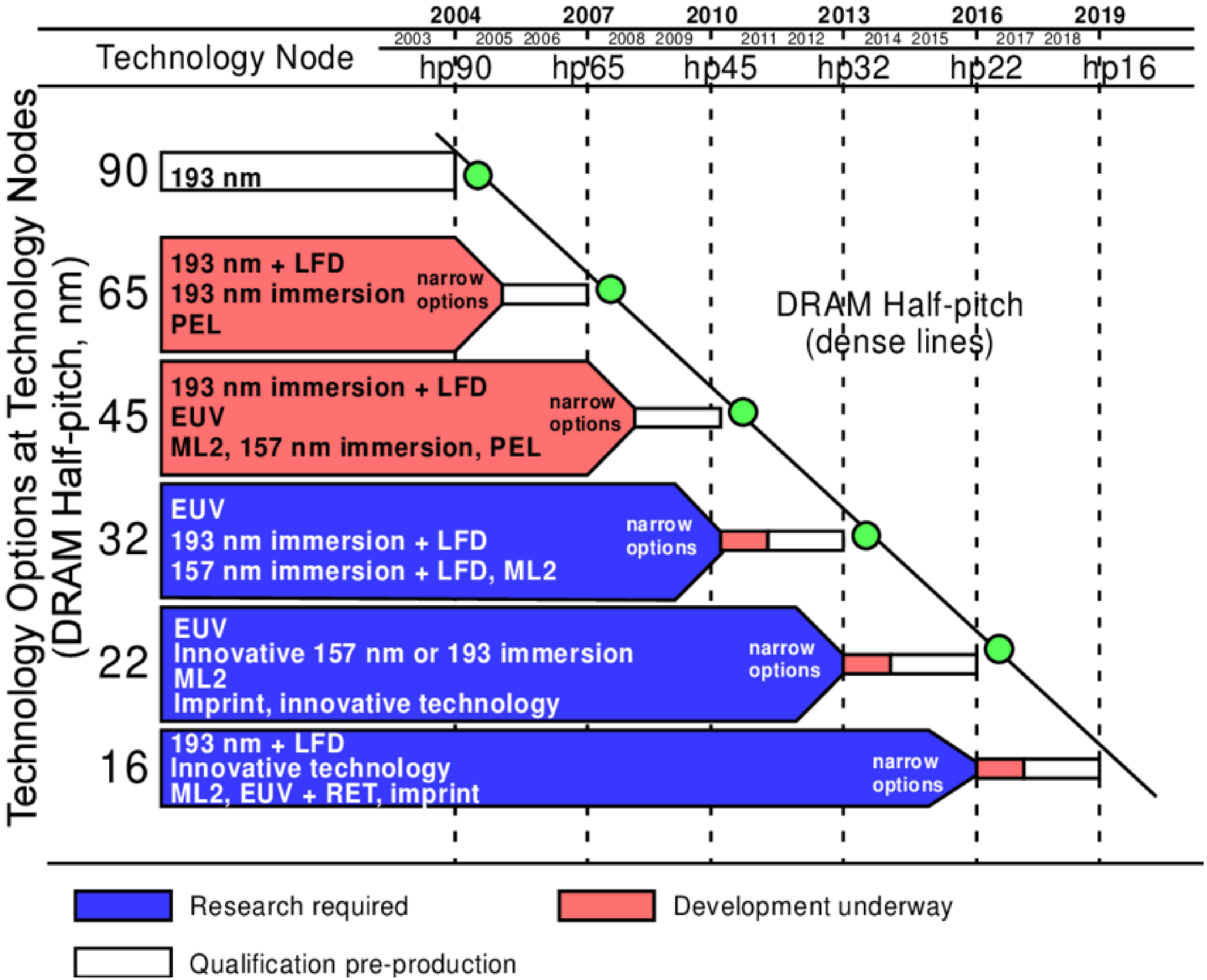
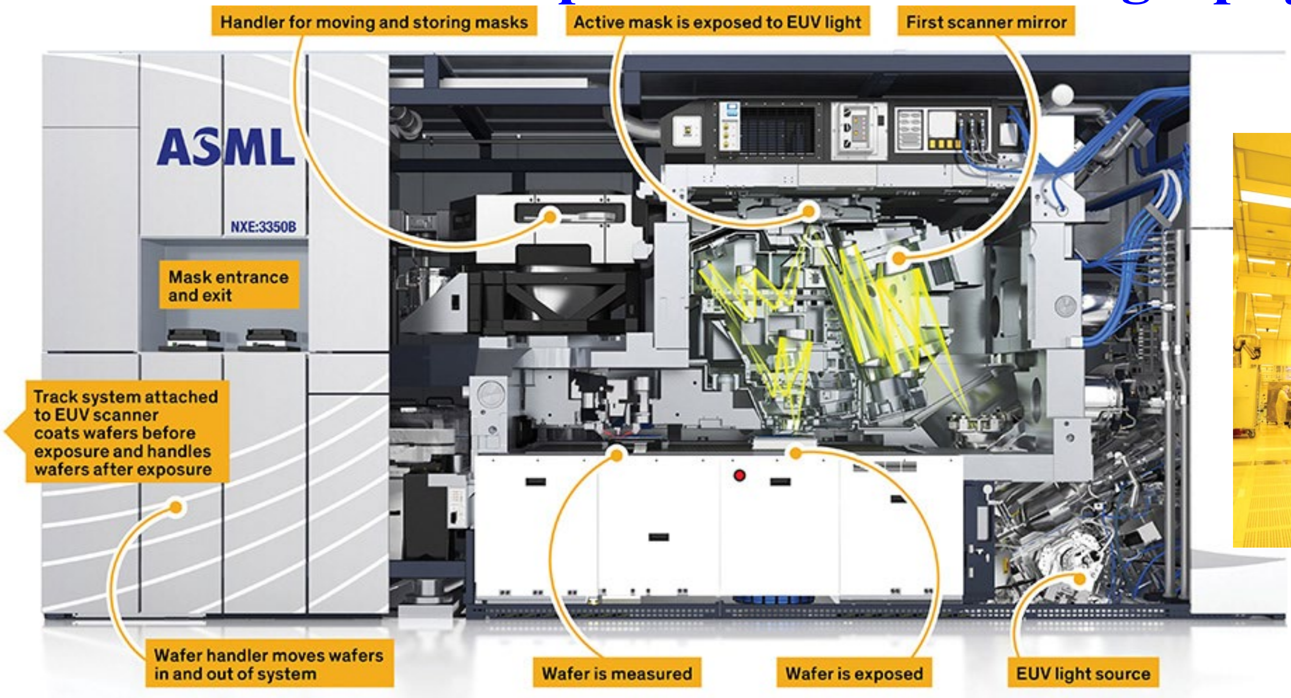
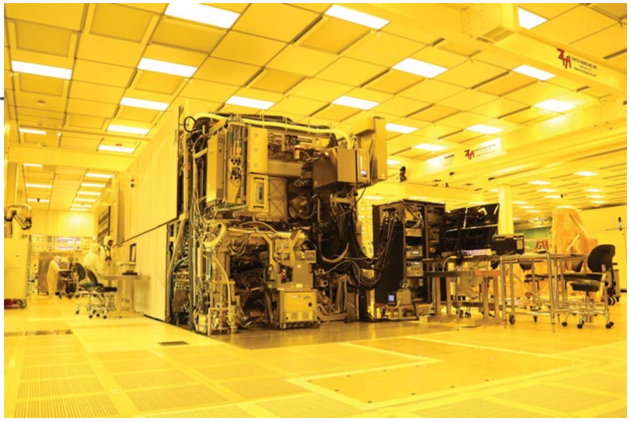


Updated Status: Lithography





Advanced EUV Stepper

https://www.youtube.com/watch?v=f0gMdGrVteI