ECE 416/516
IC Technologies
Lecture 7:
Optical Lithography

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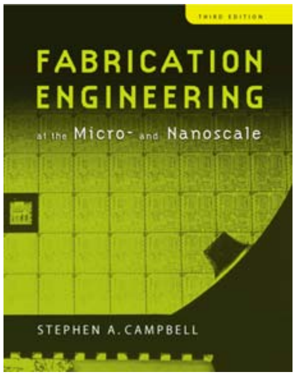
Chapter 7

Optical Lithography



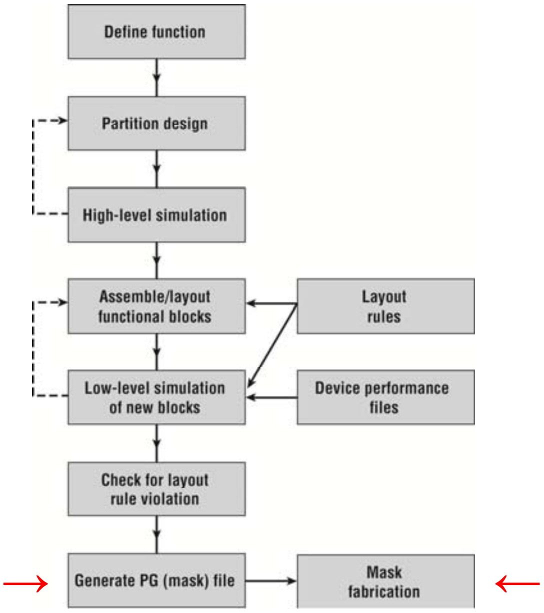


Figure 7.1 Simplified IC design process flow diagram.

Optical Lithogaphy

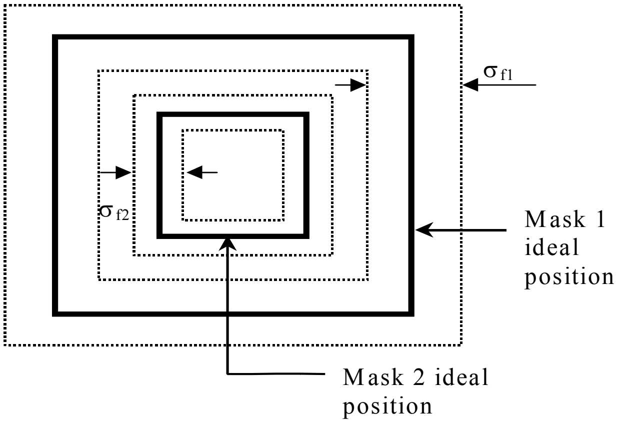
- Lecture topics:
  - A. Light sources
  - B. Wafer exposure systems
    - 1. Optics
    - 2. Projection
    - 3. Proximity/contact
    - 4. Immersion
  - C. Photoresist (also lecture 8)
  - D. Simulation
  - E. Sub-wavelength lithography
  - F. Interference effects
  - G. Minimum feature sizes
- Lecture Objectives:
  - Can calculate resolution limits and line width errors due to optical limitations
  - Can calculate PR exposure variations due to standing wave effects
- Lecture emphasis:
  - Optical Limits
    - Proximity Printing
    - Projection Printing
  - Technology Comparisons

Introduction

- Process of image transfer to wafer
    - Origin pattern drawn N x
- Images control diffusion, oxidation, & metallization sequences
    - expose parts, mask others
- "Masking levels" refer to each mask used
- Lithographic Sequence:

1. Draw mask 100-2000x final size
2. Photographically reduce to 10x final size (glass)
3. Step & repeat -> [1 x final size] x [matrix of images] (glass)
4. Spin coat substrate with photoresist
    - thickness α (spin rate)$^{-1/2}$
5. Expose PR through mask & "develop" to dissolve unwanted PR, etc.

Masking Registration #1



Registration tolerance --> design rules

Masking Registration #2

Estimated final tolerance:

- $T \approx 3[(\sigma_{f1}/2)^2 + (\sigma_{f2}/2)^2 + \sigma_r^2]^{1/2}$

  where σ_r is registration error

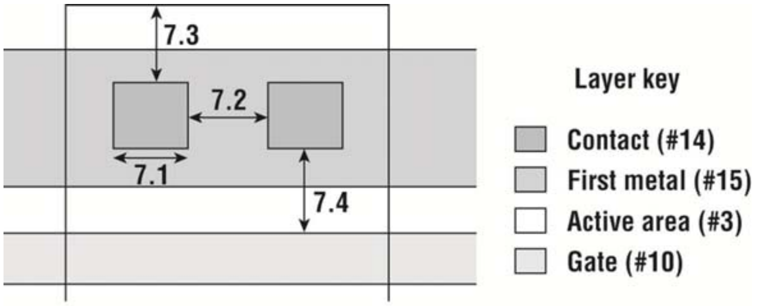
  σ's Gaussian distribution if independent

For $\sigma_{f1} \sim \sigma_{f2} \sim \sigma_r \sim \pm 0.15\mu m$

- $T \sim 0.6\ \mu m$
- limits how densely features can be packed

Ideal feature separation mask 1 to mask 2

$> 1/2\ (\sigma_{f1} + \sigma_{f2})$



7.1	Contact size (fixed)	1.0µm x 1.0µm
7.2	Minimum contact to contact space	1.2µm
7.3	Minimum active area overlap of contact	1.2µm
7.4	Minimum contact to gate spacing	0.8µm
	Maximum contact to gate spacing For standard device performance file	1.5µm
etc.		

Figure 7.2 Excerpt of typical design rule set.
This portion deals with first metal rules for a particular technology.

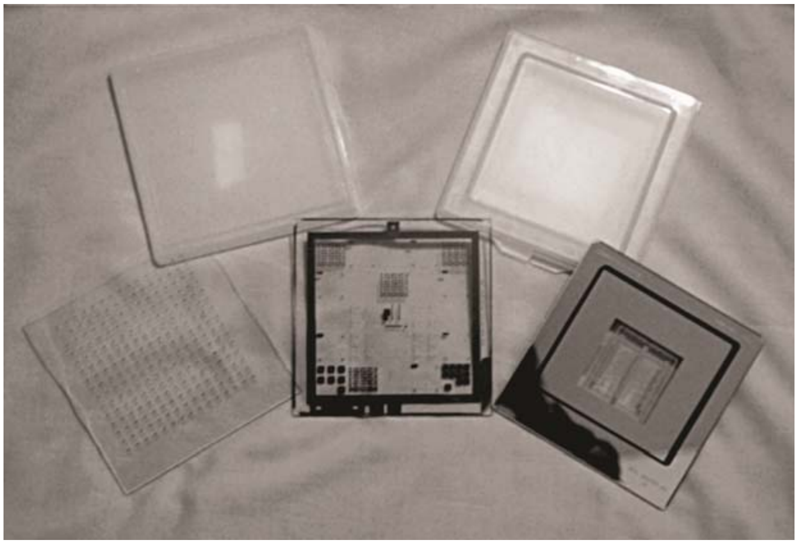


Figure 7.3 Typical photomasks including (from left) a 1´ plate for contact or projection printing, a 10´ plate for a reduction stepper, and a 10´ plate with pellicles.

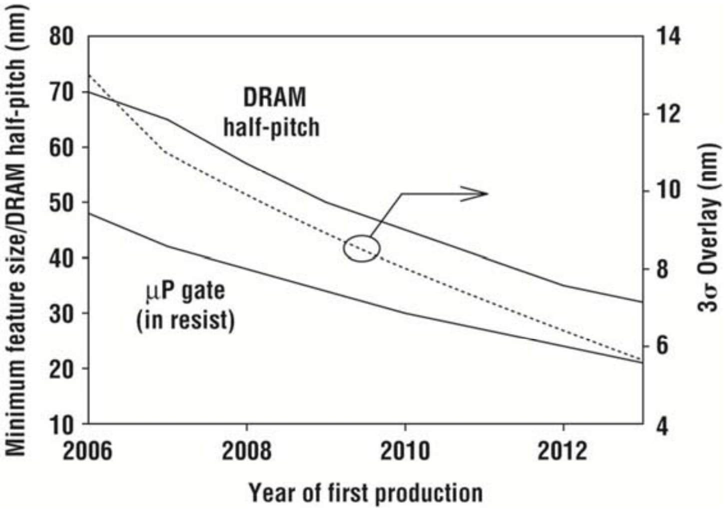


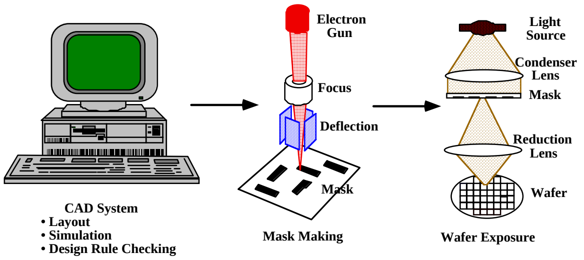
Figure 7.4 Projected lithography requirements showing overlay accuracy (right axis) and resolution requirements (left axis). Data taken from 2005 International Technology Roadmap for Semiconductors.

LITHOGRAPHY

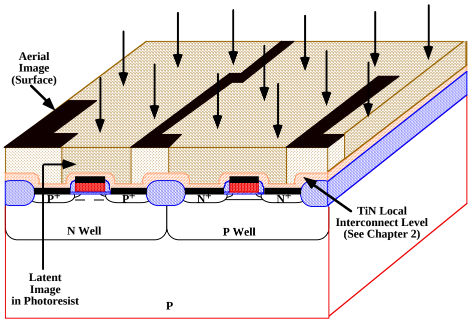
Year of Production	1998	2000	2002	2004	2007	2010	2013	2016	2018
Technology Node (half pitch)	250 nm	180 nm	130 nm	90 nm	65 nm	45 nm	32 nm	22 nm	18 nm
MPU Printed Gate Length		100 nm	70 nm	53 nm	35 nm	25 nm	18 nm	13 nm	10 nm
DRAM Bits/ Chip (Sampling)	256M	512M	1G	4G	16G	32G	64G	128G	128G
MPU Transistors/Chip ($x10^6$)				550	1100	2200	4400	8800	14,000
Gate CD Control 3σ (nm)				3.3	2.2	1.6	1.16	0.8	0.6
Overlay (nm)				32	23	18	12.8	8.8	7.2
Field Size (mm)	22x32	22x32	22x32	22x32	22x32	22x32	22x32	22x32	22x32
Exposure Technology	248 nm	248 nm	248 nm + RET	193nm + RET	193nm + RET	193nm + RET + H_2O	193nm + RET + H_2O 157nm??	???	???
Data Volume/Mask level (GB)				216	729	1644	3700	8326	12490

- 0.7X in linear dimension every 3 years.
- Placement accuracy ≈ 1/3 of feature size.
- ≈ 35% of wafer manufacturing costs for lithography.
- Note 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

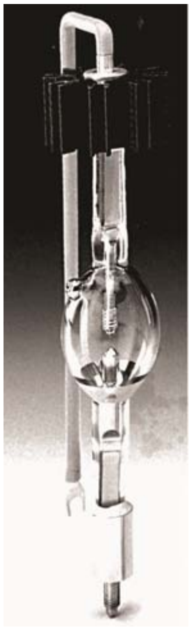
- Decreasing feature sizes require the use of shorter λ .
- Traditionally Hg vapor lamps have been used which generate many spectral lines from a high intensity plasma inside a glass lamp.
- (Electrons are excited to higher energy levels by collisions in the plasma. Photons are emitted when the energy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

$$\text{Kr} + \text{NF}_3 \xrightarrow[\text{energy}]{} \text{KrF} \rightarrow \text{photon emission} \qquad (1)$$

- KrF - $\lambda = 248\ \text{nm}$ (used for 0.25 μm, 0.18μm, 0.13 μm)
- ArF - $\lambda = 193\ \text{nm}$ (used for 0.13μm, 0.09μm, . . .)
- FF - $\lambda = 157\ \text{nm}$ (used for ??)

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

Figure 7.13 Typical high pressure, short arc mercury lamp *(courtesy Osram Sylvania).*



High-T electrons→gray body radiation, (absorbed by silica glass)

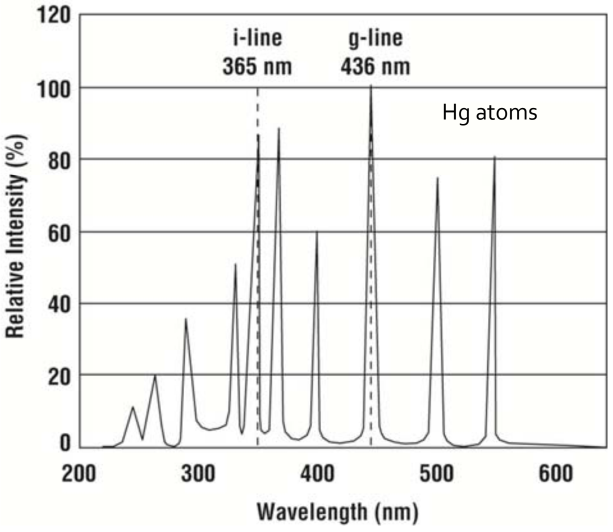


Figure 7.14 Line spectra of typical mercury arc lamp showing the positions of the two lines most commonly used in lithography.

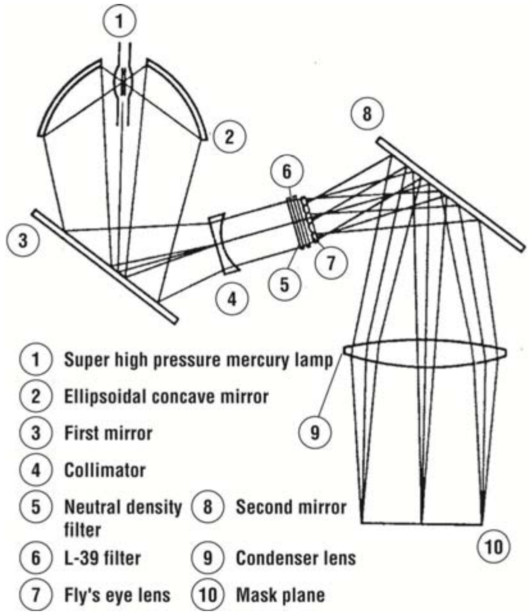


Figure 7.15 Schematic of a typical source assembly for a contact/proximity printer *(after Jain)*.

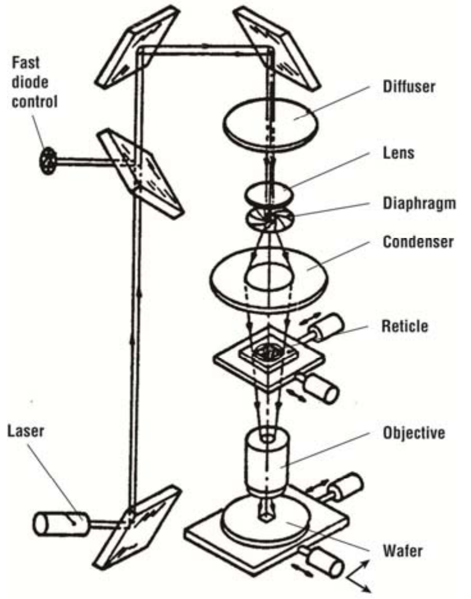
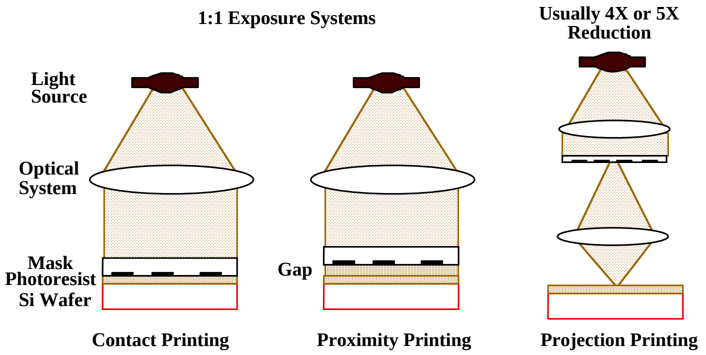


Figure 7.17 Optical train for an excimer laser stepper *(after Jain)*.

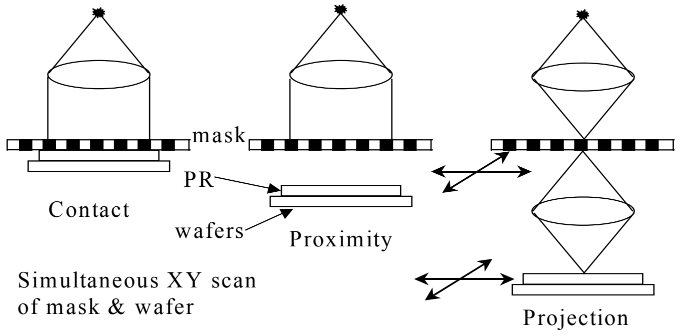
B. Wafer Exposure Systems



- **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 \$10 - 25M.**

Wafer exposure systems



Usually x, y, & θ control to align mask to substrate

- alignment marks

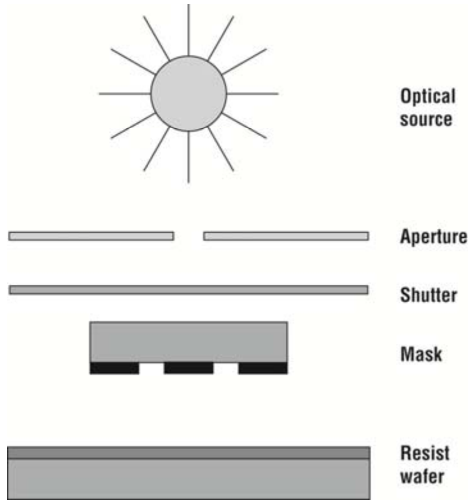
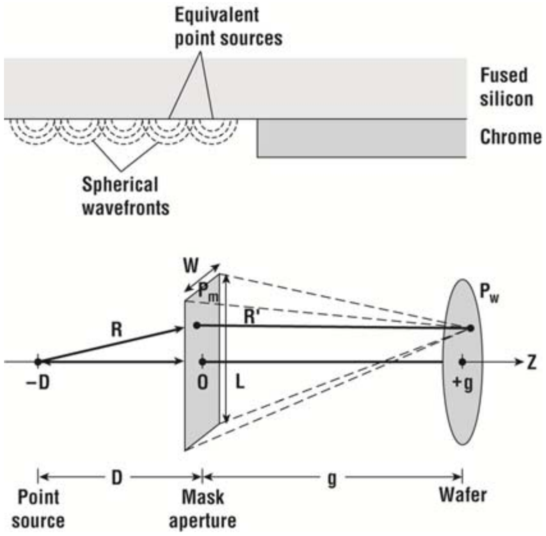


Figure 7.5 Schematic of a simple lithographic exposure system.



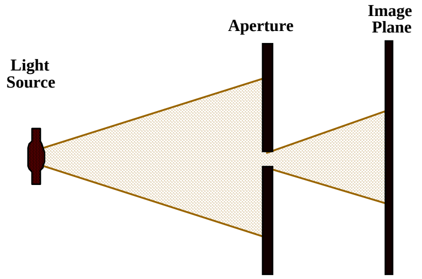
$$\xi(r,\nu) = E_0(r)e^{j\phi(r,\nu)}$$

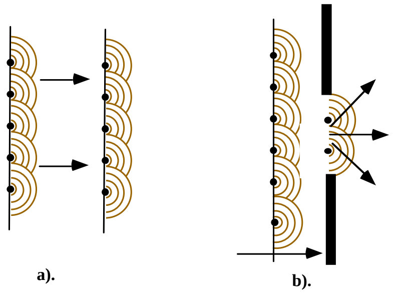
$$\xi(R') = j\frac{A}{\lambda}\iint_{\Sigma}\frac{e^{-jk(R,R')}}{RR'}d\sigma$$

Figure 7.6 Huygens's principle applied to the optical system shown in Figure 7.5. A point source is used to expose an aperture in a dark field mask.

B1. Optics - Basics and Diffraction (Huygens-Fresnel principle)

- **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.**



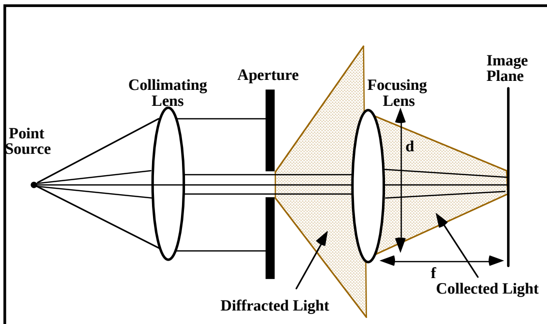


- **If the aperture is on the order of λ, the light spreads out after passing through the aperture. (The smaller the aperture, the more it spreads out.)**

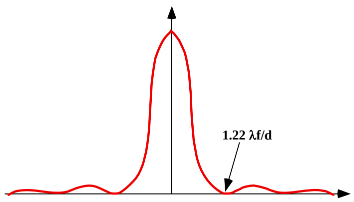
$$(a)\,W,L \to \infty \quad I = \xi\xi^* = E_0 e^{j\phi} E_0 e^{-j\phi} = E_0^2$$

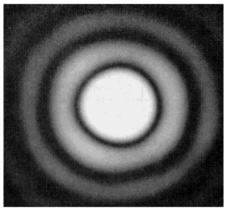
$$(b)\,W,L \to 0 \quad I = \left(E_1 e^{j\phi_1} + E_0 e^{j\phi_2}\right)\left(E_1 e^{-j\phi_1} + E_0 e^{-j\phi_2}\right) \text{for 2 point sources}$$

$$= E_1^2 + E_1^2 + E_1 E_2 \cos\left(\phi_1 - \phi_2\right)$$



- **If we want to image the aperture on an image plane (resist), we ca 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 spatial frequency components).**





Diameter of central maximum=1.22λf/d

- **A simple example is the image formed by a small circular aperture (Airy disk).**
- **Note that a point image is formed only if $\lambda \to 0$, $f \to 0$ or $d \to \infty$.**

where f=focal length,
d=focusing lens diameter

- **Diffraction is usually described in terms of two limiting cases:**
  - **Fresnel diffraction - near field.**
  - **Fraunhofer diffraction - far field.**

B2
Projection
printing

If $W^2 << \lambda\sqrt{g^2+r^2} \rightarrow$ Fraunhofer diffraction

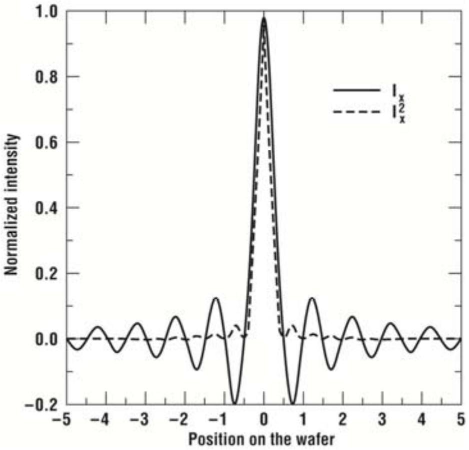


Figure 7.8 Typical far field (Fraunhofer) image.

$$I(x,y) = I_e(o)\left[\frac{(2W)(2L)}{\lambda g}\right]^2 I_x^2 I_y^2,\ I_x = \frac{\sin\frac{2\pi x W}{\lambda g}}{\frac{2\pi x W}{\lambda g}},\ I_y = \frac{\sin\frac{2\pi y L}{\lambda g}}{\frac{2\pi y L}{\lambda g}}$$

Projection

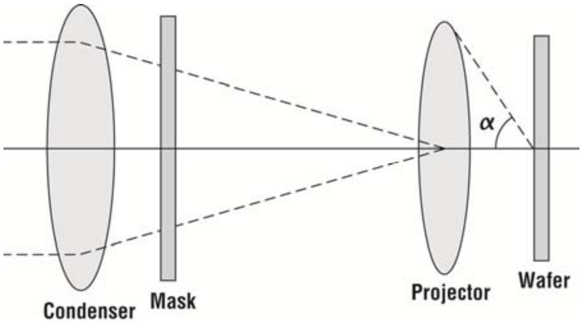
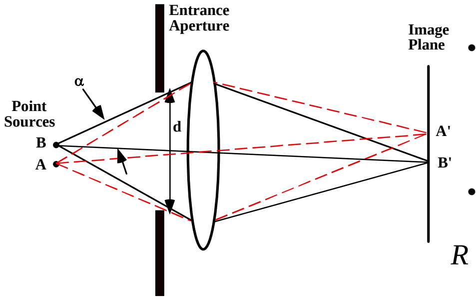


Figure 7.21 Schematic for the optical train of a simple projection printer.

NA = n sinα
Refractive index n = 1 for air
Rayleigh's resolution criterion $W_{min} = k_1\lambda/NA$

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 this basic optical projection system.
- Rayleigh suggested that a reasonable criterion for resolution is that the central maximum of each point source lie at the first minimum of the Airy pattern.
- With this definition,

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

- The numerical aperture of the lens is by definition, $\mathrm{NA} \equiv n \sin\alpha$ (3)
- NA represents the ability of the lens to collect diffracted light.

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

- k_1 is an experimental parameter which depends on the lithography system and resist properties (≈ 0.4 - 0.8).

- Obviously resolution can be increased by:
  - decreasing k_1
  - decreasing λ
  - increasing NA (bigger lenses)

- However, higher NA lenses also decrease the depth of focus. (See next slide for derivation.)

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

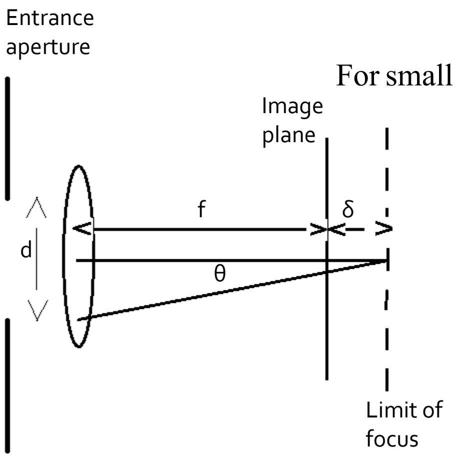
- k_2 is usually experimentally determined.

- 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).

R=W_{min} & DOF=σ in Campbell

Depth of focus

Rayleigh criterion for DOF: $\delta - \delta\cos\theta \le \lambda/4$



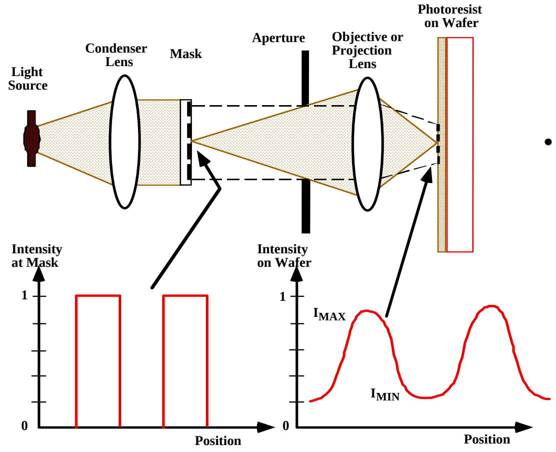
$$\text{For small } \theta: \quad \frac{\lambda}{4} = \delta\left[1-\left(1-\frac{\theta^2}{2}\right)\right] \approx \delta\frac{\theta^2}{2}$$

$$\theta \approx \sin\theta = \frac{d/2}{f} = NA$$

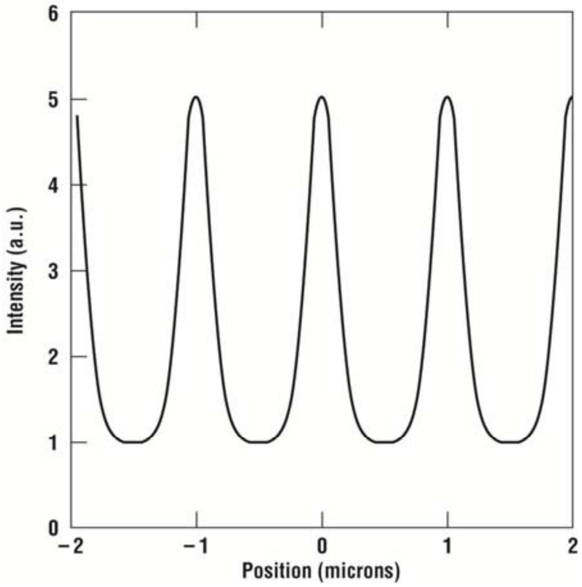
$$\therefore DOF = \delta = \pm\frac{\lambda}{2(NA)^2} \rightarrow k_2\frac{\lambda}{(NA)^2}$$

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

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



- **Note that MTF will be a function of feature size**



Define:

$$MTF = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

for an image,
e.g. for diffraction grating pattern shown

$$MTF \approx \frac{5-1}{5+1} = \frac{2}{3}$$

Figure 7.9 Far field image for a diffraction grating.

Ideally, photoresist "exposed" for Dose > D_{cr}

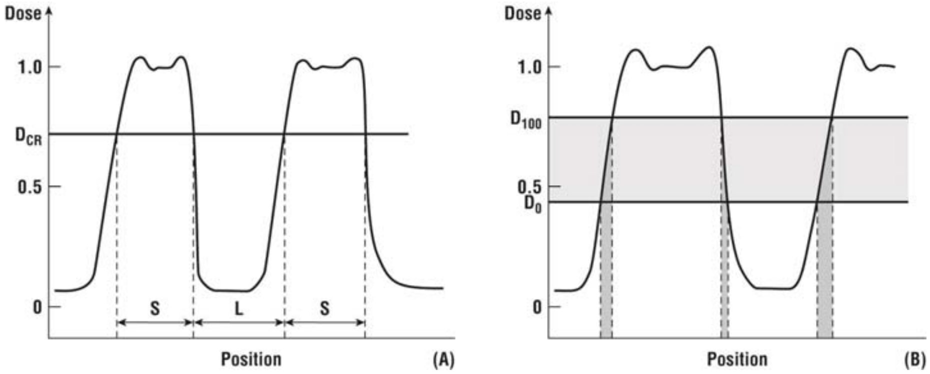
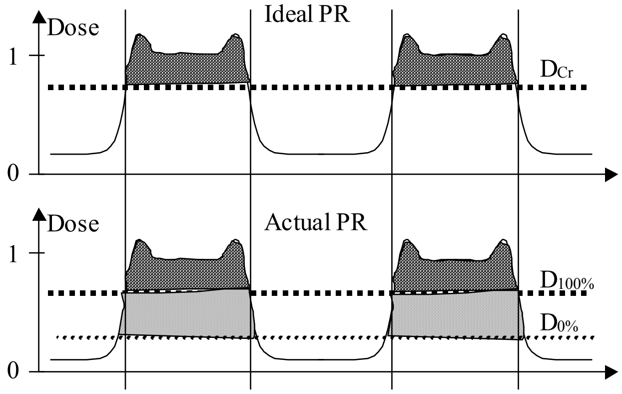


Figure 7.10 Plot of dose versus position on the wafer. Dose is given by the intensity of the light in the aereal image multiplied by the exposure time. Typical units are mJ/cm².

$D<D_0$ PR will not dissolve in developer
$D>D_{100}$ PR will completely dissolve in developer
$D_0<D<D_{100}$ PR will partially dissolve in developer

W decreases → MTF decreases
Image lost for MTF<0.4

Projection Printing Resolution #1

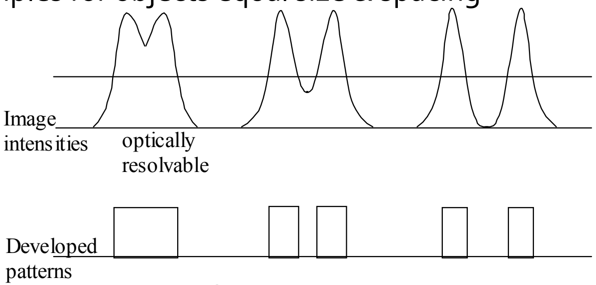


Ideal PR develops for $D>D_{cr}$ only

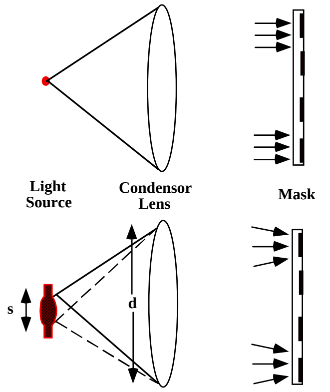
- Actual PR partially develops for $D_o > D > D_{100}$
  --> Partially dissolves

Projection Printing Resolution #2

- Rayleigh resolution limit:
  Resolvable separation $S_r = 0.6\ \lambda\ /NA$
- Examples for objects equal size & spacing



- Note square pattern from "sine" intensity allows optical print to finer lines than originally predicted (due to "clipping action" of non-linear PR)
- Note also coherence effects (Campbell Fig. 7.18)



- **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**

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

or often as

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

- **Typically, S ≈ 0.5 to 0.7 in modern systems.**

[Note: Sketch MTF vs (feature size)$^{-1}$ and variation with S next]

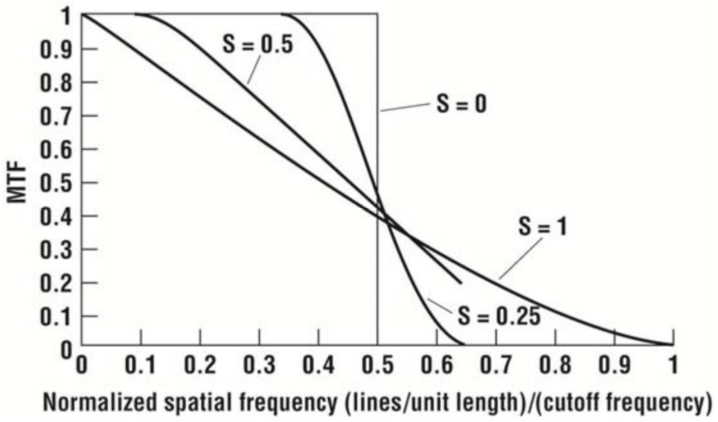
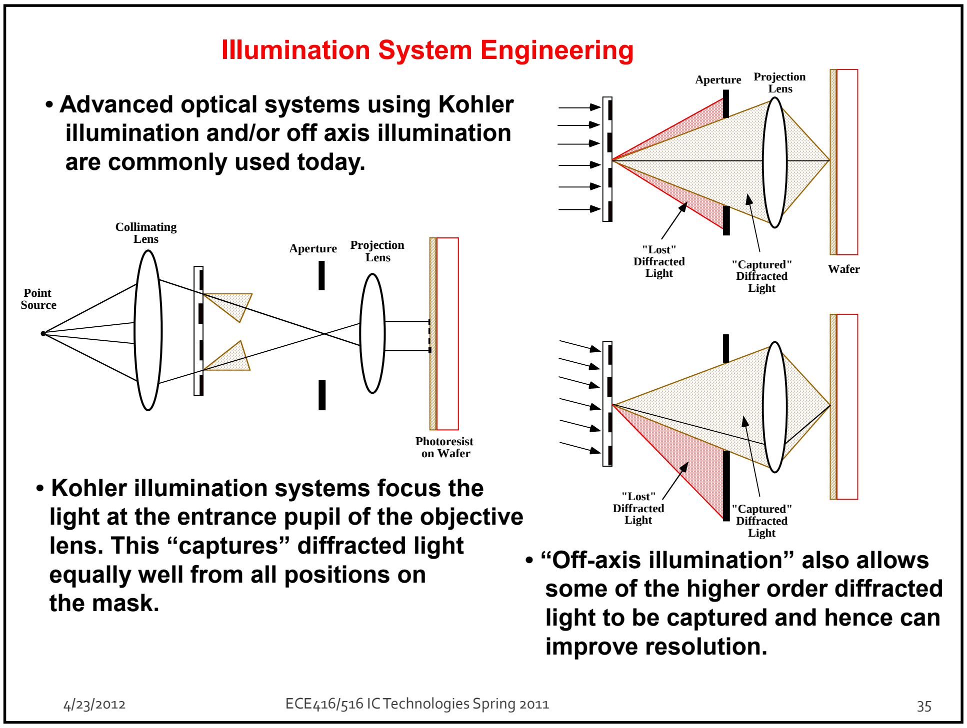


Figure 7.22 Modulation transfer function as a function of the normalized spatial frequency for a projection lithography system with spatial coherence as a parameter.

S = (Source image diameter)/(Pupil diameter)



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.

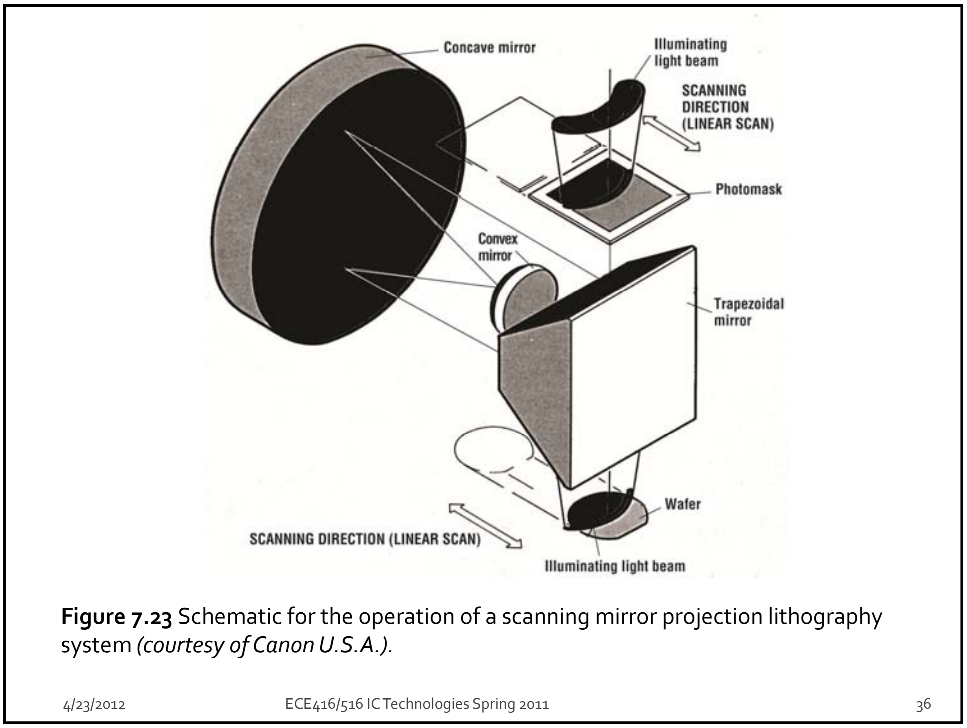


Figure 7.23 Schematic for the operation of a scanning mirror projection lithography system *(courtesy of Canon U.S.A.).*

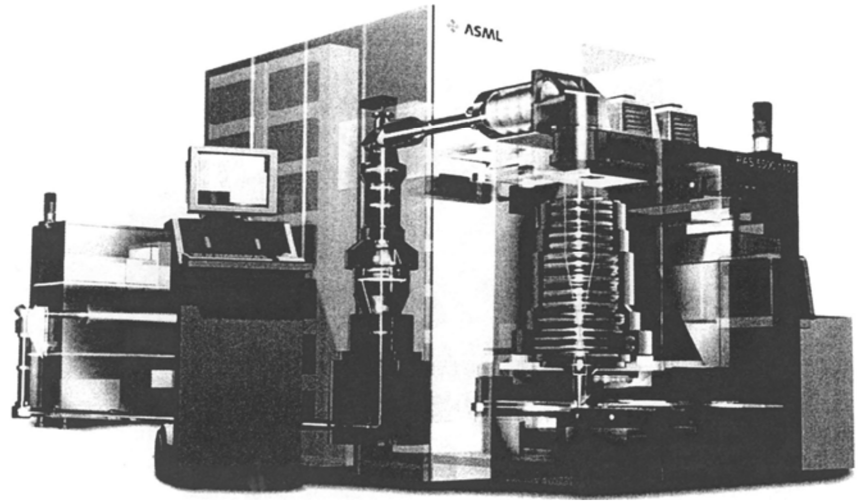


Figure 7.26 Configuration of Step-and-Scan 193-nm system. The laser is at the left. The reticle is at the upper right, while the wafer is at the lower right (*photo courtesy ASML*).

B3. Contact/proximity systems

$$\text{If } W^2 >> \lambda\sqrt{g^2 + r^2} \rightarrow \text{Fresnel diffraction}$$

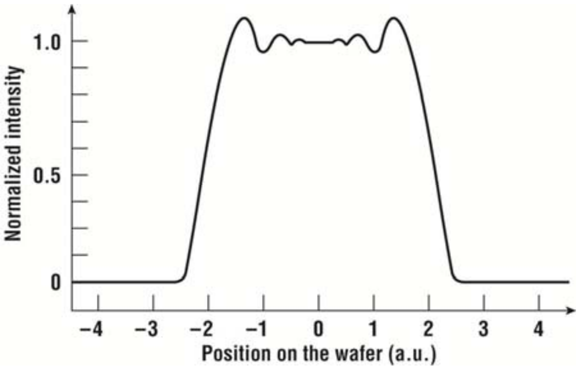
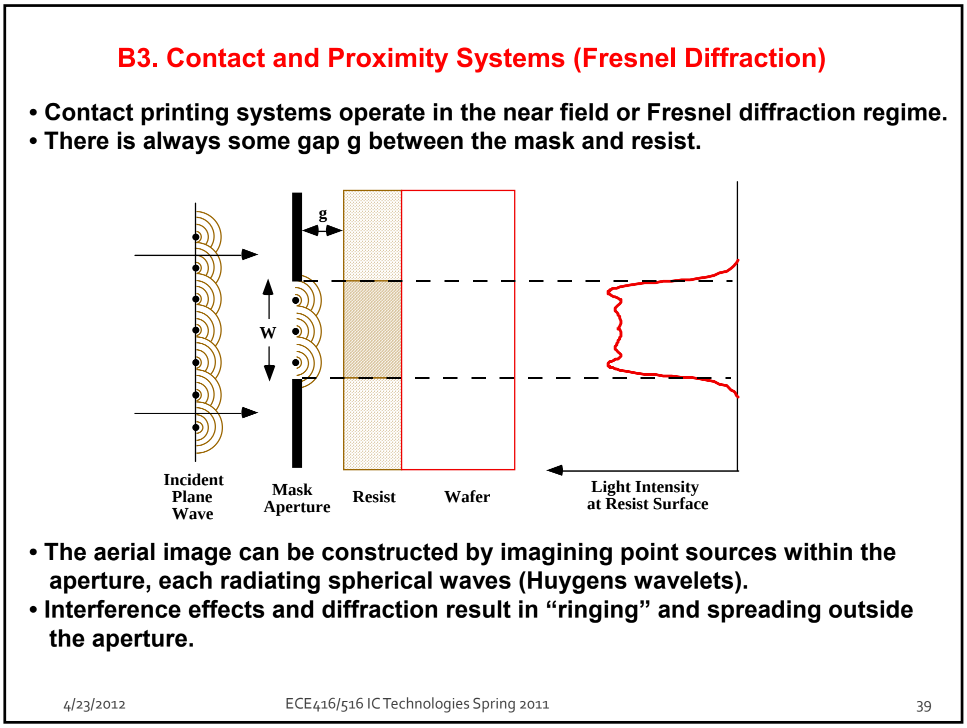


Figure 7.7 Typical near field (Fresnel) diffraction pattern.

For W very large → ray tracing

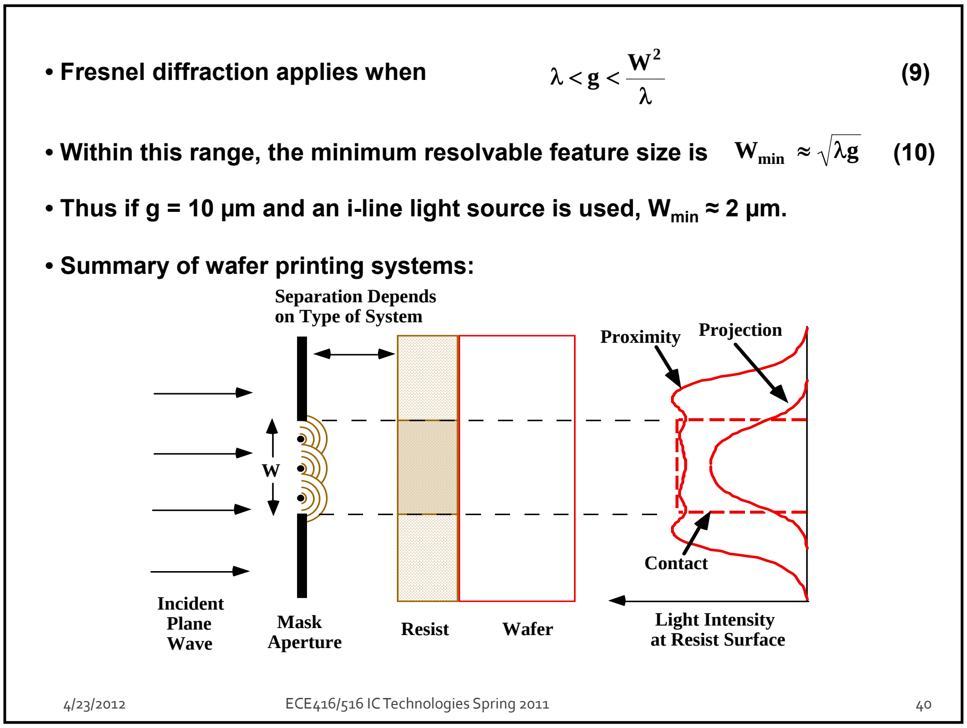
Image width on wafer $\Delta W = W(g/D)$



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.

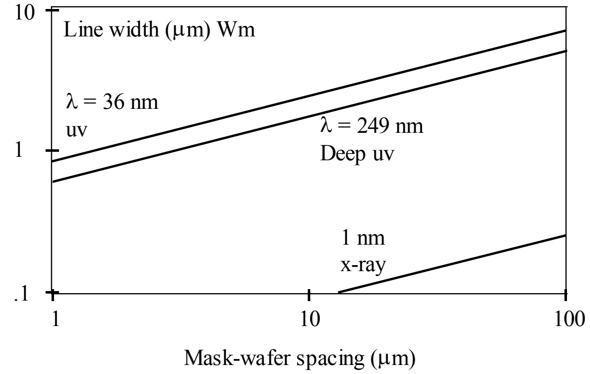
- The aerial image can be constructed by imagining point sources within the aperture, each radiating spherical waves (Huygens wavelets).
- Interference effects and diffraction result in “ringing” and spreading outside the aperture.



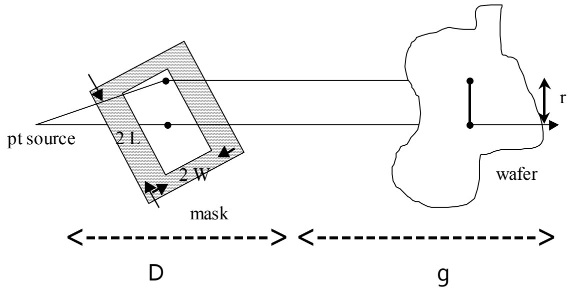
- Fresnel diffraction applies when $\lambda < g < \frac{W^2}{\lambda}$ (9)
- Within this range, the minimum resolvable feature size is $W_{min} \approx \sqrt{\lambda g}$ (10)
- Thus if g = 10 μm and an i-line light source is used, $W_{min} \approx 2$ μm.
- Summary of wafer printing systems:

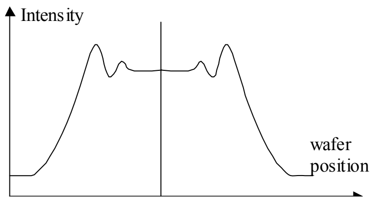
Proximity Printing:Diffraction #1

- Mask close to wafer/resist
  minimize diffraction/divergence.
- Separation ~μm → Fresnel (near-field) diffraction
- Minimum line width:
  $W_m = (d\lambda)^{1/2}$
- (d = mask-wafer
  separation)



Proximity Printing:Diffraction #2



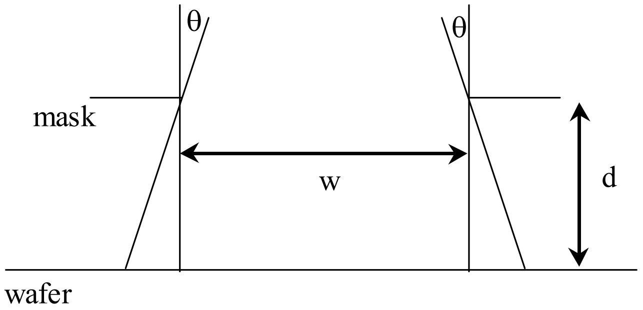


For $W^2 \gg \lambda (g^2+r^2)^{1/2}$

$\Delta W = W(g/D)$

Proximity Printing: Penumbra

- Penumbra effect on line width: $\Delta W = 2d \tan\theta$
  where θ angle off collimation



Well collimated light minimizes penumbra.

- Well collimated light maximizes diffraction.
- $\theta \sim$ few degrees for optimum balance.

Contact exposure

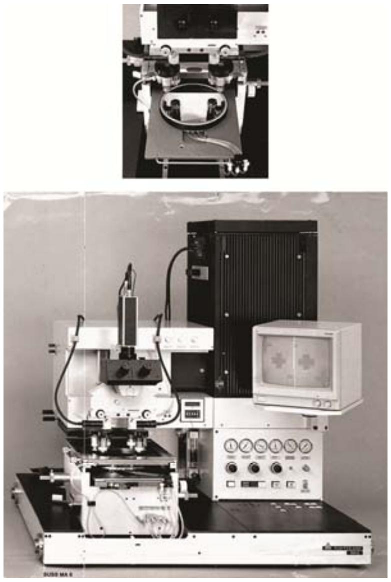
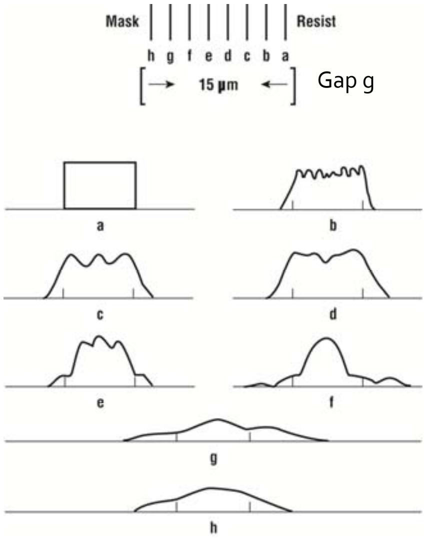


Figure 7.19 Typical contact exposure system *(courtesy of Karl Suss).*

Contact → proximity



Gap g

$\lambda < g < W^2/\lambda \rightarrow$ Fresnel near field

$g \geq W^2/\lambda \rightarrow$ Fraunhofer far field

Cannot resolve features
$< W_{min} \approx \sqrt{k\lambda g}$
(where k depends on the PR)

Figure 7.20 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)*.

Contact Printing: Dirt

Dirt can damage mask, and/or can mask exposure areas, e.g. oxide pinholes

Effect on yield:

- Total no. chips on wafer = N
- no. good chips = N_g
- no. of defects = N_d

Add another random defect -->

- probability of destroying a good chip = N_g/N

$\therefore dN_g = -(N_g/N)\, dN_d$

$dN_g/N_g = -dN_d/N$

$\therefore \ln N_g = -N_d/N + \text{const}$

$N_g = \text{const} \times \exp - N_d/N$

$= N \exp - N_d/N$

since $N_g = N$, if $N_d = 0$

$\therefore$ Fractional yield $N_g/N = \exp - N_d/N$ --> 1/e, if $N_d \sim N$

B4. Immersion

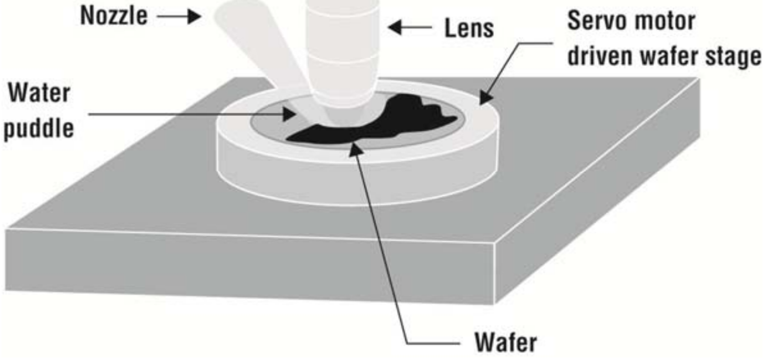


Figure 7.24 Setup of an immersion system using surface tension *(from Switkes et al., reprinted from the May 2003 edition of Microlithography World. Copyright 2003 by PennWell.)*

$$DOF = \frac{\lambda}{4n.\sin^2(\theta_P/2)} \text{ and } \frac{\text{DOF}_{\text{n(liq)}}}{\text{DOF}_{\text{n=1(air)}}} = \sqrt{\frac{n^2-(\lambda/P)^2}{1-(\lambda/P)^2}}$$

$$n = 1.43 \text{ for } \text{H}_2\text{O, and } \theta_{\text{P}} = \frac{\lambda}{n.P} \text{ where P = 2W for a uniform grating}$$

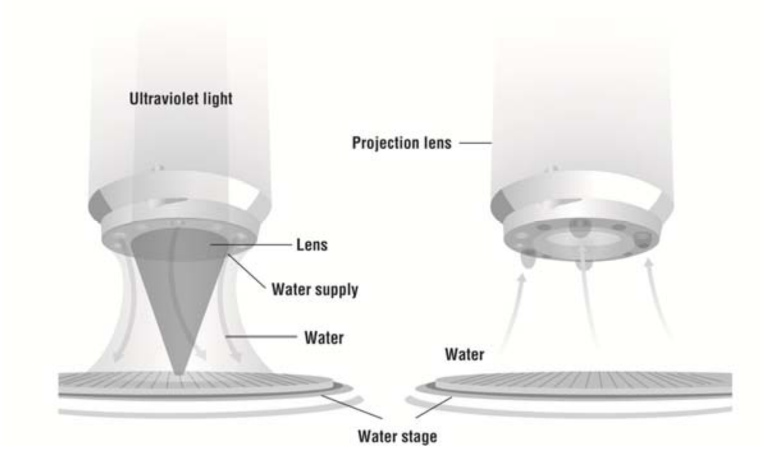
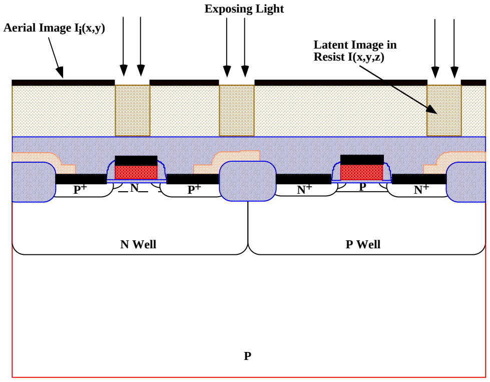


Figure 7.25 Nozzle system used by Nikon to put the water down and suction it up for each stage *(from Geppert, reprinted by permission IEEE.)*

C. Optical Intensity Pattern in the Resist (Latent Image)

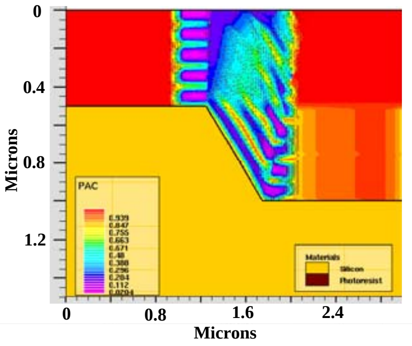


- The second step in lithography simulation is the calculation of the latent image in the resist.
- The light intensity during exposure in the resist is a function of time and position because of
  - Light absorption and bleaching.
  - Defocusing.
  - Standing waves.

- 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 $I_r(x,y,z)$ models these effects.



- 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 substra 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 depends on the resist properties and on the [PAC].**

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

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

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

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

$$\frac{\mathrm{dm}}{\mathrm{dt}} = -\mathrm{C\,Im} \qquad \text{C is 3}^{\text{rd}}\text{ Dill parameter} \qquad (26)$$

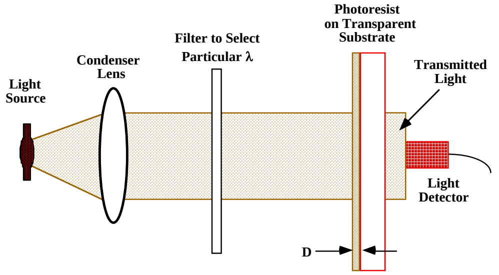
- **Substituting (24) into (23), we have:**

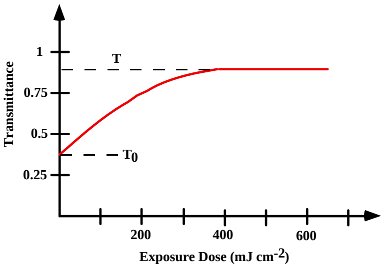
$$\frac{dI}{dz} = -\alpha I = -(Am + B)I \qquad (27)$$

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

[PAC] = photoactive compound concentration

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





$$A = \frac{1}{D}\ln\frac{T_\infty}{T_0}$$

- **By measuring T_0 and T_∞, A, B and C can be extracted.**

$$B = -\frac{1}{D}\ln T_\infty$$

$$C = \frac{A+B}{AT_0(1-T_0)T_{12}}\frac{dT}{dE}\Big|_{E=0} \text{ where } T_{12} = 1 - \left(\frac{n_{resist}-1}{n_{resist}+1}\right)^2$$

D. Simulation

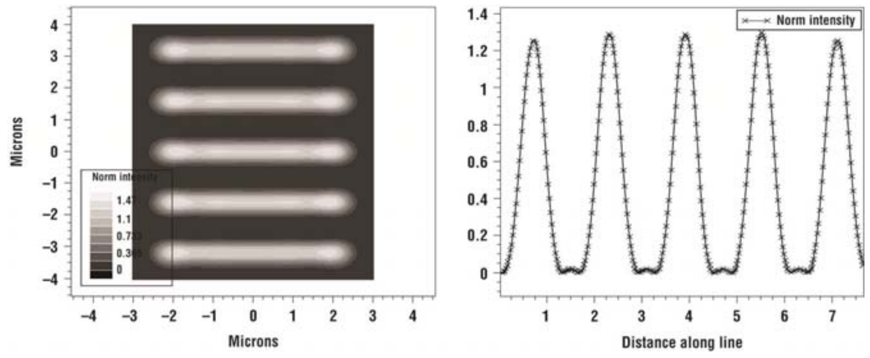


Figure 7.11 Contour plot (left) and 10 slice through the center of projected intensity as a function of position for a grating with 1.6 μm pitch, exposed at R = 436 nm and NA = 0.43.

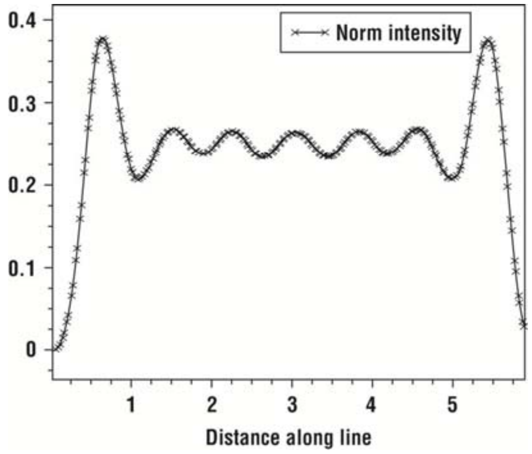


Figure 7.12 Same 1D plot for a grating with a pitch of 0.8 μm exposed on the same system.

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

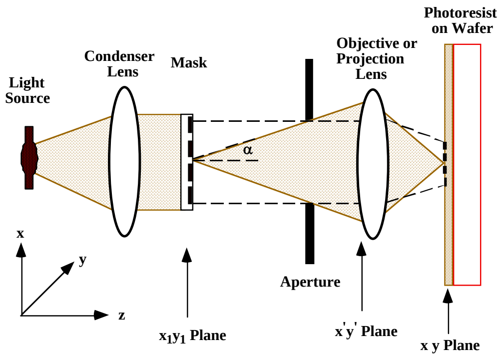
- There are several commercially available simulation tools that calculate the aerial image - PROLITH, DEPICT, ATHENA. All use similar physical models.
- We will consider only projection systems.

- Light travels as an electromagnetic wave.

$$\varepsilon(P,t) = C(W)\cos(\omega t + \phi(t)) \qquad (13)$$

or, in complex exponential notation,

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



- Consider a generic projection system:

- The mask is considered to have a digital transmission function:

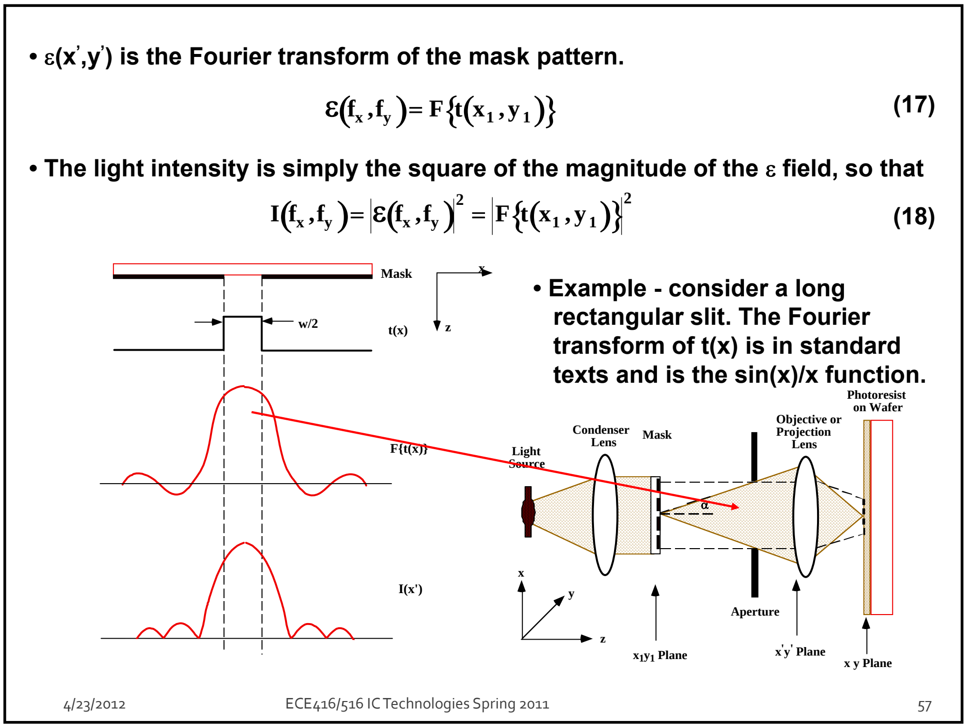
$$t(x_1, y_1) = \begin{cases} 1 \text{ in clear areas} \\ 0 \text{ in opaque areas} \end{cases} \qquad (15)$$

- After the light is diffracted, it is described by the Fraunhofer diffraction integral:

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

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

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



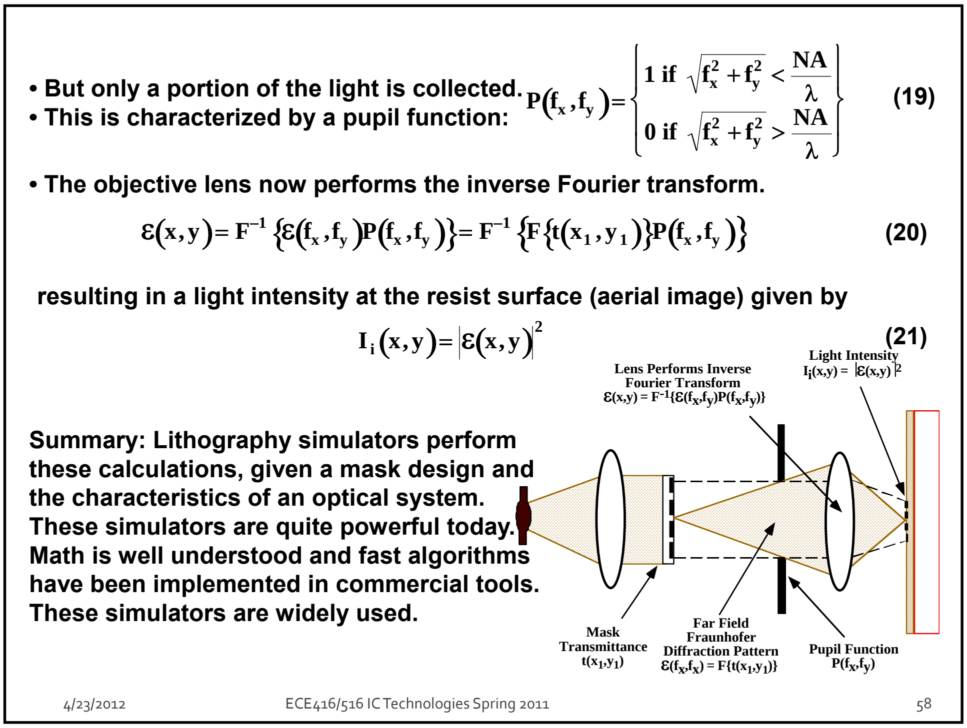
- ε(x',y') is the Fourier transform of the mask pattern.

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

- The light intensity is simply the square of the magnitude of the ε field, so that

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

- Example - consider a long rectangular slit. The Fourier transform of t(x) is in standard texts and is the sin(x)/x function.



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

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

- The objective lens now performs the inverse Fourier transform.

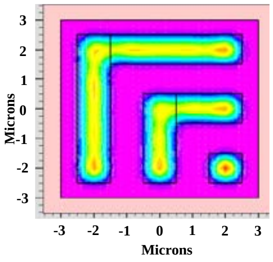
$$\varepsilon(x, y) = F^{-1}\{\varepsilon(f_x, f_y)P(f_x, f_y)\} = F^{-1}\{F\{t(x_1, y_1)\}P(f_x, f_y)\} \qquad (20)$$

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

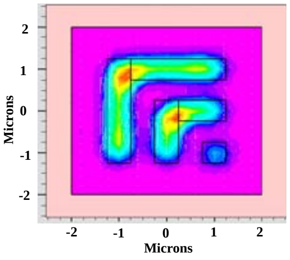
$$I_i(x, y) = \left|\varepsilon(x, y)\right|^2 \qquad (21)$$

Summary: Lithography simulators perform these calculations, given a mask design and the characteristics of an optical system. These simulators are quite powerful today. Math is well understood and fast algorithms have been implemented in commercial tools. These simulators are widely used.

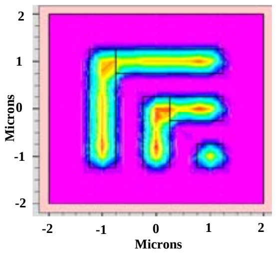
- ATHENA simulator (Silvaco). Colors correspond to optical intensity in the aerial image.



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.

E. SubWavelength Lithography

- Beginning in ≈ 1998, chip manufacturers began to manufacture chips with feature sizes smaller than the wavelength of the light used to expose the photoresist.

- This is possible because of the use of a variety of "tricks"
  - illumination system optimization
  - optical pattern correction (OPC), and
  - phase shift mask techniques.

E. 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 spatial frequencies are lost due to diffraction. These effects can be calculated and ∴ can be compensated for.

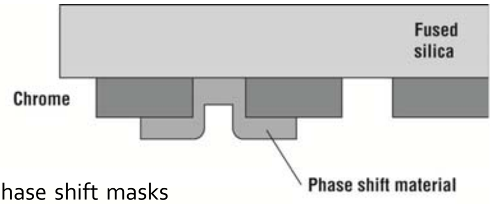
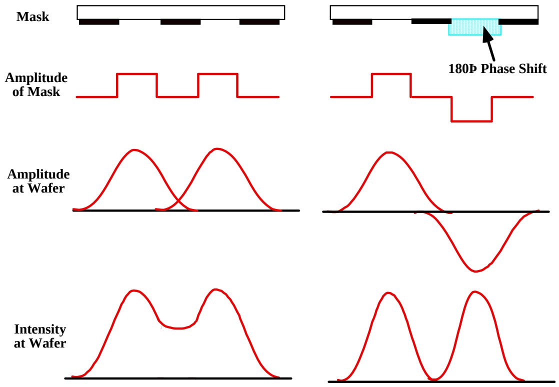


Figure 7.27 Basic concept of phase shift masks as described by Levenson *et al.* [49].

- **Creating phase shift masks involves massive numerical calculations and often the implementation involves two exposures - a binary mask and a phase shift mask - before the resist pattern is developed.**

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



- **A number of companies now provide OPC and phase shifting software services.**
- **The advanced masks which these make possible allow sharper resist images and/or smaller feature sizes for a given exposure system.**

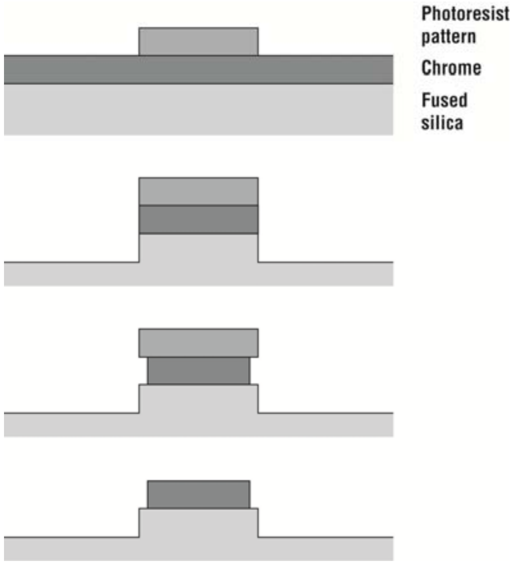


Figure 7.28 Self-aligned method of phase shifting the radiation at the edges of a pattern.

Reflection & Scattering

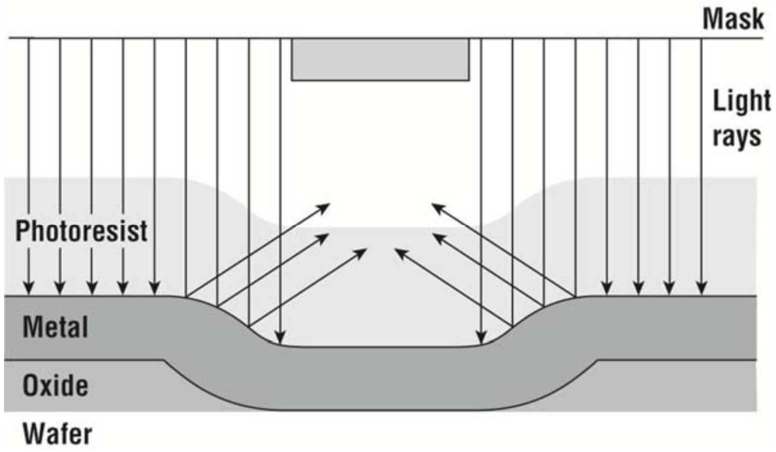


Figure 7.29 Light from the exposed regions can be reflected by wafer topology and be absorbed in the resist in nominally unexposed regions.

Here, in the later stages, with surface topography

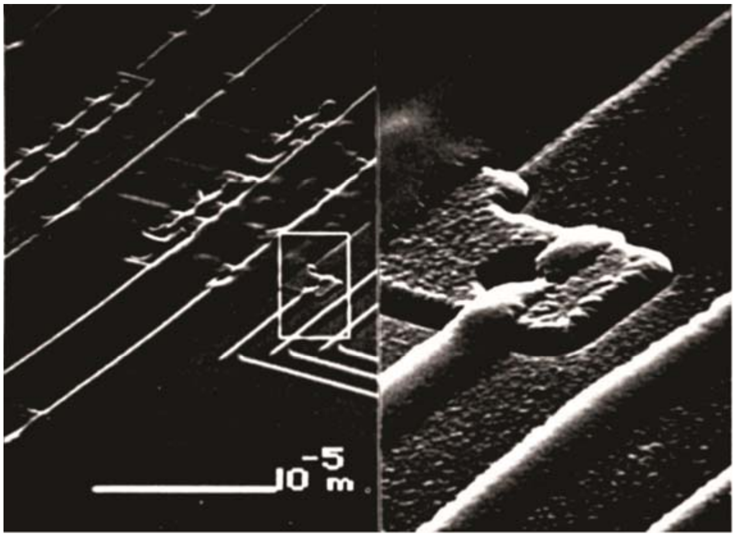


Figure 7.30 Resist lines for patterning the metal running diagonally from the lower left. On the right is an expanded view of the geometry described in Figure 7.31 *(after Listvan et al.).*

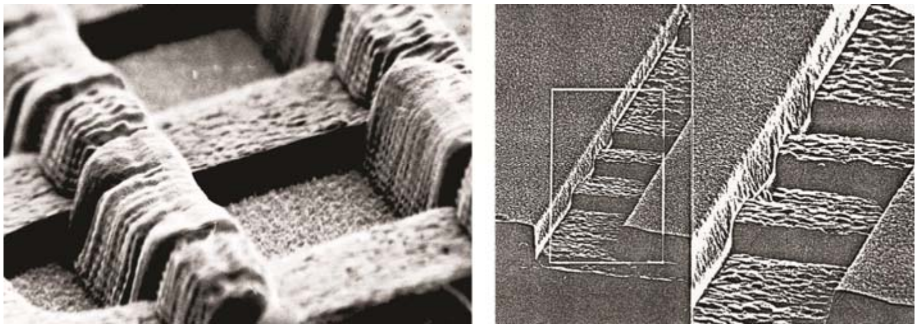


Figure 7.31 Micrographs of resist lines on reflective metal without and with a 2700-Å antireflecting layer under the resist *(after Listvan et al.)*.

F. Interference Effects

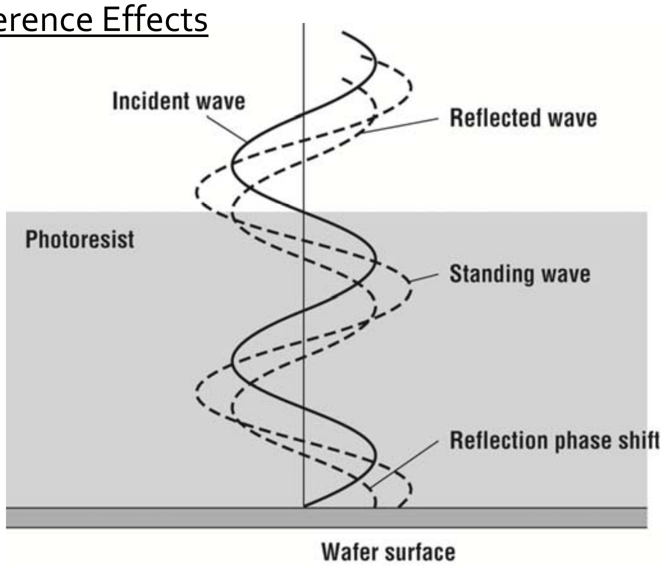


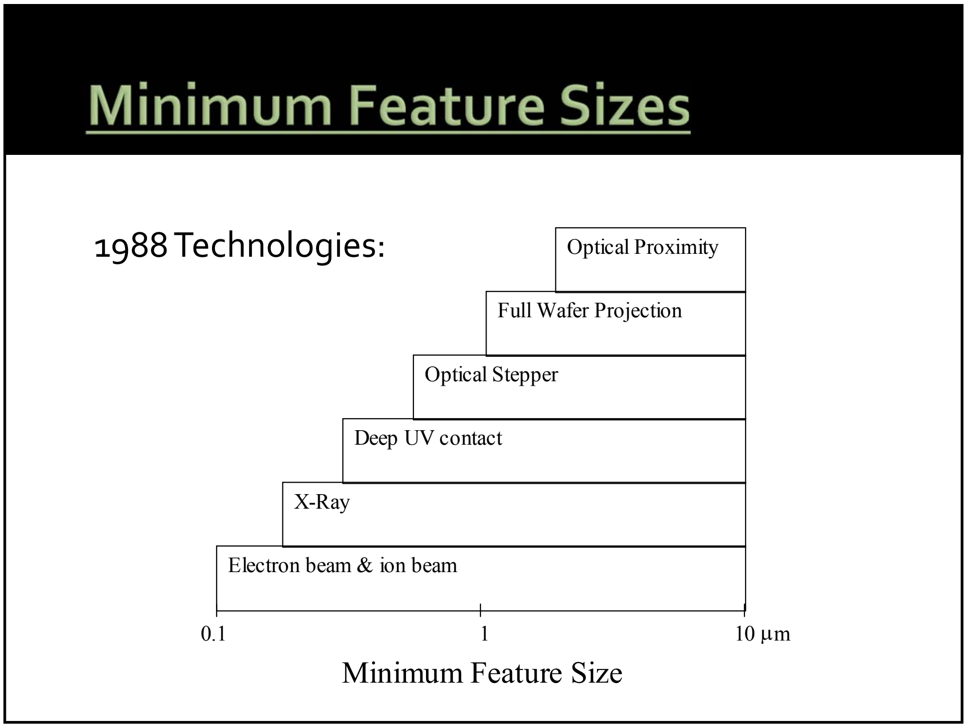
Figure 7.32 The formation of standing waves in the resist.

Reflection & Standing Waves

$E_I = E_o \cos(\omega t - \beta z)$
$E_R = RE_o \cos(\omega t + \beta z)$
$\beta = 2\pi(n - i k)/\lambda$
R = reflection coefficient = r^2
= $[(n_1-n_2)/(n_1+n_2)]^2$
n_2 = Si complex refractive index
n_1 = PR complex refractive index
$k \approx 0$ for PR or oxide, $\beta \approx 2\pi n/\lambda$

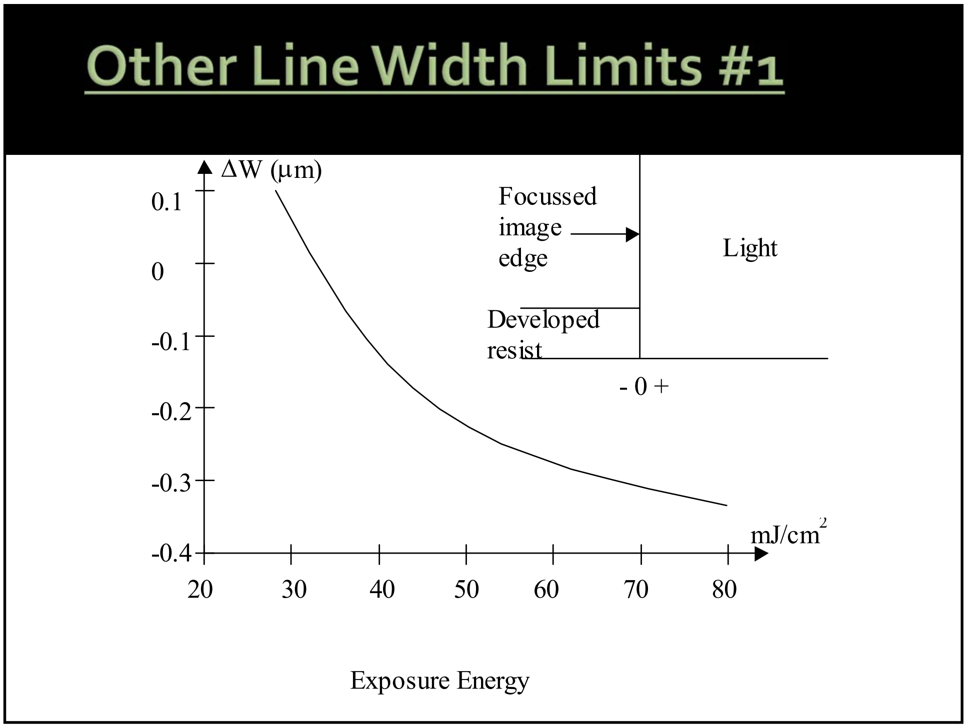
$E_I + E_R = E_o[\cos(\omega t - \beta z) + R\cos(\omega t + \beta z)]$
-->Standing Wave
$E_s = E_{so} \sin \omega t \sin((2\pi nz)/\lambda + \theta)$
Maxima/Minima separations $\lambda/2n$
Minima when $(2\pi nz/\lambda) + \theta = m\pi$
m = 0, 1, 2, . . .
For r = -1 (Si, GaAs, metals), $\theta = 0$.
minima at $z = m\lambda/2n$, m = 0, 1, 2...
& exposure due to intensity $I = I_o \sin^2 \beta z$

Notes: (1) Poor development at surface
(2) PR on oxide
--> optical properties similar,
so SW continuous across interface;
adjust thickness of oxide Z_o to get anti-node at PR/oxide interface.
$Z_o = (2m + 1)\lambda/4n$
(3)Eliminate SW formation:
(a) thin absorbing layer between Si & PR
(b) dye in PR for light scatter
(4) Plasma etch removes PR residue

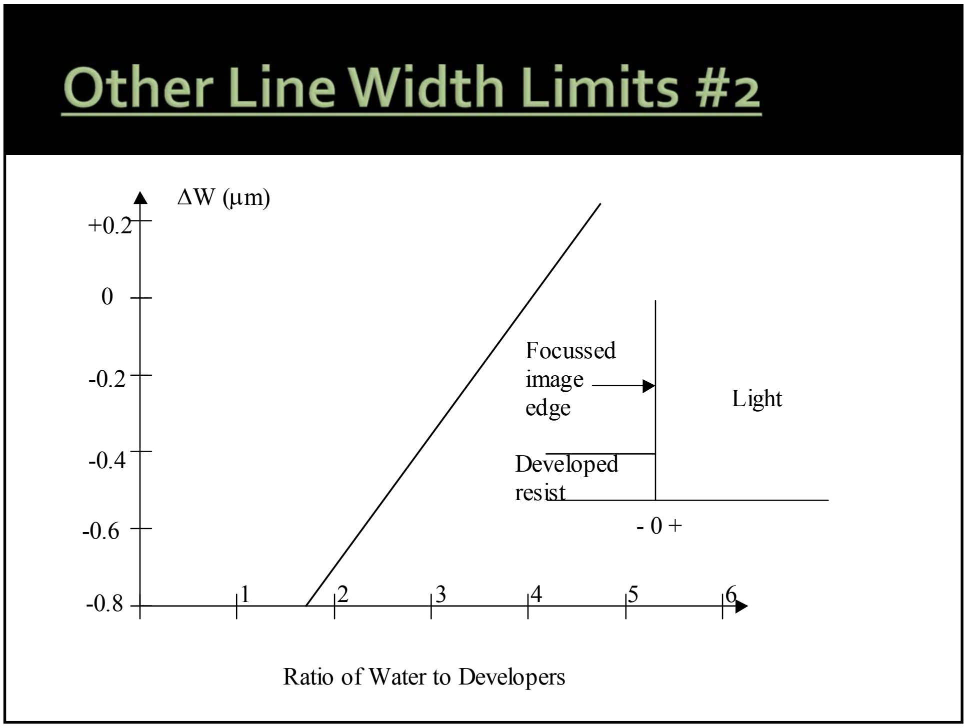


Minimum Feature Sizes

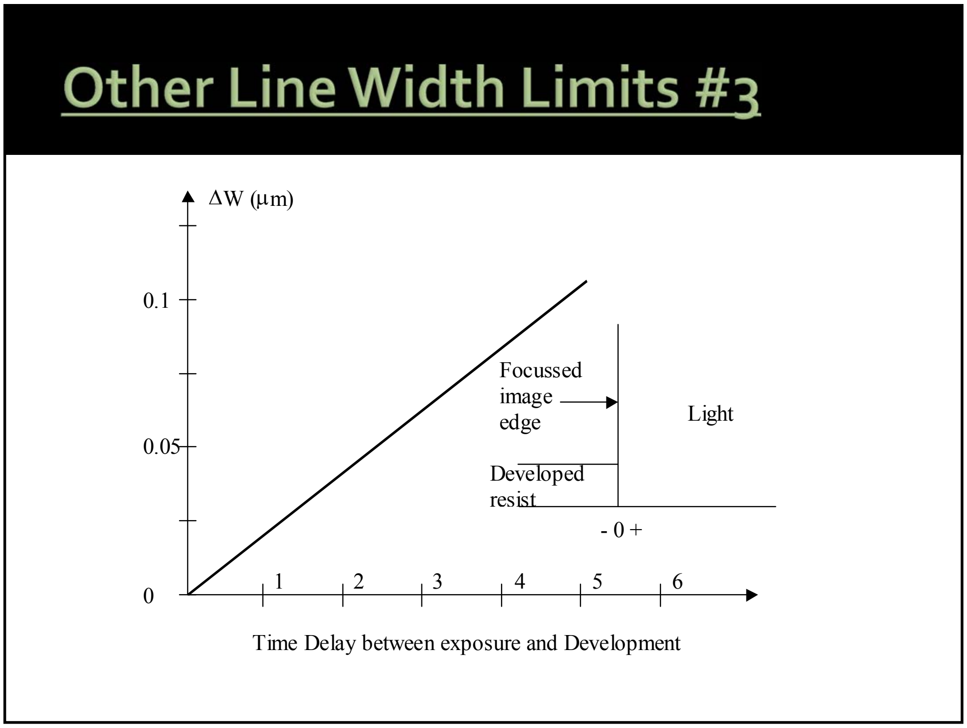
1988 Technologies:



Other Line Width Limits #1

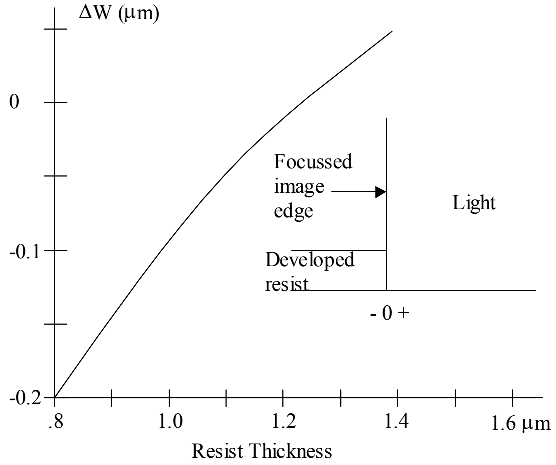


Other Line Width Limits #2

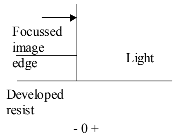


Other Line Width Limits #3

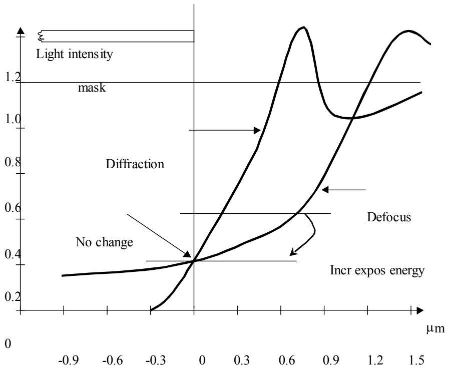
Other Line Width Limits #4



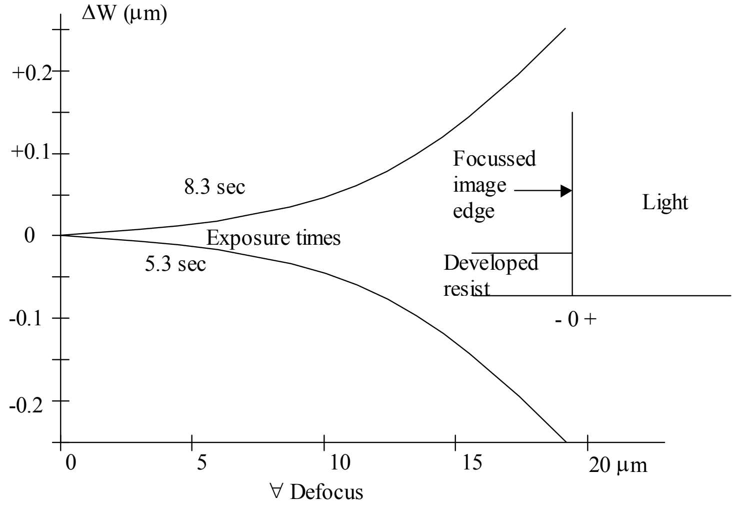
Other Line Width Limits #5

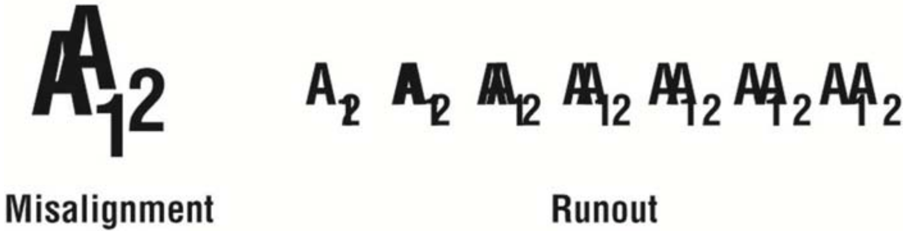


Increasing exposure time decreases intensity for threshold.



Other Line Width Limits #6

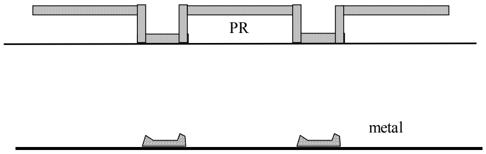




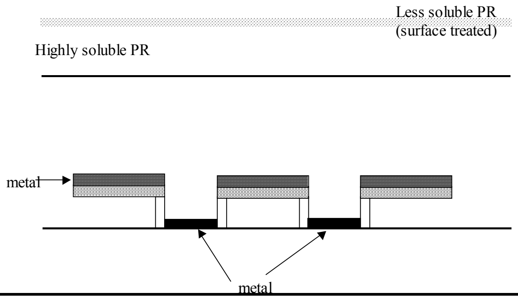
Temperature changes

Figure 7.33 Two typical registration errors.

Lift-Off Techniques



Relies on fracture of metal film



Some Final Thoughts

- **Lithography is the key pacing item for developing new technology generations.**
- **Exposure tools today generally use projection optics with diffraction limited performance.**
- **Lithography simulation tools are based on Fourier optics and do an excellent job of simulating optical system performance. Thus aerial images can be accurately calculated.**
- **A new approach to lithography may be required in the next 10 years.**

Assignment #3

Problems: 6.1 7.4
6.2 7.5
6.5 7.6/7

Mid-term course evaluation:

Summarize what you like about the course, and what you don't like.

(Suggestion: Identify 5 each.)

Consider lectures, textbook, assignments, notes, videos, etc. (Weighted as 2 problems)

Grad project topics: (PPT presentations Monday June 4th)

- Phase masking
  - Specific design example
- Optical proximity correction
  - Specific design example
- Through-silicon vias (TSVs)
  - Solid copper & barrel
- Planarization
  - Chemical/Mechanical Polishing
- On-chip resistors
  - Materials/fabrication/properties
- On-chip inductors
  - Spiral and ferrite
- Wafer thinning
  - Thin wafer applications
- Cryopumping
  - Theory and practice
- Unbalanced magnetron
  - Sources/deposition
- Thin metal film resistivity
  - (Continuous) thickness variation
- Stiction avoidance
  - Including surface structuring
- Electroless deposition
  - Theory and techniques
- Atomic layer deposition
  - Theory and techniques
- MEMS motor fabrication
  - Linear and rotational