Chapter 7

Optical Lithography
Optical Lithography

- 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 $\alpha$ (spin rate)$^{-1/2}$
  5. Expose PR through mask & “develop” to dissolve unwanted PR, etc.

Masking Registration #1

Registration tolerance --> design rules
Estimated final tolerance:

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

where \(\sigma_r\) is registration error
\(\sigma\)'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

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

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**

- 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.

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### 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.

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### Table: Lithography Overview

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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

\[
\begin{align*}
\text{Kr} + \text{NF}_3 \xrightarrow{\text{energy}} \text{KrF} \rightarrow \text{photon emission} \\
\end{align*}
\]

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

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**Wafer exposure systems**

- **Contact**: usually x, y, & θ control to align mask to substrate
- **Proximity**: alignment marks
- **Projection**: simultaneous XY scan of mask & wafer
Figure 7.5 Schematic of a simple lithographic exposure system.

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 $\lambda$.
- At smaller dimensions, diffraction effects dominate.

![Diagram of light source, aperture, and image plane with diffraction](image)

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

\[ I = \frac{2}{\pi} \frac{E_0^2}{r^2} = E_0^2 e^{i\phi} e^{-j\theta} = E_0^2 \]

\[ I = \left( E_1 e^{i\phi_1} + E_0 e^{i\phi_0} \right) \left( E_1 e^{-j\phi_1} + E_0 e^{-j\phi_0} \right) \text{ for 2 point sources} \]

\[ = E_1^2 + E_0^2 + E_1 E_2 \cos(\phi_1 - \phi_2) \]

- 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 spatial 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 $d \rightarrow \infty$.
- \[ \text{Diameter of central maximum} = 1.22 \frac{\lambda}{f} \]

- Diffraction is usually described in terms of two limiting cases:
  - Fresnel diffraction - near field.
  - Fraunhofer diffraction - far field.
If $W^2 << \sqrt{\lambda^2 g^2 + r^2}$ → Fraunhofer diffraction

$$I(x, y) = I_0 \left[ \frac{(2W)(2L)}{\lambda g} \right]^2 I_x^2 I_y^2, \quad I_x = \frac{\sin \frac{2\pi x W}{\lambda g}}{2\pi x W \lambda g}, \quad I_y = \frac{\sin \frac{2\pi y L}{\lambda g}}{2\pi y L \lambda g}$$

**Figure 7.8** Typical far field (Fraunhofer) image.

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

**Projection**

- NA = $n \sin \alpha$
- Refractive index $n = 1$ for air
- Rayleigh’s resolution criterion $W_{\text{min}} = k \lambda / NA$

4/23/2012 ECE416/516 IC Technologies Spring 2011
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,

\[
R = \frac{1.22\lambda f}{d} = \frac{1.22\lambda f}{n(2f \sin \alpha)} = \frac{0.61 \lambda}{n \sin \alpha} \quad (2)
\]

- The numerical aperture of the lens is by definition,

\[
\text{NA} \equiv n \sin \alpha \quad (3)
\]

- NA represents the ability of the lens to collect diffracted light.

\[
\therefore R = \frac{0.61 \lambda}{\text{NA}} = k_1 \frac{\lambda}{\text{NA}} \quad (4)
\]

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

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

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

\[
\text{DOF} = \pm \frac{\lambda}{2(\text{NA})^2} = \pm k_2 \frac{\lambda}{(\text{NA})^2} \quad (5)
\]

- \(k_2\) is usually experimentally determined.

- Thus a 248nm (KrF) exposure system with a NA = 0.6 would have a resolution of \(\approx 0.3 \mu m\) \((k_1 = 0.75)\) and a DOF of \(\approx 0.35 \mu m\) \((k_2 = 0.5)\).
**Depth of focus**

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

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

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

$\therefore$ 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.

$$MTF = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$$  \hspace{1cm} (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.

**Figure 7.10** Plot of dose versus position on the wafer. Dose is given by the intensity of the light in the aerial 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 $\rightarrow$ 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 $D_0 > D > D_{100}$
  --> Partially dissolves

**Projection Printing Resolution #2**

- Rayleigh resolution limit:
  
  \[ S_r = 0.6 \frac{\lambda}{\text{NA}} \]

- 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

\[ S = \frac{\text{light source diameter}}{\text{condenser lens diameter}} = \frac{s}{d} \]  

or often as

\[ S = \frac{\text{NA}_{\text{condenser}}}{\text{NA}_{\text{projection optics}}} \]  

• Typically, \( S \approx 0.5 \) to 0.7 in modern systems.

[Note: Sketch MTF vs (feature size)\(^2\) 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.

\[ S = (\text{Source image diameter})/(\text{Pupil diameter}) \]
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

If \( W^2 \gg \lambda \sqrt{g^2 + r^2} \) → Fresnel diffraction

![Diagram of Fresnel diffraction pattern](image)

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.

![Diagram of wafer printing systems](image)

- 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 $W_{\text{min}} \approx \sqrt{\frac{\lambda g}{16}}$ (10)

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

- Summary of wafer printing systems:
**Proximity Printing: Diffraction #1**

- Mask close to wafer/resist to minimize diffraction/divergence.
- Separation ~\( \mu \text{m} \) → Fresnel (near-field) diffraction
- Minimum line width:
  \[ W_m = (d\lambda)^{3/2} \]
- \((d = \text{mask-wafer separation})\)

**Proximity Printing: Diffraction #2**

For \( W^2 >> \lambda (g^2 + r^2)^{3/2} \)

\[ \Delta W = W(g/D) \]
Proximity Printing: Penumbra

- Penumbra effect on line width: \( \Delta W = 2d \tan \theta \)
  where \( \theta \) 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).
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 \( g = 15 \, \mu m \) (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 = \( N_g/N \)

\[
\begin{align*}
\frac{dN_g}{N_g} &= -\frac{N_g}{N} \, dN_d \\
\frac{dN_g}{N_g} &= -\frac{dN_d}{N} \\
\ln N_g &= -\frac{N_d}{N} + \text{const} \\
N_g &= \text{const} \times \exp - \frac{N_d}{N} \\
&= N \times \exp - \frac{N_d}{N} \\
\text{since } N_g &= N, \text{ if } N_d = 0
\end{align*}
\]

\[
\begin{align*}
\therefore \text{ Fractional yield } N_g/N &= \exp - \frac{N_d}{N} \quad \rightarrow 1/e, \text{ if } N_d \sim N
\end{align*}
\]
**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.)

\[
\text{DOF} = \frac{\lambda}{4n \sin^2 (\theta_p / 2)} \quad \text{and} \quad \text{DOF}_{n=\text{air}} = \frac{n^2 - (\lambda / P)^2}{\sqrt{1 - (\lambda / P)^2}}
\]

\(n = 1.43\) for \(H_2O\), and \(\theta_p = \frac{\lambda}{nP}\) 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:

\[ I(x,y,z) = I(x,y)I_{r}(x,y,z) \]  

(22)

where \( I_{r}(x,y,z) \) models these effects.

C. Photoresist Exposure

- 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.

- Neglecting standing wave effects (for the moment), the light intensity in the resist falls off as

\[ \frac{dI}{dz} = -\alpha I \]  

(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 \([\text{PAC}]\).

\[
\alpha_{\text{resist}} = A m + B
\]  

(24)

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

\[
m = \frac{[\text{PAC}]}{[\text{PAC}]_0}
\]  

(25)

• \(m\) is a function of time and is given by

\[
\frac{dm}{dt} = -C I m
\]  

(26)

C is 3rd Dill parameter

• Substituting (24) into (23), we have:

\[
\frac{dI}{dz} = -\alpha I = -(A m + B) I
\]  

(27)

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

\([\text{PAC}] = \text{photoactive compound concentration}\)

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

\[
A = \frac{1}{D} \ln \frac{T\infty}{T_0}
\]

\[
B = \frac{1}{D} \ln T_{\infty}
\]

\[
C = \frac{A + B}{AT_0(1 - T_B)T_{12}} \left| \frac{dI}{dz} \right|_{E \rightarrow 0} \text{ where } T_{12} = 1 - \left( \frac{n_{\text{REU}} - 1}{n_{\text{REU}} + 1} \right)^2
\]

By measuring \(T_0\) and \(T_{\infty}\), \(A\), \(B\) and \(C\) can be extracted.
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.

\[ \varepsilon(P, t) = C(W)\cos(\omega t + \phi(t)) \]  

or, in complex exponential notation,

\[ \varepsilon(W, t) = \text{Re}(U(W)e^{-j\omega t}) \]  

where \( U(W) = C(W)e^{-i\phi(t)} \)

**Consider a generic projection system:**

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

\[ t(x_1, y_1) = \begin{cases} 1 & \text{in clear areas} \\ 0 & \text{in opaque areas} \end{cases} \]  

(15)

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

\[ \varepsilon(x', y') = \frac{1}{i\lambda} \iint_{-\infty}^{\infty} t(x_1, y_1)e^{-2\pi i (x_1 x' + y_1 y')} dx_1 dy_1 \]  

(16)

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

\[ f_x = \frac{x'}{z\lambda} \quad \text{and} \quad f_y = \frac{y'}{z\lambda} \]
• \( \varepsilon(x', y') \) is the Fourier transform of the mask pattern.

\[
\varepsilon(f_x, f_y) = F\{t(x_1, y_1)\}
\]

• The light intensity is simply the square of the magnitude of the \( \varepsilon \) field, so that

\[
I(f_x, f_y) = |\varepsilon(f_x, f_y)|^2 = |F\{t(x_1, y_1)\}|^2
\]

• 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:

\[
P(f_x, f_y) = \begin{cases} 
1 & \text{if } \frac{f_x^2 + f_y^2}{\lambda} < \frac{NA}{\lambda} \\
0 & \text{if } \frac{f_x^2 + f_y^2}{\lambda} > \frac{NA}{\lambda}
\end{cases}
\]

• The objective lens now performs the inverse Fourier transform.

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

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

\[
I_i(x, y) = |\varepsilon(x, y)|^2
\]

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.
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.
• 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.

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.).
### Reflection & Standing Waves

- \( E_I = E_0 \cos(\omega t - \beta z) \)
- \( E_R = R E_0 \cos(\omega t + \beta z) \)
- \( \beta = 2 \pi (n - i k) / \lambda \)
- \( R = \text{reflection coefficient} = r^2 \)
- \( n_s = \text{Si complex refractive index} \)
- \( n_r = \text{PR complex refractive index} \)
- \( k \approx 0 \text{ for PR or oxide, } \beta \approx 2 \pi n / \lambda \)
- \( E_I + E_R = E_0 [\cos(\omega t + \beta z) + R \cos(\omega t + \beta z)] \)

**Standing Wave**

- \( E_z = E_0 \sin \omega t \sin((2\pi n z) / \lambda + \theta) \)

**Maxima/Minima separations** \( \lambda / 2n \)

**Minima when** \( (2 \pi n z / \lambda) + \theta = m \pi \)

**m = 0, 1, 2, ...**

For \( r = -1 \text{ (Si, GaAs, metals), } \theta = 0. \)

**minima at** \( z = m \lambda / 2n, m = 0, 1, 2, ... \)

**& exposure due to intensity** \( I = I_0 \sin^2 \beta z \)

**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 antinode 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:

- Optical Proximity
- Full Wafer Projection
- Optical Stepper
- Deep UV contact
- X-Ray
- Electron beam & ion beam

Minimum Feature Size

Other Line Width Limits #1

ΔW (μm)

0.1
0
-0.1
-0.2
-0.3
-0.4

0.1
0
-0.1
-0.2
-0.3
-0.4

20 30 40 50 60 70 80

mJ/cm²

Exposure Energy

Light

Developed resist

Focussed image edge

- 0 +
**Other Line Width Limits #2**

### Graph 1

- **ΔW (µm)**
- **Ratio of Water to Developers**

**Axes:**
- Vertical: ΔW (µm) ranging from -0.8 to +0.2
- Horizontal: Ratio of Water to Developers

**Key Points:**
- Focussed image edge
- Developed resist
- Light

**Data Points:**
- Time Delay between exposure and Development

**Graph 2**

- **ΔW (µm)**
- **Time Delay between exposure and Development**

**Axes:**
- Vertical: ΔW (µm) ranging from 0 to 0.1
- Horizontal: Time Delay between exposure and Development

**Key Points:**
- Focussed image edge
- Developed resist
- Light

**Data Points:**
- Time Delay between exposure and Development
Other Line Width Limits #4

Increasing exposure time decreases intensity for threshold.

Other Line Width Limits #5
Other Line Width Limits #6

Figure 7.33 Two typical registration errors.

Misalignment

Runout

Temperature changes
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