Text Book:
Silicon VLSI Technology
Fundamentals, Practice and Modeling
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Photolithography (Chap. 1)

- Basic lithography process
  - Apply photoresist
  - Patterned exposure
  - Remove photoresist regions
  - Etch wafer
  - Strip remaining photoresist
Lithography

- The ability to print patterns with submicron features and to place patterns on a silicon substrate with better than 0.1 um precision.
- Lithography is arguably the single most important technology in IC manufacturing
  - Gains have traditionally been paced by the development of new lithography tools, masks, photoresist materials, and critical dimension etch processes
- Considerations:
  - Resolution
  - Exposure field
  - Placement accuracy (alignment)
  - Throughput
  - Defect density (mask, photoresist and process)
## SIA NTRS Lithography

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<td>Technology Node (half pitch)</td>
<td>250 nm</td>
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<td>1.6</td>
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<td>0.6</td>
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<td>248 nm</td>
<td>248 nm + RET</td>
<td>193nm + RET</td>
<td>193nm + RET + H₂O</td>
<td>193nm + RET + H₂O + H₂O</td>
<td>???</td>
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</tr>
</tbody>
</table>

- 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.
Definitions

• Critical Dimensions (CD)
  – Dimensions that must be maintained

• CD Control
  – About 10% of minimum feature size.
  – Expressed as 3-sigma as three standard deviations of the
    feature size population must be within the specified 10% of
    the mean)

• Placement or Alignment Accuracy

• Optical Lithography used through 0.18um to 0.13 um generation. (described in text)

• X-ray, e-Beam and extreme ultraviolet are options beyond 0.1 um.
Wafer Exposure

• 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.

Positive Photoresist
• exposed photoresist dissolves when processed
Important Aspects

• Masks
  – Design, Fabrication, Reuse and Maintenance

• Photoresist
  – Material, material properties, develop, operation during etch or mask process, post process removal

• Wafer Exposure System
  – Exposure energy type, focus, linewidth/wavelength, diffraction effects (fringing), depth of focus

• All
  – Line width
  – Alignment
A. Light Sources

- Decreasing feature sizes require the use of shorter wavelengths, \( \lambda \).
- Traditionally mercury (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 - \( \lambda = 436 \text{ nm} \) (typical in 1990’s)
  - \( i \) line - \( \lambda = 365 \text{ nm} \) (used for 0.5 \( \mu \text{m} \), 0.35 \( \mu \text{m} \))

- Brightest sources in deep UV are excimer lasers

\[
\text{Kr} + \text{NF}_3 \xrightarrow{\text{energy}} \text{KrF} \rightarrow \text{photon emission} \quad (1)
\]
  - KrF - \( \lambda = 248 \text{ nm} \) (used for 0.25 \( \mu \text{m} \), 0.18\( \mu \text{m} \), 0.13 \( \mu \text{m} \))
  - ArF - \( \lambda = 193 \text{ nm} \) (used for 0.13\( \mu \text{m} \), 0.09\( \mu \text{m} \), . . . )
  - FF - \( \lambda = 157 \text{ nm} \) (used for ??)

- Issues include finding suitable resists and transparent optical components at these wavelengths.
B. Wafer Exposure Systems

1:1 Exposure Systems

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Optical System</th>
<th>Mask Photoresist</th>
<th>Si Wafer</th>
<th>Gap</th>
</tr>
</thead>
</table>

Usually 4X or 5X Reduction

Three types of exposure systems have been used.

<table>
<thead>
<tr>
<th>Contact Printing</th>
<th>Proximity Printing</th>
<th>Projection Printing</th>
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<tbody>
<tr>
<td>Contact printing is capable of high resolution but has unacceptable defect densities (minimal diffraction effects, low cost, contact contaminants and defects)</td>
<td>Proximity printing cannot easily print features below a few μm (diffraction effects exist, may be used for x-ray systems)</td>
<td>Projection printing provides high resolution and low defect densities and dominates today (diffraction a concern)</td>
</tr>
<tr>
<td>• 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.</td>
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</table>
• A simple example is the image formed by a small circular aperture (Airy disk).

• Note that a point image is formed only if:
  – $\lambda \to 0$, $d \to \infty$, or $f \to 0$

\[
R = \frac{1.22\lambda \cdot f}{d}
\]

• Diffraction is usually described in terms of two limiting cases:
  – Fresnel diffraction - near field (proximity and contact systems)
  – Fraunhofer diffraction - far field (projection systems)
Resolution

• The denominator is defined as the numerical aperture:

\[
NA \equiv n \sin \alpha
\]

Where \( \alpha \) represents the ability of the lens to collect diffracted light.

• The Resolution is then defined as

\[
R = \frac{0.61 \lambda}{NA} = k_1 \frac{\lambda}{NA}
\]

• \( k_1 \) 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)
Depth of Focus

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

- Higher NA lenses also decrease the depth of focus (DOF).
  (See text for derivation.)

$$R = \frac{0.61 \lambda}{NA} = k_1 \frac{\lambda}{NA}$$  \hspace{1cm} (4)

$$DOF = \delta = \pm \frac{\lambda}{2(NA)^2} = \pm k_2 \frac{\lambda}{(NA)^2}$$  \hspace{1cm} (5)

- $k_2$ is usually experimentally determined.

Thus a 248nm (KrF) exposure system with a NA = 0.6 would have a resolution of $R \approx 0.3 \, \mu m$ ($k_1 = 0.75$) and a DOF of $\approx \pm 0.35 \, \mu m$ ($k_2 = 0.5$).
Modulation Transfer Function

- Another useful concept is the modulation transfer function or MTF, defined as shown below.
  - MTF depends on the **feature size** and on the **spatial coherence** of the light source.

\[
MTF = \frac{I_{\text{MAX}} - I_{\text{MIN}}}{I_{\text{MAX}} + I_{\text{MIN}}}
\]  

(6)

- Typically require MTF > 0.5 or resist has exposure problems.
Spatial Coherence

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

• Practical light sources are not point sources.

• Therefore, the light striking the mask will not be plane waves.

• The spatial coherence of the system is defined as

\[ S = \frac{\text{light source diameter}}{\text{condenser lens diameter}} = \frac{s}{d} \]  \hspace{1cm} (7)

or often as

\[ S = \frac{\text{NA}_{\text{condenser}}}{\text{NA}_{\text{projection optics}}} \]  \hspace{1cm} (8)

• Typically, \( S \approx 0.5 \) to 0.7 in modern systems
Modulation Transfer Function

Small degradation for large features

S ≈ 0.5-0.7 for $s \to 0$ optical intensity decreases

Less coherent light

Improvement for very small features

$S = \text{light source diameter} / \text{condenser diameter}$

$S = \frac{s}{d}$

$S = \frac{\text{NA}_{\text{condenser optics}}}{\text{NA}_{\text{projection optics}}}$
Photoresist

• Designed to respond to incident photons by changing their properties when exposed to light.
  – Long-lived response require a chemical change

• Most resists are hydrocarbon-based materials.
  – Photons break chemical bonds

• Positive resists become more soluble in the developer solution
  – Typically used and have better resolution

• Negative resists do the opposite.

• Spin coating typically employed
Processing

• Start with clean wafer
• Spin-on photoresist
  – Adhesion promoter may be required
  – Viscosity and spin rate determine thickness and uniformity
  – Create a film of 0.6 to 1 um depth
• Prebake to drive off solvents
• Alignment and Exposure
  – Possible postbake
• Develop (remove unwanted photoresist)
• Etch
• Postbake to harden as an etchant mask
• Remove Photoresist
  – Chemically or in an oxygen plasma
Resist Important Parameters

• Sensitivity
  – How much light is required to expose the resist.
  – g-line and i-line typically 100 mJ cm$^{-2}$
  – Too sensitive, unstable, temp. dependent, noise prone

• Resolution
  – Diffraction limited resolution in the resist image

• “Resist”
  – The ability to withstand etching or ion implantation or whatever after postbake
Basic Properties of Resists

- Two basic parameters are used to describe resist properties, contrast and the critical modulation transfer function or CMTF.
- Contrast allows distinguishing light and dark areas on the mask.

- Contrast (the slope) is defined as
  \[
  \gamma = \frac{1}{\log_{10} \frac{D_f}{D_0}} \quad (11)
  \]

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

\[
CMTF_{\text{resist}} = \frac{D_f - D_0}{D_f + D_0} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1}
\]

(12)

Typical CMTF values for g and i-line resists are about 0.4. Chemically amplified DUV resists achieve CMTF values of 0.1 - 0.2.

Lower values are better since in general CMTF < MTF is required for the resist to resolve the aerial image.
Manufacturer Methods and Equipment

- Full wafer scanning system
  - Typically 1:1 mask to image
  - Limited to larger features

- A slit is scanned across the wafer
  - Slit and lens system minimize aberrations
  - Difficult full wafer alignment

- The systems use global alignment - difficult alignment on each die
  - full mask difficult → use steppers instead to improve overlay accuracy

Figure 5-27 Conceptual diagram of a scanning projection printer.
Manufacturing Methods and Equipment

- **Stepper System**
  - 4x to 5x mask
  - Step, align, scan-slit

Combined stepper + scanner 4X-5X larger mask pattern - difference in scanning speeds.

**Figure 5-30** Step and scan system. Stepping accomplishes the major moves from one exposure field to another. Within each exposure field, the mask pattern is scanned across the field.
Measurements of Masks

- Check Masks for Features and Defects
  - Scan
  - Make a new mask or Correct the errors

Image Sensors

Lens

Mask

Light Sources

Database Comparison
Electronics
(Used if only 1 die
on mask)

Die Comparison
Electronics

Corrections = repairs made by lasers
(evaporation of Cr=excess by focusing)

Defects of sizes below critical dimensions will not print on PR

Figure 5-32 Mask inspection system. Such systems operate by comparing the feature information on the mask either with the original design database or with an identical feature on an adjacent mask site. In this example three identical die are shown on the mask.
Measurement of Photoresist Patterns

- SEM has typically replaced optical microscopes

(Photo courtesy of A. Vladar and P. Rissman, Hewlett Packard.)

Figure 5-33 Cross section (left) and top (right) view SEM images of developed photoresist features showing well-developed lines with sub 0.25-μm lines and spaces. Courtesy of A. Vladar and P. Rissman, Hewlett Packard.
Electrical Line Width Monitor

- Test structures to determine the effective line width
  - Van der Pauw cross used to determine sheet resistivity
  - The cross-bridge test structure

\[ \rho_s = \frac{\rho}{t} = \frac{\pi}{\ln(2)} \cdot \frac{V_{3-4}}{I_{5-6}} \]

\[ R = \frac{V_{2-3}}{I_{1-5}} = \rho \cdot \frac{L}{t \cdot W} = \rho_s \cdot \frac{L}{W} \]

\[ W = \rho_s \cdot L \cdot \frac{I_{1-5}}{V_{2-3}} \]

**Figure 5-34** Test structure designed to electrically extract sheet resistance and linewidth \( W \).
Electrical Alignment Monitors

- Based on the cross bridge design
- Place an alternate mask layer to form a potentiometer.
  - If centered, two resistors equal
  - If not centered, resistance indicates distance offset

\[
R_i = \rho_s \cdot \frac{L_i}{W} \\
\Delta L_i = \left( R_i - \frac{R_1 + R_2}{2} \right) \cdot \frac{W}{\rho_s}
\]
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.

\[ \mathcal{E}(P, t) = C(W) \cos(\omega t + \phi(t)) \]  \hspace{1cm} (13)

or, in complex exponential notation,

\[ \mathcal{E}(W, t) = \text{Re}\{U(W)e^{-j\omega t}\} \text{ where } U(W) = C(W)e^{-j\phi(P)} \]  \hspace{1cm} (14)
• The mask is considered to have a digital transmission function:

\[
t(x_1, y_1) = \begin{cases} 
1 & \text{in clear areas} \\
0 & \text{in opaque areas}
\end{cases}
\]  \quad (15)

• After the light is diffracted, it is described by the Fraunhofer diffraction (far field) integral:

\[
\mathcal{E}(x', y') = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} t(x_1, y_1) e^{-2\pi i (f_x x + f_y y)} \, dx \, dy
\]  \quad (16)

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

\[
f_x = \frac{x'}{z\lambda} \quad \text{and} \quad f_y = \frac{y'}{z\lambda}
\]
\[ \mathcal{E}(f_x, f_y) = F\{t(x_1, y_1)\} \]  

(17)

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

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

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

(18)

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

\[ I(x') = F\{t(x)\} \]
• But only a portion of the light is collected. This is characterized by a pupil function:

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

(19)

• The objective lens now performs the inverse Fourier transform.

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

(20)

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

\[
I_i(x, y) = |\mathcal{E}(x, y)|^2
\]  

(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 (\(\lambda = 436 \text{ nm}\)). No aberrations or defocusing. Minimum feature size is 1 \(\mu\text{m}\).

Same example except that the feature size has been reduced to 0.5 \(\mu\text{m}\). Note the poorer image.

Same example except that the illumination wavelength has now been changed to i-line illumination (\(\lambda = 365 \text{ nm}\)) and the NA has been increased to 0.5. Note the improved image.
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:

\[ I(x, y, z) = I_i(x, y)I_r(x, y, z) \]  

(22)

where \( I_i(x,y) \) is the AI intensity and \( I_r(x,y,z) \) models latent image effects.
ATHENA Simulation

- 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 photoactive compound (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.
Photoresist Exposure

• The light incident is primarily absorbed by the PAC which is uniformly distributed in the resist.
  – Note: this analysis neglects standing wave effects
• Resist bleaching:
  – PAC becomes more transmissive as it becomes exposed, as the PAC converts to carboxylic acid
• Modeling: The probability of absorption is proportional to the light intensity and the absorption coefficient.

\[
\frac{dI}{dz} = -\alpha(z,t) \cdot I \tag{23}
\]
Exposure Model

• The absorption coefficient depends on the resist properties and on the PAC

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

(24)

where A and B are resist parameters (first two “Dill” parameters) with A the absorption coefficient of bleached and B nonbleached resist. Defining the percentage of unexposed resist

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

(25)

• m is a function of time (m=1 unexposed t=0, m=0 fully exposed) and is given by (with C another “Dill” parameter)

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

(26)

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

\[ \frac{dI}{dz} = -(A \cdot m(z,t) + B) \cdot I \]  

(27)

• Eqns. (26) and (27) are coupled equations which are solved simultaneously by resist simulators.
A transparent substrate with a backside antireflective coating is used.

By measuring $T_0$ and $T_\infty$, the Dill parameters, $A$, $B$ and $C$, can be extracted.
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).

- Simulation on right after a post exposure bake of 45 minutes at 115 °C. 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.
Photoresist Developing (1)

- A number of models for resist developing have been proposed and implemented in lithography simulators.
- The simplest is purely empirical (Dill et.al).

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

(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.
Photoresist Developing (2)

- A more physically based model has been developed by Mack which models developer diffusion and reaction (much like the deposition models discussed in Chap. 9).
- See the text for details on this development model.

\[ F_1 = k_D \cdot (C_D - C_S) \iff F_2 = k_R \cdot C_S \cdot [PAC]^n \]

In steady state \( F_1 = F_2 \) and

\[ F_1 = F_2 = \frac{k_D \cdot k_R \cdot C_D \cdot [PAC]^n}{k_D + k_R \cdot [PAC]^n} \]

But the rate is then \( r = F_1 = F_2 \) and

\[ r = \frac{k_D \cdot C_D \cdot (1 - m)^n}{k_D} + r_{\text{min}} \frac{k_R \cdot C_D \cdot [PAC]^n}{k_R \cdot [PAC]^n} + (1 - m)^n \]
• 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.

• Center - part way through development.
• Right - complete development.
Future Trends

• Optical lithography will be extendible to the 65 nm generation (maybe further).
• Beyond that, there is no general agreement on which approach to use.
• Possibilities include e-beam, e-beam projection (SCALPEL), x-ray and EUV.
• New resists will likely be required for these systems.
Techniques for Future Electronics

- Lithography and Other Patterning Techniques for Future Electronics
  - By R. Fabian Pease, Fellow IEEE, and Stephen Y. Chou, Fellow IEEE

- Projection Optics
  - Light Sources: 248–193 nm (KrF and ArF excimer lasers)

- Immersion Optics: use a fluid instead of air

- Extreme Ultraviolet Lithography (EUVL)

- Resolution Enhancement Technology (RET)

- Absorbance Modulation Optical Lithography (AMOL)

- Electron and Ion Beam Lithography

- X-ray Lithography

- Nanoimprint Technology
Summary of Key Ideas

• Lithography is the key pacing item for developing new technology generations.
• Exposure tools today generally use projection optics with diffraction limited performance.
• g and i-line resists based on DNQ materials and were used down to 0.35 µm.
• DUV resists use chemical amplification and are generally used below 0.35 µm.
• 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.
• Photoresist modeling (exposure, development, postbake) is less advanced because chemistry is involved which is not as well understood. Thus latent images are less accurately calculated today.
• A new approach to lithography may be required in the next 10 years.