The lithographic process

Design => Mask => Wafer
### Photolithographic Process

(a) Substrate covered with silicon dioxide barrier layer
(b) Positive photoresist applied to wafer surface
(c) Mask in close proximity to surface
(d) Substrate following resist exposure and development
(e) Substrate after etching of oxide layer
(f) Oxide barrier on surface after resist removal
(g) View of substrate with silicon dioxide pattern on the surface

### Photomasks - CAD Layout

- Composite drawing of the masks for a simple integrated circuit using a four-mask process
- Drawn with computer layout system
- Complex state-of-the-art CMOS processes may use 25 masks or more
Photo Masks

- Example of 10X reticle for the metal mask - this particular mask is ten times final size (10 µm minimum feature size - huge!)
- Used in step-and-repeat operation
- One mask for each lithography level in process

Lithographic Process

1. Starting wafer with layer to be patterned
2. Coat with photoresist
3. Bake the resist to set its dissolution properties
4. Expose resist by shining light through a photomask
5. Immerse exposed wafer in developer
6. Etch the film

*Optional steps:
- Develop cycle
- Hardbake
- Resist stabilization
- Post-exposure bake
- Exposure
- Softbake
- Resist application
- Adhesive remover application
- Dehydration bake
Printing Techniques

- Contact printing damages the mask and the wafer and limits the number of times the mask can be used.
- Proximity printing eliminates damage.
- Projection printing can operate in reduction mode with direct step-on-wafer.

Contact Printing

- Resolution $R < 0.5 \mu m$
- Mask plate is easily damaged or accumulates defects.
**Proximity Printing**

Resolution: \( R \propto \sqrt{\lambda g} \)

- \( \lambda \): wavelength of the light source
- \( g \): gap

\(~ 1\mu m\) for visible photons, much smaller for X-ray lithography

**Projection Printing**

De-Magnification: nX

- 10X stepper
- 4X stepper
- 1X stepper

Resolution: 250 nm to < 100 nm

(The Deep-UV stepper at Berkeley's Marvell Nanolab, ASML 5500/300, has 250 nm resolution)
Diffraction

Aerial Images
formed by Contact Printing, Proximity Printing and Projection Printing
Light Sources

- Hg Arc lamps 436(G-line), 405(H-line), 365(I-line) nm
- Excimer lasers: KrF (248nm) and ArF (193nm)
- Laser pulsed plasma (13nm, EUV)
- Source Monitoring
  - Filters can be used to limit exposure wavelengths
  - Intensity uniformity has to be better than several % over the collection area
  - Needs spectral exposure meter for routine calibration due to aging

Optical Projection Printing Modules

- Source
- Aperture
- Condenser Lens
- Mask
- Projection Lens
- Wafer

Optical System: illumination and lens
Resist: exposure, post-exposure bake and dissolution
Mask: transmission and diffraction
Wafer Topography: scattering
Alignment:
Optical Stepper

- scribe line
- wafer
- Image field
- Translational motion
- field size increases with future ICs

Resolution in Projection Printing

\[ f = \text{focal distance} \]
\[ d = \text{lens diameter} \]

\[ 1.22 \frac{\lambda f}{d} \]
**Resolution Limits in Projection Printing**

\[ l_m = k_1 \frac{\lambda}{NA} \left[ 0.6 \frac{\lambda}{NA} \text{ typical} \right] \]

\( NA \equiv \text{numerical aperture of lens} \)

\[ = n \cdot \sin \theta, \] where \( n \) is the index of refraction

\( k_1 \) is a constant between 0.25 and 1, depending on optics, resist, and process latitude

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**Depth of Focus (DOF)**

\[ \Delta z = k_2 \frac{\lambda}{(NA)^2} \]

\[ 0.5 < k_2 < 1 \]

\[ = \pm \frac{l_m}{2 \tan \theta} = \pm \frac{l_m}{2 \sin \theta} = \pm \frac{\lambda}{2(NA)^2} \]

\( \text{for small } \theta \)
Example of DOF problem

Trade-offs in Projection Lithography

\begin{align*}
(1) \quad l_m & \approx 0.6 \frac{\lambda}{NA} \quad \text{want small } l_m \\
(2) \quad DOF & = \pm \frac{\lambda}{2(NA)^2} \quad \text{want large DOF}
\end{align*}

(1) and (2) require a compromise between \( \lambda \) and NA!
Sub-Resolution Exposure: Phase Shift Masks

Pattern transfer of two closely spaced lines
(a) Conventional mask technology - lines not resolved
(b) Lines can be resolved with phase-shift technology

Immersion Lithography

- A liquid with index of refraction $n > 1$ is introduced between the imaging optics and the wafer.

Advantages

1) Resolution is improved proportionately to $n$. For water, the index of refraction at $\lambda = 193$ nm is 1.44, improving the resolution significantly, from 90 to 64 nm.

2) Increased depth of focus at larger features, even those that are printable with dry lithography.

\[ l_m = 0.6 \frac{\lambda_{\text{water}}}{NA} \]

\[ \lambda_{\text{water}} = \frac{\lambda}{1.3} \]
Image Quality Metric: Contrast

Contrast:

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

The contrast is always between 0 (no variation) and 1 (perfect minimum).

Contrast is also sometimes referred as the Modulation Transfer Function (MTF)

Questions:

How does contrast change as a function of feature size?

How does contrast change for coherent vs. partially coherent light?
The Need for High Contrast

Optical image

Infinite contrast

Finite contrast

Position x

* simulated aerial image of an isolated line

Image Quality metric:
Slope of image

$S_1 = 0.6$ Feature

Slope: $2.5/(\lambda \cdot NA)$

Mask Opening

Finite contrast

Infinite contrast

Position x
Resists for Lithography

• Resists
  – Positive
  – Negative

• Exposure Sources
  – Light
  – Electron beams
  – X-ray sensitive

Two Resist Types

• Negative Resist
  – Composition:
    • Polymer (Molecular Weight (MW) ~65000)
    • Light Sensitive Additive: Promotes Crosslinking
    • Volatile Solvents
  – Light breaks N-N in light sensitive additive => Crosslink Chains
  – Sensitive, hard, Swelling during Develop

• Positive Resist
  – Composition
    • Polymer (MW~5000)
    • Photoactive Dissolution Inhibitor (20%)
    • Volatile Solvents
  – Inhibitor Looses N2 => Alkali Soluble Acid
  – Develops by “etching” - No Swelling.
Positive P.R. Mechanism

Photons deactivate sensitizer

\[ \text{polymer + photosensitizer} \xrightarrow{\text{dissolve in developer solution}} \]

Positive Resist

\[ \text{hv-mask} \]

exposed part is removed

\[ \begin{array}{c}
\text{resist thickness remaining} \\
Q_0 \rightarrow Q_f
\end{array} \]

exposure photon dose (log scale)

\[ \text{Resist Contrast} = \frac{1}{\log_{10} \left( \frac{Q_f}{Q_0} \right)} \]
Negative P.R. Mechanism

hv => cross-linking => insoluble in developer solution.

Positive vs. Negative Photoresists

- **Positive P.R.**:
  - ✓ higher resolution
  - ✓ aqueous-based solvents
  - ✗ less sensitive

- **Negative P.R.**:
  - ✓ more sensitive => higher exposure throughput
  - ✓ relatively tolerant of developing conditions
  - ✓ better chemical resistance => better mask material
  - ✓ less expensive
  - ✗ lower resolution
  - ✗ organic-based solvents
(1) Thermal Run-in/Run-out errors

\[ R = r \cdot (\Delta T_m \cdot \alpha_m - \Delta T_{si} \cdot \alpha_{si}) \]

\( \Delta T_m, \Delta T_{si} \) = change of mask and wafer temp.
\( \alpha_m, \alpha_{si} \) = coefficient of thermal expansion of mask & Si
Rotational / Translational Errors

(2) Translational Error

(3) Rotational Error

Overlay implications: Contacts

Alignment error

Solution: Design n+ region larger than contact hole
Overlay implications: Gate edge

“Ideal”

“With alignment error”

Solution: Make poly gate longer to overlap the FOX

Total Overlay Tolerance

$$\sigma^2_{total} = \sum_i \sigma^2_i$$

$$\sigma_i = \text{std. deviation of overlay error for } i^{\text{th}} \text{ masking step}$$

$$\sigma_{total} = \text{std. deviation for total overlay error}$$

Layout design-rule specification should be > $\sigma_{total}$
Standing Waves

Higher Intensity  
Faster Development rate  
Lower Intensity  
Slower Development rate

Substrate

After development

Positive Photoresist

hv

Positive Photoresist

Substrate

Standing waves in photoresists

SiO₂/Si substrate

Intensity = minimum when
\[ x = d - m \frac{\lambda}{2n} \]
\[ m = 0, 1, 2, \ldots \]

Intensity = maximum when
\[ x = d - m \frac{\lambda}{4n} \]
\[ m = 1, 3, 5, \ldots \]

n = refractive index of resist
Proximity Scattering

Approaches for Reducing Substrate Effects

• Use absorption dyes in photoresist
• Use anti-reflection coating (ARC)
• Use multi-layer resist process
  – 1: thin planar layer for high-resolution imaging
  – 2: thin develop-stop layer, used for pattern transfer to 3
  – 3: thick layer of hardened resist
Electron-Beam Lithography

\[ \lambda = \frac{12.3 \text{ Angstroms}}{\sqrt{V}} \text{ for } V \text{ in Volts} \]

**Example:** 30 kV e-beam

\[ \Rightarrow \lambda = 0.07 \text{ Angstroms} \]

**NA = 0.002 – 0.005**

Resolution < 1 nm

But beam current needs to be 10’s of mA for a throughput of more than 10 wafers an hour.

Types of Ebeam Systems
Resolution limits in e-beam lithography

resolution factors

• beam quality (~1 nm)
• secondary electrons (lateral range: few nm)

performance records

organic resist PMMA ~ 7 nm
inorganic resist, b.v. AlF₃ ~ 1-2 nm

The Proximity Effect
1985: Tom Newman, Fabian Pease (Stanford University) used e-beam lithography to write part of *A Tale of Two Cities* at the length scale requested by Feynman.
Nanoimprint lithography (NIL)

The mold is typically patterned SiO$_2$ on Si. It is made with e-beam lithography.

The mold is pressed on the substrate. The resist is heated above its glass transition temperature.

The mold is removed.

An anisotropic reactive ion etch is used to remove the resist until the substrate is exposed.

The substrate is patterned by etching or lift-off techniques.

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SEM image of mold

This mold consists of SiO$_2$ pillars on an Si wafer.

It had already been used 10 times before the image was taken. The quality of the mold was not degraded by use.
Holes imprinted into a PMMA resist layer


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Metal dots after lift-off

Dip Pen Nanolithography

Dip-Pen Nanolithography: Transport of molecules to the surface via water meniscus.

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market: they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2069, when they look back at this age, they will wonder why it was not until the year 1959 that anybody began seriously to move in this direction.

Richard P. Feynman. 1959
Patterning of individual Xe atoms on Ni, by Eigler (IBM)