Section 2: Lithography

Jaeger Chapter 2
Litho Reader

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

- Dehydration bake
- Adhesion promoter application
- Resist application
- Softbake
- Exposure
- Post exposure bake*
- Develop cycle
- Hardbake
- Resist stabilization*

*Optional steps
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**

\[ R \text{ is proportional to } (\lambda g)^{1/2} \]

\[ \sim 1 \mu m \text{ for visible photons, much smaller for X-ray lithography} \]

**Projection Printing**

\[ \sim 0.2 \mu m \text{ resolution (deep UV photons)} \]

\[ \text{tradeoff: optics complicated and expensive} \]
Diffraction

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

Incident Plane Wave

Mask Aperture

Resist

Wafer

Light Intensity at Resist Surface

Separation Depends on Type of System

Projection

Contact
 Photon 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

Optical System: illumination and lens

Resist: exposure, post-exposure bake and dissolution

Mask: transmission and diffraction

Wafer Topography: scattering

Alignment:
Optical Stepper

- Scribe line
- Image field
- Wafer
- Translational motion

Field size increases with future ICs

Resolution in Projection Printing

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

Minimum separation of a star to be visible.
Resolution limits in projection printing

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

\( NA \equiv \text{numerical aperture of lens} \equiv n \sin \theta \), where \( n \) is the index of refraction

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

---

Depth of Focus (DOF)

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

\( 0.5 < k_2 < 1 \)

\[ \approx \pm \frac{l_m}{2 \tan \theta} \approx \pm \frac{l_m}{2 \sin \theta} = \pm \frac{\lambda}{2(NA)^2} \text{ for small } \theta \]
Focus versus Extreme Defocus (an illustration)

Large P features

Small P features

For Reference only

Best focus

Extreme Defocus

Example of DOF problem

Photo mask

Field Oxide

Different photo images
Tradeoffs in projection lithography

(1) \( l_m \approx 0.6 \frac{\lambda}{NA} \)  want small \( l_m \)

(2) \( \text{DOF} = \pm \frac{\lambda}{2(NA)^2} \)  want large \( \text{DOF} \)

(1) and (2) require a compromise between \( \lambda \) and NA!

Sub-resolution exposure: Phase Shifting 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.

---

**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?

* simulated aerial image of an isolated line

Image Quality metric: Slope of image

k₁ = 0.6 Feature

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

Mask Opening

* simulated aerial image of an isolated line
The need for high contrast

Resists for Lithography

- Resists
  - Positive
  - Negative

- Exposure Sources
  - Light
  - Electron beams
  - Xray 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 sensitiser

polymer + photosensitizer
⇒ dissolve in developer solution
**Positive Resist**

\[ \text{Resist contrast} = \frac{1}{\log_{10} \left( \frac{Q_f}{Q_0} \right)} \]

**Negative P.R. Mechanism**

hv \rightarrow \text{cross-linking} \rightarrow \text{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

**Overlay Errors**

- Alignment marks from previous masking level
- Photomask plate
- Wafer
(1) **Thermal Run-in/Run-out errors**

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

\(\Delta T_m, \Delta T_{si} = \text{change of mask and wafer temp.}\)

\(\alpha_m, \alpha_{si} = \text{coefficient of thermal expansion of mask & Si}\)

---

**Rotational / Translational Errors**

(2) **Translational Error**

(3) **Rotational Error**
**Overlay implications: Contacts**

- **Ideal**
  - n⁺ region aligned with contact hole
  - p-Si and SiO₂ layers

- **Alignment error**
  - n⁺ region overlapping contact hole
  - "short", ohmic contact
  - Δ symbol indicating misalignment

**Solution:** Design n⁺ region larger than contact hole

**Overlay implications: Gate edge**

- **Ideal**
  - S/D implant aligned with poly-gate
  - Fox structure

- **With alignment error**
  - S/D implant overlapping poly-gate
  - Electrical short indicated

**Solution:** Make poly gate longer to overlap the FOX

EE143 – Ali Javey
**Total Overlay Tolerance**

\[ \sigma^2_{total} = \sum_{i} \sigma_i^2 \]

- \( \sigma_i \) = std. deviation of overlay error for \( i^{th} \) masking step
- \( \sigma_{total} \) = std. deviation for total overlay error

Layout design-rule specification should be \( > \sigma_{total} \)

---

**Standing Waves**

- Higher Intensity
- Lower Intensity
- Faster Development rate
- Slower Development rate

After development:

- Positive Photoresist.
- Substrate
**Standing waves in photoresists**

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**

Mask

Light rays

Photoresist

Metal

Oxide

Wafer
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 (imaging layer)
  2: thin develop-stop layer, used for pattern transfer to 3 (etch stop)
  3: thick layer of hardened resist (planarization layer)

Electron-Beam Lithography

\[ \lambda = \frac{123}{\sqrt{V}} \text{ Angstroms for } V \text{ in Volts} \]

Example: 30 kV e-beam

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

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.
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

2nd Feynman Prize

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 SiO₂ 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.

SEM image of mold

This mold consists of SiO₂ 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


EE143 – Ali Javey
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 2060, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Richard P. Feynman, 1960

“Tunable Bond”

- Chemical bonding force enables atom manipulation

Tip

Adatom

Surface
Patterning of individual Xe atoms on Ni, by Eigler (IBM)

EE143 – Ali Javey