Optical lithograph
Campbell, Chapter 7

- overview
- optical diffraction
- light sources
- printers – contact or proximity
- projection printers
- advanced mask design issues
- surface reflection effects
- alignment
Lithography -- an overview

- Lithography is the **single most important manufacturing technique** for making small devices
- “It is the most complicated, expensive, and critical process in mainstream microelectronic fabrication”
- Lithographic processes utilize **optics** (Campbell, Chapter 7) and **photoresists** (Campbell, Chapter 8)

<table>
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<th>DRAM size</th>
<th>Chip size (mm²)</th>
<th>Minimum feature size (μm)</th>
<th>Overlay accuracy (μm)</th>
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Lithography impacts every step in the semiconductor fabrication process.
The basic lithographic process (1)

- light source
- optical system
- mask
- wafer coated with photoresist
The basic lithographic process (2)

1. Substrate
2. Photoresist
3. UV radiation
4. Thin film
5. Photomask
6. Final result
Requirements for optical lithography

**Resolution** – the minimum feature size that can be exposed
depends on *optics* and their *interaction* with photoresist

**Registration** – the ability to overlay one exposure on another
a typical silicon device will require 15 to 25 mask levels

**Throughput** – the number of wafers per hour
optical lithography → 60 - 90 wafers/hour
electron beam lithography → <1 wafer/hour
Diffraction of the light as it goes through openings in the mask causes the actual pattern that is transferred to differ from the ideal pattern.

\[ 2b_{\text{min}} \approx 3 \sqrt{s \lambda} \]
Introduction to diffraction

*Intensity distribution of a light ray as it passes a straightedge – geometric optics* ($\lambda \to 0$)

- Point source
- Straightedge
- Geometric shadow

*Intensity distribution of a light ray as it passes a straightedge with diffraction*

- Screen
- Intensity distribution graph
**Introduction to diffraction**

- **Diffraction** refers to the apparent deviation of light from rectilinear propagation as it passes an obstacle such as an opaque edge.
- Light is not “bent” – diffraction arises as a natural consequence of the way that light propagates.
- When a plane wave impinges on any disturbance, that disturbance will serve as a source of spherical waves that propagate outward from the point of disturbance (Huygen’s Principle, left).
- Diffraction effects occur whenever there is any limitation of the width of a beam of light.
**Optical diffraction (1)**

- Light from a point source has an amplitude given by:
  \[ \mathcal{E}(\vec{r}, \nu) = E_o(r)e^{i\phi(\vec{r}, \nu)} \]

- For an infinitely large slit the intensity is given by:
  \[ I = \mathcal{E}\mathcal{E}^* = E_o e^{i\phi} E_o e^{-i\phi} = E_o^2 \]

- For a finite (2-element) slit the intensity is given by:
  \[ I = E_1^2 + E_2^2 + 2E_1E_2 \cos(\phi_1 - \phi_2) \]
Optical diffraction (2)

\[ W^2 \gg \lambda \sqrt{g^2 + r^2} \]

"near field" (Fresnel) diffraction

spherical waves and small separation

Normalized intensity

Position on the wafer (a.u.)
Optical diffraction (3)

\[ W^2 \ll \lambda \sqrt{g^2 + r^2} \]

“far field” (Fraunhofer) diffraction

plane waves and large separation

![Graph showing normalized intensity versus position on the wafer]
Modulation Transfer Function (MTF)

- The MTF is a measure of image contrast: 

\[
MTF = \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \right)
\]

We want the MTF to be as large as possible for reliable exposure—depends on l, light source size (coherency), and optical system.
Coherency: “the state or quality of being together”

- **Temporal coherence** refers to photons that are related in time (i.e. emitted simultaneously)
  - an extended source can be divided into an infinite number of independent point sources
  - it is impossible for a finite source to be temporally coherent

- **Spatial coherence** refers to photons that are related in phase (i.e. photons are in phase at every point along a wave front)
  - a perfectly coherent source will radiate a series of spherical wave fronts
  - spatial coherence can be achieved by moving the observation point $P$ to infinity so both $\alpha$ and the area of emission go to zero
Spatial coherence of the light source

- A light source with high spatial coherence has a small effective radiating source (a “point source”)
- Poor spatial coherence degrades resolution
Light sources

• The first minimum in a (Fraunhofer) diffraction pattern of a circular aperture of diameter $d$ is given by

$$\sin \theta = 1.22 \frac{\lambda}{d} \} \text{ we want the diffracted image to be as small as possible, so we want } \lambda \text{ to be as small as possible}$$

• Optical lithography used ultraviolet (UV) light sources:
  - **Xenon arc lamps** – near-continuous spectrum in the visible (200 nm to 750 nm) with Xe lines above 800 nm
  - **Mercury arc lamps** – high energy output in the UV with intense lines between 240 nm and 600 nm
  - **Hg-Xe lamps** – combines the spectra from Hg and Xe; the Xe gas improves start-up and extends life
Aspects of UV light sources

• UV arc lamps operate by passing an electrical discharge through a gas to form a plasma

• Pressure at start ~ 1 atm, pressure during operation ~ 40 atm (explosion hazard!)

• Spectral qualities of arc lamps
  – continuous spectrum due to high energy electrons
  – discrete spectrum due to electronic transitions in gas

  \[ \rightarrow \text{Hg “g-line” at 436 nm} \]
  \[ \rightarrow \text{Hg “h-line” at 405 nm} \]
  \[ \rightarrow \text{Hg “i-line” at 365 nm} \]

• The UV light is always collected by mirrors or lenses (or both) to provide a more concentrated intensity into the photomask and onto the photoresist (increased throughput)
Effect of wavelength on minimum achievable linewidth
Excimer laser sources

- A mixture of gases (noble + halogen) are mixed in a tube
- A short (~20 nanosecond) high voltage (~12,000 volt) charge is applied:

  \[ \text{Kr}^* + \text{F}_2 \rightarrow \text{KrF}^* + \text{F} \]

- Decay of the \( \text{KrF}^* \) to the ground state releases DUV (deep UV) radiation (248 nm for KrF, 193 nm for ArF)
- Can be turned into a laser with a pulse rate of ~1000 Hz
- High output power (joule/pulse) in a very narrow wavelength range

→ Problem: the light devitrifies the lenses!
Contact/proximity printers

The simplest form of photolithography:

- **Contact printing:** the photomask is placed in contact with the photoresist-covered wafer and exposed to light
  - advantages: excellent resolution, simple optics, inexpensive
  - disadvantages: defect generation on both the mask and wafer

- **Proximity printing:** mask is separated by a thin gas cushion
  - advantages: defect generation is reduced
  - disadvantages: resolution is reduced: $W_{\text{min}} \approx \sqrt{k\lambda g}$
The contact printing process

- optically align wafer to mask
- compress wafer and mask; clamp together
- expose to UV light
- remove mask and develop the resist
Proximity printing

- In **proximity printing** the wafer and mask are separated by a small (10 to 50 \( \mu \text{m} \)) cushion of gas (just like an **air bearing**)

- The resolution is a sensitive function of the size of the gap between the mask and the wafer

  - small gap \( \lambda < g < W^2/g \) → near-field (Fresnel) diffraction

  - large gap \( g > W^2/g \) → system approaches Fraunhofer (far-field) diffraction

\[
g \ll \frac{W^2}{\lambda} \quad \text{or} \quad \frac{W^2}{g} \gg \lambda
\]
Projection printing

- In *projection printing* the image of the mask is projected onto the wafer by an optical system.

![simplified optical system diagram]
Comparison of exposure tools

contact

proximity

projection

Relative intensity
Projection printing -- a “real” system

(from IBM Journal of Research and Development)
The Numeric Aperture

- The numeric aperture (NA) measures the light gathering capability of a lens:
  \[ NA = n \sin \alpha \]
- The larger the NA, the more light flux is collected
- The NA is related to the “f-number” of a lens where \( f/# = F/D \)
- For optical lithography, we want the largest NA possible; however, lens aberrations (optical defects) increase very rapidly with increasing NA
Factors affecting focus and resolution

- **Rayleigh’s criterion**: the diffraction limitation of an aberration-free optical system is given by:

  \[ W_{\text{min}} \approx k \frac{\lambda}{\text{NA}} \quad (k \sim 0.61) \]

- **Depth of focus**: the distance along the optic axis the wafer can be moved and still be kept in focus:

  \[ \sigma = \frac{\lambda}{(\text{NA})^2} \]

- **Spatial coherence** of the source: the distance along the optic axis the wafer can be moved and still be kept in focus:

  \[ S \approx \frac{\text{source image diameter}}{\text{pupil diameter}} \]
Spatial coherence of the light source

- A light source with high spatial coherence has a small effective radiating source (a “point source”)
- Poor spatial coherence degrades resolution
Scanning projection lithography systems

- In scanning projection systems the wafer and 1:1 mask are moved together as a light beam illuminates both.
Steppers

• Steppers are the principal lithographic tools used today

• A field is exposed at one time (typically ~ cm²)

• The wafer is translated and a new field is exposed

• Steppers permit the use of high NA optics, thus improving resolution and reducing minimum feature size

• Masks are typically 4:1 or 5:1 reduction

• Steppers require state-of-the-art mechanical precision along with optical precision

• Each mask ~$50K
Common terms in lithography

**Mask** (a.k.a. full field mask) – a 1X mask that in a single exposure transfers to a resist-covered wafer all the patterns corresponding to all the chips on a wafer

**Reticle** – a mask that is usually demagnified by a factor of 5 to 10 and is used in a projection exposrer; reticles usually contain only one (maybe two or more) chip images and must be stepped across the wafer

**Pellicle** – a thin polymer or plastic film that keeps particulate contamination away from the focal plane of a mask or reticle
Errors observed in steppers

- reticle plane
- wafer plane
- reduction lens
- field

Translation
Rotation
Magnification
Tilt
Lens distortion
Alignment

- **Alignment** is the process of positioning a mask producing one circuit level on top of a previously exposed level.
- Registration errors should be 1/4 to 1/3 of the resolution.
- **Alignment marks** are contained on different mask levels.

![Diagram of alignment marks](image-url)

- Mask mark
- Wafer mark
Manual vs. automatic alignment

- Manual alignment is typically used for contact and proximity printers (low throughput)
- Automatic alignment need for high throughput projection printers — photomultiplier tube, photodiode array, TV camera

![Diagram of manual vs. automatic alignment]
Phase shift mask technology

- Light (electromagnetic wave) has both *amplitude* and *phase*
- A conventional photomask consists of a quartz plate with a patterned opaque layer
- Constructive interference between openings enhance both the electric field and intensity, reducing both contrast and resolution
- By shifting the phase in adjacent openings by 180°, destructive interference can minimize unwanted intensity between openings
Phase-shifted mask technology

conventional mask

phase shift mask

mask

phase shifter

electric field at mask

electric field at wafer

intensity at wafer
Standing wave effects

- The projection of a perfect image onto a resist surface will not necessarily result in the replication of that image!
- With monochromatic light, standing waves create a periodic intensity distribution perpendicular to the plane of the resist.
- Standing waves cause “steps” to occur at the edge of an exposed pattern; minimized by baking the photoresist so that it will “flow” or by using an antireflection coating at the wafer surface
Reflections off topographic features

- Interference between the imaging beam and its reflection off of the surface of the wafer and topographic features is a major cause of linewidth variations.
- Variations can be minimized by planarizing the wafer either by etching or by chemical-mechanical polishing.
- Antireflective polymers underneath the resist also help.
- Both planarization and a.r. coatings help, but both increase the complexity of the process.