Chap. 7
Optical Lithography
Patterning elements in Microelectronics is done using radiation: primarily uv (Ch. 7) but also by x-rays or electron beam (Ch. 9)

**Photolithography**: process of using an optical image and a photosensitive film, photoresist (Ch. 8) to produce a pattern on a substrate

**Visible light**: $\lambda \sim 400$-$700$ nm

It all starts with a circuit design using CAD tools; the circuit layout is transformed into a set of *photomasks*; each photomask contains an image of 1 layer of the process.

**Lithography** is one of the most complicated, expensive, and critical processes in microelectronic fabrication; it accounts for about 1/3 of the total fabrication costs.

Depending on complexity of circuit, 15-20 masks may be used, even more now.

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**Figure 7.1** Simplified IC design process flow diagram.
An example of design rules for a metal contact layout

Figure 7.2 Excerpt of typical design rule set. This portion deals with first metal rules for a particular technology.
A photomask is a fused silica plate of high clarity and polished to a smooth surface with a chromium pattern on one side. Needs to be defect free (no pinholes in Cr, no dust particles, sharp Cr images) because any defect will be reproduced on the wafer. Depending on the tool, masks are same size as wafer final image (1×) or the image may be reduced during exposure (5× or 10×); the masks are also called reticles. A pellicle is a transparent film covering the reticle.

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.
Decreasing Feature size (and overlay accuracy) over time

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.
Optical source shines light through the photomask; image is projected onto the wafer that is coated with photoresist.

Two things happening:

1) exposure tool that creates the image of the photomask at the surface of the wafer and

2) chemical processes that occur once radiation of the image is absorbed in the resist and pattern is developed. The pattern of radiation that strikes the wafer surface is called the areal image of the mask.

Figure 7.5 Schematic of a simple lithographic exposure system.
Objective: transfer photomask pattern into an underlying film

First have to transfer that image into the resist, develop the resist (solubility of the resist depends on chemical changes upon exposure to light); that film now acts as a mask so that the photomask image can be transferred to the underlying film (oxide, nitride, metal, etc).

From:
Optical source is either visible, UV, DUV, EUV light. Tools that perform the exposure are called aligners because they must also align successive layers to previous ones; photomasks contain alignment marks to help with this step.

**Measures of performance:**

1) Resolution – minimum feature size that can be exposed; combination of the optical tool and resist system have to be optimized.

2) Registration (overlay) – measure of the overlay accuracy from layer to layer

![Diagram showing misalignment and runout](https://via.placeholder.com/150)

*Figure 7.33* Two typical registration errors.

3) Throughput – how many wafers processed/unit time
Image creation – Huygen’s principle:

Every point on a primary wave front serves as a source of spherical secondary waves. Ideally, edges of an opaque object placed between a point source and a screen should cast a sharp shadow on the mask; in reality the shadow cast by the edge is diffuse and this apparent bending of light around the edge is diffraction. Diffraction is just a consequence of the way light propagates in space from point to point.

Source of image: wikipedia

Figure 7.6  Huygens's principle - A point source is used to expose an aperture in a dark field mask.
Diffraction: Two limiting cases

1) Mask and wafer separated by a very short distance (contact/proximity printing)

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

Interference (constructive and destructive) between the wavelets gives rise to the oscillations that are a characteristic part of the diffracted image.

**Figure 7.7** Typical near field (Fresnel) diffraction pattern.
2) Mask and wafer separated by a large distance (projection printing)

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

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

Much more complicated –

• light source is not a point,
• light source emits a number of wavelengths,
• light is collected through a lens/mirror assembly,
• all optical components have some imperfections,
• mask will reflect, absorb, phase-shift radiation,
• reflections on surface of wafer.
Modulation Transfer Function (MTF)

**Diffraction grating** – rather than a single rectangle, look at a series of lines and spaces. Useful when discussing resolution of a system.

\[ 0 \leq MTF \leq 1 \]

One can think of MTF as a measure of the optical contrast in the areal image; the higher the MTF, the more you will discern the final image. Optical system will modulate the maximum and minimum intensities unless \( MTF = 1 \); adjust focus and exposure times to maximize MTF.

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

For Fig. 7.9:

\[
MTF = \frac{(5 - 1)}{(5 + 1)} = \frac{4}{6} = 0.67
\]

**Figure 7.9** Far field image for a diffraction grating.
(A) Simple Fresnel diffraction; if resist responds ideally, a single line exists at an exposure energy density, $D_{cr}$. All regions of resist that receive exposures $> D_{cr}$ will completely dissolve during the develop process.

(B) A more realistic model: two critical exposure energy densities exist; For $D_0 < D < D_{100}$, image will partially develop.

**Figure 7.10** Plot of dose versus position on the wafer. Dose is given by the intensity of the light in the areal image multiplied by the exposure time. Typical units are mJ/cm$^2$. 
Optical Sources – light source and reflecting and/or refracting optics for collecting, collimating, filtering, and focusing the source.

Arc lamps contain mercury vapor; they have two conducting electrodes with a gap of $\approx 5$ mm, sealed in a fused silica envelope. High voltage (kV) applied across the gap to ionize gas inside creating a plasma (glow discharge).

Mercury atoms excited into high energy states; as they decay to lower energy states, they emit optically at a $\lambda$ corresponding to the energy transition.

Lamps are cooled with fans during operation and replaced after a set number of hours.

Figure 7.13 Typical high pressure, short arc mercury lamp (courtesy Osram Sylvania).
Complicated system to collect radiation, filter, make radiation uniform, collimate…

**Figure 7.15** Schematic of a typical source assembly for a contact/proximity printer (*after Jain*).
Older equipment: g-line (436 nm) and i-line (365 nm)

Xenon as the fill gas can extend mercury arc lamps to around 290 nm but **excimer lasers** are more popular sources for $\lambda < 365$ nm.

**Excimer**: excited dimer (molecules with 2 atoms of same element, $F_2$). Chemical reaction leads to lasing and excited molecule emits in the deep UV. Brightest optical source in DUV.

- $F_2$: 157 nm
- ArF: 193 nm
- KrF: 248 nm

**Figure 7.14** Line spectra of typical mercury arc lamp showing the positions of the two lines most commonly used in lithography.
Photolithographic systems
1) Contact Printing
2) Proximity Printing
3) Projection Printing
Contact Printing:

• Requires intimate contact between mask and wafer;
• Simplest type of aligner;
• Illumination comes from a high intensity lamp (usually a mercury vapor lamp);
• Small features can be created with relatively inexpensive equipment;
• Alignment done with microscope and x-y controls to position wafer properly under mask.

Advantages/Disadvantages

• Good resolution of images (~ 1 or 0.5 µm); Simple design, therefore easy to operate and maintain equipment.
• Masks may be damaged due to contact with wafer so this technique is limited to research labs or applications that can tolerate the defects.

Figure 7.19 Typical contact exposure system (courtesy of Karl Suss).
Proximity Printing:

- Similar equipment to contact printing;
- Mask is brought in close proximity to wafer (gap is 10-50 μm);
- Minimum line-width that can be printed is given by

$$W_{\text{min}} \approx \sqrt{k\lambda g}$$

where \(g\) is gap, \(\lambda\) is wavelength of exposure radiation, and \(k\) is a resist constant (indicator of ability of resist to distinguish between small changes in intensity).

For a \(\lambda\) of 248 nm and gap of 15 μm, \(W_{\text{min}} = 1.93\) μm

Advantages/Disadvantages

- Masks are less defect prone than in pure (hard) contact.
- Harder to align and will lose some resolution of images due to the small gap resulting in diffraction at feature edges.
Loss in resolution for increasing gap size

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 \( g = 15 \, \mu \text{m} \) (after Geikas and Ables).
Projection Printing:

• Mask image is projected onto wafer by means of a reflective or refractive optical system;

• Wafer is located some distance from the mask since lens elements are used to focus image; only a small portion of the mask is exposed at a time;

• Pellicles (thin mylar) is used to keep particles off mask;

• Very complex and expensive aligner systems → Scanners, step and repeat systems (steppers), combination of scanning/stepping.
Advantages/Disadvantages

• High resolution of images (sub-micron); no mask damage;
• Complex equipment so high maintenance;
• Throughput is low (depends on #die/wafer, exposure time, stage movement/settling times, auto focus time, time to load/unload, and site by site alignment);
• Requires an environmental chamber for reducing noise, vibrations, controlling Temp, humidity.
Figure 7.21 Schematic for the optical train of a simple projection printer.

Mask is held between the condenser and projector (objective) lenses; lenses used for collimation and refocusing light onto the wafer.

Numerical aperture (NA) = \( n \sin (\alpha) \) where \( n \) is refractive index of media between objective and wafer (usually air, \( n = 1 \)); typical values for NA are 0.16 – 0.8 (much work has gone into ↑ NA)
Resolution is limited by the ability to reimage the light and this limit is referred to as Rayleigh’s criteria

\[ W_{\text{min}} \approx k_1 \frac{\lambda}{NA} \]

If \( k = 0.75 \), \( NA = 0.4 \) and \( \lambda = 436 \text{ nm} \), \( W_{\text{min}} = 0.8 \mu m \)

One way to \( \downarrow W_{\text{min}} \) is to \( \uparrow NA \), however increasing NA affects depth of focus (\( \sigma \)): the distance the wafer can be moved and still keep image in focus.

\[ \sigma = \frac{n\lambda}{NA^2} \]

So increasing NA increases resolution linearly but \( \downarrow \sigma \) quadratically. There has to be some compromise between resolution and DOF.
MTF versus spatial frequency for varying spatial coherence of the optical source. A source with perfect spatial coherence, $S=0$.

Spatial frequency normalized to the Rayleigh criterion:

$$\nu_o = \frac{1}{W_o} = \frac{NA}{0.61\lambda}$$

**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.
Scanning mirror projection system:

In early systems, an arc of light that shines through the mask reflects off 2 mirrors. System less sensitive to chromatic aberrations (lenses); however, NA only 0.16.

Figure 7.23 Schematic for the operation of a scanning mirror projection lithography system (courtesy of Canon U.S.A.).
Step and Repeat (stepper) system:

Refractive systems using lenses to further reduce images on mask. Only a small region (field) of the wafer is exposed at a time. Systems can have high NAs and therefore, high resolution.

Disadvantage is throughput.
Two developments in last decade:

1) Replacing steppers with step/scan systems. NAs of 0.7 and can accommodate large exposure areas.

2) Immersion Lithography. Replace air gap with liquid (↑n) to reduce minimum feature size. Water has n = 1.43.

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).

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.)
Summary:

To obtain **maximum performance** from the lithographic equipment, need to understand **inherent limitations**:

- Basic laws of light transmission
- Nature of image formation
- Physical limits on image reproduction