Chapter 9

Nonoptical Lithographic Techniques
X-Ray Printing System

X-ray source

Vac or He chamber mask

wafer

Alignment Electronics

Alignment sensor

X-Ray Mask materials (Campbell Table 9.2):
Si$_3$N$_4$, Si, BN, SiC, W, Au, diamond.
See also: X-Ray generation, X-Ray optics.

X-ray photons: 1-10keV (\(\lambda=0.1\text{nm}=1\text{Å}\)) → electron-photon interaction

(typical lithography energies) 

\(~10\text{keV}\)

\(\gamma_1\)

\(\gamma_2\)

\(\lambda_2-\lambda_1=\lambda_0(1-\cos\theta)\)

where \(\lambda_0=0.0243\text{Å}\) and \(\theta=\text{angle between } \gamma_1, \gamma_2 \text{ directions}\)

2ndary e\(^-\) energies<0.1x e-beam e\(^-\) energies so less energy spread

Absorption \(\alpha(\lambda)=\sigma(\lambda)\rho/m\)

Figure 9.1 The two dominant interaction processes for high energy photons with matter: the photoelectric effect and Compton scattering.
Figure 9.2. Absorption coefficients for some common materials as a function of photon energy (after Glendenning and Cerrina [29], reprinted by permission, Noyes Publications).

Absorption coefficient $\alpha$

Low energy, high $\alpha$ → need bleaching effects

Discontinuous due to different energy levels

X-Ray Printing Resolution #1

source

mask

wafer

Diffraction Blur $\delta_d$

source

Penumbral Shadow $\delta_s$

finite thk mask

Mask shadow $\delta_m$
**X-Ray Printing Resolution #2**

**Diffraction Blur:** \[ \delta_d = 0.4(\lambda d/2)^{1/2} \]

**Pennubral Shadow:** \[ \delta_S = S_d d/B \]

where \( S_d \) = Source diameter

**Mask Shadow:** \[ \delta_m = r t / B \]

**Electron generation in PR:** Range \( \delta_e = 10^{-23} \lambda^{-7/4} \) (in m)

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**X-Ray Printing Resolution #3**

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<th>( \delta_d )</th>
<th>( \delta_s )</th>
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<td>80</td>
<td>300</td>
<td>50</td>
<td>17</td>
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for: \( B = 40 \text{ cm}, d = 40 \mu\text{m}, S_d = 3 \text{ mm} \)
\( r = 20 \text{ mm}, t = 1 \mu\text{m} \)
Electron beam lithography (EBL)

Elastic scattering: neutrons (eq’ns 9.3/9.4)

Inelastic scattering: See next slide

Figure 9.3 Deposited energy density for various energy electron beams incident on silicon as a function of depth.

Monte Carlo simulations, or Bethe equation:

\[
\frac{dE}{dx} = \left( \frac{N_A e^4}{2 \pi \varepsilon_0^2} \right) \frac{Z^2 \rho}{A \ln \left( \frac{E}{E_0} \right)}
\]

where  
- \( N_A \) = Avogadro’s number  
- \( Z \) = atomic number  
- \( A \) = atomic weight  
- \( \rho \) = density  
- \( J \) = mean ionization potential \( \approx 11.5 \text{eV} \)

Range \( R_p = \int_0^{R_p} dx = \int_{E_0}^{E} \left( \frac{dE}{dx} \right)^{-1} dE \)
**Thermionic electron sources**

Richardson - Dushman equation

\[ J_C = A T^2 \exp \left( \frac{E_m}{kT} \right) \]

W: 0.5A/cm² at 10⁻⁴torr  
LaB₆: 20A/cm² at 10⁻⁴torr

Brightness β: Collected current

**Future:**  
Zr/W/O field emission: 1000A/cm² at 10⁻⁸torr  
with 10nm spot

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**Figure 9.4** Simplified cross section schematics of field emission and thermionic emission electron guns

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**Spot diameter:** \( d^2 = d_0^2 + d_s^2 + d_c^2 \approx d_0^2 \)

where  
\( d_0 \) due to lens diameter  
(source size and space charge)  
\( d_s \) due to spherical aberration  
\( d_c \) due to chromatic aberration

Normally:  
EBL raster scans  
Gaussian beam shape

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**Figure 9.5** System schematic of an early EBES system. The basic column is similar in current generation EBL systems (after Herriot et al., reprinted by permission, © 1975 IEEE).
Figure 9.6 The use of stencil masks with EBL to improve system throughput. This type of exposure is useful only for exposing highly repetitive designs.

Shaped beams
Sequential rastering limits throughput
e.g. “flat top” from multiple Gaussians

← Multiple pattern replication
plus blank area where EB rastered for special patterns

Figure 9.7 A variable shaped beam exposure system using mechanical beam stops for beam shaping. The broad beam exposes many pixels simultaneously, but dimensional control is not as reliable as in standard EBL.

Use to expose rectangles of varying size
Figure 9.8 Exposure matrix in a variable shaped beam system (after Hohn, reprinted by permission of SPIE).

Figure 9.9 A comparison of scanning methodologies: raster scan (A) and vector scan (B).

EB ~ (0.2-0.5) x min feature size
Multiple scans, beam scan passes every pixel
To minimize scatter broadening, EBL needs a thin resist layer.

Double Gaussian exposure distribution:

\[ I = I_0 \left( e^{-r^2/2\alpha^2} + \eta e^{-r^2/2\beta^2} \right) \]

Where:
- \( I \) is the intensity,
- \( I_0 \) is the initial intensity,
- \( \alpha \) and \( \beta \) are parameters of the Gaussian distributions,
- \( \eta \) is the proportion of backscattered intensity.

**Figure 9.10** Monte Carlo simulation of electron trajectories during an EBL exposure. The upper curve indicates the forward- and backscattered components of the beam (after Hohn, reprinted by permission, SPIE).

**Figure 9.11** Small and large figures to be patterned with EBL requires position-dependent dosage to compensate for proximity effects.

Doses adjusted to account for scattering effects.
Figure 9.12  (A) Map of (i) desired deposited energy, (ii) uniform dose deposited energy, and (iii) dose map needed to produce a uniform deposited energy; (B) electron micrograph of EBL exposures with and without proximity correction (reprinted by permission, SPIE, after C.-Y. Chang et al., 1992).

EBL: 5nm features
Best UV: 50nm features → 22nm node

EBL serial → throughput limited

Figure 9.13  A JEOL-6000FS EBL system (courtesy of JEOL Corporation).

Future:
Scanning tunneling microscopy (STM) EBL (mechanically scanned)
**X-Ray**

Core levels excited
→ electron returns to core level
→ characteristic energy X-ray photon emitted

Heat → H2O cooled &/or move target

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**Figure 9.14** A simple rotating electron impact x-ray source uses electron beams focused on a rotating tungsten anode.

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**Plasma generated X-rays**

Heat plasma:
- Electron discharge, or
- Laser

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**Figure 9.15** Laser plasma-heated x-ray source uses a focused high intensity pulsed laser to ablate a metal film. The superheated metal atoms radiate x-rays.
Figure 9.16 Basic schematic of an electron storage ring for XRL. Several exposure stations are indicated (after Glendenning and Cerrina, reprinted by permission, Noyes Publications).

\[ E \sim \left( \frac{0.3 \text{ GeV}}{T \text{ m}} \right) B r \]

field ↑ ↑ radius

\[ \lambda_s (nm) = 0.56 \frac{r(m)}{E(\text{GeV})} = \frac{1.864}{B(T)E(\text{GeV})^2} \]

\[ \sim 1 - 2 \text{nm} \]

Figure 9.17 Commercial x-ray exposure tool (courtesy Karl Suss).
Figure 9.18 Simple proximity x-ray lithography aligner. The basic system is very similar to optical proximity systems.

Figure 9.19 Geometry of the exposure system shown in Figure 9.18.

1nm photons, features $>> \lambda$, so use ray tracing

Source aperture ← Problems due to finite size

Pattern distortion:
$$R_w = r_m (1 + G/D)$$

Penumbral blur:
$$\delta = G(d/D)$$ (resolution)
Figure 9.20 Possible choices for x-ray optics systems include glancing angle metal mirrors (A), Kumakhov lenses (B), and multilayer mirrors (C).

Reduce distortions by using X-ray lenses

Glass capillary tubes

Alternating layers:
- High/low mass
- High/low electron concentrations
  e.g. Mo/Si
- Constructive reinforcement

Figure 9.21 X-ray mask blank fabrication process produces a membrane stretched across a mechanical support ring.

Mask substrate (blank) must transmit X-rays, i.e. low-Z thin film

Starting material: blank Si wafer

Deposit membrane film

Pattern wafer backside

Etch wafer

Bond to support ring

Starting material: e.g. Si₃N₄, SiC (Table 9.2)
Figure 9.22 Additive process for x-ray mask fabrication.

Figure 9.23 Subtractive process for x-ray mask fabrication.

Problem: RIE stop accuracy
Figure 9.24 An x-ray projection lithography system using x-ray mirrors and a reflective mask (after Zorpette, reprinted by permission, © 1992 IEEE).

Figure 9.25 SCALPEL principle of operation.
Figure 9.26  Cross-linking of an e-beam resist where the basic PMMA structure has been modified through the addition of a C—C side chain to promote cross-linking.

..... but PMMA scission dominant (Positive resist)

Positive e-beam PR Chemistry

Note:  PMMA (polymethyl methacrylate) is similar; radiation --> scission + CO₂↑
For negative resists:

(a) Chloromethyl styrene

(b) Epoxies

(c) Vinyl

**Figure 9.27** Common groups used to promote cross-linking.

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**Figure 9.28** Radiation damage flow path

(after Ma and Dressendorfer, reprinted by permission, Wiley).
Damage example:

Strained Si-Si bond in SiO$_2$ due to O-vacancy $\rightarrow$ hole capture

![Diagram of hole capture](image1)

**Figure 9.29** An example of a trap creation process believed to occur upon x-ray irradiation of MOS structures. The larger atoms are silicon, the smaller are oxygen. Due to an oxygen vacancy, the two silicon atoms are initially bonded together.

Damage MAY anneal out with later processing (400°C) but some need 700-1000°C

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**Figure 9.30** Schematic description for the (μcp fabrication of Au patterns using an elastomer called PDMS (Sylgard 184, Corning): (A) PDMS stamp fabrication, (B) PDMS detach from the master, (C) exposure to the alkanethiol ink, (D) contacting with Au substrate, and (E) etching Au on the substrate (reprinted with permission from Applied Physics Letters, from Ref. 88.)

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Figure 9.31  Schematic of a 3D micromolding process using a gold layer to form fluid flow channels (reprinted with permission from Nanoletters, from Ref. 92). Copyright 2003, American Chemical Society.

Figure 9.32  Process diagrams for (A) thermal nanoimprint lithography (NIL) and (B) ultraviolet-assisted NIL. In both processes, a mold is pressed into a soft material to form a physical relief image of the mold (reproduced by permission of the MRS bulletin, from Ref. 103).
### Assignment #4 (due 4th May)

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