E-Beam Lithography

Ivor Brodie and Julius Muray
"The Physics of Micro/Nano-Fabrication"

E-Beam Lithography: Some Pros and Cons

- Spot size <100 Å as compared to photolithography (5000 Å).
- High speed and precision of e-beam deflection and modulation.
- Good control over the energy and dose delivered to resist.

- Either scanning the beam by controlling its deflection from a computer (sequential exposure) or electron imaging through a special mask (parallel exposure).
- Exposure in the spot takes $\sim 10^{-7}$ s, but there are $\sim 10^{10}$ spots that are typically required → high speed is important.
- $10^{10}$ spots requires also a precision of $\sim 1$ppm along each of the axis → strict demands on DA converters, max areas of up to 1 mm$^2$ can be exposed by direct beam deflection.
- Also, a mechanical table is used to move the beam along larger distances.

(Then, alignment is made for each table position, either by checking for registration marks, or use laser interferometers to precisely measure the table movement.)
Types of E-Beam Machines

- **Scanning systems**
  - Single beam system
  - Multiple beam system
  - Vector
  - Raster

- **Hybrid systems**
  - Shaped beam
  - Character projection

- **Parallel exposure systems**
  - Photocathode projection
  - e-Image projection
  - Fly’s eye lens projection

- **Pattern information**
  - Stored in masks
  - High throughput
  - Less expensive

- **Pattern information**
  - In computer’s memory
  - Distortion- and proximity corrections needed
  - Expensive but flexible

**Two distinct uses of e-beam lithography:**
1. Direct exposure of resist for device fabrication
2. Mask fabrication for subsequent optical lithography

**Raster- vs Vector Control**

- The raster-scan systems meticulously cover the area of pattern, *switching the e-beam on and off as required* by the pattern’s shape

- The vector-control systems deflect the beam to follow paths dictated by the pattern. *“Go to that address and do exposure there”.*

**Analogy:**

Compare the bitmap- and vector formats for digital-image files (i.e. “.bmp” vs “.eps”)
Typical Schematics

A heated source giving rise to thermionic emission of electrons

Electron Beam

- In general, our ability to view or fabricate small objects depends on availability of strongly focused particle beams.
- Diffraction limits the spot size. The smaller the wavelength, the smaller the spot.

Particle wavelength (Å) at various energies

<table>
<thead>
<tr>
<th>Particle:</th>
<th>Particle energy $E_0$ (eV)</th>
<th>(1)</th>
<th>(10)</th>
<th>(10^2)</th>
<th>(10^3)</th>
<th>(10^4)</th>
<th>(10^5)</th>
<th>(10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>photons</td>
<td></td>
<td>1240</td>
<td>1240</td>
<td>124</td>
<td>12.4</td>
<td>0.124</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>electrons</td>
<td></td>
<td>12.3</td>
<td>3.89</td>
<td>1.23</td>
<td>0.39</td>
<td>0.12</td>
<td>0.037</td>
<td>8.7e-3</td>
</tr>
<tr>
<td>protons</td>
<td></td>
<td>0.29</td>
<td>0.091</td>
<td>2.9e-2</td>
<td>9.1e-3</td>
<td>2.9e-3</td>
<td>9.1e-4</td>
<td>2.8e-4</td>
</tr>
</tbody>
</table>

\[
\lambda = \frac{1240}{E_0} \text{ (photons)}; \\
\lambda = \frac{12.3}{(E_0+1e-6E_0^2)^{0.5}} \text{ (electrons)}; \\
\lambda = 0.28/E_0^{0.5} \text{ (protons)}.
\]
Electron Emission

- Fermi-Dirac energy distribution of conduction electrons in metals.
- The energy required to remove an electron from metal into free space is called the work function, $\phi$ (1.5–6 eV).
- The electric field $E$ and temperature $T$ can lower $\phi$.

$$\phi = \phi_0 - \alpha T - \frac{eE}{4\pi\varepsilon_0}$$

$$\Delta\phi_{(at)} \approx 3.8 \times 10^{-11} \sqrt{E_{\text{IN}}(\text{V/cm})}$$

$\phi$ can be substantially modified by foreign atoms adsorbed at the metal surface (electropositive Ba & Th decrease, while electronegative O or F increase $\phi$).

Thermionic and Field Emission

$$j = 120.4 \cdot T^2 \cdot \exp\left(-\frac{\phi_0 - 3.8 \cdot 10^{-5} \sqrt{E}}{k_B T}\right) \text{ [A/cm}^2\text{]}$$

$$j = 1.5 \cdot 10^{10} \cdot \frac{E^2}{\phi} \exp\left(\frac{10.4}{\sqrt{\phi}} \frac{6.44 \cdot 10^7}{E - \phi^{1/2}}\right)$$

Supply function $N$: $N_{j}(\varepsilon)d\varepsilon$ is the No. of e incident upon the surface per unit area per second with velocity component $\perp$ to the surface in the energy range from $\varepsilon$ to $\varepsilon + d\varepsilon$.

$D$ is the probability of an electron with energy to penetrate the barrier when an electric field $E$ is applied.

Electric field $E$ vs. Temperature $T$ graph.
Cathodes

Cathode Requirements
• The uniformity of emission over the cathode surface
• The current density required from the cathode
• The energy distribution of the emitted electrons
• The current fluctuations as a function of time
• The evaporation of material from the cathode surface
• The ability of the cathode to operate in a given environment
• The lifetime of the cathode under given operating conditions

Practical Cathodes

• Thermionic cathodes:
  thoriated tungsten (1700 C & 3 A/cm²); WC+ThO₂→W + Th + CO₂ (→ bad vacuum)
  lanthanum hexaborid;
  oxide coated (750 C & 0.5 A/cm²); Ni coated by Sr-O, Ba-O, Ca-O; can be poisoned
  tungsten sponge filled with Ba/Ca aluminate (1100 C & 5 A/cm²)

• Field-Emission cathodes (best but most expensive):
  - emission occurs in "lobes" because of crystal facets present at the surface
  - emission can be unstable.

<table>
<thead>
<tr>
<th>Type of emission</th>
<th>Type of cathode</th>
<th>Operating temperature (T₀) (K)</th>
<th>Upper pressure limit (Torr)</th>
<th>Brightness (β) (A/cm² - sr at 20 kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermionic</td>
<td>Tungsten</td>
<td>2470</td>
<td>10⁻⁵</td>
<td>1.8 × 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Lanthanum</td>
<td>2600</td>
<td>10⁻⁵</td>
<td>1.9 × 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Thoriated tungsten</td>
<td>2000</td>
<td>5 × 10⁻⁵</td>
<td>3.75 × 10⁻⁶ → 11 × 10⁻⁶</td>
</tr>
<tr>
<td></td>
<td>Oxide coated</td>
<td>1650</td>
<td>10⁻⁵</td>
<td>3.4 × 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Barium disperser</td>
<td>1150 - 1400</td>
<td>5 × 10⁻⁶</td>
<td>3.3 × 10⁻⁵ → 3.2 × 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Lanthanum hexaborid</td>
<td>2100</td>
<td>10⁻⁵</td>
<td>9.5 × 82</td>
</tr>
<tr>
<td>Field</td>
<td>Single-crystal tungsten</td>
<td>1 to 10⁵</td>
<td>Room</td>
<td>10⁻⁶</td>
</tr>
<tr>
<td>Temperature-field</td>
<td>Fermi-attached tungsten</td>
<td>1400-1800 (1.5 eV)</td>
<td>Room</td>
<td>10⁻⁵</td>
</tr>
<tr>
<td>Photo</td>
<td>Pd</td>
<td>3 × 10⁻⁹</td>
<td>Room (2 eV)</td>
<td>10⁻⁵</td>
</tr>
<tr>
<td>Photo</td>
<td>Col</td>
<td>3 × 10⁻⁹</td>
<td>Room (0.5 eV)</td>
<td>10⁻⁵</td>
</tr>
</tbody>
</table>
e-Beam Characteristics

Assumptions:
- e-beams are circular;
- emitted e have Maxwell velocity distribution, both axially and radially;
- object and image are related by the Helmholtz-Lagrange relation;
- space-charge forces are neglected.

The brightness is the e-current per unit solid angle

$$\beta_{\text{max}} = \frac{j eV}{\pi kT}$$

- $j$ is the current density at the cathode;
- $e$ is the electron charge;
- $V$ is the acceleration energy;
- $T$ is the cathode temperature.

E-Guns: Self-bias

A bias resistor allows the gun to be self-regulating. Any increase of the emission current causes a larger voltage drop across the bias resistor and a larger negative voltage is applied to the Wehnelt, reducing the current. As the emission increases, so does the voltage difference between Wehnelt and filament, reducing the anode to cathode. Proper bias voltage also optimizes the electron beam brightness.
Crossover Spot Size Limits the Resolution

\[ r_c^{\text{max}} = a \sqrt{\frac{V_0}{V}} \]

To a first approximation, the crossover radius does not depend on the area of the emissive surface and is only determined by the initial energy of the electrons relative to their energy in the crossover region.

The current density at the crossover center:

\[ J_0 = \frac{f eV}{kT} \sin^2(\theta) \]

\( J \) is the cathode emission current.

Non-Idealities

- Space-charge effects are not very important in micro lithography but can be essential in higher-current applications, like ion-implantation. (number of crossing paths should be minimized)
- Aberrations and diffraction
  1) Spherical aberration: the minimum diameter resulting from crossing of trajectories that do not come to a focus at the same axial position. It is impossible to compensate for this aberration later on using any subsequent electron optics. Trade-offs for thermionic sources.
  2) Chromatic aberration, i.e. sensitivity of focus to the energy of the electrons (slow e is easier to focus)
  3) Astigmatism or asymmetric focal spot (non-circular apertures, misalignment relative to the optical axis).
  4) Diffraction

![Electro trajectories in the near-cathode region.](image_url)
Electrostatic Optics

\[ \int ds = \left( A \cdot v \right) \delta \]

Fermat’s law:
\[ \delta \frac{1}{c} ds = \delta \frac{1}{V} n ds = 0 \]

A light ray will take that path that has the shortest transit time.

Corresponding principle governs the motion of particles in the conservative force fields (the principle of least action):
\[ \delta \int \frac{mv}{2} ds = 0 \]
\[ \frac{mv^2}{2} = eV \Rightarrow n = \sqrt{V} \]

Unlike electrostatic case, the magnetic focusing depends on e/m ratio of a particle. A: the vector potential, s trajectory.

Light- vs. Electron Optics

- Unlike photons, the energy of electron may change
- In the electron optics, the refraction index changes continuously
- The electron interact with each other
- Electron lenses are always converging
- Magnetic lenses twist the beam
- Electrostatic optics has larger aberrations than magnetic
Electron Optics

1) Axially symmetric lenses where trajectories are || to field
   Longitudinal systems : focusing by small perp. Component
2) Transverse systems (field perp. to the beam) more effective

\[
\frac{1}{f} = \frac{1}{8d} \left( \frac{V_f - V_i}{V_i} \right)^2
\]

Quadrupole lenses

The quadrupole lens (stigmator) is used to compensate for astigmatism. Focuses in one direction and defocuses in the perpendicular one.

Doublet – two quadrupole lenses: point image of a point object

Pros:
- Compensation for the spherical aberrations can be made;
- Achromatic combination of electrostatic and magnetic quadrupoles can be built.

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\]
### e-Beam Systems

A reduction type electron beam projection system developed at IBM.

**Projection Systems**

- Electron Gun
- Blanking Plates
- Condenser Lens No. 1
- Condenser Lens No. 2
- Mask
- Projection Lens No. 1
- Registration Aperture and Alignment Coils
- Projection Lens No. 2
- SAEFO

**Optical Components**

- Apertures: the beam limiting apertures; Spray aperture stops any stray electrons
- Blanking aperture for deflecting the beam out of the aperture hole;
- Deflectors: Magnetic ones have lower aberrations but the electrostatic ones are much faster (important for writing $10^{10}$ points)
- Beam blanking: high-speed electrostatic deflectors.
- Stigmator: compensate for astigmatism \( \rightarrow \)
- Faraday cage measures current below the final aperture
- Electron detection (for focusing, deflection calibration, alignment)

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**Parallel-Image Projection System**

The optical components of the EBBE-4 column.
Beam-shaping

Increasing throughput by beam shaping:

Raster vs. Vector Scan

Raster scan. A scanning technique where the beam scans line by line a section of the surface. The beam is turned on or off depending on whether the current pixel is to be exposed or not.

- The chip is divided into strips of ~2^8 pixels
- The selected strip is written onto the substrate
- The beam scans over the substrate line by line
- If the current pixel is to be exposed, the beam is on
- If the current pixel is not to be exposed, the beam is off
- The substrate is moved perpendicular to the scan lines by a laser-controlled table

Vector scan. A scanning technique where the beam is positioned over an area of the substrate, and the features in that area (according to the pattern data) are drawn out using lines. The beam remains on at all times.

- An area of an individual die is aligned under the electron beam
- The beam is deflected so as to draw out the features in that area of the chip
- The chip is completed either by a step-and-repeat method, or by continually moving the substrate
- The alignment of features in adjacent scanning areas is important. A measure of misalignment is the butting error, i.e. a measure of the misalignment between adjacent scan areas
Registration Marks

- Signals:
  - Backscattered electrons
  - Secondary electrons
  - Luminiscent radiation

- Detectors:
  - Scintillation detector
  - Solid-state detector
  - Photomultiplier

Backscattered electrons are better for the mark detection because of the resist that can absorb the secondary electrons.

Multiple e-Beam Exposure

- Single cathode
  - Single electron beam
- Multiple cathodes
  - Multiple electron beams
Effects in the Resist

Negative resist (SAL601-SR7)
6-8 μC/cm² @ 55kV (medium resolution, high sensitivity)

Positive resist (e.g. PMMA, ZEP7000)

Development:
For a given polymer, organic solvents dissolve polymer chains of molecular weight below some critical value $M_c$.

Organic E-Beam Resists

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Tone</th>
<th>Sensitivity (C/cm²)</th>
<th>Resolution (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>Positive</td>
<td>$4 \times 10^{-5}$, $8 \times 10^{-9}$</td>
<td>0.1</td>
</tr>
<tr>
<td>P(GMA-co-EA)</td>
<td>Negative</td>
<td>$3 \times 10^{-7}$ (10 kV)</td>
<td>1.0</td>
</tr>
<tr>
<td>PBS</td>
<td>Positive</td>
<td>$8 \times 10^{-7}$ (10 kV)</td>
<td>0.5</td>
</tr>
<tr>
<td>COP</td>
<td>Negative</td>
<td>$4 \times 10^{-6}$</td>
<td>1.0</td>
</tr>
<tr>
<td>P(GMA-co-EA)</td>
<td>Negative</td>
<td>$3 \times 10^{-7}$ (10 kV)</td>
<td>1.0</td>
</tr>
<tr>
<td>PGMA</td>
<td>Negative</td>
<td>$5 \times 10^{-7}$ (20 kV)</td>
<td>1.0</td>
</tr>
<tr>
<td>PCA</td>
<td>Positive</td>
<td>$5 \times 10^{-7}$ (20 kV)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

PMMA: polymethyl methacrylate;
P(GMA-co-EA): poly(glycidyl methacrylate-co-ethyl acrylate);
PBS: poly(butene-1-sulfone);
COP: copolymer methyl methacrylate;
PGMA: poly(glycidyl methacrylate);
PCA: copolymer of α-cyano ethyl acrylate and α-amine ethyl acrylate.
High-Res. Positive
Inorganic Resists

<table>
<thead>
<tr>
<th>Resist</th>
<th>Minimum linewidth</th>
<th>Typical aspect ratio</th>
<th>Deposition</th>
<th>Dose at 100 keV to expose 500-nm-thick layer (C/cm²)</th>
<th>Mechanism of exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>6-10 nm</td>
<td>&gt;40</td>
<td>Spinning 40-Å grain</td>
<td>5 x 10^{-4}</td>
<td>Bond breaking of Cl₂</td>
</tr>
<tr>
<td>NaCl</td>
<td>1.5 nm</td>
<td>&gt;40</td>
<td>Sublimation 50-Å grain</td>
<td>10^{-3} - 10^{-2}</td>
<td>Diffusion of Na</td>
</tr>
<tr>
<td>LiF</td>
<td>1.5 nm</td>
<td>&gt;40</td>
<td>Sublimation 50-Å grain</td>
<td>1 - 10^{-2}</td>
<td>Diffusion of Li</td>
</tr>
<tr>
<td>MgF₂</td>
<td>1.5 nm</td>
<td>&gt;40</td>
<td>Sublimation 50-Å grain</td>
<td>1 - 10^{-2}</td>
<td>Diffusion of F₂</td>
</tr>
<tr>
<td>AlF₃</td>
<td>1.5 nm</td>
<td>&gt;40</td>
<td>Amorphous</td>
<td>1 - 10^{-2}</td>
<td>Diffusion of Al</td>
</tr>
<tr>
<td>KCl</td>
<td>1.5 nm</td>
<td>&gt;40</td>
<td>Deposition 50-Å grain</td>
<td>1 - 10^{-2}</td>
<td>Diffusion of Cl₂</td>
</tr>
<tr>
<td>Metal-</td>
<td>1.5 nm</td>
<td>&gt;40</td>
<td>Cut thin-film slabs</td>
<td>1 x 10^{-2}</td>
<td>Diffusion of K</td>
</tr>
<tr>
<td>alumina</td>
<td></td>
<td></td>
<td>(2000 Å thick)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sensitivity

Contrast γ = log(D₀/Dₘ)⁻¹ (negative resists)

D₀ is the dose required to polymerize 100% of thickness;
Dₘ is the minimum dose required for any detectable polymerized layer to form
Scattering Effects

Proximity corrections are required

High-Energy e-Beam Lithography
Less prone to proximity effects

Specifications for E-Beam Exposure System

\[ t \] – the pixel exposure time (s);
\[ D \] – the dose for large areas (C/cm\(^2\));
\[ fD \] – the dose for one pixel;
\[ Pp \] – the pixel area;
\[ Pp/t \] – the area exposed per second;
\[ j \] – the current density in the spot (A/cm\(^2\))

- The bandwidth of the deflection and focusing systems as well as resist sensitivity limit the speed of pattern writing: