MSN551
Introduction to Micro and Nano Fabrication

LITHOGRAPHY II

E-Beam, Focused Ion Beam and Soft Lithography
Why need electron beam lithography?

• Smaller features are required
  – By electronics industry:
    • Smaller transistors, higher device density
    • Novel quantum devices: Single electron transistors etc.
  – By photonics industry
    • Integrated optics
    • Photonic crystals
  – Sensors
    • Sometimes small becomes very advantegous

E-Beam can achieve 10 nm resolution
Other methods to generate nm scale structures?

- **Optical lithography:**
  - Deep UV and X-Rays may be useful
  - We still need a MASK

- **Nanoimprinting**
  - Still need initial master (mask) that has to be produced by ion or e-beam lithography

- **AFM based methods**
  - Tooo slow...
E-Beam Lithography

- Can be performed in a regular electron microscope
- Dedicated e-beam writers still have a lot in common with the electron microscope.

Let's remember the electron microscope operational principles
Why electron microscopy

• Primary reason: Spot size

$$\lambda = \frac{h}{p} = \frac{h}{mv} \sqrt{1 - \frac{v^2}{c^2}}$$

DeBroglie wavelength of a particle

If speeds are large or total acceleration voltage is close to rest mass of particle
You should better use relativistic formulas for energy, momenta etc.

For an electron with KE = 1 eV and rest mass energy 0.511 MeV, the associated DeBroglie wavelength is 1.23 nm, about a thousand times smaller than a 1 eV photon.
SEM Anatomy

Preparation of proper illuminating beam

XY scanning

Focusing objective
Ion and Electron Optics

- We need something that changes the direction of electrons or ions in a beam, depending on initial direction and radial location within the beam.

An electrostatic lens
Ion and Electron Optics

- Magnetic Lens

Cylindrically symmetric magnetic Field with radial gradients
Sources

Electron emission can be achieved by different physical mechanisms.
Emission

- Thermal emission

\[ j = A \cdot T^2 \cdot \exp \left( - \frac{E_A}{kT} \right) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Fe</th>
<th>Ni</th>
<th>Pt</th>
<th>Ta</th>
<th>W</th>
<th>Cs</th>
<th>LaB₆</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>26</td>
<td>30</td>
<td>32</td>
<td>55</td>
<td>60</td>
<td>162</td>
<td>25</td>
</tr>
<tr>
<td>( E_A )</td>
<td>4,5 - 4,8</td>
<td>5,15 - 5,35</td>
<td>5,65</td>
<td>4,15 - 4,8</td>
<td>4,2</td>
<td>1,8 - 2,14</td>
<td>2,6</td>
</tr>
<tr>
<td>( T_m )</td>
<td>1 535</td>
<td>1 452</td>
<td>1 755</td>
<td>2 850</td>
<td>3 410</td>
<td>28,4</td>
<td>2 210</td>
</tr>
</tbody>
</table>
Emission

- Field emission

Field emission starts for $E > 10^7 \text{ V/cm}$
High current density: $J(E) = A \cdot E^2 \varphi \exp (-B \varphi^{1.5} / E)$

Strong nonlinear current-voltage characteristic
Very short switching time ($t < \text{ns}$)

Small spot size due to field enhancement at the tip apex
Ion and Electron Optics

- Electron beam sources

**TABLE 2.1** Properties of the electron sources commonly used in electron beam lithography tools.

<table>
<thead>
<tr>
<th>source type</th>
<th>brightness ((A/cm^2/sr))</th>
<th>source size (\text{nm})</th>
<th>energy spread (\text{eV})</th>
<th>vacuum requirement (\text{Torr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>tungsten thermionic</td>
<td>(~10^5)</td>
<td>25</td>
<td>2-3</td>
<td>(10^{-6})</td>
</tr>
<tr>
<td>LaB(_6)</td>
<td>(~10^6)</td>
<td>10</td>
<td>2-3</td>
<td>(10^{-8})</td>
</tr>
<tr>
<td>thermal (Schottky) field emitter</td>
<td>(~10^8)</td>
<td>20</td>
<td>0.9</td>
<td>(10^{-9})</td>
</tr>
<tr>
<td>cold field emitter</td>
<td>(~10^9)</td>
<td>5</td>
<td>0.22</td>
<td>(10^{-10})</td>
</tr>
</tbody>
</table>
Various factors affecting spot diameter
Some other issues

- Raith 150
  - Schottky thermal-field emission filament, resolution: 2 nm @ 20 kV
  - Acceleration voltage: 200 V – 30 kV
  - Beam current: 4 pA – 350 pA
  - Working distance: 2 – 12 mm
  - Writefield: 1 µm – 1 mm
  - 16 bits / 10 MHz pattern generator
  - Samples: 1 mm – 6”
  - Interferometer stage, 2 nm positioning accuracy
  - Overlay and stitching accuracy: better than 20nm
  - High degree of automation for automatic pattern placement and long exposures
Electron Beam Resists

- PMMA
- ZEP
- HSQ
- SU8
- ............
PMMA modification
PMMA Resist (950 K PMMA 3%, 6%)

Characteristics:

- Positive tone
- Very high resolution (20 nm), low contrast
- Poor dry etch resistance
- Several dilutions available, allowing a wide range of resist thickness
- No shelf life or film life issues
- Not sensitive to white light
- Developer mixtures can be adjusted to control contrast and profile

ZEP SERIES

Characteristics:

- Positive tone
- Resolution at least 20nm
- Dry etch resistance comparable to most photo resists
- Film Life
- Wide process margin
## III. Resist Summary

<table>
<thead>
<tr>
<th>Resist</th>
<th>Tone</th>
<th>Resolution</th>
<th>Contrast</th>
<th>Etch Resistance</th>
<th>Thickness</th>
<th>Shelf Life</th>
<th>Film Life</th>
<th>Sensitive To White Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>Positive</td>
<td>Very High</td>
<td>Low</td>
<td>Poor</td>
<td>Many dilutions</td>
<td>Long @ RT</td>
<td>Long</td>
<td>No</td>
</tr>
<tr>
<td>P(MMA-MAA)</td>
<td>Positive</td>
<td>Low</td>
<td>Low</td>
<td>Poor</td>
<td>Many dilutions</td>
<td>Long @ RT</td>
<td>Long</td>
<td>No</td>
</tr>
<tr>
<td>SU-8</td>
<td>Negative</td>
<td>High</td>
<td>Low</td>
<td>Good</td>
<td>Many Dilutions</td>
<td>Long @ RT</td>
<td>Long</td>
<td>Yes</td>
</tr>
<tr>
<td>ZEP</td>
<td>Positive</td>
<td>Very High</td>
<td>High</td>
<td>Good</td>
<td>Several Dilutions</td>
<td>Long @ RT</td>
<td>Short</td>
<td>Yes</td>
</tr>
<tr>
<td>EBR-9</td>
<td>Positive</td>
<td>Low</td>
<td>Low</td>
<td>Poor</td>
<td>Single Dilution</td>
<td>Long @ RT</td>
<td>Long</td>
<td>No</td>
</tr>
</tbody>
</table>
HSQ

- Negative resist
- The highest resolution ebeam resist available?
- Very low line edge roughness (LER)
- Good etch mask for dry-etching

23 nm period grating in HSQ on diamond

3 nm NiCr wire
Bilayers for lift-off

1. High molecular weight PMMA
2. Low molecular weight PMMA/MMA
3. Substrate

PMMA is developed in a mixture of MiBK and IPA.

4. High molecular weight PMMA
5. Low molecular weight PMMA/MMA
6. Evaporated metal

PMMA is dissolved in Acetone or other suitable solvent leaving the metal film on the substrate surface.
Electron Beam and Sample Interaction

- Depends on energy of beam, material of the sample. The beam penetrates the sample.
- Beam Spot size isn’t everything
Proximity effects

- Primary electrons (direct from the beam) can expose
- Secondary electrons (scattered from inside the sample) can also expose

**Figure 1a:** Proximity effect: exposure at pixel A affects pixel B.
Proximity effects

Fig. 2 SEM image of a series of doughnut structures patterned on a ZEP520A coated spin valve structure. The line on the image links the doughnut whose inner circle starts to disappear.
Proximity Effects: Point Spread Function

Models of the energy profile

A proximity effect correction algorithm requires an accurate knowledge of the energy density profile deposited in the electron resist layer due to a point or pixel exposure (often called point spread function). In general, this profile is a function of the system setup. An important property of these profiles is that the shape is independent of dose as well as position, assuming a planar and homogeneous substrate[8]. This profile is often approximated by the sum of two Gaussian distributions [9]:

\[ f(r) = C_1 \exp\left(-\left(\frac{r}{B_1}\right)^2\right) + C_2 \exp\left(-\left(\frac{r}{B_2}\right)^2\right) \]  \hspace{1cm} (2)

representing the forward and the backscattered electrons. \( C_1, C_2, B_1 \) and \( B_2 \) are constants and \( r \) is the distance from the point of electron incidence. More popular is to write this expression as follows [10]

\[ f(r) = \frac{1}{1+\eta} \left( \frac{1}{\pi\alpha^2} \exp\left(-\frac{r^2}{\alpha^2}\right) + \frac{\eta}{\pi\beta^2} \exp\left(-\frac{r^2}{\beta^2}\right) \right) \]  \hspace{1cm} (3)
Proximity Effects: Point Spread Function

\[ f(r) = \frac{1}{1 + \eta \left( \frac{1}{\pi \alpha^2} \exp\left(-\frac{r^2}{\alpha^2}\right) + \frac{\eta}{\pi \beta^2} \exp\left(-\frac{r^2}{\beta^2}\right) \right)} \]

Table I. Proximity parameters as a function of the beam energy [13]

<table>
<thead>
<tr>
<th>Beam energy (keV)</th>
<th>( \alpha ) (\text{um})</th>
<th>( \beta ) (\text{um})</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.33</td>
<td>[0.18]</td>
<td>[0.74]</td>
</tr>
<tr>
<td>10</td>
<td>0.39</td>
<td>[0.60]</td>
<td>[0.74]</td>
</tr>
<tr>
<td>20</td>
<td>0.12</td>
<td>2.0</td>
<td>0.74</td>
</tr>
<tr>
<td>50</td>
<td>0.024</td>
<td>9.5</td>
<td>0.74</td>
</tr>
<tr>
<td>100</td>
<td>0.007</td>
<td>31.2</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Proximity Effects: Point Spread Function

\[ f(r) = \frac{1}{1 + \eta \left( \frac{1}{\pi \alpha^2} \exp\left(-\frac{r^2}{\alpha^2}\right) + \frac{\eta}{\pi \beta^2} \exp\left(-\frac{r^2}{\beta^2}\right) \right)} \]

Figure 2. Energy deposition profile or point spread function (PSF) for 50KeV E-beam on the substrate consisting of 500 nm PMMA on Silicon.
Proximity Effects

Figure 10. Exposure simulation of a circuit pattern.

Exposure correction methods

Dose modification
Shape modification
Figure 12: reducing rectangle size for exposure compensation

Figure 13: Shape modification of critical points.
Development

Figure 9. Edge profile in positive resist (a) high dose and short development time, (b) medium dose and development time, and (c) low dose and long development time.
Stiching

- E-beam column and pattern generator electronics can write a finite field size (maximum about a mm)
- Mechanical Stage is used for writing multiple fields.
- Blind mechanical alignment is prone to errors
Proper alignment of fields and structures is important.
Proper alignment of fields and structures is important
Focused Ion Beam lithography

• Can be used with or without a resist
• Lower resolution than best possible with EBL
  – Ion source has larger diameter than a field emitter because it is a thermal process
• Ion beam damage to the underlying material
• Redeposition
• Arbitrary 3D structures can be fabricated.
FIB (Focused Ion Beam)

- Ga ions (heavy nuclei) melt at low temperature
- Can be used to mill (etch by impact) with 20 nm resolution
- Works like an SEM
Figure 7. Schematic diagram of FIB milling.
Fig. 1.6: Schematic of liquid metal ion source with enlarged view of tip showing liquid pulled into a cusp by the electric field [10].
Ion Beam Distributions

- Focus dependent

![Graph showing ion beam distributions with focus dependent variations at Z = -1.6 mm and Z = -0.18 mm.](image)
Direct 3D fabrication
Fig. 1.10: Schematics of (a) FIB milling and (b) FIB induced deposition.
Focused Ion beam effects the surface in a variety of ways

- Swelling (Amorphization)
- Milling
- Deposition
- Ion implantation
- Backscattering
Swelling

Fig 1. (a) AFM measurement showing the volume increase of a silicon surface after low dose FIB processing (30 keV, $5 \times 10^{15}$ cm$^{-2}$). (b) AFM measurement of a silicon surface processed by a high dose FIB (30 keV, $5 \times 10^{16}$ cm$^{-2}$). (c) Volume change for 30 keV gallium ions on silicon dependent on the ion dose.
Implantation

FIGURE 2  Transmission electron microscopy image of formation of gallium precipitates in silicon in a trench sputtered by 30-keV gallium ions
Redeposition

- Sputtered ions may strike to the sidewalls and build up there

**Figure 12.** The effect of the dose on the geometry. The top left image shows a top view of all holes. The SEM images of the cross-sections in the top row are taken at a 52° angle, and the bottom row at 45°. The holes were designed using the FIB built-in procedure to an average diameter of 300 nm and the current and dwell time were fixed at 48 pA and 0.1 μs, respectively.
Scanning strategies: Single vs Multiple

- Multiple scans may help get what you need
Scanning strategies: Even direction affects the result

(a) size: 5µm x 15µm  Image Mode: SEM Ele

(b) sequence: from edge to center
Scanning Probe Lithography

• Using an AFM or STM tip to write features on the surface

• First room temperature single electron transistor was fabricated by this method.

• Much cheaper than an electron beam or ion beam system
  – Good for prototyping

• Harder to master
Ways to pattern

- Atomic force microscope and Scanning tunneling microscope
  - Oxidation
  - Material deposition
  - Monolayer modifications
  - Thermal processes
  - Electrochemical processes
Tip induced oxidation

- Electric field helps thin metal film or silicon surface to oxidize
Can modify self-assembled monolayers

Figure 14. Schematic diagram illustrating dip-pen nanolithography (DPN). A tip coated with “ink” molecules was brought into contact with the substrate. A water meniscus formed between the tip and the substrate, which facilitated the transport of the ink to the substrate.
Dip-pen Lithography

- Can deposit organic layers or even DNA
Direct metal deposition

- Local ark on the nanoscale deposits metal

Fig. 4. Nanostructures on Si substrates by direct STML deposition of sequential dots: (a) STM image of Ag characters “A” by Ag-coated tip (courtesy of Daisuke Fujita of National Institute for Materials Science, Japan) and (b) AFM image of Au lines by Au-coated tip (courtesy of H. Abed of Faculté des Sciences de Luminy, France).