Planar Processing with Semiconductors (Silicon): Course Map

- Crystal growth (semiconductors)
- Wafer doping (*in situ*)
- Wafer characteristics
- SiO$_2$ growth*
- Defects and impurities

- SiO$_2$ growth*
- **LITHOGRAPHY**
- Masked diffusion doping
- Vacuum Systems
- Thin Films: CVD, MBE, PVD, ALD
- Implantation
- Wet and Dry Etching
- Integration
Diffraction through a single slit

\[ W = \frac{2L\lambda}{b} \]
Resolution and Depth-of-focus of an optical system

\[ l_m = k_1 \frac{\lambda}{NA} \]

\[ DOF = k_2 \frac{\lambda}{(NA)^2} \]

\[ NA \equiv \frac{D}{f} \equiv n \sin \theta \]
The challenges of registration illustrated by the 7 nm transistor

Gatan, 2003
An example of registration in e-beam lithography
An example of registration in e-beam lithography
Phase Shifting
Optical Proximity Correction (OPC)
Electron-beam lithography
An example of electron-beam lithography
Simulating proximity effect with CASINO

monte CArlo SImulation of electroN trajectory in sOlids

300 nm PMMA, Si Substrate
10 nm beam diameter

10 keV  
100 keV
The proximity effect limits e-beam resolution.
Extrem UV (100 eV) lithography
Double Patterning

Mask

Exposure dose

Positive develop

Negative develop
## Roadmap

<table>
<thead>
<tr>
<th>Node</th>
<th>180 nm</th>
<th>130 nm</th>
<th>90 nm</th>
<th>65 nm</th>
<th>45 nm</th>
<th>32 nm</th>
<th>22 nm</th>
<th>15 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leading chipmaker</strong></td>
<td>KrF + OPC</td>
<td>KrF + OPC + RET</td>
<td>ArF + OPC + RET</td>
<td>ArF + immersion + OPC + RET</td>
<td>ArF + immersion + OPC + strong RET</td>
<td>45 nm + DP</td>
<td>45 nm + DP + restricted layout</td>
<td>45 nm + MP</td>
</tr>
<tr>
<td><strong>Lagging chipmaker</strong></td>
<td>KrF + OPC</td>
<td>KrF + OPC + RET</td>
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</tbody>
</table>

**Increasing cost barrier**

wikipedia
Photoresist Materials
Exposure-Response Curves of Photoresist

\[ Sensitivity \propto \frac{1}{D_0} \quad \gamma = \frac{1}{\log \frac{D_{100}}{D_0}} \quad (Contrast) \]
An example of calculating $\gamma$

\[ D_0 = 0.6 \]
\[ D_{100} = 1.8 \]

\[ \gamma = 1 / \log \frac{1.8}{0.6} = 2.1 \]
Exposure-Response Curves of Photoresist: Sensitivity and Contrast

Sensitivity

Contrast
Resist contrast determines resolution, sidewall angle and line width (minimum feature size)
SU-8 is a negative tone resist with high contrast.
Critical resist Modulation Transfer Function (CMTF) and the Modulation Transfer Function (MTF)

\[ \frac{D_{100} - D_0}{D_{100} + D_0} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1} \]

\[ M_T = \frac{M_{\text{image}}}{M_{\text{mask}}} \quad M = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

No image is formed if \( CMTF > MTF \).
Modulation Transfer Function

(b) Mask

(c) Image

(e) Mask

(f) Image
SU-8 Thickness vs. spin-speed curve

Microchem