Lecture 48
Lithography: Resolution and Immersion

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Improving Lithography

• Every couple of years we need to improve resolution while keeping costs in control

90 nm → 65 nm → 45 nm → 32 nm → 22 nm

• How is this regular improvement in resolution accomplished?

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The Rayleigh Resolution Equation

\[ R = \frac{k_1}{NA} \]

Lower the wavelength

Increase the Numerical Aperture

R = the smallest “half pitch” that can be printed (pitch = center-to-center distance of a repeating pattern, a measure of how closely features can be packed together)

Lowering the Wavelength

• Wavelength is a property of the light source
  – Early tools used lamps with 436-nm wavelength
  – Today's tools use 193-nm excimer lasers

• Lowering wavelength is hard
  – New light source
  – New lens materials
  – New photoresist

• The transition to the next wavelength (13.5 nm, Extreme Ultraviolet, EUV) is way behind schedule (and may never happen)

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Lowering the “k₁” Factor

• The “k₁” factor is a collection of everything else that can be done to improve resolution
  – Improve the photoresist
  – Use “resolution enhancement” technologies like phase-shifting masks and off-axis illumination (fancy optical “tricks”)

• The physical limit for k₁ is 0.25 (the lowest we can go, using 2-beam imaging)
  – Early processes had k₁ = 1.0
  – Today’s best processes have k₁ = 0.28

Increasing the Numerical Aperture (NA)

• Numerical Aperture is a property of the lens – how much light information can it capture?
  – Early tools had NA = 0.16
  – \[ NA = n \sin \theta \], the largest practical lens gives \[ \sin \theta = 0.93 \]

• To increase NA beyond this, we must use immersion imaging (increase \( n \))

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Immersion Lithography:
printing through water

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Wafer
Water
Projection Lens
Immersion Lithography:
The Fluid Refractive Index

- At 193 nm, water has a refractive index of 1.436
  - Water can be made very pure, and has low absorption
- Adding water doesn’t increase the NA, it allows an increased NA lens to be designed and built
- Spatial frequency: \( f = \frac{\pi \sin \theta}{\lambda} \)
- Rayleigh DOF for large angles (high NA):
  \[
  DOF = \frac{k_1}{2} \frac{\lambda}{n(1 - \cos \theta)}
  \]

Immersion Conclusions

- For the same NA, immersion has DOF better than dry by a factor of at least the fluid index
- Thus, immersion enables better resolution without as big a drop in DOF as one would expect
- Of course, some practical issues had to be worked out...
  - Fluid flow during high-speed scanning
  - Bubbles, defects
  - Water interaction with photoresist

Immersed DOF (same NA)

\[
\frac{DOF(\text{immersion})}{DOF(\text{dry})} = \frac{1 - \frac{1}{n^2} - \left(\frac{\lambda}{p}\right)^2}{\frac{1}{n^2} - \left(\frac{\lambda}{p}\right)^2}
\]

Improving Resolution 1975 – 2010

<table>
<thead>
<tr>
<th>1975</th>
<th>2010</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>436</td>
<td>193</td>
</tr>
<tr>
<td>Numerical Aperture (NA)</td>
<td>0.16</td>
<td>1.35</td>
</tr>
<tr>
<td>(k_1) Factor</td>
<td>1.0</td>
<td>0.28</td>
</tr>
<tr>
<td>Overall Resolution (nm)</td>
<td>2700</td>
<td>40</td>
</tr>
</tbody>
</table>

Hitting the Resolution Limit

- Wavelength is stuck at 193 nm, the highest NA we have is 1.35, and \(k_1\) is limited to 0.25
  \[
  R = \frac{k_1 \lambda}{NA} \geq 0.25 \frac{193\text{nm}}{1.35} = 36\text{nm}
  \]
- This resolution limit is technically the smallest “half pitch” that can be printed in a single pattern
  - Practical half-pitch limit is more like 38 – 40 nm
  - Minimum pitch is therefore 75 – 80 nm

Lecture 48: What have we Learned?

- What are the three ways to improve resolution in optical lithography
- Which of those three ways has had the biggest impact on resolution over the years?
- What currently limits our ability to improve each of these three factors?
- What is the current resolution limit for single patterning?