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Chemical Processes for Micro- and Nanofabrication
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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?

Improving Lithography

- The Rayleigh Resolution Equation

Use "Resolution Enhancement" Technologies to lower k_1

Lower the wavelength

$$R = k_1 \frac{\lambda}{NA}$$

***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)

Increase the Numerical Aperture

Lowering the Wavelength

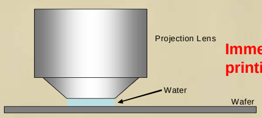
- Wavelength is a property of the light source
  - Early tools used lamps with 436-nm wavelength
  - Today's tools use 193-nm excimer lasers
- Lowering wavelength is hard
  - New light source
  - New lens materials
  - New photoresist
- The transition to the next wavelength (13.5 nm, Extreme Ultraviolet, EUV) is way behind schedule (and may never happen)

Lowering the "k_1" Factor

- The "k_1" 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 k_1 is 0.25 (the lowest we can go, using 2-beam imaging)
  - Early processes had k_1 = 1.0
  - Today's best processes have k_1 = 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 $\sin\theta \approx 0.93$
- To increase NA beyond this, we must use immersion imaging (increase *n*)



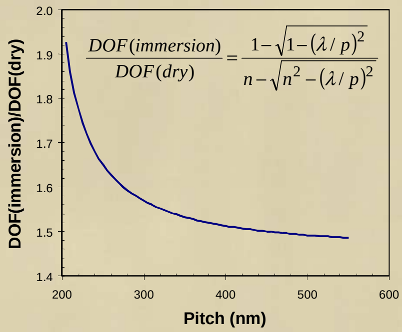
Immersion Lithography: printing through water

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: $f = n\sin\theta/\lambda$
- Rayleigh DOF for large angles (high NA):

$$DOF = \frac{k_2}{2}\frac{\lambda}{n(1-\cos\theta)}$$

Immersion DOF (same NA)



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

Improving Resolution 1975 – 2010

	1975	2010	Improvement
Wavelength (nm)	436	193	2.3X
Numerical Aperture (NA)	0.16	1.35	8.4X
k_1 Factor	1.0	0.28	3.5X
Overall Resolution (nm)	2700	40	68X

How much further can resolution be improved?

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

$$R = k_1\frac{\lambda}{NA} \geq 0.25\frac{193nm}{1.35} = 36\,nm$$

- 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?