CHE323/CHE384
Chemical Processes for Micro- and Nanofabrication
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Lecture 58
Lithography: Resolution Enhancement Technologies, part 2

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Resolution Enhancement Technologies (RET)

- Optical Proximity Correction (OPC)
- Off-Axis Illumination (OAI)
- Phase-Shifting Masks (PSM)

Optical Proximity Correction (OPC) — Mask, Wafer
Off-Axis Illumination (OAI) — Lens; Conventional, Annular, Quadrupole
Phase Shifting Mask (PSM) — Quartz; Phase Shifted Space

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Typical Illumination Shapes

Objective Lens
Source Shape
Conventional
Annular
Dipole
Quadrupole

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OAI Resolution

- OAI enables the switch from 3-beam interference to 2-beam interference for small pitch patterns
- The smallest pitch possible with OAI is 0.5λ/NA (smallest half-pitch is 0.25λ/NA) – 2X better than coherent (normally incident) resolution
- Note: OAI loses one of the 1st orders, thus degrading the in-focus aerial image quality (lower NILS and thus lower exposure latitude)

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OAI Depth of Focus

- The effect of focus is to cause a phase error for each diffraction order about proportional to the square of the distance from the center of the pupil.
- Since phase is relative, it is the *difference* in phase between diffraction orders which degrades image quality.
- Placing the 0th and 1st diffraction orders the same distance from the center of the lens minimizes the phase difference and maximizes DOF
- DOF is maximized only for *one pitch*

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OAI Depth of Focus

NA = 0.85
λ = 193nm
COG, 120nm l/s

Optimized Dipole
Conventional σ = 0.5
NILS (0.0–3.5)
Defocus (μm) (0–0.5)

- In-focus image quality is reduced
- Out-of-focus image quality is improved

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Phase-shifting Masks

- Light has both amplitude and phase
  - Phase influences how light interferes
- A standard chrome-on-glass (COG) mask modulates only the amplitude of the transmitted light
- Any mask that purposely modulates the phase of the transmitted light is called a phase-shifting mask (PSM)
  - First invented by Marc Levenson of IBM in 1982

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Making a "Phase Shift"

Light of wavelength λ

Mask Blank

t glass index = n

air index = 1

Phase shift caused by optical path difference: $\Delta\phi = 2\pi t(n-1)/\lambda$

To get 180º (π) phase shift: $t = \lambda/2(n-1)$

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The Phase Shift Principle

Cr

π-shifter

Electric Field at Mask 0

0

Electric field at Wafer 0

Intensity at Wafer 0

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How to Use Phase-Shift

- Adjust the shifter to give a 180º phase shift
- Combine shifted and unshifted light to produce darkness where needed
  - PSM is very good at making small dark features (small bright features are harder)
- Types of PSM
  - Alternating (Levenson): phase-shift every other space
  - Chromeless: phase edge prints as a small dark line
  - Rim Shifter: put a ring of phase-shift around feature
  - Attenuated (embedded): "dark" features have 6 – 9 % transmittance + 180º phase compared to clear regions

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Phase Conflict Problem for Alternating PSM

- We want every high-resolution feature (line) to have alternating phase on either side of the feature
- An arbitrary mask layout with 0 and 180º phase patterns will produce phase conflicts
- Restricted layouts must ensure no phase conflicts – but automated design tools are still not perfect

180º 180º

0º 180º

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Lecture 58: What have we Learned?

- What are the three main RET approaches?
- How does OAI improve resolution?
- How does OAI improve depth of focus?
- What phase-shift do we want in a mask to produce destructive interference?
- Which PSM approach is most common in manufacturing today?
- Explain the phase conflict problem for alternating PSM

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