Resolution Enhancement Technologies (RET)

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

**Optical Proximity Correction (OPC)**

- Mask
- Wafer
- Conv.-Axial
- Annular
- Quadrupolar

**Off-Axis Illumination (OAI)**

- Source Shape
- Objective Lens
- Conventional
- Annular
- Quadrupole

**Phase-Shifting Masks (PSM)**

Typical Illumination Shapes

- Conventional
- Annular
- Dipole
- Quadrupole

**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
- The 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)

**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

**OAI Depth of Focus**

- NA = 0.85
- λ = 193nm
- COG, 120nm l/s

- Conventional n = 0.5
- Optimized Dipole

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

Making a “Phase Shift”

\[ \Delta \phi = \frac{2\pi(n-1)}{\lambda} \]

To get 180° (\( \pi \)) phase shift:

\[ t = \frac{\lambda}{2(n-1)} \]

The Phase Shift Principle

The electric field and intensity at the wafer change with the phase shift at the mask.

How to Use Phase-Shift

- Adjust the shifter to give a 180° 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 + 180° phase compared to clear regions

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 180° phase patterns will produce phase conflicts
- Restricted layouts must ensure no phase conflicts – but automated design tools are still not perfect

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