CHE323/CHE384
Chemical Processes for Micro- and Nanofabrication
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Lecture 46 Lithography: Defocus and DOF

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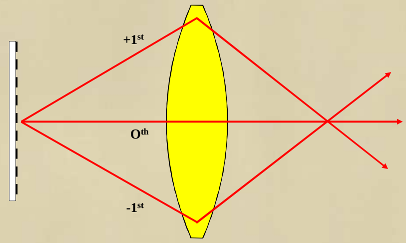
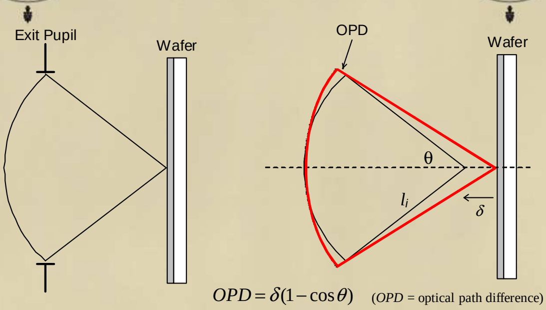
Defocus

- Best focus occurs when the optical path length of all the rays are equal (all orders arrive in phase)



Defocus as an Aberration



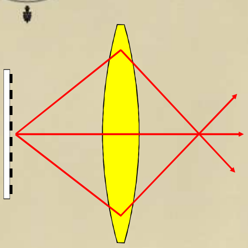
$OPD = \delta(1-\cos\theta)$ (OPD = optical path difference)

For small angles, $OPD \approx \frac{\delta \sin^2\theta}{2} = \frac{\delta\lambda^2 f^2}{2}$

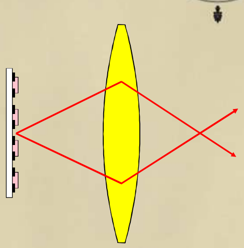
Defocus as an Aberration

- Defocus causes a phase error that goes approximately as the spatial frequency squared
  - For a line/space pattern, the zero order will see no phase error, but the first order will see a phase error proportional to about f^2 (= $1/p^2$)
  - The result is a phase difference between 0th and 1st orders, so that there is less interference
  - Smaller pitches experience greater phase errors
  - When the phase difference equals 90º, the 0th and 1st orders do not interfere at all – no image!

Defocus



Three beam imaging (highest sensitivity to focus)



Two beam imaging (lowest sensitivity to focus)

Image Example: equal lines and spaces

Consider coherent illumination, equal lines and spaces, only 0th and ±1st orders going through the lens:

$$P(f_x)T_m(f_x) = \frac{1}{\pi}\delta\left(f_x + \frac{1}{p}\right) + \frac{1}{2}\delta(f_x) + \frac{1}{\pi}\delta\left(f_x - \frac{1}{p}\right)$$

-1st order 0th order +1st order

Defocus by an amount δ will add a phase error to the ±1st orders equal to:

$$\Delta\Phi = 2\pi(OPD)/\lambda = 2\pi\delta(1-\cos\theta)/\lambda \qquad \cos\theta = \sqrt{1-\sin^2\theta} = \sqrt{1-(\lambda f_x)^2}$$

$$P(f_x)T_m(f_x) = \frac{1}{\pi}\delta\left(f_x + \frac{1}{p}\right)e^{i\Delta\Phi} + \frac{1}{2}\delta(f_x) + \frac{1}{\pi}\delta\left(f_x - \frac{1}{p}\right)e^{i\Delta\Phi}$$

Image Example: equal lines and spaces

- The resulting electric field image is:

$$E(x)=\frac{1}{2}+\frac{2}{\pi}e^{i\Delta\Phi}\cos(2\pi x/p)$$

- The intensity of the image is:

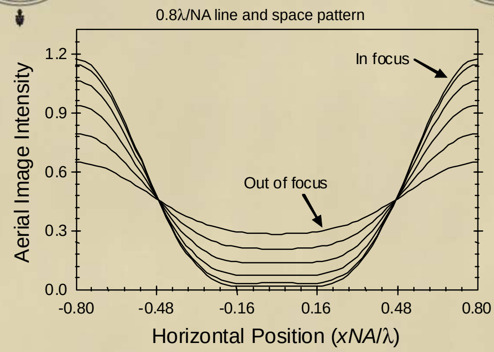
$$I(x)=\frac{1}{4}+\frac{2}{\pi}\cos(\Delta\Phi)\cos(2\pi x/p)+\frac{2}{\pi^2}\left[1+\cos(4\pi x/p)\right]$$

From 0th order

±1st orders interfering with the 0th order

±1st orders interfering with each other

Effect of Defocus



Depth of Focus

- When out of focus, the image gets "blurry"
  - The intensity in the space region goes down
  - The intensity in the line region goes up
  - The slope of the image at the line edge decreases
- How much defocus can we tolerate before these problems become unacceptable?
  - This is called the depth of focus (DOF)
  - Lord Rayleigh defined DOF using a maximum phase error of 90º (quarter wave)

$$OPD=\delta(1-\cos\theta) \qquad OPD_{max}<\frac{\lambda}{4} \qquad DOF=2\delta_{max}<\frac{1}{2}\frac{\lambda}{(1-\cos\theta)}$$

Rayleigh Depth of Focus (Paraxial Approximation)

- Using the small angle approximation,

$$1-\cos\theta\approx\frac{1}{2}\sin^2\theta$$

$$DOF<\frac{\lambda}{\sin^2\theta}=\frac{p^2}{\lambda}$$

(small features have less DOF)

- For the case of imaging at the resolution limit, the smallest pitch occurs when $\sin\theta$ = NA, giving

$$DOF<\frac{\lambda}{NA^2} \quad or \quad DOF=k_2\frac{\lambda}{NA^2} \quad where \quad k_2<1$$

Assumptions of the Rayleigh Depth of Focus

- Three-beam imaging: lines and spaces where only the 0th and ±1st orders are used
- Low numerical apertures (< 0.5)
- Feature is at the resolution limit
- k_2 is unknown (but it must be < 1)

$$DOF=k_2\frac{\lambda}{NA^2}$$

Doesn't work for today's lithography!

Lecture 46: What have we Learned?

- How does defocus affect the optical path difference (OPD) of light exiting the imaging lens?
- What is the "paraxial approximation"?
- Name three things that happen to an image as it goes out of focus
- What is the Rayleigh depth of focus equation?
- What assumptions used in the Rayleigh DOF don't often apply to lithography today?

