CHE323/CHE384
Chemical Processes for Micro- and Nanofabrication
www.lithoguru.com/scientist/CHE323

Lecture 43
Lithography: Projection Imaging, part 1

Chris A. Mack

Adjunct Associate Professor

Reading:
Chapter 7, *Fabrication Engineering at the Micro- and Nanoscale*, 4th edition, Campbell

 www.lithoguru.com

Diffraction Review

- *Diffraction* is the propagation of light in the presence of boundaries
- In lithography, diffraction can be described by Fraunhofer diffraction - the diffraction pattern is the *Fourier Transform* of the mask transmittance function
- Small patterns diffract more: frequency components of the diffraction pattern are inversely proportional to dimensions on the mask
- For repeating patterns (such as a line/space array), the diffraction pattern becomes discrete *diffracted orders*
- Information about the pitch is contained in the positions of the diffracted orders, and the amplitude of the orders determines the duty cycle (w/p)

 2

Fourier Transform Properties

$$\mathcal{F}\{g(x,y)\} = G(f_x, f_y)$$

Linearity: $\mathcal{F}\{af(x,y) + bg(x,y)\} = aF(f_x,f_y) + bG(f_x,f_y)$

Shift Theorem: $\mathcal{F}\{g(x-a, y-b)\} = G(f_x,f_y)e^{-i2\pi(f_x a + f_y b)}$

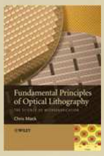
Similarity: $\mathcal{F}\{g(ax,by)\} = \frac{1}{|ab|}G\left(\frac{f_x}{a},\frac{f_y}{b}\right)$

Convolution: $\mathcal{F}\left\{\int_{-\infty}^{\infty}\int g(\xi,\eta)h(x-\xi,y-\eta)d\xi\, d\eta\right\} = G(f_x,f_y)H(f_x,f_y)$

 3

Fourier Transform Examples

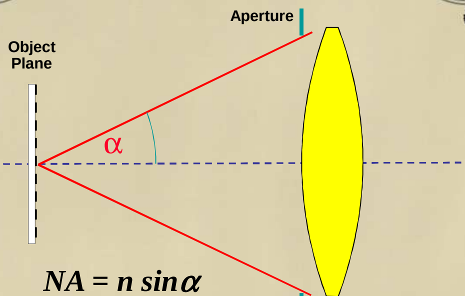
From *Fundamental Principles of Optical Lithography*, by Chris A. Mack (Wiley & Sons, 2007)



$g(x)$	Graph of $g(x)$	$G(f_x)$
$rect(x) = \begin{cases}1, & \lvert x\rvert < 0.5\\ 0, & \lvert x\rvert > 0.5\end{cases}$		$\frac{\sin(\pi f_x)}{\pi f_x}$
$step(x) = \begin{cases}1, & x > 0\\ 0, & x < 0\end{cases}$		$\frac{1}{2}\delta(f_x) - \frac{i}{2\pi f_x}$
Delta function $\delta(x)$		1
$comb(x) = \sum_{j=-\infty}^{\infty}\delta(x-j)$		$\sum_{j=-\infty}^{\infty}\delta(f_x - j)$
$\cos(\pi x)$		$\frac{1}{2}\delta\left(f_x+\frac{1}{2}\right)+\frac{1}{2}\delta\left(f_x-\frac{1}{2}\right)$
$\sin(\pi x)$		$\frac{i}{2}\delta\left(f_x+\frac{1}{2}\right)-\frac{i}{2}\delta\left(f_x-\frac{1}{2}\right)$
Gaussian $e^{-\pi x^2}$		$e^{-\pi f_x^2}$
$circ(r) = \begin{cases}1, & \lvert r\rvert < 1\\ 0, & \lvert r\rvert > 1\end{cases}$ $r = \sqrt{x^2+y^2}$		$\frac{J_1(2\pi\rho)}{\pi\rho}$ $\rho = \sqrt{f_x^2 + f_y^2}$

 4

Numerical Aperture

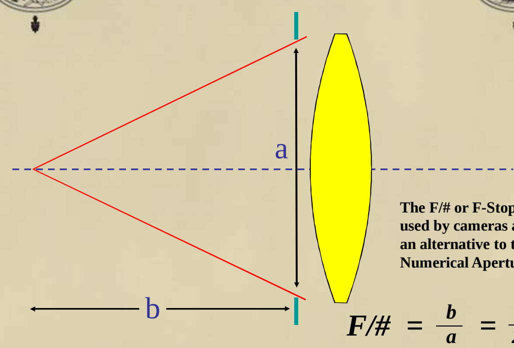


$$NA = n \sin\alpha$$

n = index of refraction of media (air in this case)
α = maximum half-angle of light making it through the lens

 5

F - Number



The F/# or F-Stop is used by cameras as an alternative to the Numerical Aperture

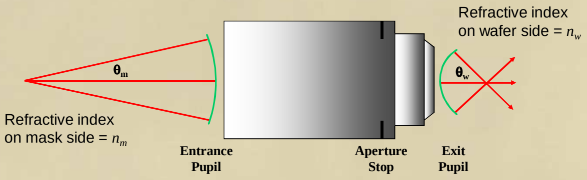
$$F/\# = \frac{b}{a} = \frac{1}{2NA}$$

 6

Magnification/Reduction

- Given the reduction ratio R:

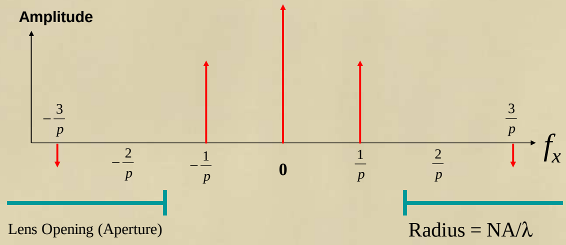
$$n_w \sin\theta_w = R\, n_m \sin\theta_m$$



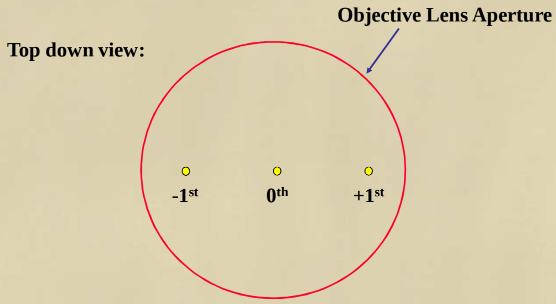
- ***Entrance Pupil*** - the image of the aperture stop as seen from the front of the lens
- ***Exit Pupil*** - the image of the aperture stop as seen from the back of the lens

Numerical Aperture

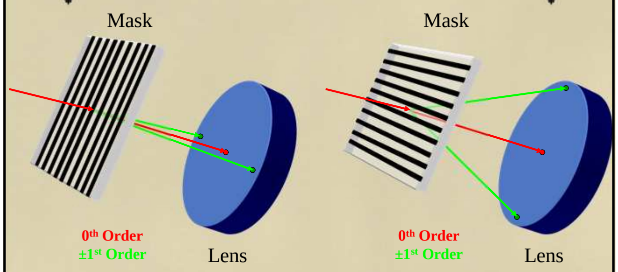
- Graphing the diffraction pattern with the aperture:



Numerical Aperture

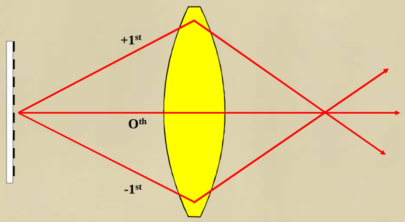


Numerical Aperture



Forming an Image

- The objective lens focuses the diffraction orders onto the wafer



- The *image plane* is defined as the plane where all diffraction orders arrive "in phase"

Fourier Optics

- The objective lens produces an image equal to the Fourier transform of the light entering the lens.
- The combination of diffraction followed by the imaging lens produces a Fourier transform of a Fourier transform, which gives back the original pattern.
- However, the objective lens cuts off the high spatial frequencies of the diffraction pattern.

Fourier Optics

- The objective lens is described by its *pupil function*, $P(f_x,f_y)$. For an ideal lens, this function just describes the size of the aperture.

$$P(f_x,f_y)=\begin{cases}1, & \text{when} \sqrt{f_x^2+f_y^2}\le NA/\lambda \\ 0, & \text{otherwise}\end{cases}$$

© Chris Mack

Fourier Optics

- Given a diffraction pattern T_m and a pupil function P, the light which makes it into the lens is just PT_m.
- The lens then takes the inverse Fourier transform of this light to give the electric field of the image, E.

$$E(x,y)=\mathcal{F}^{-1}\{PT_m\}$$

$$I(x,y)=\left|E(x,y)\right|^2$$

© Chris Mack

Lecture 43: What have we Learned?

- Define “numerical aperture”
- What are the entrance and exit pupils of an imaging lens?
- How can one determine which diffraction orders pass through an imaging lens?
- What is the pupil function of a lens?
- Explain the concept of Fourier Optics

© Chris Mack