Photolithography: The Basics of Projection Printing

Photolithography



Photolithography Types



Wave

Aperture



Block diagram of a generic projection imaging system



✓Adequate uniformity across the field



Illumination System

Mask

 \checkmark changes the transmittance of the light

✓ Causes diffraction



Objective lens

 \checkmark Picks up a portion of the diffraction pattern

 \checkmark Projects the image onto the photoresist

Diffraction Analysis



Illumination System

Mask

 \checkmark changes the transmittance of the light

✓ Causes diffraction

Diffraction

Theory of propagation of light

- Solution to Maxwell's Equations: complicated

- Diffraction Integrals for far field: simpler
 - Light propagation in homogenous medium



Fraunhofer Diffraction Integral

- ✓ Mask Transmittance Function: $t_m(x, y)$
 - How does the mask transmit light?
 - Requires the solution of Maxwell's equations for that material: complicated!
- ✓ Kirchhoff boundary condition
 - Feature size > $2\lambda \&\&$ chrome thickness < $\lambda/2$
 - Ignore diffraction caused by mask topography
 - $t_m(x, y) = 1$ transparent region = 0 chrome

Fraunhofer Diffraction Integral

Given

x - y plane: mask plane

x'-y' plane : diffraction plane

 λ : wavelength of light

z: distance from mask to diffraction plane

n:refractive index of the medium

 $t_m(x, y)$: mask transmittance function

E(x, y): Electric field incident at the mask

$$T_m(f_x, f_y) = \int_{-\infty-\infty}^{\infty} \int_{-\infty-\infty}^{\infty} E(x, y) t_m(x, y) e^{-2\pi i (f_x x + f_y y)} dx dy$$

where

 $T_m(f_x, f_y)$: Electric field of the diffraction pattern f_x, f_y : Spatial frequencies of diffraction pattern $f_x = \frac{nx'}{z\lambda}, f_y = \frac{ny'}{z\lambda}$ *Fourier Optics The diffraction pattern is just the fourier transform of the mask pattern transmittance!*

 $T_m(f_x, f_y) = F(E(x, y)t_m(x, y))$

Diffraction Examples



Two typical mask patterns, an isolated space and an array of equal lines and spaces, and the resulting Fraunhofer diffraction patterns assuming normally incident plane wave illumination. Both t_m and T_m represent electric fields.



Magnitude of the diffraction pattern squared (intensity) for a single space (thick solid line), two spaces (thin solid line), and three spaces (dashed lines) of width *w*. For the multiple-feature cases, the linewidth is also equal to *w*.

Image Formation: Imaging Lens



✓ Projects the image onto the photoresist

Imaging Lens

- The diffraction pattern extends throughout the x'-y' plane
- The objective lens (finite size) can only capture a part of this pattern
 - Higher spatial frequencies lost





<u> NA/λ </u>: The maximum spatial frequency that can enter the lens <u>Large NA</u> => larger portion of diffraction pattern is captured => better image

$$R = K_1 \frac{\lambda}{NA}$$

Formation of the Image

- Lens Pupil Function
 - Mathematical description of the amount of the light entering the lens $P(f_x, f_y) = 1, \ \sqrt{f_x^2 + f_y^2} < \frac{NA}{\lambda}$
- = 0, $\sqrt{f_x^2 + f_y^2} < \frac{NA}{\lambda}$ • Lens performs the inverse fourier transform of the transmitted diffracted pattern

$$F\{F\{g(x, y)\}\} = g(-x, -y)$$

$$E(x, y) = F^{-1}\{T_M(f_x, f_y)P(f_x, f_y)\}$$



Aerial images for a pattern of equal lines and spaces of width *w* as a function of the number of diffraction orders captured by the objective lens (coherent illumination). N is the maximum diffraction order number captured by the lens.

PSF: Point Spread Function

- Means of characterizing the resolving capability of an imaging system
- Normalized image of an infinitely small contact hole $t_m(x, y) = \delta(0,0) => T_m(f_x, f_y)$



$$t_{m}(x, y) = \delta(0,0) \Longrightarrow T_{m}(f_{x}, f_{y}) = 1$$

$$E(x, y) = F^{-1} \left\{ P(f_{x}, f_{y}) \right\} = \frac{J_{1}(2\pi\rho)}{\pi\rho}$$

$$\rho = \frac{rNA}{\lambda}$$

$$PSF_{ideal} = \left| \frac{J_{1}(2\pi\rho)}{\pi\rho} \right|^{2}$$

$$R = 0.66 \frac{\lambda}{NA} \text{ to } 0.7 \frac{\lambda}{NA}$$

Oblique Illumination

- Plane wave strikes at an angle Θ'
 - Phase differs for different points on mask
- Shift in the position of the diffraction pattern

