Photolithography: The Basics of Projection Printing
Photolithography is at the Center of the Wafer Fabrication Process
Photolithography Types

**Contact Aligner**
- UV lamp
- Lens
- Mask
- PR
- Substrate wafer

2 operating modes:
- Contact for expose
- Separate for align

Examples:
- Kaspar 17A
- Oriel
- Karl Suss MJBS

**Proximity Aligner**
- Less wear on mask, but poorer image than from a contact aligner.

Examples:
- Kaspar-Cobilt

**Projection Aligner**
- Projection systems use imaging optics in between the mask and the wafer

Examples:
- Perkin-Elmer Micralign
Block diagram of a generic projection imaging system
Illumination system delivers light to the mask
✓ Sufficient intensity
✓ Proper directionality
✓ Proper spectral characteristics
✓ Adequate uniformity across the field
Mask
✓ changes the transmittance of the light
✓ Causes diffraction
**Projection System**

- **Light Source**
- **Condenser Lens**
- **Mask**
- **Objective Lens**
- **Wafer**

**Illumination System**

**Objective lens**
- Picks up a portion of the diffraction pattern
- Projects the image onto the photoresist

**Image Formation**
Diffraction Analysis

Mask
✓ changes the transmittance of the light
✓ Causes diffraction

Light Source

Condenser Lens

Objective Lens

Wafer

Illumination System

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

\[ t_m(x, y) = \begin{cases} 1 & \text{transparent region} \\ 0 & \text{chrome} \end{cases} \]
Fraunhofer Diffraction Integral

Given

- \(x - y\) plane: mask plane
- \(x' - y'\) plane: diffraction plane
- \(\lambda\): 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

\[
T_m(f_x, f_y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x, y) t_m(x, y) e^{-2\pi i (f_x x + f_y y)} \, dx \, dy
\]

where

- \(T_m(f_x, f_y)\): Electric field of the diffraction pattern
- \(f_x, f_y\): Spatial frequencies of diffraction pattern

\[
f_x = \frac{nx'}{z\lambda}, \quad f_y = \frac{ny'}{z\lambda}
\]
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

Illumination System

Objective lens
✓ Picks up a portion of the diffraction pattern
✓ Projects the image onto the photoresist

Light Source
Condenser Lens
Mask
Objective Lens
Wafer
Image Formation
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
Aperture ($x', y'$)-plane

Object Plane

Entrance Pupil

Objective Lens

$$NA = n \sin \theta_{\text{max}}$$

$$f_x = \frac{nx'}{z \lambda} = \frac{n \sin \theta_x}{\lambda}$$

$$f_y = \frac{ny'}{z \lambda} = \frac{n \sin \theta_y}{\lambda}$$

$$\frac{1}{p_{\text{min}}} = \frac{NA}{\lambda}$$

$NA/\lambda$: The maximum spatial frequency that can enter the lens

Large $NA$ => 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
    \[ P(f_x, f_y) = 1, \quad \sqrt{f_x^2 + f_y^2} < \frac{NA}{\lambda} \]
    \[ = 0, \quad \sqrt{f_x^2 + f_y^2} < \frac{NA}{\lambda} \]

• 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

\[ t_m(x, y) = \delta(0,0) \Rightarrow T_m(f_x, f_y) = 1 \]

\[ E(x, y) = F^{-1}\{P(f_x, f_y)\} = \frac{J_1(2\pi\rho)}{\pi\rho} \]

\[ \rho = \frac{rNA}{\lambda} \]

\[ PSF_{ideal} = \left| \frac{J_1(2\pi\rho)}{\pi\rho} \right|^2 \]

\[ R = 0.66 \frac{\lambda}{NA} \text{ to } 0.7 \frac{\lambda}{NA} \]
Oblique Illumination

• Plane wave strikes at an angle $\Theta'$
  – Phase differs for different points on mask
• Shift in the position of the diffraction pattern

\[ E(x, y) = e^{\frac{i2\pi \sin \theta' x}{\lambda}} \]
\[ f_x' = \frac{\sin \theta'}{\lambda} \]
\[ E(x, y, f_x', f_y') = F^{-1} \{ T_m(f_x - f_x', f_y - f_y')P(f_x, f_y) \} \]
\[ R = \frac{k_1 \lambda}{2NA} \]