Advanced Issues and Technology (AIT) Modules

Purpose: Explain the top advanced issues and concepts in optical projection printing and electron-beam lithography.

AIT-1: LER and Chemically Amplified Resists
AIT-2: Resolution Enhancement and PSM
AIT-3: Small Features and Defects

* AIT-4: Aberrations

AIT-5: Maskless, High-NA, Immersion, EUV, Imprint
AIT-6: Electron Beam Lithography

Each module is a 20-25 min presentation of about a dozen slides.

Suggested reading:
Griffin: Plummer, Deal and Chapter 5
Wong: 31-45, 55-58, 71-90, Fig 4.1, Fig. 4.10

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Optical System as Fourier Optics

- The lens is in the far field of the mask and sees the Fraunhoffer diffraction electric field which is the \textbf{Fourier transform} of the electric field emerging from the mask.

- The lens passes only rays with wave angles inside the NA circle and is thus a 2D \textbf{low pass filter}.

- The lens re-phases the remaining emerging rays so that they re-converge at the wafer with the same relative phases which is equivalent to the \textbf{inverse Fourier transform}. 

\textbf{Relationship for electric fields}
(Sin\(\theta_x\), Sin\(\theta_x\)) wave accounting system

Lens Pupil
Sin\(\theta_{MAX}\) = NA

Lens Illumination
Sin\(\theta_{MAX}\) = \(\sigma\)NA

Location (Sin\(\theta_x\), Sin\(\theta_x\)) corresponds to a ray making angles \(\theta_x\) and \(\theta_y\) with the downward z-axis

Renormalize so that this point is 1.0
**Pupil position accounting system**

- Divide by NA
- New variables
  - \( r = \{0,1\} \)
  - \( \alpha = \{0, 2\pi\} \)

Lens Pupil

\[
\sin\theta_{\text{MAX}} / NA = 1
\]

Lens Illumination

\[
\sin\theta_{\text{MAX}} / NA = \sigma
\]

Location \((\sin\theta_x/NA, \sin\theta_y/NA)\) corresponds to a ray making angles \(\theta_x\) and \(\theta_y\) with the downward z-axis.
Optical Path Difference

The optical path difference (OPD) is the phase error over the pupil between rays for the actual lens and those for a perfect diffraction limited lens. The OPD is usually normalized to wavelengths.

The OPD contributes an additional phase factor of $e^{i(2\pi/\lambda)\text{OPD}}$ in the integration of the rays in computing the electric field at the image.

For primary aberrations like tilt, defocus, spherical, coma, and astigmatism a power series is used

$$\Phi = A'_{n,m} \rho^n \cos^m \theta$$

Zernike introduced the so called “circle polynomials” that are orthonormal on the unit circle to describe aberrations.

$$\Phi = A_{00} + \frac{1}{\sqrt{2}} \sum_{n=2}^{\infty} A_{n0} R_n^\infty (\rho) + \sum_{n=1}^{\infty} \sum_{m=1}^{n} A_{nm} R_n^m (\rho) \cos m \theta$$

Primary Coma => orthogonal components => tilt + balanced coma
Expansion of Zernike

The Zernike polynomials are individual functional variations in radius \( r \) and angle \( \alpha \) in an orthonormal expansion over the lens pupil normalized to radius 1.

**Z2** Tilt in \( x \) is \( r \cos(\alpha) \)

**Z7** is Coma in \( x \) with Tilt removed or so called balanced coma.

Sheats and Smith, pp. 224
Strehl Ratio

The peak value of the point spread function decreases proportionally to the square of the RMS value of the aberrations present.

The Strehl Ratio is defined as the ratio of the peak value with aberrations to the peak value without aberrations.

\[ \text{RMS OPD} = \frac{(P-V \text{ OPD})}{3.5} \]

The Strehl Ratio is approximately

\[ 1 - 4\pi^2(\text{RMS OPD})^2 \]

Sheats and Smith pp 255

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Strehl Ratio vs. Peak-to-Valley OPC

New projection printers have Strehl Ratios over 0.975 => aberrations of 0.05 RMS or 0.09 PV

The human eye works best in bright light when the pupil is small and typically has a Strehl ratio of 0.6.
Mathematics of Aberrations and OPD

The electric field produced by the convergence of the cone of plane waves from the pupil at any point \( x \) on the wafer is given by integrating the waves over the pupil.

\[
E(\vec{x}) = \frac{1}{\pi} \int_0^1 \int_0^{2\pi} E(r, \alpha) e^{-jkOPD(r, \alpha)} e^{-j\vec{k} \cdot \vec{x}} r \, \delta r \, \delta \alpha
\]

When OPD is small

\[
e^{jkOPD} \approx 1 - jkOPD
\]

\[
E(\vec{x}) = \frac{1}{\pi} \int_0^1 \int_0^{2\pi} E(r, \alpha)[1 - jkOPD(r, \alpha)] e^{-j\vec{k} \cdot \vec{x}} r \, \delta r \, \delta \alpha
\]
Finding the Strehl Ratio

\[ E(\bar{x}) = \frac{1}{\pi} \int_{0}^{1} \int_{0}^{1} E(r, \alpha) e^{-j \bar{k} \cdot \bar{x}} e^{-j k OPD(r, \alpha)} r \delta r \delta \alpha \]

To find the Strehl ratio (relative value the peak intensity in the presence of an aberration) we only need look at \( x = 0 \) and assume that \( E(r,a) \) is produced by a small pin hole and thus constant. This greatly simplifies the integral to

\[ E(0) = \frac{1}{\pi} \int_{0}^{1} \int_{0}^{1} e^{-j k OPD(r, \alpha)} r \delta r \delta \alpha \]

When the OPD is small

\[ E(0) = \frac{1}{\pi} \int_{0}^{1} \int_{0}^{1} [1 - jk OPD(r, \alpha) - \frac{k^2}{2} OPD^2(r, \alpha)] r \delta r \delta \alpha = 1 - jk \bar{\Phi} - \frac{k^2}{2} \overline{\Phi} \]

Where \( \overline{\Phi} \) is the average of \( OPD^2 \) over the pupil

The intensity is given by

\[ |E(0)|^2 = \left| 1 - jk \bar{\Phi} - \frac{k^2}{2} \overline{\Phi} \right|^2 \approx \left| 1 - k^2 \bar{\Phi} + k^2 \left( \overline{\Phi} \right)^2 \right|^2 = 1 - 4 \pi^2 \overline{\Phi} = 1 - 4 \pi^2 \sum_{n,m} \overline{\Phi}_{n,m} = 1 - 4 \pi^2 \sum_{n,m} A_{n,m} \]

Zero for Zernike’s

Orthogonal for Zernike’s
Simple Coma 0.10 Waves

3 space pattern

Coma

Unaberrated

This bump suggests ways to monitor coma.
Aberration E-Field Point-Spread Functions

Each aberration has a characteristic e-field point spread function. Note that the sidelobe levels are as high (0.15) as those for the diffraction limited point-spread function and have maxima at various radii.

Garth Robins and Kostas Adam
Programmed-Probe Aberration Targets

The 0.4 l/NA by 0.4 λ/NA programmed 180° phase defect provides an interferometric like reference electric field with magnitude 0.43 and phase of 180° compared to the clear area field.

Coma Sidelobe
-0.1 wave => 0.40
0.0 wave => 0.30
0.1 wave => 0.21

Detect Sidelobe by over exposing 2.5x and using automatic wafer inspection
Defect-Probe Aberration Targets

Dark Field Patterns

Probe

Spherical

Coma

Grid is 0.1 \( \lambda/\text{NA} \)

Astigmatism

1 at 90\(^\circ\)

Trefoil

1 at 0\(^\circ\)

1 at 180\(^\circ\)

Lens aberrations cause lateral spillover of light in imaging in directions related to the aberration symmetry.
Pattern-and-Interferometric-Probe Aberration Monitors

Defocus target
Experiment on AIMS at low NA looks just like simulation!

Discovered through simulation
Lead to a new theory
Becoming a practical technology
Phase Shift Mask Monitors Developed for:

- **Polarization Monitoring**
  - Take advantage of high-NA vector effects
  - Image (simulated)
  - Design

- **Illumination Monitoring**
  - Beam steering with 4-phase grating
  - Proximity effect and beam steering

- **PSM Performance**
  - Use orthogonality of phase and transmission errors
  - Mask
  - Resist

Greg McIntyre

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Interferometric Probe Monitors: Verification

PSM Monitors: Limits of Nature or Man?

1. Orientation dependence
2. Feature size/depth error

Garth Robins and Greg McIntyre
Projection Printer Examples

Figure 75  An all-refractive lens design for a 5× i-line reduction system.

Figure 77  The 4× catadioptric MSI design.
Impact of Aberrations: Magnitude $\frac{1}{2}$ OPC

0.025 waves of RMS aberration $\rightarrow$ Strehl Ratio = 0.975

- The effects of aberrations are typically half that of the proximity effect of an adjacent figure

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Basic Aberrations in Projection Printing

These are simple aberrations that are not always orthogonal to each other (e.g. coma contains tilt.)