Basic Projection Printing (BPP) Modules

Purpose: Explain the top 10 phenomena and concepts key to understanding optical projection printing

BPP-1: Resolution and Depth of Focus (1.5X)
BPP-2: Bragg condition and Mask scattering (1.5X)

**BPP-3: Electric fields and Intensity (1.5X)**

BPP-4: Resists and Standing Waves (2X)
BPP-5: Partial Coherence
BPP-6: Integral Representation of Fresnel and Fraunhoffer

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

Suggested reading:

Griffin: Plummer, Deal and Chapter 5
Sheats and Smith: 188-196, 124-133, 148-152, 182-188, 121
Wong: 31-45, 55-58, 83
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 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 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 inverse Fourier transform.
Transformations from wave angles \((\sin \theta_x, \sin \theta_x)\) to the pupil, FT, and wave-vectors

Pupil Coordinates: Divide \((\sin \theta_x, \sin \theta_x)\) by NA so that the lens radius becomes unity.

Fourier Transform (as used by Smith): Divide \((\sin \theta_x, \sin \theta_x)\) by \(\lambda\) to get \((u = \sin \theta_x / \lambda, v = \sin \theta_x / \lambda)\).

Electromagnetic propagation wave vector (k-vector): Multiply \((\sin \theta_x, \sin \theta_x)\) by \(k_0 = 2\pi / \lambda\) to get \((k_x = k_0 \sin \theta_x, k_y = k_0 \sin \theta_x)\).

Example: Grating first order \(\sin \phi = \lambda / P\) \(k_{x1} = [(2\pi) / \lambda] \sin \phi = [(2\pi) / \lambda] (\lambda / P) = 2\pi / P\)
**Electric Field: Sinusoids**

Binary Mask with period P and opening space s

When filtered to three waves (0, +1, and -1)

\[
E(x) = E_0 + 2E_1 \cos\left(\frac{2\pi x}{P}\right)
\]

\[
E_n = \frac{A}{2} \sin\left(n\pi\left(\frac{s}{P}\right)\right)
\]

\[
k_{x1} = \frac{2\pi}{P}
\]

When \(s = \frac{P}{2}\)

\[
E(x) = 0.5 + \left(\frac{2}{\pi}\right) \cos\left(\frac{2\pi x}{P}\right)
\]
Intensity as Square of Electric Field

The energy carried by a wave and the work done on a material are proportional to the time average of the square of the electric field.

Thus the intensity is proportional to $E^2$ when the field is real and $EE^*$ when phasors are used and $E$ is complex.

Intensity = $EE^*$ gives

$$I(x) = EE^* = E_0^2 + 2E_0E_1\cos\left(\frac{2\pi x}{P}\right) + 4E_1^2\cos^2\left(\frac{2\pi x}{P}\right)$$

Since the Fourier transform converges to the average at a discontinuity, the electric field at the mask edge will be about 0.5, and the intensity at a mask edge will be about 0.25.

#5 The intensity at a mask edge is only 30% of the clear field intensity regardless of feature type and size.
Intensity at the mask edge is about 0.30 for all feature types

Convention: Line is a line in positive resist.

Image Contrast
\[ C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \]
#6 Superposition Fails for Images!
(but superposition holds for Electric-Fields instead)

Peak intensity initially increases as the square of linewidth.

Consequence of $I = EE^*$

This messes up fast OPC based on linear transforms!!
Mask Error Factor (MEF)

Another Consequence of

I = EE*

\[ \Delta CD_{PRINTED} = MEF \frac{\Delta CD_{MASK}}{M} \]

MEF = MEEF = Mask Error Enhancement Factor
Normalized image Log Slope (NILS)

• A high image slope is desirable for CD control

• Since exposure can be increased arbitrarily a high slope normalized to the intensity is desired

• To scale to smaller features the slope should also be scaled to feature size

\[ S_{Norm} = \frac{L}{I} \left( \frac{\partial I}{\partial x} \right) \quad \frac{\partial (\ln I)}{\partial x} = \frac{1}{I} \left( \frac{\partial I}{\partial x} \right) \]

\[ S_{Norm} = L \frac{\partial (\ln I)}{\partial x} = NILS \]
Sensitivity of a Function to a Parameter

• Sensitivity

\[ S_F^P = \frac{P}{F} \left( \frac{\partial F}{\partial P} \right) \]

• Chain rule for derivatives

\[ \frac{\partial L}{\partial x} = \frac{\partial L}{\partial R} \frac{\partial R}{\partial M} \frac{\partial M}{\partial I} \frac{\partial I}{\partial x} \]

• Chain Rule for Sensitivities

\[ S_L^x = \frac{L}{x} \frac{\partial L}{\partial x} = \frac{L}{R} \frac{\partial L}{\partial R} \frac{M}{R} \frac{\partial R}{\partial M} \frac{I}{M} \frac{\partial M}{\partial I} \frac{x}{I} \frac{\partial I}{\partial x} = S_L^x S_R^M S_M^I S_I^x \]

L = linewidth; R = rate of development; M = chemical state; I = intensity

Copyright 2004, Regents of University of California
Normalized image Log Slope (NILS)

\[ S_{\text{Norm}} = \text{NILS} = L \frac{\partial (\ln I)}{\partial x} = \frac{L}{I} \left( \frac{\partial I}{\partial x} \right) \]

\[ S_{\text{Norm}} = \frac{L}{I} \left( \frac{\partial I}{\partial x} \right) = S_I^x = S_I^E S_E^X \]

Since

\[ I = E^2 \]

\[ S_I^E = \frac{E}{E^2} \cdot 2E = 2 \]

\[ \text{I = EE}^* \text{ helps the NILS 2X} \]

Since

\[ E(x) = E_0 + 2E_1 \cos \left( \frac{2 \pi x}{P} \right) \]

\[ S_E^X = \frac{P}{E_0} \left| - \frac{2 \pi}{P} \cdot 2E_1 \sin \left( \frac{2 \pi P}{4} \right) \right| = \pi \frac{E_1}{E_0} = \pi \frac{\pi}{0.5} = 2 \]

and

\[ S_{\text{Norm}} = \frac{L}{I} \left( \frac{\partial I}{\partial x} \right) = S_I^x = S_I^E S_E^X = 2 \cdot 2 = 4 \]
**MEF = Mask Error Enhancement Factor**

\[ \text{MEEF} = S^L_I = S^E_I S^L_E \]

So we need to find

\[ S^L_E = \frac{E}{L} \left( \frac{\partial E}{\partial L} \right) \]

At \( x = P/4 \) using \( L+S = P \) and

\[ E(x) = E_0 + 2E_1 \cos \left( \frac{2\pi x}{P} \right) \quad E_n = \frac{A}{2} \sin \left[ n\pi \left( \frac{s}{P} \right) \right] \]

Gives

\[ S^L_E \frac{L}{E} \left( \frac{\partial E}{\partial L} \right) = \frac{P}{2} \left( \frac{1}{2} \frac{\pi}{P} \frac{1}{0.5} \right) = 1 \]

And

\[ \text{MEEF} = S^L_I = S^E_I S^L_E = 2 \cdot 1 = 2 \]

\[ \text{I} = \text{EE}^* \text{ creates MEEF} = 2 \]
Sensitivity of Linewidth to Exposure

Can the exposure latitude be related to the 3 wave image?

\[ \text{ExposureLatitude in } \% = \frac{\text{AllowedLinewidthLatitude in } \%}{S_D^L} \]

\[ S_D^L = \frac{D}{L} \left( \frac{\partial L}{\partial D} \right) \]

Work out how to get the sensitivity of linewidth to exposure

\[ \frac{\Delta L}{L} = \frac{1}{L} \text{ Slope} = \frac{1}{L} \frac{\Delta I}{\partial x} = \frac{\Delta I}{I} \frac{1}{L} \frac{\partial I}{\partial x} = \frac{\Delta I}{I} \frac{1}{S_i^L} \]
Electric Field and Intensity: Defocus

\[ E_{TOTAL} = E_{-1}e^{-j\left(-\frac{2\pi}{\lambda}x + \frac{2\pi}{\lambda}\cos(\theta_{+1})z\right)} + E_{0}e^{-j\left(0\cdot\frac{2\pi}{\lambda}x + \frac{2\pi}{\lambda}\cos(\theta_{0})z\right)} + E_{+1}e^{-j\left(\frac{2\pi}{\lambda}x + \frac{2\pi}{\lambda}\cos(\theta_{+1})z\right)} \]

Note that \( \cos(\theta_{-1}) = \cos(\theta_{+1}) \) and \( \cos(\theta_{0}) = 1 \)

And that \( E_{-1} = E_{+1} \) for a binary (real transmission function) mask

\[ E_{TOTAL} = +E_{0}e^{-j\left(\frac{2\pi}{\lambda}z\right)} + 2E_{+1}\cos\left(\frac{2\pi}{\lambda}\right)e^{-j\left(\frac{2\pi}{\lambda}\cos(\theta_{+1})z\right)} \]

The Rayleigh defocus \( z \) value to give \( \lambda/4 \) is

\[ z = \frac{\lambda}{4\left|1-\cos(\theta_{+1})\right|} \]
Aerial Image: Effect of Focus

Linewidth/2
Underexpose

Linewidth/2
Overexpose

Isofocal Point
Linewidth
independent of
focus
Focus Behavior: Bossong Plot (SMILE)

Dense Line = Space = 180 nm

Line = 300 nm

JSR M91Y resist, 248nm, NA = 0.63, 0.8/0.4 annular illumination

C. Mack SPIE SC 2004
Process Window: Exposure/Focus

Percent Exposure Variation

Contour Map for 10% linewidth change

Percent Exposure Latitude

C. Mack SC 2000
LAVA Applet: Pattern and Aberration

This applet is one of mask type choices in the interaction of defects with features applet.
Image Quality: Across Line

$k_1 = 0.6$ Feature

Slope: $2.5/(\lambda/NA)$

This 1D image slope is nearly doubled by $I = EE^*$. Another Consequence of $I = EE^*$

This 1D image slope is nearly independent of feature size.
Image Quality: Line End

$k_1 = 0.6$ Feature

Slope: $1.8/\left(\frac{\lambda}{NA}\right)$

Mask Opening

#7 The slope of the 2D image at the end of the line is only 72% as large.