Optical Projection Printing and Modeling

Purpose: Explain 8 of the top 10 phenomena and concepts key to understanding optical projection printing

Basic Parameters: Resolution and Depth of Focus
Optical Proximity Effects
Bragg Diffraction and Image Calculation
Image Characterization: \( I = EE^* \Rightarrow 0.25, NL, MEEF \)
LAVA Website: Simulation; Mask Viewer

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

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ASML 5500/90 Tool

- Mask Port
- Objective Lens
- To Wafer
- Light path
- Sigma Aperture
- Hexagonal Light Pipe Output
- Condenser Lens
- Fly’s Eye

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Projection Printer Examples

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

**Figure 77** The 4x catadioptric MSI design.

Sheats and Smith

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Optical Projection Printing Parameters

#0 Key Parameters: \( \lambda, NA, \sigma \)

- **Wavelength** \( \lambda = 248 \text{ nm} \)
- **Numerical Aperture** \( NA = \sin(\theta) = 0.5 \)
- **Partial Coherence Factor** \( \sigma = \frac{NAc}{NAo} = 0.3 \)
## Parameters for Microlab Projection Printers

### Working Resolution

<table>
<thead>
<tr>
<th>Tool</th>
<th>λ (nm)</th>
<th>NA</th>
<th>σ</th>
<th>k₁</th>
<th>θ_{LEN} (deg)</th>
<th>θ_{ILL} (deg)</th>
<th>k₁λ/NA (nm)</th>
<th>λ/(4NA) (nm)</th>
<th>TFR (nm)</th>
<th>M</th>
</tr>
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<tbody>
<tr>
<td>Canon-gh</td>
<td>436</td>
<td>0.28</td>
<td>0.7</td>
<td>0.8</td>
<td>16</td>
<td>11</td>
<td>1250</td>
<td>390</td>
<td>5500</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>405</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCA-g</td>
<td>436</td>
<td>0.28</td>
<td>0.7</td>
<td>0.8</td>
<td>16</td>
<td>11</td>
<td>1250</td>
<td>390</td>
<td>5500</td>
<td>10</td>
</tr>
<tr>
<td>GCA-i</td>
<td>365</td>
<td>0.32</td>
<td>0.5</td>
<td>0.8</td>
<td>19</td>
<td>13</td>
<td>900</td>
<td>285</td>
<td>3500</td>
<td>10</td>
</tr>
<tr>
<td>ASML-DUV</td>
<td>248</td>
<td>0.5</td>
<td>0.25</td>
<td>0.7</td>
<td>30</td>
<td>7.2</td>
<td>350</td>
<td>125</td>
<td>990</td>
<td>5</td>
</tr>
</tbody>
</table>

\[ TFR = \text{Total focus range} = 2 \times \text{Rayleigh Depth of Focus} = 2\text{DOF} \]

\[ M \text{ is the demagnification factor} \]

\[ L_{\text{LINEWIDTH}} = k_1 \frac{\lambda}{NA} \quad \text{DOF} = k_2 \frac{\lambda}{2(NA)^2} \]

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Optical System Point Spread Function

- The small pinhole due to its size diffracts uniformly over all angles.
- This diffraction uniformly fills the lens pupil.
- The lens re-phases the remaining emerging rays so that they re-converge at the wafer with the same relative phases and uniform magnitude.
- The electric field at the wafer is thus the inverse Fourier transform of a disk = Airy Function.
- The intensity is the time average of the square of the electric field = (Airy function)^2
- The pattern shape is independent of the shape of the pin hole with diameter 1.22λ/NA.
- The peak E is proportional to pin hole area the peak I is proportional to Area^2 or (dimension)^4.
Resolution in Projection Printing

\[ f = \text{focal distance} \]
\[ d = \text{lens diameter} \]

Point spread function

\[ 1.22 \lambda \left( \frac{f}{d} \right) = 0.61 \lambda \left( \frac{f}{d} \right) = 0.61 \frac{\lambda}{NA} \]

Null position

\[ F\# = \frac{f}{d} \]

Minimum separation of a star to be visible.

PDG Fig. Ch 5
Resolution ~ Transverse Variation

Larger angles give higher resolution

\[ \lambda_{\text{TRANS}} = \lambda / \sin \phi = 3.22\lambda = 800\,\text{nm} \]

The most useful rays in forming an image are those with the same pitch as the pattern

#1 Resolution \( = P/2 = \frac{\lambda}{2 \sin \phi} = 0.5(\lambda/\text{NA}) \)

Assumes one wave is on-axis and the other off-axis

\( \phi \)

\( \lambda = 248\,\text{nm} \)

Wave graphic by Ongi Englander and Kien Lam
Depth of Focus: Phase change on vertical axis

Wave graphic by Ongi Englander and Kien Lam

Observe phase along a vertical line

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Depth of Focus in Projection Printing

Result must be modified for
a) High NA, and
b) Two waves at arbitrary angles.

\#2 Depth of Focus = \( \lambda/(2NA^2) \)

\[
\frac{\lambda}{4} = \delta - \delta \cos \Theta
\]

\[
\frac{\lambda}{4} = \delta \left[ 1 - \left( 1 - \frac{\Theta^2}{2} \right) \right] \equiv \delta \frac{\Theta^2}{2}
\]

\[
\Theta \equiv \sin \Theta = \frac{d}{2f} = NA
\]

\[
\therefore \frac{\lambda}{4f} = \delta = \pm \frac{\lambda}{2(NA)^2} = \pm \frac{k_1}{(NA)^2}
\]

PDG Fig. Ch 5
Normalized Parameters

For any wavelength $\lambda$ and numerical aperture $NA$.

$$L_{LINEWIDTH} = k_1 \frac{\lambda}{NA} \quad DOF = k_2 \frac{\lambda}{2(NA)^2}$$

$\lambda = 365, 248, 193, 157, 13.4 \text{ nm}$

$NA = 0.167, 0.38, 0.5, 0.63, 0.7, 0.75, 0.80$

Instead of recalculation for every new combination of $\lambda$ and $NA$ a universal catalog of image behavior can be utilized if we first determine the $k_1$ and $k_2$ factors in the actual system for the linewidth and defocus and look up results in a data base based on $\lambda = 0.5 \mu m$ and $NA = 0.5$.

$$L_{LINEWIDTH} = k_1 \frac{\lambda}{NA} = k_1 \frac{0.5 \mu m}{0.5} = k_1 \mu m$$

$$DOF = k_2 \frac{\lambda}{2(NA)^2} = k_2 \frac{0.5 \mu m}{2(0.5)^2} = k_2 \mu m$$
Optical Proximity Effect
- lateral influence function

E-field Point Spread Function for Coherent Imaging:

- Finite size of projection lens (i.e. low-pass filter) images point on mask as Airy pattern on wafer.

\[ \text{Airy} = \text{IFT (disk)} = f(l/\text{NA}) \]

\[ E(x_2) = E_0 \left[ \frac{2J_1(\nu)}{\nu} \right] \]

\[ \nu = 2\pi \left( \frac{\lambda}{NA} \right)(x_2 - x_1) \]
Various Types of Image Distortion

Proximity effect with neighbors

End shortening

Nonlinearity with size

Corner rounding

Figure 4.1: Various types of image distortion.
Optical Proximity Correction (OPC)

Called Optical Process Proximity Correction (OPP) when compensations for other process effects are included.  

Wong
Qualitative Explanation of image degradation by lens

\[ P \sin \phi = n \lambda \]

\[ n = 0, \pm 1, \pm 2, \ldots \]

\[ \sin \phi < \text{NA of lens} \]

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Bragg Condition

\[ P \sin \phi_n = n\lambda \]

\#3 The Bragg condition sets the diffraction angles
Pupil Wave Traffic: Partial Coherence

#4 Lens is a low pass filter of mask diffraction at Bragg angles

Lens Pupil

$\sin\theta_{\text{MAX}} = NA$

Cone of Incident Light

Some misses pupil

Diffraction Orders from a mask with period P

Shifted by $\sin\phi = \lambda/P$

Potential for entering the pupil
**Electric Field: Sinusoids**

Binary Mask with period $P$ and opening space $s$

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

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

$k_{x1} = \frac{2\pi}{P}$

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

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
\[ C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

\[ C_{\text{DENSE}} = \frac{(1.18 - 0.01)}{(1.18 + 0.01)} = 0.98 \]

Sigma 0.5
Dense L = S

0.01

Mask Edge

Space

Line
#6 Superposition Fails for Images!
(but superposition holds for Electric-Fields instead)

\[ \frac{0.3 \lambda}{\text{NA}} \]
\[ \frac{0.5 \lambda}{\text{NA}} \]
\[ \frac{0.8 \lambda}{\text{NA}} \]

Much taller and wider.

Peak intensity initially increases as the square of linewidth.

Consequence of \( I = \text{EE}^* \)

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

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

**Another Consequence of**

\[ I = EE^* \]

**Effect is larger at**

\[ k_1 < 0.6 \]

**Expected Lines (2x slope)**

**Contacts (4x slope)**
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

Contour Map for 10% linewidth change

C. Mack SC 2000
**OPC Scatterbars or Assist Features**

Main Feature

Add nonprinting adjacent features

The isolated main pattern now acts somewhat more like a periodic line and space pattern which has a higher quality image especially with focus when off-axis illumination is used.

The bars must be small enough that the image at their location does not print.

A typical size is about 1/3 of the minimum feature size and they are placed about a minimum feature size from the feature edge.
Resolution Enhancement Techniques

Resolution Enhancement **Emphasizes High Frequencies**

Conventional Illumination

Binary Mask

Lens Capture

Modified Illumination

Phase Mask

In-Lens Filter

Bokor, Neureuther, Oldham, Circuits and Devices, 1996
Two Ray Infinite DOF

When $\theta_1 = \theta_2$ the contributions from Ray #1 and Ray #2 track each exactly with axial distance and an INFINITE depth of focus is produced.

\[
\text{Period} = \text{Pitch} = \frac{2\pi}{\Delta k_{\text{Transverse}}}
\]

\[
\Delta k_{\text{Transverse}} = 2k_0 \sin(\theta)
\]

\[
\text{Pitch} = \frac{\lambda}{2 \sin(\theta)} \xrightarrow{\sin(\theta) = NA} \frac{\lambda}{2NA}
\]

Doubled Resolution! With infinite DOF
Illumination Schemes

- **Top Hat – General Shapes**
  - \( k_1 = 0.67 \)
  - \( k_2 = 1.3 \)

- **Annular – DOF, Contacts**
  - \( k_1 = 0.55 \)
  - \( k_2 = 1.7 \)
  - \( \sigma_{IN} = 0.55 \)
  - \( \sigma_{OUT} = 0.85 \)

- **Quadruple – H,V lines, DOF**
  - \( k_1 = 0.45 \)
  - \( k_2 = 2.0 \)

- **Dipole – V lines, DOF**
  - \( k_1 = 0.35 \)
  - \( k_2 = 3.0 \)
  - H lines and contacts formed via a double exposure

- The \( k_1 \) factor is inversely proportional to the lateral separation of the illumination \( k_1 = 1/(2 \times \text{separation}) \)
Phase-Shifting Mask Types

- **Alternating (Strong)**
  - Used for Contacts
  - 6% to 10% gives slope improvement of 30%. Sidelobe issue.

- **Attenuating (Weak)**
  - Requires second trim mask exposure.

- **Phase Edge**
  - Chromeless (Only 0 order)
Attenuating Phase-Shifting Masks

Intensity of 6% comes from an electric field of -0.25

Going from positive electric fields to negative electric fields increases edge slope and creates darker intensity near edge.

Figure 6.2: Coherent images of an edge.
Phase-Shifting Mask: Electric Fields

Figure 19  The amplitude spectrum of a rectangular wave, $A/2 \sin(\omega_0 t / 2A_0)$. This is equivalent to the discrete order of the coherent Fraunhofer diffraction pattern.

Figure 65  Spatial frequency distribution $m(\omega)$ resulting from coherent illumination of an alternating phase shift mask, as decomposed into $m_1(x)$ and $m_2(x)$.

Sheats and Smith
Resolution Enhancement: In-Lens Filter

\[ T(r) = \cos(2\pi\beta r^2 + \frac{\Theta}{2}) \]

\[ \cos(2\pi\beta r^2) = 0.5e^{j2\pi\beta^2 r} + 0.5e^{-j2\pi\beta^2 r} \]

Defocus away and toward the lens.

- The \( \cos(2\pi\beta r^2) \) filter creates dual defocused images that are very effective in increasing the total focal range of contact patterns.

Fukuda, Hitachi

Fukuda JVST B Nov/Dec 91
‘Hands On’ Exploration

Lithography Analysis using Virtual Access 2001

Welcome to Volcano on Cuervo.eecs!

EE423 Students: Having problems running SPLAT? Something not working? Contact the Advanced Lithography Group!

Due to space constraints, sessions older than a week will be deleted. Please email the webmaster if you would like to keep a particular session.

Bookmark this page: cuervo.eecs.berkeley.edu/volcano

http://cuervo.eecs.berkeley.edu/Volcano/

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Basic Projection Printing Applet

- Mask
- Lens
- Wafer

- Line width (um): 0.30
- Space width (um): 0.80
- Sigma: 0.5
- Sigma in: 0.3
- Wavelength (um): 0.5
- Numerical aperture (um): 0.5
- Defocus (um): 0.0

Options:
- Iso Line
- Iso Space
- Dense
- Submit to SPLAT

Dense  Defocus
Annular Illumination: $k_1 = 0.4$ Large DOF

$L = S = 0.4$

$\sigma_{IN} = 0.5$

$\sigma_{OUT} = 0.8$

DOF = 2.0

Contrast = 0.61
This applet is one of mask type choices in the interaction of defects with features applet.
Image Quality: Across Line

This 1D image slope is nearly independent of feature size.

$k_1 = 0.6$ Feature

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

This 1D image slope is nearly doubled by $I = EE^*$. Another Consequence of $I = EE^*$
Image Quality: Line End

$k_1 = 0.6$ Feature

Slope: $1.8/(\lambda/\text{NA})$

Mask Opening

#7 The slope of the 2D image at the end of the line is only 72% as large.
Basic Aberrations in Projection Printing

These are simple aberrations that are not always orthogonal to each other (e.g. coma contains tilt.)
Simple Coma 0.10 Waves

This bump suggests ways to monitor coma.
#8A Interference in the resist produces standingwaves with a period = $\lambda/2n_{RESIST}$
Double Exposure Sharp Tip

uv210 on bare silicon
Apex-E on bare silicon
Apex-E on 80nm silicon nitride

STORM simulation of uv210 DEST assuming quencher loss on the substrate and acid loss on the surface
STORM simulation of APEX-E DEST assuming acid loss on the substrate

Lei Yuan SPIE 05

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Immersion Lithography

• Concept
  – Imaging in a liquid medium with refractive index $n$ offers an a factor of $n$ reduction in resolution
  – $n_{\text{WATER}}$ @ 193 nm = 1.44 to 1.46
  – $n_{\text{FUTURE}}$ @ 193 nm = 1.7?

• Implementation: Drop and Drag
  – Dispense water from front side of lens, use the surface tension to make the drop follow the lens, and suck in the liquid on the back of the lens.
**Immersion Lithography: Results and Promise**

- **Promise**
  - Improve resolution of 193 to that of 157 using a lower NA (0.9 => 0.77) and an increase (1.5X) in DOF.
  - NA = 1.25 for 45 nm generation
  - NA = 1.55 for 32 nm generation

- **Issues**
  - Liquid (optics), liquid (resist), liquid (machine)

Larger DOF at 90nm

ASML web site
**EUV Projection (X-Ray) Lithography**

**13.5 nm Sn**

13.4 nm wavelength

$0.7\lambda/NA = 31$ nm

$TFR = \lambda/NA^2 = 149$ nm

- NA = 0.3
- $\lambda/2$ layer pairs

Absorbing Mask used off-axis

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**Figure 9.24** An x-ray projection lithography system using x-ray mirrors and a reflective mask (after Zorpette, reprinted by permission, © 1992 IEEE).

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Nano-imprint Lithography

Step&Flash Imprint Lithography

(a) 
(b) 
(c) UV 
(d) 
(e) 

(G. Willson, UT Austin)

30 nm dense

20 nm isolated

Issues: Masks, Alignment, Inspection
Simpl_display PC Layout Viewer for GDSII

Frank Gennari
2004 SRC

Abacus Chip Example

Right mouse click and drag to enlarge
Then “f” key to return to fit to window
Simpl_display PC Layout View Manipulation

Numbers on keyboard toggle mask levels: 1 = poly, 2 = con, 3 = met

Lower case “s” saves current view as jpg in an image file

Stipple patterns are possible with 8 x 8 fill pattern:

NAME POLY
RGB 956 0 50
FILL 136 34 136 34 136 34 136 34