Basic Optics : Microlithography
Optics Part 3

• Numerical Aperture
• Resolution, Depth of Focus, and Depth of field (Text pp208-213)
• Partial Coherence ( sigma or fill factor) (Text pp196-202)
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• MTF and Contrast (Text pp202-205) (Text pp 535)
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• Optical Designs (Text pp261-268)
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**Numerical Aperture**

- The f-number of a lens (f/#) is the focal length divided by the diameter. It is a measure of the light gathering ability.
- The numerical aperture (NA) of a lens is $n \sin \alpha$, where $\alpha$ is the half-angle of the largest cone of light entering the lens.

\[
\frac{f}{D} = \frac{D}{2f} = \frac{1}{2 \cdot f/#}
\]

\[
NA = n \sin \alpha
\]

\[
NA = \frac{1}{\sqrt{\frac{1}{4}D^2 + f^2}} \approx \frac{D}{2f} = \frac{1}{2 \cdot f/#}
\]
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Numerical Aperture

http://www.microscopyu.com/tutorials/java/objectives/immersion/

- \( \text{NA} = n \sin \theta \)
  - Typically \( n = 1.00 \) for air
  - But you could use a higher refractive index medium to increase the effective NA!!
  - This increase in NA allows one to capture higher diffracted order rays.
  - This has not been done on exposure tools yet

High Refractive index medium effect:

NA is greater than 1.00!!
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Resolution, Depth of Focus, and Depth of field

- Resolution for coherent illumination:
  \[ R = k_1 \lambda / NA \]
  - \( R \) measured as minimum usage feature size in microns
  - \( k_1 \) process factor; \( \lambda \) = exposure wavelength; \( NA \) numerical aperture

- Resolution for partially coherent system
  \[ R = k_1 \lambda / NA(1+\sigma) \]
  - \( \sigma \) = partial coherence factor

- Resolution for Off axis illumination system
  \[ R = k_1 \lambda / (NA + NA^* \sigma + \sin \theta) \]
  - \( \sin \theta \) = off axis illumination incident angle on ret.

- Depth of Focus (DOF) at image plane (wafer):
  \[ DOF = k_2 \lambda / NA^2 \]
  - \( k_2 \) process factor

- Depth of field (DF) at object plane (reticle):
  \[ DF = DOF/m^2 \]
  - \( m \) = magnification of optical system, i.e. 5X = 0.2
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Resolution, Depth of Focus, and Depth of field

• **Depth of field (DF)** at object plane (reticle):
  • DF = DOF/$m^2$
  • ($m$ = magnification of optical system, i.e. $5X = 0.2$)

• **Depth of Focus (DOF)** at image plane (wafer):
  • DOF = $k_2\lambda/NA^2$ ($k_2$ process factor)
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Resolution, Depth of Focus, and Depth of Field

- **Special Case: Single slit diffraction:** Approximation > Phase of a wave from a point in the slit or aperture varies linearly across the slit!
- Slit width = b; y is position across slit;

\[ r = R - y \sin \theta \]
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Resolution, Depth of Focus, and Depth of field

Special Case: Single slit diffraction:

Fraunhofer diffraction

Integral across the slit. $E =$ electric field

$$E \propto \int_{-b/2}^{+b/2} e^{-iKR + iky \sin \theta} \, dy$$

$$= e^{-ikR} \int_{-b/2}^{+b/2} e^{iky \sin \theta} \, dy$$

$$= e^{-ikR} \left( \frac{e^{ikb \sin \theta}}{ik \sin \theta} - e^{-ikb \sin \theta} \right)$$

$$= e^{-ikR} \frac{\sin \beta \sin \theta}{\beta}, \text{ where } \beta = \frac{k b}{2} \sin \theta.$$
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Resolution, Depth of Focus, and Depth of field

Special Case: Single slit diffraction:

Fraunhofer Diffraction pattern
integral for electric field

\[ E \propto \int_{-b/2}^{+b/2} e^{-ikR + iky \sin \theta} dy \]

\[ = e^{-ikR} \int_{-b/2}^{+b/2} e^{iky \sin \theta} dy \]

\[ = e^{-ikR} \frac{e^{ik\frac{b}{2} \sin \theta} - e^{-ik\frac{b}{2} \sin \theta}}{ik \sin \theta} \]

\[ = e^{-ikR} \frac{b \sin \beta}{\beta}, \text{ where } \beta = k \frac{b}{2} \sin \theta \]

The intensity \( I \) is not influenced by the leading term \( e^{-ikR} \) and hence only the term \( \sin \beta / \beta \) = sinc\( \beta \) (pronounced “sink beta”) gives the change in diffraction pattern with \( \theta \).

Intensity of diffraction pattern
for slit: sinc\( \beta \)\(^2\) function

\[ I = I(0) \left( \frac{\sin \beta}{\beta} \right)^2 \]
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Resolution, Depth of Focus, and Depth of Field

Special Case: Single slit diffraction:

\[ I = I(0) \left( \frac{\sin \beta}{\beta} \right)^2 \]

The sinc\(\beta^2\) function has equally spaced zeros when \(b = n\pi\) (\(n\) not equal to 0)

Hence the zeros of the diffraction pattern occur when

\[ n\pi = \beta = \frac{kb\sin\theta}{2} = \frac{\pi b\sin\theta}{\lambda} \]

i.e.

\[ b\sin\theta = n\lambda \]

This is the same as the first equation we introduced \(m\lambda = b\sin\theta\)

\(b = \) slit width; \(\theta = \) diffraction angle; \(k = 2\pi / \lambda\) phase term
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Resolution, Depth of Focus, and Depth of field

Circular aperture diffraction: diameter d and radius a

Diffraction pattern is given in terms of a Bessel function $J_1$ of the first kind (order 1)

$$I = I(0) \left( \frac{2J_1(ka \sin \theta)}{ka \sin \theta} \right)^2$$

$$= I(0) \left( \frac{2J_1(\beta)}{\beta} \right)^2$$, where $\beta = ka \sin \theta$

Diffraction pattern is given the name “airy” disk after George Airy an English Astronomer in the 1800’s who worked out the math.

Looks very similar to the sinc$\beta^2$ function for the single slit diffraction case
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Resolution, Depth of Focus, and Depth of field

**Circular aperture diffraction:** diameter \( d \) and radius \( a \)

Looks very similar to the \( \text{sinc}\beta^2 \) function. The first minimum of the Airy pattern occurs when

\[
\text{kasin}\theta = 1.22\pi
\]

i.e. at \( \sin\theta = 1.22\lambda/2a = 1.22\lambda/d \) (\( d \) = diameter of aperture)

\( \theta \) = diffraction angle; \( k = 2\pi/\lambda \) phase term
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Resolution, Depth of Focus, and Depth of field

- Image of point source with diffraction = Airy disk (sinc function)
- Assume optical system is perfect and aberration free!

\[ l = -\frac{w}{2\sin \alpha} \]

Small angle \( \alpha \):

\[ Z = l\alpha/n = \frac{\alpha w}{2n\sin U} \]
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Resolution, Depth of Focus, and Depth of field

- Image of point source with diffraction = Airy disk (sinc function)
- Assume optical system is perfect!

<table>
<thead>
<tr>
<th>Diffraction ring</th>
<th>Z circular aperture</th>
<th>units</th>
<th>Energy in Ring %</th>
<th>Z slit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 central Maximum</td>
<td>0</td>
<td>(\lambda/NA)</td>
<td>83.9</td>
<td>0</td>
</tr>
<tr>
<td>1st dark</td>
<td>0.61</td>
<td>(\lambda/NA)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1st bright</td>
<td>0.82</td>
<td>(\lambda/NA)</td>
<td>7.1</td>
<td>0.72</td>
</tr>
<tr>
<td>2nd dark</td>
<td>1.12</td>
<td>(\lambda/NA)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2nd bright</td>
<td>1.33</td>
<td>(\lambda/NA)</td>
<td>2.8</td>
<td>1.23</td>
</tr>
<tr>
<td>3rd dark</td>
<td>1.62</td>
<td>(\lambda/NA)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>3rd bright</td>
<td>1.85</td>
<td>(\lambda/NA)</td>
<td>1.5</td>
<td>1.74</td>
</tr>
<tr>
<td>4th dark</td>
<td>2.12</td>
<td>(\lambda/NA)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4th bright</td>
<td>2.36</td>
<td>(\lambda/NA)</td>
<td>1</td>
<td>2.24</td>
</tr>
</tbody>
</table>

Z values in table above derived from:

**Circular aperture**

\[
I = I(0) \left( \frac{2 J_1(\beta)}{\beta} \right)^2, \text{ where } \beta = k a \sin \theta
\]

**Rectangular slit**

\[
I = I(0) \left( \frac{\sin \beta}{\beta} \right)^2
\]
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*Resolution, Depth of Focus, and Depth of field*

- Resolution Criteria: $b = \text{Sparrows}$; $c = \text{Rayleighs}$

**Definition: Lord Rayleigh’s Criterion** for limiting resolution of an optical system:

When the image separation $Z$ reaches $0.61\lambda/\text{NA}$, the maximum of one image coincides with the first minimum (dark ring) of the other pattern.
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*Resolution, Depth of Focus, and Depth of field*

- Rayleigh resolution Criteria:
- Two overlapping sinc functions (red and blue) the black is their summation. The maximum of one image coincides with the first minimum (dark ring) of the other pattern.

- The limit in the angular separation of two adjacent objects (stars) in terms of lens diameter \(w\) is given by:
  \[
  \alpha = \frac{1.22\lambda}{w}
  \]

For example, the entrance pupil of a telescope limits the resolution observable in object space. ‘d’ will then be \(d_0\), the diameter of the objective. E.g. a 100mm diameter objective will define a diffraction-limited resolution at a wavelength of 500 nm of \(\Delta \theta = 1.22 \times 5 \times 10^{-7}/1 \times 10^{-1} = 6.1 \times 10^{-6} \) radians = 1.26” arc.
8. Resolution and DOF

- Depth of Focus (DOF) at image plane (wafer):
- \[ \text{DOF} = \frac{k_2 \lambda}{NA^2} \] (\(k_2\) process factor) Criteria based on CD and sidewall angle specifications!

![Diagram of depth of focus and blur circle relationship]
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Resolution KLA-Tencor Chris Mack Answers

Q The Rayleigh equation says depth of focus decreases with shorter wavelengths. I’ve also heard the opposite, that shorter wavelengths give more depth of focus. Which is correct?

A Both answers are correct, depending on the details of the specific question. The Rayleigh equation says depth of focus (DOF) is directly proportional to wavelength. This equation, however, is derived for a very specific case: when the feature being printed is at the resolution limit of the imaging tool. Rayleigh’s resolution equation (the other Rayleigh equation) says the resolution limit is also directly proportional to wavelength. Thus, when the wavelength is reduced, the Rayleigh DOF equation says the DOF of the smaller feature is less. This is not an astounding conclusion – small features have less DOF.

Suppose the question were asked in a different way: for a given feature to be printed (say, 130 nm lines and spaces), how does wavelength affect DOF, all other things being equal? Is there a difference in DOF using 193 nm exposure tools versus 248 nm? The Rayleigh DOF equation by itself cannot answer this question. In fact, the lower wavelength will always give more depth of focus for a given feature size.
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Resolution, Depth of Focus, and Depth of field

Consider point source imaged by a lens

Image is “In Focus” if

\[ \frac{1}{z_0} + \frac{1}{z_1} = \frac{1}{f} \]

Move \( P_2 \) system is “Defocused”.

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Resolution, Depth of Focus, and Depth of field

Define Defocus Parameter, \( D \) as:

\[
D = \frac{1}{z_0} + \frac{1}{z_1} - \frac{1}{f}
\]

Then if

\[
D < 0 \quad \text{Negative Defocus, \( (z_1 \) too large)}
\]

\[
D > 0 \quad \text{Positive Defocus, \( (z_1 \) too small)}
\]
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Resolution, Depth of Focus, and Depth of field

Ray Optics: Defocus system by $\Delta z$

Focus

Radius of the spot is given by similar triangles to be

$$ r_0 = \frac{\Delta z d}{2z_1} $$

where the lens is of diameter $d$. So larger defocus, large PSF. OK for
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Resolution, Depth of Focus, and Depth of field

Defocus Wavefront approach: Defocus is an aberration: Zernike coefficient# Z3

To get ideal PSF (sharp focus), we need Parabolic Wave front behind the lens.

Actual wavefront may vary from this ideal.
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Resolution, Depth of Focus, and Depth of field


Wavefront aberration approach

Under defocus, the wavefront aberration is

\[ W(x, y) = \frac{D}{2} (x^2 + y^2) \]

Measure the Defocus as the extent of the wavefront aberration at the edge of the lens, at

\[ x^2 + y^2 = \alpha^2 \]
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Resolution, Depth of Focus, and Depth of field

Wavefront aberration approach

Denote wavefront aberration at edge by $\Delta W$, so wavefront aberration is:

$$W(x,y) = \Delta W \left( \frac{x^2 + y^2}{a^2} \right)$$

so

$$D = \frac{2 \Delta W}{a^2}$$

No easy solutions for PSF under defocus.
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Resolution, Depth of Focus, and Depth of field

- Focus: In focus no aberrations
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Resolution, Depth of Focus, and Depth of field

- Focus: Out of focus: Waves arrive out of phase (OPL difference)
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Partial Coherence (sigma or fill factor)

Practical light sources are not point sources.
∴ the light striking the mask will not be plane waves.
The spatial coherence of the system is defined as

\[ S = \frac{\text{light source diameter}}{\text{condenser lens diameter}} = \frac{s}{d} \]

or often as

\[ S = \frac{\text{NA}_{\text{condenser}}}{\text{NA}_{\text{projection optics}}} \]
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Partial Coherence (sigma or fill factor)

Illumination Systems: Partially Coherent (On-Axis)

Kohler illumination $\sigma$ (sigma) is the so-called *partial coherence factor or fill factor*. 
Sigma = $\frac{N_{Ac}}{N_{Ap}}$

Focus effective source diameter in entrance pupil
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*Partial Coherence (sigma or fill factor)*

\( \sigma \) (sigma) *partial coherence factor or fill factor*. The influence of is demonstrated in Figure by showing the image intensity near a simple knife-edge. \( \sigma = \infty \) = lowest contrast

- Decreasing \( \sigma \) increases the edge slope and contrast
- Intensity at edge
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Partial Coherence (sigma or fill factor)

http://www.mmresearch.com/articles/article4/

• Typical setup:
• Focus source in entrance pupil:
• Called Kohler Illumination:
• ie. At Fourier Transform plane

\[ \sigma = \frac{NAC}{NAP} \]
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Partial Coherence (sigma or fill factor)

Partial Coherence and Advanced Apertures

Two aspects of coherence play an important role in lithography. Firstly, the light is strongly coherent in the time (temporal) domain (color) because of the required monochromaticity of the light source. The coherence in the spatial domain (phase), however, is an adjustable parameter that has great influence on the imaging performance. The illumination is said to be partially coherent, if a certain amount of spatial coherence exists. The amount of partial coherence is governed by the ratio of the numerical aperture of the condenser lens $NA_c$ and projection lens $NA_p$.

$$\sigma = \frac{NA_c}{NA_p}$$
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Partial Coherence (sigma or fill factor)

- Partial Coherence setup:
  Focus source in entrance pupil

\[ \sigma = \frac{NA_c}{NA_p} \]

- Lower \( k_1 \):
  - Resolution enhancement techniques
  - Optics utilization improvement
  - Process improvement
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Partial Coherence (sigma or fill factor)

\( \sigma \) (sigma) partial coherence factor or fill factor. \( \text{Sigma} = \frac{N_{Ac}}{N_{Ap}} \)

Partial coherence and diffraction: Fourier transform plane
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MTF and Contrast

\[ MTF = \frac{I_{\text{MAX}} - I_{\text{MIN}}}{I_{\text{MAX}} + I_{\text{MIN}}} \] (6)
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*MTF and Contrast*

**MTF** : Modulation Transfer function: Ratio of output to input as

\[
\text{MTF} = \frac{M_i}{M_o} \text{ at specified frequency}
\]

- \( M_i \) = Modulation of image at specified frequency
- \( M_o \) = Modulation of object at specified frequency

\( M = \frac{[I_{\text{max}} - I_{\text{min}}]}{[I_{\text{max}} + I_{\text{min}}]} \) for periodic feature of specified frequency

\( I \) = intensity

Frequency is measured in \( N \) lines/mm typically: period = \( 1/N \)

![Diagram of MTF and Contrast](image.png)
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*MTF and Contrast*

**MTF**: \( M_T = \frac{M_i}{M_o} \) at specified frequency

---

**Diagram**: Spread function + object (edge) → (edge) image

**Object brightness**

**Image illumination**

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MTF and Contrast

MTF Curve and cut off frequencies: i.e diffraction limited frequency >> not captured by the lens!!

Coherent illumination $v_{\text{cutoff}} = \frac{\text{NA}}{\lambda}$;

Incoherent illumination $v_{\text{cutoff}} = \frac{2\text{NA}}{\lambda}$;
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Resolution: Sub-resolution: How do we do that?
Resolution: Sub-resolution: How do we do that?

How can you print a linewidth less than the wavelength of the exposing radiation?

Resolution equation for coherent light is: \( R = \frac{k_1 \lambda}{NA} \)

While for partially coherent it is: \( R = \frac{k_1 \lambda}{NA(1+s)} \) \( s \) = partial coherence factor

The diffraction relationship we looked at before still is true, but for partially coherent illumination the **Fraunhofer Diffraction** pattern order pattern is spread out (not a point). These “spread” order patterns contain the transformed object information like before. If only part of these “spread” orders are captured by the lens, a image can be constructed. Part of the information is lost and the modulation (output/input) is less than 1!

- \( m \lambda = d \sin \theta \); \( m \) = diffraction order; \( \lambda \) = coherent illumination
- \( d = 2y \) = slit width; \( \theta \) = diffraction angle
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Resolution: Sub-resolution: How do we do that?

How can you print a linewidth less than the wavelength of the exposing radiation?

Partially coherent illumination Vs Coherent: Effectively higher diffraction angles are captured, but with less information. Hence resolution is increased!

Coherent illumination (pt source): orders lost: no image formation

Partially Coherent illumination (extended source): at same diffraction angle information captured = image formation
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Resolution: Sub-resolution: How do we do that?

Partially coherent illumination!

3 beam image formation

Partially Coherent illumination (extended source): at same diffraction angle information captured = image formation
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Resolution: Sub-resolution: How do we do that?

Coherent illumination : Fraunhofer diffraction pattern in entrance pupil:

- All information captured $= 1.00$
- Diffracted orders just missed!

Coherent illumination Modulation $= 1.00$

Entrance pupil diameter

Coherent illumination Modulation $= 0.00$ no image formation
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Resolution: Sub-resolution: How do we do that?

**Partially coherent illumination**: Effectively higher diffraction angles are captured. Fraunhofer diffraction pattern in entrance pupil:

Part of information captured = modulation <1.00

Entrance pupil diameter

Partially Coherent illumination
Extended source: Higher orders captured with lower modulation

In partially coherent imaging the resolution limit is achieved when

\[
\frac{\lambda}{p} = NA + NA \cdot \sigma
\]

\[
p \ (\text{pitch}) = \frac{\lambda}{NA(1+\sigma)}
\]
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Resolution: Sub-resolution: How do we do that?

**Definition:** Lord Rayleigh’s Criterion for limiting resolution of an optical system:

\[ R = 0.61\frac{\lambda}{NA}, \]

Our original resolution definitions

\[ R = k_1\frac{\lambda}{NA} \]

coherent light: Coherent resolution cutoff limit is \( \lambda/NA \)

- \( R = k_1\frac{\lambda}{NA}(1+\sigma) \) \( \sigma \) = partial coherence fill factor
- Resolution for Off axis illumination system
  \[ R = k_1\frac{\lambda}{(NA + NA*\sigma + \sin \theta )} ; \sin \theta \] = off axis illumination incident angle on ret.

Now define in terms of pitch \( p \) for partial coherent illumination as:

\[ P(pitch) = k_1\frac{\lambda}{NA(1+\sigma)} ; \text{Partially coherent resolution cutoff limit is } \lambda/NA(1+\sigma) \]
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Partial Coherence (sigma or fill factor)

\( \sigma \) (sigma).

Observations:

1) Diffraction patterns are not the same from dense to isolated

2) Lens act as “low-pass” filter, only lower diffraction order light beams can get through lens
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Partial Coherence (sigma or fill factor)
from: Chris Mack “Optical Proximity Effects”
http://www.usa.canon.com/indtech/semicondeq/news_optical2.html

σ (sigma) partial coherence factor or fill factor. Sigma = NA_c/Na_p

Partial coherent has a large effect on optical proximity effects

Figure 1. The impact of partial coherence on linewidth is very different for isolated and dense lines (in this case, i-line exposure with NA = 0.48 was used for nominal 0.5 μm lines).
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*Off Axis illumination*

- Off Axis Illumination: Tilt the illuminator! Capture only 0 and +1 orders = 2 beam image formation! Effectively doubles the captured diffraction angle.
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*Off Axis illumination*

- Three Beam Imaging conventional illumination (partially coherent) Vs Two beam Imaging Off axis.

- **KEY RESULT:** 2 beam = no phase shift when focal plane moves = increased DOF!
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Off Axis illumination

- Three Beam Imaging conventional illumination (partially coherent) Vs Two beam Imaging Off axis.

Three-Wave Interference:

Plane wave: \( E = E_0 \exp(iku) = E_0 \exp(2i\pi/\lambda (x \sin \alpha + z \cos \alpha)) \)

Sum of 3 waves with angles 0, \( \alpha \) and \(-\alpha\):

\[
E = E_0 \exp((2i\pi/\lambda) z) + E_1 \exp((2i\pi/\lambda) (x \sin \alpha + z \cos \alpha)) + E_1 \exp((2i\pi/\lambda) (-x \sin \alpha + z \cos \alpha))
\]

\[
E = E_0 \exp((2i\pi/\lambda) z) + 2E_1 \exp((2i\pi/\lambda) z \cos \alpha) \cos((2\pi/\lambda) x \sin \alpha)
\]

\[
I = E \ast E^* = E_0^2 + 4E_1^2 \cos^2((2\pi/\lambda) x \sin \alpha) + 2E_0E_1 \cos((2\pi/\lambda) x \sin \alpha) \cos((2\pi/\lambda) z (1-\cos \alpha))
\]

\( z \) dependence (finite depth of focus)

Two-Wave Interference:

Sum of 2 waves with angles \( \alpha \) and \(-\alpha\):

\[
E = E_0 \exp((2i\pi/\lambda) (x \sin \alpha + z \cos \alpha)) + E_0 \exp((2i\pi/\lambda) (-x \sin \alpha + z \cos \alpha))
\]

\[
E = 2E_0 \exp((2i\pi/\lambda) z \cos \alpha) \cos((2\pi/\lambda) x \sin \alpha)
\]

\[
I = E \ast E^* = 4E_0^2 \cos^2((2\pi/\lambda) x \sin \alpha)
\]

Pitch = \( \lambda / (2 \sin \alpha) \), no \( z \) dependence (infinite depth of focus)

Two-Wave Interference: alternating aperture phase-shifting masks, off-axis illumination (when 0 and +/- 1 are symmetrical around the optical axis (\( \alpha \) and \(-\alpha\))

Three-Wave Interference: on-axis illumination
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*Off Axis illumination: Two beam Imaging*

Incident Off axis illumination angle = $\theta$

Diffraction angle = $2\theta = \lambda/p$

Maximum DOF requires:

$$\sin \theta = \lambda/2p$$

- Resolution (pitch $p$) limit for Off axis illumination system

$$p = \lambda/NA \left(1 + \sin \frac{\theta}{NA}\right); \quad \sin \theta = \text{off axis illumination incident angle on ret.}$$

- Let $\sin \frac{\theta}{NA} = \sigma_o$

$$\sigma_o = \lambda/2pNA$$

$$p = \lambda/NA \left(1 + \sigma_o\right)$$
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*Off Axis illumination: Improved resolution and DOF*

**Resolution Improvement:** in theory pitch down to $\lambda/2.NA$

**Depth of Focus Improvement:** Defocus creates a phase error for each diffraction order which is proportional to the square of the radial position within the pupil. For off-axis illumination the 0th and 1st order can have the same distance from the center of the pupil. The relative phase difference between the 0th and 1st orders due to defocus will be zero thus leading to less sensitivity through focus.

The maximum DOF requires only two beam 0 and +1 orders entering the lens E.P.

Means:

Max DOF: $\text{NA}-(\text{NA} \sigma_o) < \lambda/p$ or $1 - \sigma_o < \lambda/2pNA$

Worst case Pitch: $1 - \sigma_o = \lambda/pNA$ or

$\sigma_o > 1 - \lambda/pNA$ and $p_w = \lambda/NA \ (1 - \sigma_o)$

$\sigma_o = \lambda/2pNA$

$p = \lambda/NA \ (1 + \sigma_o)$
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Partial Coherence (sigma or fill factor)


• Imaging: projection optics and illumination impact on resolution

\[ R_{\text{limit}} \propto \frac{\lambda}{\text{NA}\left(1 + \sigma + \frac{\sin(\Theta)}{\text{NA}}\right)} \]

where \( \left(\sigma + \frac{\sin(\Theta)}{\text{NA}}\right) < 1 \)

\[ \Theta = \text{angle of incident rays on the reticle. } \Theta > 0 = \text{Off axis illumination (OAI)} \]
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*Off Axis illumination*


- **ASML Illuminator for both partial coherence and off axis!**
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Off Axis illumination

OAI : annular good for all for features

Quadrapole biggest benefit for vertical and horizontal dense linewidths

Off-axis illumination (OAI)

220 nm

180 nm

150 nm

Annular

Quasar

Dipole
Basic Optics : Microlithography

*Off Axis illumination*: NILS

NILS : Normalized image log slope: slope of aerial image intensity (NILS) pattern multiplied by the feature width. This is a metric for the quality of the aerial image. Values between 6 – 8 are good! Can use in Prolith for quick Simulations

\[
NILS = w \frac{d \ln(I)}{dx}
\]  

(3)

The NILS is the best single metric to judge the lithographic usefulness of an aerial image.

Figure 2. Image Log-Slope (or the Normalized Image Log-Slope, NILS) is the best single metric of image quality for lithographic applications.
Basic Optics: Microlithography

Off Axis illumination

NILS

Illumination enhancement techniques

OAI and Normalized Image Log Slope

\[ k_1 = CD \times \frac{NA}{\lambda} \]

“normalized CD”

NA = 0.7  \( \lambda = 248 \) nm

simulation for L/S (1:1)

\( \sigma = 0.85 \) (conv.)

\( \sigma_0 = 0.85 \)

\( \sigma_i = 0.55 \) (ann, QUASAR)
Basic Optics: Microlithography

MTF and Contrast


- MTF curves for incoherent, partially coherent, and off axis illumination.

OAI: 2 diffracted beams out of phase for low frequencies reduces image modulation.

OAI: 2 diffracted beams in phase and larger diffraction angle captured for high frequencies increases image modulation.

Figure 2
Contrast curves for different illumination conditions and spatial frequencies (image size).
Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

• Forbidden Pitch
  • Understanding the Forbidden Pitch Phenomenon and Assist Feature Placement
  • Xuelong Shi¹, Stephen Hsu¹, Fung Chen¹, Michael Hsu¹, Robert J. Socha², Micea Dusa²

  1. ASML MaskTools, Inc. 4800 Great America Parkway, Suite 400, Santa Clara, CA 95054
  2. ASML, TDC Group 4800 Great America Parkway, Suite 400, Santa Clara, CA 95054

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  • Abstract

• Optical proximity effect is a well-known phenomenon in photolithography. Such an effect results from the structural interaction between the main feature and the neighboring features. Recent observations have shown that such structural interactions not only affect the critical dimension of the main feature at the image plane, but also the exposure latitude of the main feature. In this paper, it has been shown that the variation of the critical dimension as well as the exposure latitude of the main feature is a direct consequence of light field interference between the main feature and the neighboring features. Depending on the phase of the field produced by the neighboring features, the main feature exposure latitude can be improved by constructive light field interference, or degraded by destructive light field interference.

• The phase of the field produced by the neighboring features can be shown to be dependent on the pitch as well as the illumination angle. For a given illumination, the forbidden pitch lies in the location where the field produced by the neighboring features interferes with the field of the main feature destructively. The theoretical analysis given here offers the tool to map out the forbidden pitch locations for any feature size and illumination conditions. More importantly, it provides the theoretical ground for illumination design in order to suppress the forbidden pitch phenomenon, and for scattering bar placement to achieve optimal performance as well.
Basic Optics: Microlithography

**OAI Forbidden Pitch**

Off axis Incident angle

0 order beam

Diffraction angle

+1 order beam

Equal path lengths = optimal mask pitch increased res & DOF

Unequal path lengths = bad or forbidden pitch = reduced image contrast and resolution
Basic Optics: Microlithography

**OAI Forbidden Pitch**

Unequal path lengths = bad or forbidden pitch = reduced image contrast and resolution

Unequal path lengths result in poor image contrast
Basic Optics: Microlithography

OAI Forbidden Pitch

Unequal path lengths +1,0,-1 orders result in very poor image contrast and DOF

Unequal path lengths and +1,0,-1 orders entering lens = bad or forbidden pitch = reduced DOF and resolution
Basic Optics : Microlithography

Resolution  KLA-Tencor Chris Mack Answers

• Forbidden Pitch

Q I read a paper that talked about “forbidden pitches”. What is a forbidden pitch and why can’t I use them?

A The term “forbidden pitch” is frequently used when imaging with off-axis illumination, such as quadrupole or annular illumination. These illuminations bring light to the mask at an oblique angle. Diffraction of light from the patterns on the mask occurs at angles that depend on the pitch of the patterns. Off-axis illumination is optimized so that the angle of illumination striking the mask matches the angle of diffraction for a given pitch to give optimum performance (usually be spacing the diffraction orders evenly about the center of the stepper lens). This angle of illumination is only optimum at this one pitch. When the off-axis illumination is optimized for one pitch (usually the smallest pitch on the mask), there will always be some other pitch where the angle of the illumination works with the angle of diffraction to produce a very bad distribution of diffraction orders in the lens (one diffraction order in the middle of the lens and the others at the outer edges of the lens), resulting in poor depth of focus for that pitch. We call this pitch “forbidden” because of its poor lithographic response, and because we hope the chip designers will listen to us and avoid putting that pitch on the mask.
Basic Optics : Microlithography

*Off Axis illumination Forbidden Pitch or Worse Pitch*

Off-Axis Illumination: Optimum and Worse Pitch vs. Sigma (NA=0.248, NA=0.75)

For example:
for sigma=0.6,
optimum pitch=0.28 micron
worse pitch=0.83 micron

Optimum pitch \( p_o = \frac{\lambda}{2 \cdot \sigma_o \cdot NA} \)
Worse pitch: \( p_w = \frac{\lambda}{(1 - \sigma_o) \cdot NA} \)

Basic Optics : Microlithography

*Off Axis illumination* Forbidden Pitch

**Annular Illumination**

First pass approximation: \( \sigma_{op} = (\sigma_o + \sigma_i)/2 \)

Optimum sigma \( \sigma_{op} = \lambda / 2 \cdot p_o \cdot NA \)

Minimum sigma \( \sigma_{op} = 1 - \lambda / p_o \cdot NA \)

Worse pitch: \( p_w = \lambda / (1 - \sigma_o) \cdot NA \)

**Quadrupole Illumination**

First pass approximation: \( \sigma_{op} = \sigma_e / \sqrt{2} \)

Optimum sigma \( \sigma_{op} = \lambda / 2 \cdot p_o \cdot NA \)

Minimum sigma \( \sigma_{op} = 1 - \lambda / p_o \cdot NA \)

Worse pitch: \( p_w = \lambda / (1 - \sigma_o) \cdot NA \)

Like spatial filtering only vertical and horizontal diffracted orders get through

More accurate optimization requires simulation and experimental work

Basic Optics : Microlithography

Projection printing: Telecentric system

• Telecentricity: Source is focused in entrance pupil:
• Image side: Image size (magnification) is invariant with wafer defocus!
• Object side: Image size (magnification) is invariant with object position.
Basic Optics: Microlithography

Projection printing: Telecentric system

- The source in focused in the Entrance pupil. The chief ray from this properly focused condenser emerges from parallel to optical axis! This causes the Exit Pupil to be focused at infinity.

Figure 1. In a conventional imaging system, each scene point produces a light-cone. The orientation as well as the half-angle of the light-cone varies with the location of the scene point.

Figure 2. A telecentric system is obtained by placing a small aperture at the front focal plane. In this case, the axis of the light-cone is parallel to the optical axis for any scene point. The half-angle \( \theta \) of the cone, is a system constant determined by the \( f \)-number of the system, \( f_\theta = \frac{f}{a} \).
Basic Optics : Microlithography

Projection printing: Telecentric system

- The condenser lens is used to focus the source in the entrance pupil.
- **PROPER CONDENSER FOCUS:** Source focused in Entrance pupil: chief ray emerges from parallel to optical axis! This causes the Exit Pupil to be focused at infinity. Image location (i.e. defocused) does not change image size (magnification).
- **POSITIVE CONDENSER FOCUS:** Source focused before entrance pupil: chief ray emerges converging! Image location (i.e. defocused) causes change in image size (magnification). Image is smaller as the image plane moves away from the optical best focus.
- **NEGATIVE CONDENSER FOCUS:** Source focused behind entrance pupil: chief ray emerges diverging! Image location (i.e. defocused) causes change in image size (magnification). Image is larger as the image plane moves away from the optical best focus.
Basic Optics : Microlithography

Projection printing: Telecentric system

- **Single side telecentric (object):** This is how older ASML’s adjusted magnification

![Diagram of single side telecentric system](image)

- **Double side telecentric (typical modern exposure tool)**

![Diagram of double side telecentric system](image)
Basic Optics: Microlithography

Projection printing: Telecentric system

- Nikon stepper: telecentric lens
Basic Optics: Microlithography

Projection printing: Telecentric system

Scanner / stepper lenses are doubly telecentric -- telecentric in both mask illumination plane and at object wafer plane.

Doubly telecentric design ensures a constant magnification over the working distance -- very important for overlay.
Basic Optics : Microlithography

*Optical Designs*

- Basic microlithographic exposure tool Optical designs:
- Dioptric: All refractive optics (lens): most common
- Catoptric: All Reflective optics (Mirrors): Micralign
- Catadioptric: Combination of refractive and reflective optics: SVGL scanner, Ultratech 1 X
Basic Optics: Microlithography

Optical Designs: Dioptric

Feature Size = \( k_1 \frac{\lambda}{\text{NA}} \)

\[ \text{NA} = \sin \theta \approx \frac{1}{2f\#} \]

Available excimer laser wavelengths:
- 248 nm
- 193 nm
- 157 nm
Basic Optics : Microlithography

*Optical Designs: Catoptric*

- **Offner design:** Old Perkin Elmer 1X scanner
Basic Optics : Microlithography

*Optical Designs: Catadioptric*

- SVGL: design beamsplitter (ArF)
Basic Optics: Microlithography

Optical Designs: Catadioptric

• Ultratech: Wynne-Dyson Design (1959)