Optics: Basics of Diffraction

• Ray tracing (assuming light travels in straight lines) works well as long as the dimensions are large compared to $\lambda$.
• At smaller dimensions, diffraction effects dominate.

Airy’s disc

Optics: Basics of Diffraction

• If we want to image the aperture on an image plane (resist), we can collect the light using a lens and focus it on the image plane.
• But the finite diameter of the lens means some information is lost (higher frequency components).

Single Slit Diffraction

• According to Huygen’s principle, each portion of the slit acts as a source of waves.
• The light from one portion of the slit can interfere with light from another portion.
• The resultant intensity on the screen depends on the direction $\theta$.
• All the waves that originate at the slit are in phase.
• Wave 1 travels farther than wave 3 by an amount equal to the path difference $(a/2)\sin\theta$.
• If this path difference is exactly half of a wavelength, the two waves cancel each other and destructive interference results.
• In general, destructive interference occurs for a single slit of width $a$ when $\sin\theta = m\lambda/a$,
  $m = \pm 1, \pm 2, \pm 3, \ldots$
Diffraction

- Long and narrow aperture
- Rectangular aperture

Source: http://hyperphysics.phy-astr.gsu.edu/

Contact and Proximity Systems (Fresnel Diffraction)

- Contact printing systems operate in the near field or Fresnel diffraction regime.
- There is always some gap g between the mask and resist.
- The aerial image can be constructed by imagining point sources within the aperture, each radiating spherical waves (Huygens wavelets).
- Interference effects and diffraction result in “ringing” and spreading outside the aperture.

Diffraction

- Diffraction is usually described in terms of two limiting cases:
  - Fresnel diffraction - near field.
  - Fraunhofer diffraction - far field.

Resolution

- Rayleigh criterion:
  - Minimum angular ray separation to resolve two spots from one is: \( \sin \theta_{\text{min}} = \frac{1.22 \lambda}{D} \).
  - Since \( \theta_{\text{min}} \) is small, \( \theta_{\text{min}} = 1.22 \lambda / D \), \( \rightarrow 2b/f=1.22 \lambda / D \).
  - \( b=0.61 \lambda (2f)/D \), \( \rightarrow 2b=0.61 \lambda / NA \).
  - \( D \) is the diameter of a circular aperture.
  - 1.22 is the first zero of the Bessel function \( J_m(x) \).
  - An Airy function results from Fraunhofer diffraction from a circular aperture.
- Straight line pattern:
  - Minimum angular ray separation to resolve two lines from one is: \( \sin \theta_{\text{min}} = \lambda / D \), or approximately \( \theta_{\text{min}} \approx \lambda / D \).
Contact and Proximity Litho Resolution

\[ 2b = 3\sqrt{s(0.5s + z)} \]

- Contact Printing:
  - At \( l = 400 \text{ nm} \), \( z = 1 \mu \text{m} \), obtain \( b = 0.7 \mu \text{m} \)
- Proximity Printing:
  - At \( l = 400 \text{ nm} \), \( s = 10 \mu \text{m} \), \( z = 1 \mu \text{m} \), obtain \( b = 3.0 \mu \text{m} \) linewidth.

\[ \lambda = \text{exposure wavelength} \]

\( z = \) resist thickness

\( 2b = \) minimum pitch of line-space pattern

\( s = \) spacing between the mask and the resist

\[ S = 0 \text{ for contact litho} \]

Diffraction Effect in Proximity Printing

Projection Printing

- Advantages:
  - Mask does not contact wafer
  - No mask wear or contamination
  - Decapsulation: 1X to 10X
  - Simpler to make optical lens mask at shorter demagnification
  - Smaller temperature difference (mask and wafer)

- Disadvantages:
  - Longer time to expose entire wafer
  - Mask requires to be exposed separately due to high demagnification
  - Uses complex and expensive, requires precision stepper motor

Optics: Basics of Projection Systems

- Consider the basic optical projection system below.

Note that the aperture (or lens) diameter determines the value of \( a \)

Numerical Aperture

- The numerical aperture of the lens is by definition,

\[ \text{NA} = n \sin \alpha \]  

(3)

- NA represents the ability of the lens to collect diffracted light.

\[ R = \frac{0.61 \lambda}{\text{NA}} - k_3 \frac{\lambda}{\text{NA}} \]  

(4)

- \( k_3 \) is an experimental parameter which depends on the lithography system and resist properties and is \( \approx 0.6 - 0.8 \).

- Obviously resolution can be increased by
  - Decreasing \( \lambda \)
  - Increasing NA (bigger lenses)
Lens 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(α), where α is the half-angle of the largest cone of light entering the lens.

\[ \frac{f}{D} = \frac{f}{D - \frac{D}{2}} \]

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

Calculation Example

- A reduction camera uses a projection lens with f/6.8 and f = 9.5 in. = 241.3 mm. Lens diameter is D = 241.3 mm/6.8 = 35.5 mm = 1.40 in. The numerical aperture is NA = 1/2*6.8 = 0.074. For exposure in the middle green, λ = 550 nm.
- Thus, the minimum feature size is b = 550 nm/2*0.074 = 3.72 mm for a line, or 1.220 * 3.72 mm = 4.56 mm for a spot.
- The tightest grating pitch that could be printed using this lens is therefore 2b = 7.44 mm.

Inmersion Lithography

- A liquid with index of refraction n>1 is introduced between the imaging optics and the wafer.
- Advantages:
  1) Resolution is improved proportionally to n. For water, the index of refraction at λ = 193 nm is 1.44, improving the resolution significantly, from 90 to 64 nm.
  2) Increased depth of focus at larger features, even those that are printable with dry lithography.

Depth of Focus (DOF)

- The Rayleigh criterion for depth of focus is simply that these two lengths not differ by more than 1/4 λ.
- Assuming φ is small, \( \lambda = 4\theta(1 - \cos(\theta)) \).
- The path length difference for a ray from the edge of the entrance aperture is simply \( \delta \cos \theta \).
- DOF = \( \delta = \frac{\lambda}{2(NA)^2} \).

NA and Depth of Focus

- However, higher NA lenses also decrease the depth of focus.
  \[ DOF = \frac{\lambda}{2(NA)^2} \pm B \]
- B is usually experimentally determined.
- Thus a 248nm KrF exposure system with a NA = 0.6 would have a resolution of \( \lambda/2 \times (B_1 = 0.75) \) and a DOF of \( \lambda/2 \times (B_1 = 0.75) \).

Depth of focus

Source: https://depthoffocus.com
Example of Depth of Field problem

Modulation Transfer Function (MTF)
A measurement of the imaging system's ability to transfer contrast from the specimen to the intermediate image plane at a specific resolution.

Modulation Transfer Function

Summary of Printing Systems

Making Masks
- CAD system used to describe the circuit patterns electrically.
- Digital data produced by CAD system drives a pattern generator that transfers the patterns directly to electron-sensitized mask.
- Mask consists of a fused silica substrate covered with chromium.
- Circuit pattern is first transferred to the electron-sensitized layer (electron resist), which is transferred into the underlying chromium layer for the finished mask.

Mask Generation
Photo Mask

• Composite layout is broken into mask levels that correspond to the manufacturing process sequence.

• 15 – 20 different mask levels are typically required for a complete IC process.

Effect of Fourier Components on Aerial Image of a Rectangular Waveform

Alignement

• 3 degrees of freedom between mask and wafer: (x, y, θ)
• Use alignment marks on mask and wafer to register patterns prior to exposure.
• Modern process lines (steppers) use automatic pattern recognition and alignment systems.
• Usually takes 1/5 seconds to align and expose on a modern stepper.
• Human operators usually take 30-40 seconds with well-designed alignment marks.

Alignment mark on mask, open window in chrome through which mark on wafer can be seen

Mask Engineering

OPC

• Optical Proximity Correction (OPC) can be used to compensate somewhat for diffraction effects.

• Sharp features are lost because higher frequencies are lost due to diffraction. These effects are calculable and can be compensated for.
Optical Proximity Correction (OPC)

Conventional mask

Rule-based OPC

Model-based OPC

Model-based OPC enables 100nm

Wafer

Rule-based OPC improves 130nm

Conventional mask

180nm

Mask

Mask Engineering: OPC

Desired

With OPC

Printed

Phase Shifting Masks

Pattern transfer of two closely spaced lines

(a) Conventional mask technology - lines not resolved

(b) Lines can be resolved with phase-shift technology

Phase Shifting Mask Basics

Quartz Etched to Induce Shift in Phase

In Phase

Bright (+)

Dark (0)

Out Of Phase

Bright (-)

Light Waves

In Phase

Bright (+)

Dark (0)

180º Out of Phase

Bright (-)

Light Waves

Out of Phase

Binary Technology Limits

Source: Photronics.com

Top View of Mask

Cross Section

Bright (+)

Dark (0)

Wafer

Source: Photronics.com

Source: Photronics.com
**Alternating Aperture PSM**

![Diagram of Alternating Aperture PSM](source: Photronics.com)

**Illumination System Engineering**

*Off-axis illumination* also allows some of the higher order diffracted light to be captured and hence can improve resolution.

**Resolution Enhancement**

- Shorter Wavelength (HgII, EUV, ArF, etc)
- Off-axis illumination (OAI)
- Central illumination
- Low order circular illumination
- Polarization control

- Weakly aberrated/shifted rays
- Optical path length correction
- Specular reflectance
- Aberration control/contrast

- Water: Siemens star
- Round mask schemes
- Non-linear schemes
- Substrate reflectivity control techniques
- Hard mask schemes

**Off Axis Illumination**

*Improving DOF*

**Modeling**

- Lenses: spherical aberration, coma, astigmatism
- Focusing: spherical aberration, coma, astigmatism
- Phase function factor
- Light intensity distribution

- Mask
- Substrate
- Wafer
Simulation of Exposure

- ATHENA simulator (Silvaco). Colors correspond to optical intensity in the aerial image.

Exposure system: NA = 0.43, partially coherent g-line illumination (λ = 436 nm). No aberrations or defocusing. Minimum feature size is 1 µm.

• Same example except that the feature size has been reduced to 0.5 µm. Note the poorer image.

• Same example except that the illumination wavelength has now been changed to i-line illumination (λ = 365 nm) and the NA has been increased to 0.5. Note the improved image.

Simulation of Photoresist Baking

- A post-exposure bake is sometimes used prior to developing the resist pattern.
- This allows limited diffusion of the exposed PAC and smoothes out standing wave patterns.
- Generally this is modeled as a simple diffusion process (see text).

• Simulation on right after a post-exposure bake of 45 minutes at 115 °C. The color contours again correspond to the [PAC] after exposure. Note that the standing wave effects apparent earlier have been "smeared out" by this bake, producing a more uniform [PAC] distribution.

Simulation of Resist Development

- Example of calculation of light intensity distribution in a photoresist layer during exposure using the ATHENA simulator. A simple structure is defined with a photoresist layer covering a silicon substrate which has two flat regions and a sloped sidewall. The simulation shows the [PAC] calculated core exposure after an exposure of 200 mJ cm⁻². Lower [PAC] values correspond to more exposure. The color contours thus correspond to the integrated light intensity from the exposure.

- Example of calculation of light intensity distribution in a photoresist layer during exposure using the ATHENA simulator. The resist was exposed with a dose of 200 mJ cm⁻², a post-exposure bake of 45 min at 115 °C was used and the pattern was developed for a time of 60 seconds, all normal parameters. The Dill development model was used. Center - part way through development. Right - complete development.

- Example of the calculation of a developed photoresist layer using the ATHENA simulator. The resist was exposed with a dose of 200 mJ cm⁻², a post-exposure bake of 45 min at 115 °C and the pattern was developed for a time of 60 seconds, all normal parameters. The Dill development model was used. Center - part way through development. Right - complete development.

Simulation of Exposure

• Neglecting standing wave effects (for the moment), the light intensity in the resist falls off as

\[ \frac{di}{dz} = -\alpha I \]  

(The probability of absorption is proportional to the light intensity and the absorption coefficient.)

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