EE-527: MicroFabrication

Exposure and Imaging
Exposure Sources

• Photons
  – white light
  – Hg arc lamp (all lines)
  – filtered Hg arc lamp (g-line 435 nm, h-line 405 nm, i-line 365nm)
  – excimer laser (KrF 248 nm, ArF 193 nm, F₂ 157 nm)
  – x-rays from synchrotron

• Electrons
  – focused electron beam (e-beam) direct write

• Ions
  – focused ion beam (i-beam) direct write
A Hg arc has a fairly complex spectrum.
Outside of a laser, a DC short arc lamp is one of the brightest available optical sources. The short arc creates nearly a point source which can be easily focused or collimated.

- **Xe-Arc Lamp**
  - $P_{\text{cold}} = 8-10 \text{ atm}$
  - $P_{\text{hot}} = 30-40 \text{ atm}$
  - $T_{\text{color}} = 6000-6500 \text{K}$ (close to that of the Sun)
  - (Xe-Arc Only)
  - Longer Lifespan
  - Sharper UV Lines
  - More Spectrally Pure
  - For Lithography

- **Hg-Arc Lamp**
  - $P_{\text{cold}} = 1.5-2.0 \text{ atm}$
  - $P_{\text{hot}} = 70-80 \text{ atm}$
  - $T_{\text{startup}} = 10-20 \text{ mins.}$
  - Sharper UV Lines
  - More Spectrally Pure
  - For Lithography

**Wrong Electrical Polarity Will Melt the Cathode!**

**Wrong Vertical Orientation Will Not Properly Vaporize The Mercury!**
DC Short Arc Lamp Source and Housing

- DC short arc Hg lamp
- Parabolic reflector
- Igniter
- Transformer
- Cooling fan
- Dichroic mirror
- Shutter
- Lenslet integrator
- Turning mirror
- Photofeedback integrator
- Collimating lens
- Mounting base
High Pressure Hg Arc Lamp Characteristics

Temperatures inside the quartz envelope can reach ~700°C.

Image from Zeiss

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Exposure Options: The Hg Arc Spectral Lines

- 578.2 nm: (yellow-orange)  
  Useful for visible illumination, but too long in wavelength for lithography.
- 546.1 nm: (green)  
- 435.8 nm: g-line (blue)  
- 404.7 nm: h-line (violet)  
- 365.4 nm: i-line (UVA)  
- 334-335 nm: (UVA)  
- 312-313 nm: (UVB)  
- 297-302 nm: (UVB)  
- 253.7 nm: (UVC)  
- 184.45 nm: (UVC)  

Sharp emission lines which are best suited for photolithography exposure and matched well to the absorption characteristics of most photoresists.

Emission lines are blurred together and difficult to separate. Imaging optics would have to employ significant color correction. Not that much intensity, either.

Shorter wavelengths produce ozone and are useful for sterilization, but have insufficient intensity for use in photolithography.
Refractive Power of a Surface

- The refractive power $P$ is measured in diopters when the radius is expressed in meters.
- $n_1$ and $n_2$ are the refractive indices of the two media.

$$P = \frac{n_2 - n_1}{R}$$
Thin Lenses

\[ d_1 = \text{object distance} \]
\[ d_2 = \text{image distance} \]
\[ f_1, f_2 = \text{focal lengths} \]
\[ e_1, e_2 = \text{extrafocal distances} \]
\[ h_1, h_2 = \text{object/image heights} \]
Thick Lenses

Cardinal Points of a Lens:
- Focal Points: $F_1, F_2$
- Nodal Points: $N_1, N_2$
- Principal Points: $H_1, H_2$

Object Image

$d_1$ = object distance
$d_2$ = image distance
$f_1, f_2$ = focal lengths
$e_1, e_2$ = extrafocal distances
$h_1, h_2$ = object/image heights
Lens-Maker’s Formula

\[
\frac{n_1}{d_1} + \frac{n_2}{d_2} = \frac{n-n_1}{R_1} + \frac{n-n_2}{R_2}
\]

If \( n_1 = n_2 = 1 \), then

\[
\frac{1}{d_1} + \frac{1}{d_2} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = P = \frac{1}{f}
\]

This can also be expressed as: \((d_1 - f)(d_2 - f) = f^2\)

or: \(e_1e_2 = f^2\)
Lens Apertures

- 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.

\[
f/# = \frac{f}{D}
\]

\[
NA = n \sin \alpha
\]

\[
NA \approx \frac{D}{2f} = \frac{1}{2 \cdot f/#}
\]
Resolving Power of a Lens

• Rayleigh criterion (circular aperture):
  – Minimum angular ray separation to resolve two spots from one is:
    \[ \sin \theta_{\text{min}} = 1.220 \frac{\lambda}{D}. \]
  – Since \( \theta_{\text{min}} \) is small, \( \theta_{\text{min}} \approx 1.220 \frac{\lambda}{D}. \)
  – \( D \) is the diameter of a circular aperture.
  – 1.220 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:
    \[ \sin \theta_{\text{min}} = \frac{\lambda}{D}, \text{ or approximately } \theta_{\text{min}} \approx \frac{\lambda}{D}. \]
  – Here, \( D \) is the width of the printed line.
  – A sinc function results from Fraunhofer diffraction from a straight slot aperture.
Projection Lithography Requirements

- b = minimum feature size (spot or line)
- 2b = minimum period of line-space pattern
- λ = exposure wavelength
- Using b = f θ_{min}, obtain that b \approx \lambda f/D = \lambda/2NA.
- The depth of focus can be shown to be d_f = \pm \lambda/(2(NA)^2)
- A “voxel” is a volume pixel.
- For the highest resolution lithography, desire the tallest aspect ratio voxel.
- Thus, wish to maximize the ratio d_f/b = 1/NA.
- So: it all depends upon the NA of the lens!

Want the tallest aspect ratio of the exposed voxel.
Sample Calculation

– A primary reduction camera uses a projection lens with f/6.8 and f = 9.5 in. = 241.3 mm.
– The 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, \( \lambda = 550 \text{ nm} \).
– Thus, the minimum feature size is \( b = 550 \text{ nm}/2*0.074 = 3.72 \mu\text{m} \) for a line, or \( 1.220 * 3.72 \mu\text{m} = 4.56 \mu\text{m} \) for a spot.
– The tightest grating pitch that could be printed using this lens is therefore \( 2b = 7.44 \mu\text{m} \).
The Laws of Optical Lithography

- $CD_{\text{min}}$ = minimum critical dimension: The smallest feature that needs to be imaged.
- DOF = depth of field: At least the thickness of the photoresist.
- $N_{\text{pixel}}$ = pixel count: The maximum number of image pixels as set by the minimum critical dimension.
- $k_1$ = resolution prefactor. Usually about 0.3 – 0.6.
- $k_2$ = depth of field prefactor. Usually about 1.0 – 1.2.
- $k_1$ can be reduced and $k_2$ can be increased by various optical projection enhancement techniques.

$$CD_{\text{min}} = \frac{k_1 \lambda}{NA} \quad DOF = \frac{k_2 \lambda}{(NA)^2} \quad N_{\text{pixel}} = \frac{A_{\text{image}}}{CD_{\text{min}}^2}$$
Lithography Resolution Enhancements

- Various optical engineering techniques have been employed to reduce the resolution prefactor $k_1$.
- Brunner provides a nice summary of the trend, repeated here:

[Diagram showing a graph with various nodes and wavelengths]

Figure from J. H. Brunner, SPIE vol. 6520, 2007.
Contact and Proximity Lithography Resolution

- $\lambda$ = exposure wavelength
- $d$ = resist thickness
- $2b$ = minimum pitch of line-space pattern
- $s$ = spacing between the mask and the resist

- **Contact Printing:**

  \[
  2b = 3\sqrt{0.5\lambda d}
  \]

  \* At $\lambda = 400$ nm, $d = 1$ $\mu$m, obtain $b = 0.7$ $\mu$m linewidth.

- **Proximity Printing:**

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

  \* At $\lambda = 400$ nm, $s = 10$ $\mu$m, $d = 1$ $\mu$m, obtain $b = 3.0$ $\mu$m linewidth.
Standing Waves - 1

- Short exposure wavelengths can create standing waves in a layer of photoresist. Regions of constructive interference create increased exposure.
- These can impair the structure of the resist, but can be eliminated by:
  - use of multiple wavelength sources
  - postbaking
- Effects are most noticeable at the edge of the resist.
Standing Waves - 2

- Standing waves are enhanced by reflective wafer surfaces.
- If the wafer or substrate is transparent, reflections from the aligner chuck can create standing wave patterns, also.
  - This can be eliminated by using:
    - a flat black chuck (anodized aluminum)
    - an optical absorber under the wafer (lint free black paper)
    - a transparent glass chuck (used on Karl Suss MJB3)
- Exposures can be greatly miscalculated by the presence of standing waves and reflective wafers or chucks.
Mask Pellicles

• Pellicles are thin, transparent polymer sheets spaced above either or both sides of a mask plate to protect the image plane from contamination.

• Contaminant particles can land on the pellicle, but they will not be on the focal plane and therefore will not image onto the substrate.
Photographic Exposure Equation

\[ T = \frac{f^2}{SB} \]

- \( T \) = exposure time in seconds
- \( f \) = f-number of projection lens
- \( S \) = ASA or ISO film speed
- \( B \) = scene brightness in candles/\( \text{ft}^2 \)

American Standards Association (ASA) film speed is the dose required to produce an optical density of 0.1 in a film media.

German DIN film speed is:

\[ \text{DIN} = 10 \log_{10}(\text{ASA}) + 1 \]

100 ASA = 21 DIN
Optical Absorbance and Density

\[ T = \frac{I_2}{I_1} \]  
transmittance

\[ A = \frac{1}{T} = \frac{I_1}{I_2} \]  
absorbance

\[ OD = \log_{10}(A) \]  
optical density

Typical optical densities:
- xerox transparency:  OD = 1
- photographic emulsion plate:  OD = 2-3
- chrome photomask:  OD = 5-6
Exposure Latitude

Dimensional Latitude:
(typically want less than 0.05)

$$\delta = \left| \frac{L' - L}{L'} \right|$$

![Graph showing the relationship between exposure and line width, with negative PR and positive PR regions.](image-url)
Optimum exposure depends upon the pattern!!!

Adjacent clear (bright) regions add additional exposure to a given region because of overlap from Gaussian tail of the linespread function.
Spread Functions

Line Spread Function $L(x)$

$J(x) = \frac{dJ(x)}{dx}$

Edge Spread Function $J(x)$

$J(x) = \int_{-\infty}^{x} L(x') \, dx'$
Optical Modulation

\[ I = \text{optical intensity, W/cm}^2 \]
\[ M = \text{optical modulation within a scene or image} \]
\[ MT = \text{modulation transfer factor for an optical element} \]

\[ M = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad \text{if} \quad M \rightarrow 1 \text{ when } I_{\text{min}} \rightarrow 0. \]

\[ MT = \frac{M_{\text{out}}}{M_{\text{in}}} \]
Modulation Transfer Function

The modulation transfer function (MTF) is the modulus of the Fourier transform of the linespread function:

\[ MTF(f) = \left| \int_{-\infty}^{\infty} L(x) e^{-2\pi ifx} \, dx \right| \]

\( f \) is the spatial frequency

Optics obeys linear system theory:

\[ \text{MTF(system)} = \text{MTF(element}_1) \times \text{MTF(element}_2) \times \text{MTF(element}_3) \times \ldots \]
Modulation Transfer Function in Photolithography

\[ \text{MTF(system)} = \text{MTF(mask)} \times \text{MTF(optics)} \times \text{MTF(resist)} \]
Proximity (Diffraction) Effects on Feature Corners

Exterior corners are cut back; interior corners are filled in. If the prebake/exposure/development is adjusted for optimal lines, the corners will inevitably be incorrect.
Corner Compensation of Features

Corner compensation can reduce the proximity effect on corners. However, it requires experimentation to determine the correct size of corner compensation to best achieve this.
Proximity Exposure Effect - 2
Phase Shifting Masks

[Diagram showing a photomask with a phase shifting layer marked as $\lambda/2$ phase shifting layer and a chrome layer.]

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Projection Optics

• It is exceedingly difficult to make large NA refractive optics due to aberration limits.
  – The best lenses used in projection lithography have NA = 0.3 - 0.4
  – A lens with NA = 0.50 is a f/1.00 lens: its focal length and effective diameter are the same!
  – The largest NA single-element lenses ever made were a NA = 0.54 and a NA = 0.60 by Nikon.

• Reflective optics are better suited for large NA applications.
  – But they are physically larger, and usually require close temperature stability to keep their proper contours and alignment.

• Combinations (catadioptric) systems are also used.
  – This is very common in DSW (stepper) lithography equipment.
Lens Aberrations

• Chromatic aberration
  – Dispersion: change of refractive index with wavelength

• Monochromatic aberrations
  – transverse focal shift
  – longitudinal focal shift
  – spherical aberration
  – coma
  – astigmatism
  – field curvature
  – distortion
Projection Exposure Systems: PE Micralign 100

Perkin-Elmer Micralign 100 patented in 1970 introduced in 1973
NA < 0.167
high pressure Hg arc lamp

concentric spherical mirrors “Offner relay” creates a perfectly flat image plane (zero Petzval sum)

mask and wafer are held in a fixed relative position on the carriage while the optics scans around an axis between mask and wafer.
Advanced Exposure Techniques

• Liquid Immersion Lenses
• Off-Axis Sources
• Scanning Exposure Systems
• Excimer Laser Sources:
  – KrF: 248 nm
  – ArF: 193 nm
  – F$_2$: 157 nm, but currently there are problems with CaF$_2$ glass optics which limit its further development.
Reduction Steppers

• By making the mask plate larger, the defect tolerance can be greatly improved.
• Projection and reduction optics are now required.
• Originally, most systems were 10:1 reduction.
• The first commercially successful one was the GCA 4800 DSW system.
• Now, most DSW systems are 4:1 reduction.
  – Less reduction allows for larger step areas and larger chips.
Evolution of Stepper Projection Lenses – GCA/Tropel

Figure from J. H. Brunner, SPIE vol. 6520, 2007.
Evolution of Stepper Projection Lenses – Nikon

Figure from J. H. Brunner, SPIE vol. 6520, 2007.
Water Immersion Projection Lenses – Carl Zeiss

- Water immersion lenses can increase the NA well above 1.0.
- The designs are usually catadioptric and very challenging.
- These are used with 193 nm ArF excimer exposure sources.

Figure and table from J. H. Brunner, SPIE vol. 6520, 2007.
A Modern Wafer Stepper

Image from ASML
A Modern Wafer Stepper

Image from ASML

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