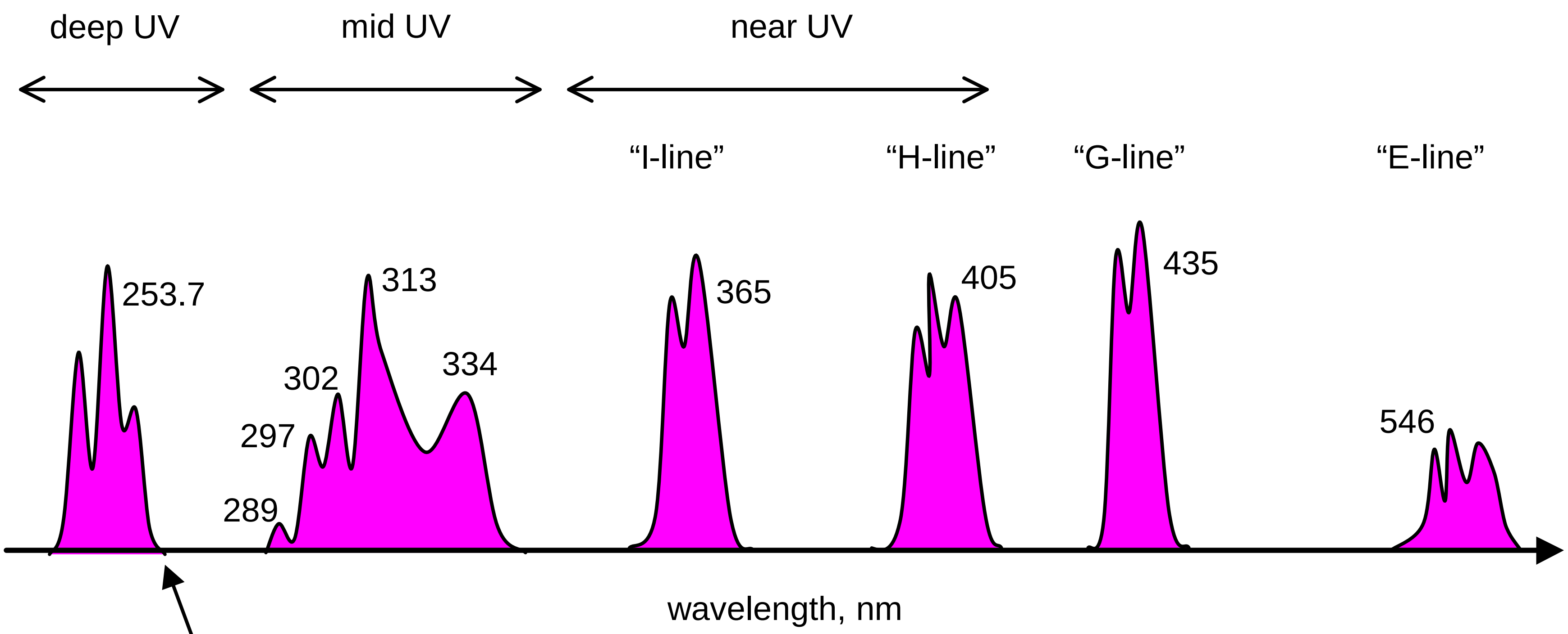
EE-527: MicroFabrication

Exposure and Imaging

Exposure Sources

- Photons
  - white light
  - Hg arc lamp
  - filtered Hg arc lamp
  - excimer laser
  - x-rays from synchrotron
- Electrons
  - focused electron beam direct write
- Ions
  - focused ion beam direct write

High Pressure Hg Arc Lamp Spectrum



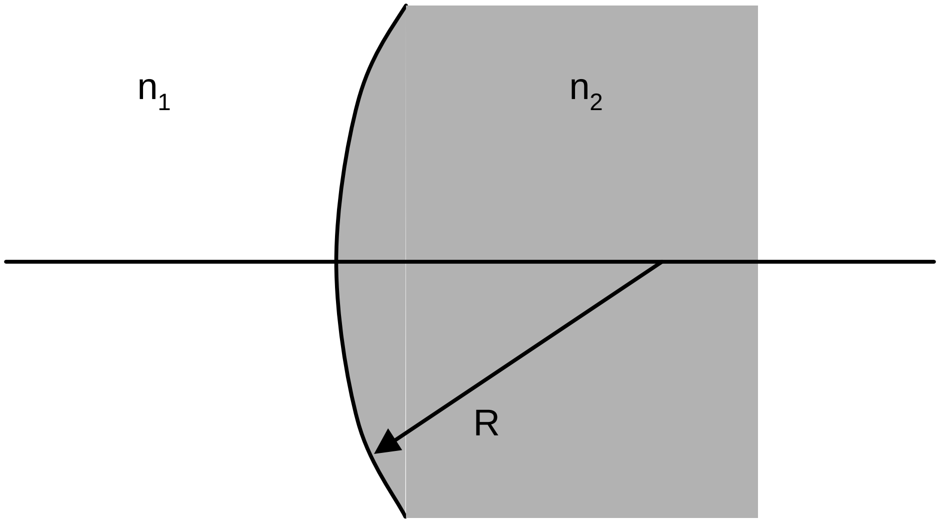
spectral reference;
also used for sterilization

The I-line at 365 nm is the strongest.

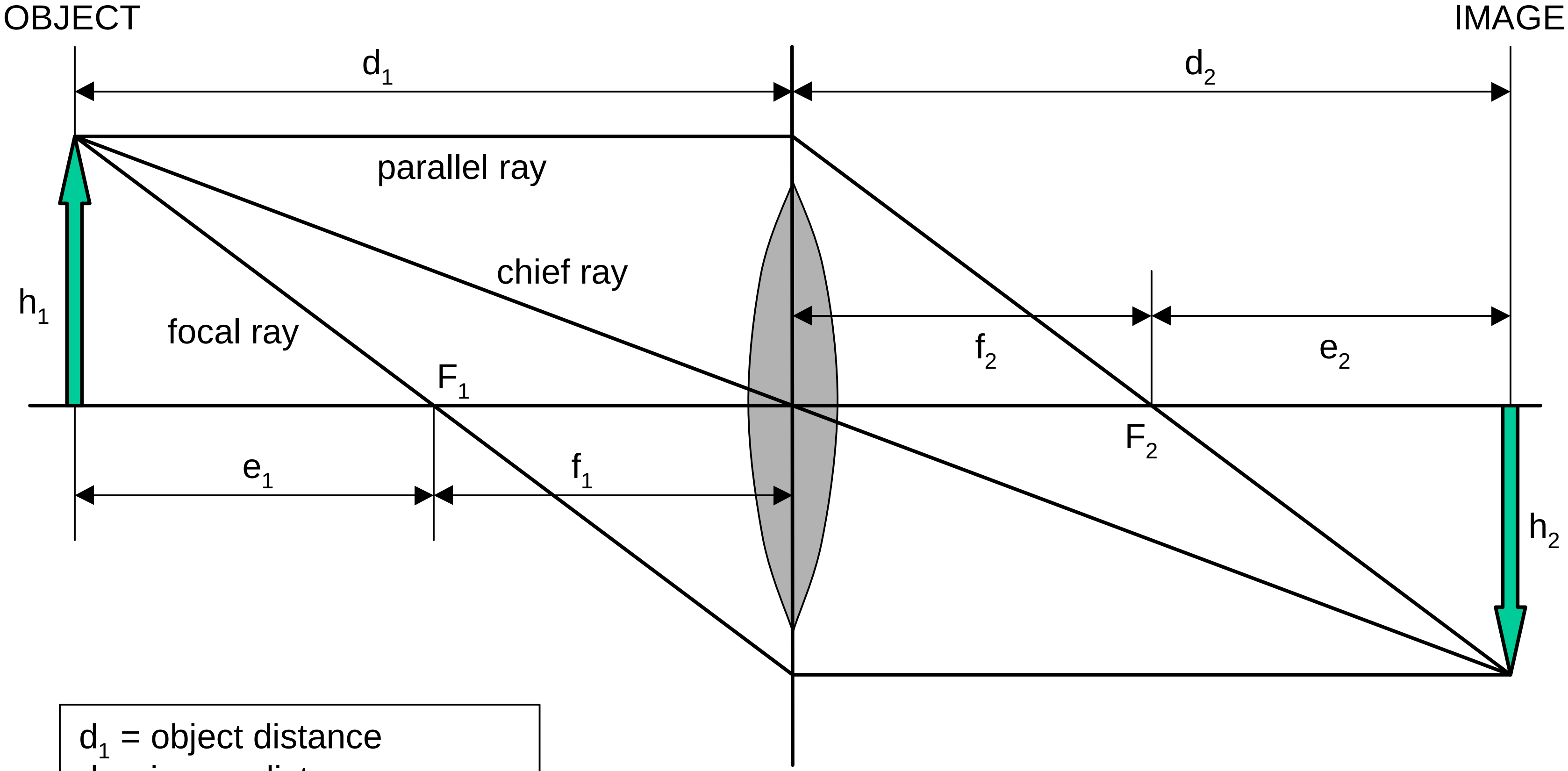
Refractive Power of a Surface

- 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.

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

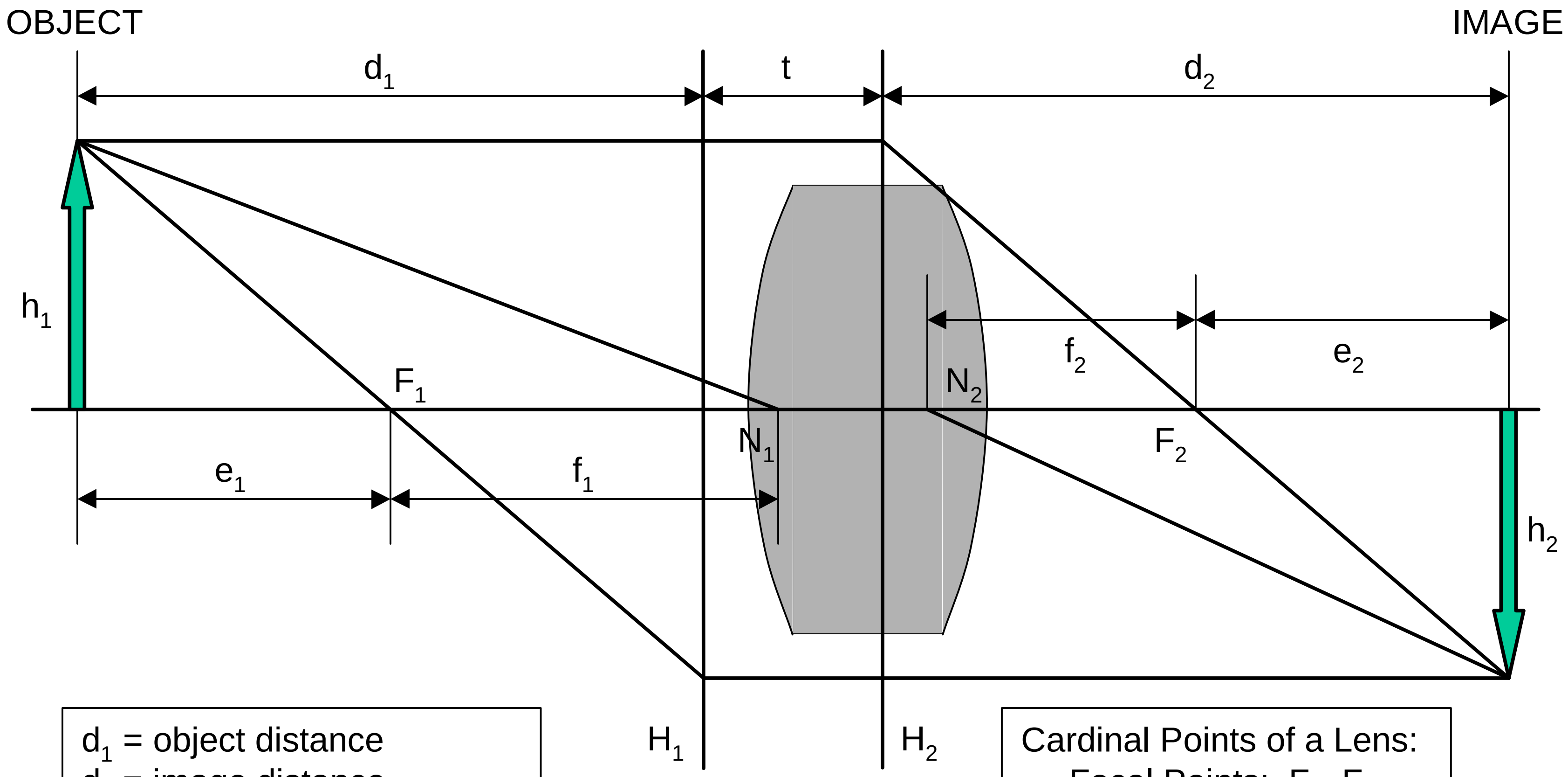


Thin Lenses



d_1 = 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

Thick Lenses



d_1 = object distance
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Cardinal Points of a Lens:
Focal Points: F_1, F_2
Nodal Points: N_1, N_2
Principal Points: H_1, H_2

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

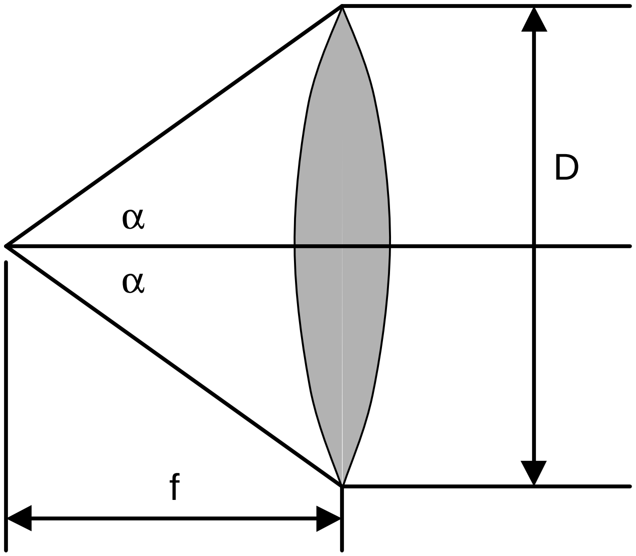
$$\frac{1}{d_1}+\frac{1}{d_2}=(n-1)\left(\frac{1}{R_1}+\frac{1}{R_2}\right)=P=\frac{1}{f}$$

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 α, where α is the half-angle of the largest cone of light entering the lens.



$$f\ /\# = \frac{f}{D}$$

$$NA = n \sin \boldsymbol{a}$$

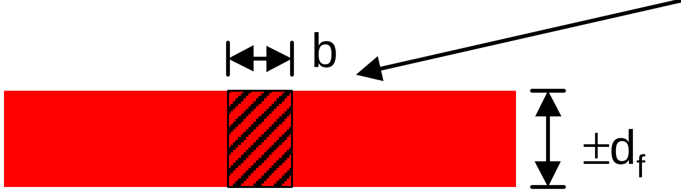
$$NA = \frac{\frac{1}{2} D}{\sqrt{\frac{1}{4} D^2 + f^2}} \approx \frac{D}{2f} = \frac{1}{2 \cdot f\ /\#}$$

Resolving Power of a Lens

- Rayleigh criterion:
  - Minimum angular ray separation to resolve two spots from one is: $\sin\theta_{min} = 1.220\ \lambda/D$.
  - Since θ_{min} is small, $\theta_{min} \approx 1.220\ \lambda/D$.
  - 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: $\sin\theta_{min} = \lambda/D$, or approximately $\theta_{min} \approx \lambda/D$.

Projection Lithography Requirements

- b = minimum feature size (spot or line)
- 2b = minimum period of line-space pattern
- λ = exposure wavelength
- Using $b = f\,\theta_{min}$, obtain that $b \approx \lambda/2NA$.
- The depth of focus can be shown to be $d_f = \pm\,\lambda/2(NA)^2$
- A “voxel” is a volume pixel.
- For highest resolution lithograpy, 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

- Primary reduction camera in WTC-MFL 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 μm for a line, or 1.220 * 3.72 μm = 4.56 μm for a spot.
- The tightest grating pitch that could be printed using this lens is therefore 2b = 7.44 μm.

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 Optics

- It is exceeding 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 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.

Contact and Proximity Lithography Resolution

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

– Contact Printing:

$$2b = 3\sqrt{0.5\; l d}$$

  - At λ = 400 nm, d = 1 μm, obtain b = 0.7 μm linewidth.

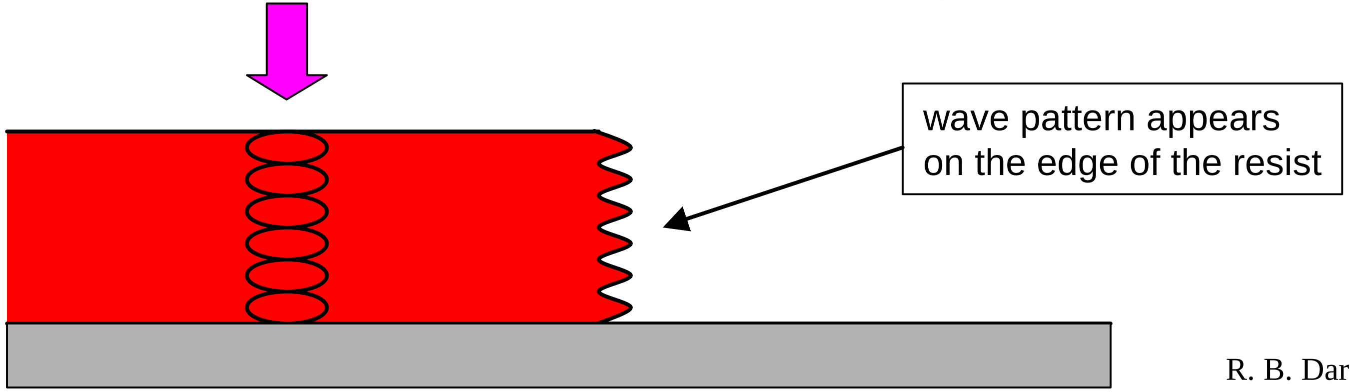
– Proximity Printing:

$$2b = 3\sqrt{\; l(s + 0.5d)}$$

  - At λ = 400 nm, s = 10 μm, d = 1 μm, obtain b = 3.0 μm 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.



wave pattern appears on 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.

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/ft^2

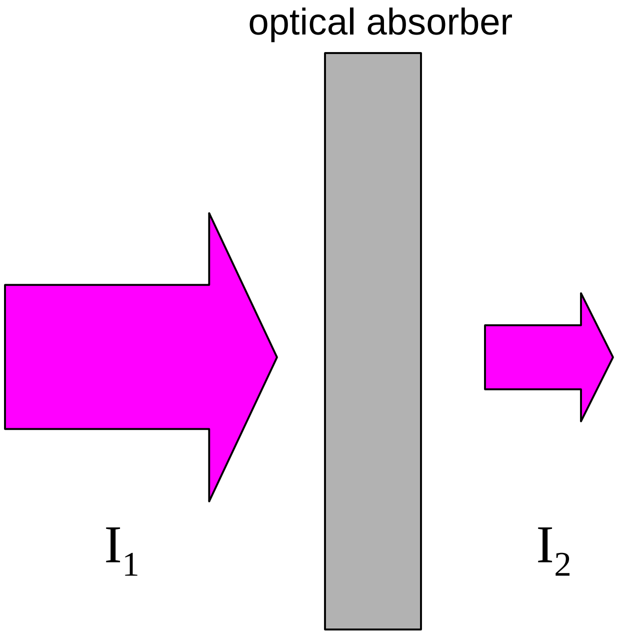
American Standards Association (ASA) film speed is the dose required to produce an optical density of 0.1 in a film media.

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

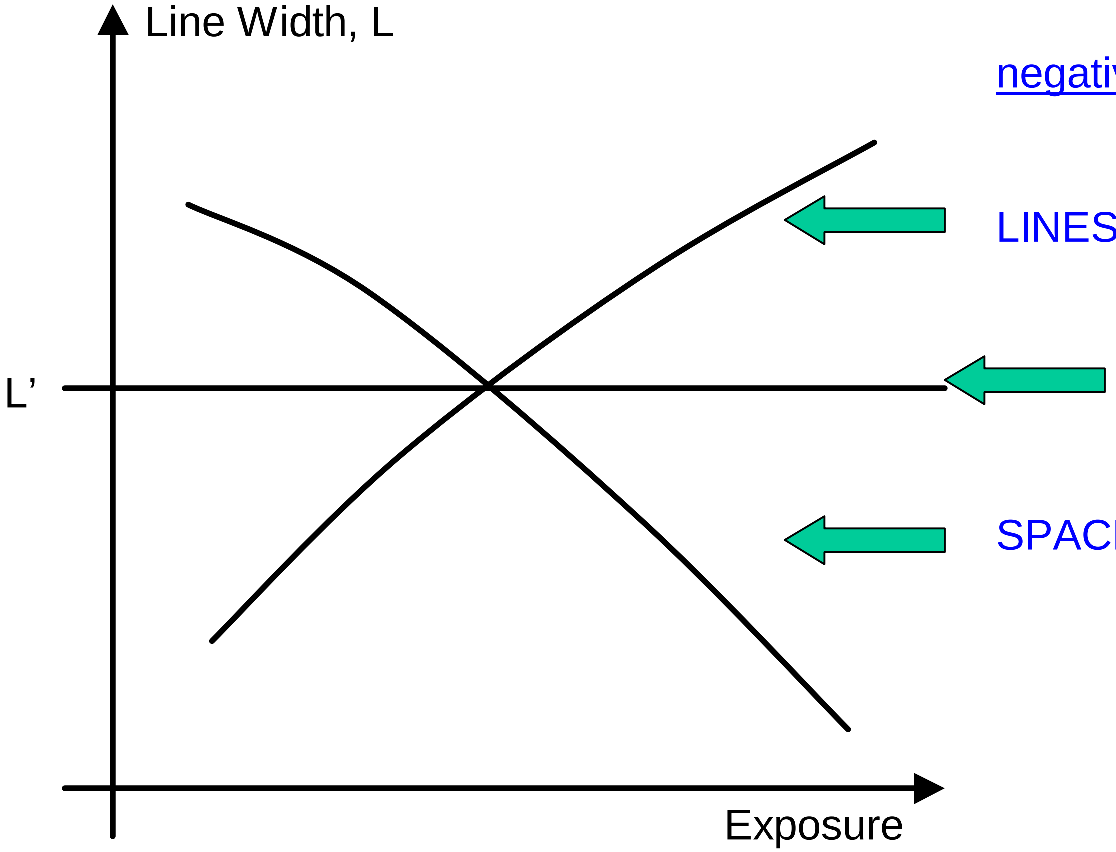
$$OD = \log_{10}(A)$$ optical density

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)

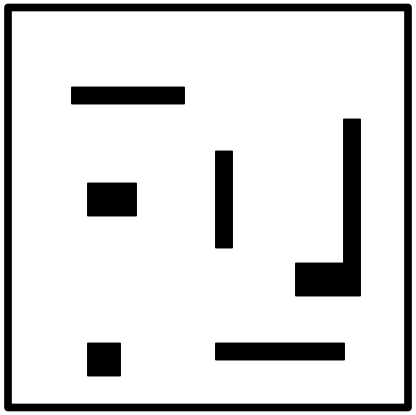
$$d = \left| \frac{L' - L}{L'} \right|$$



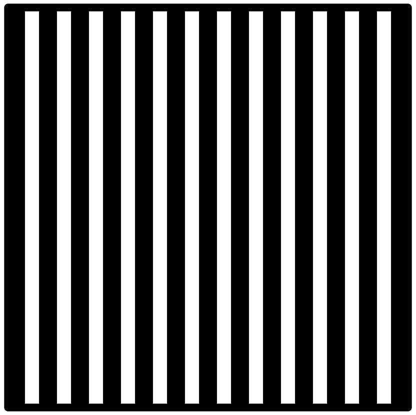
negative PR	positive PR
LINES	SPACES
SPACES	LINES

drawn mask feature size

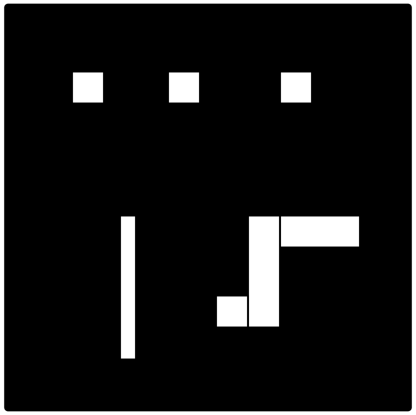
Proximity Exposure Effect - 1



light field



50:50 grating

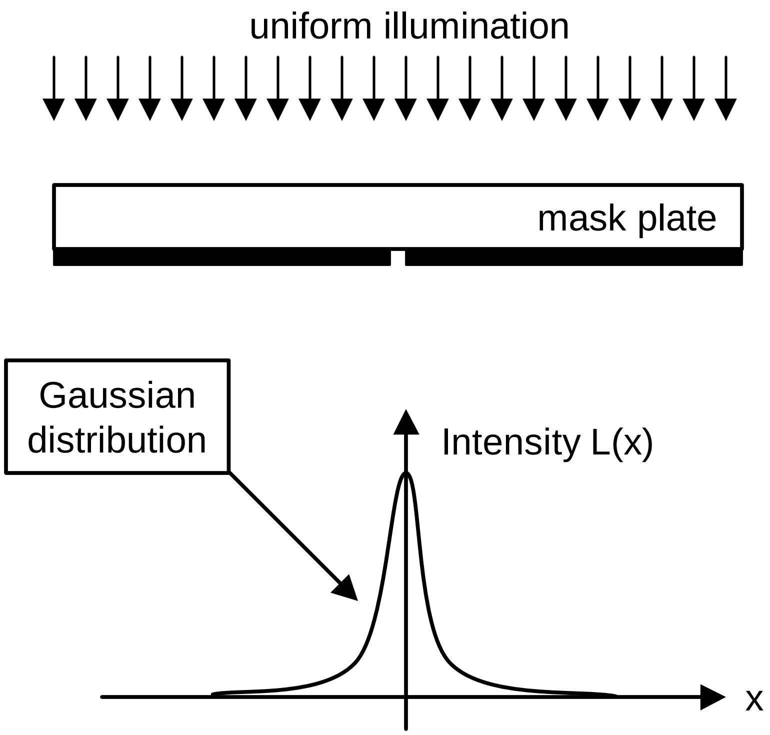


dark field

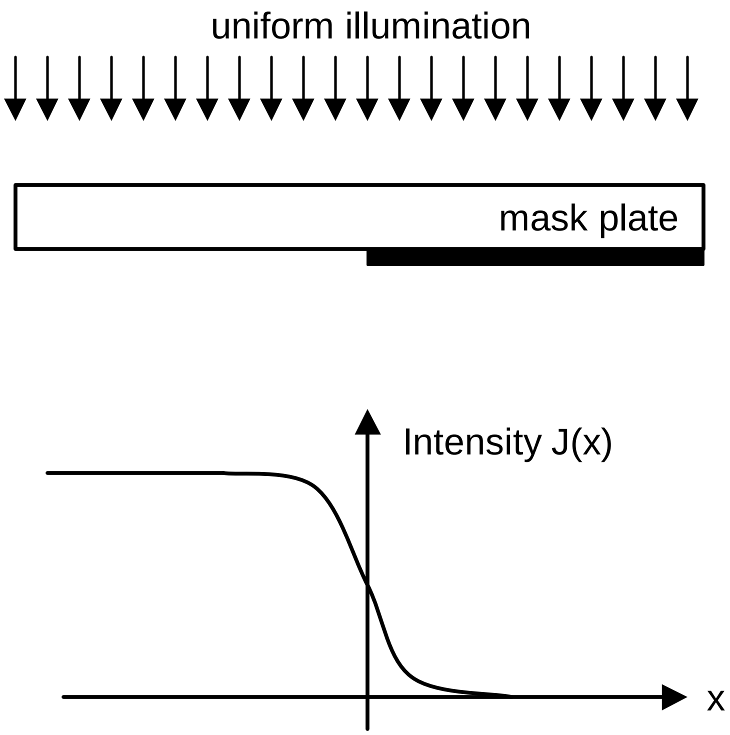
Optimum exposure depends upon the pattern!!!

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)



Edge Spread Function J(x)

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

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

Optical Modulation

I = optical intensity, W/cm^2
M = optical modulation within a scene or image
MT = modulation transfer factor for an optical element

$$M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$M \rightarrow 1$ when $I_{\min} \rightarrow 0$.

$$MT = \frac{M_{out}}{M_{in}}$$

Modulation Transfer Function

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

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

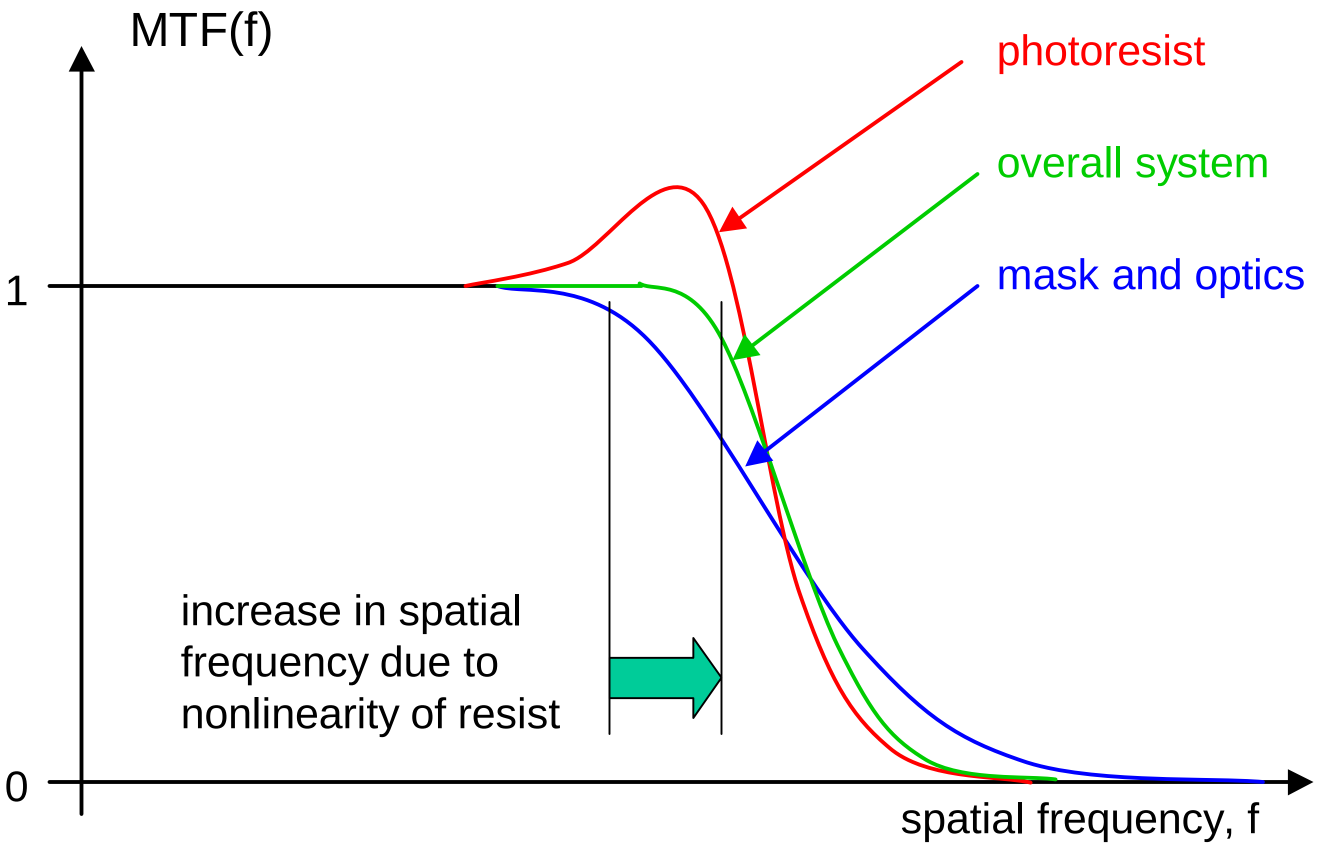
f is the spatial frequency

<u>Optics obeys linear system theory:</u>

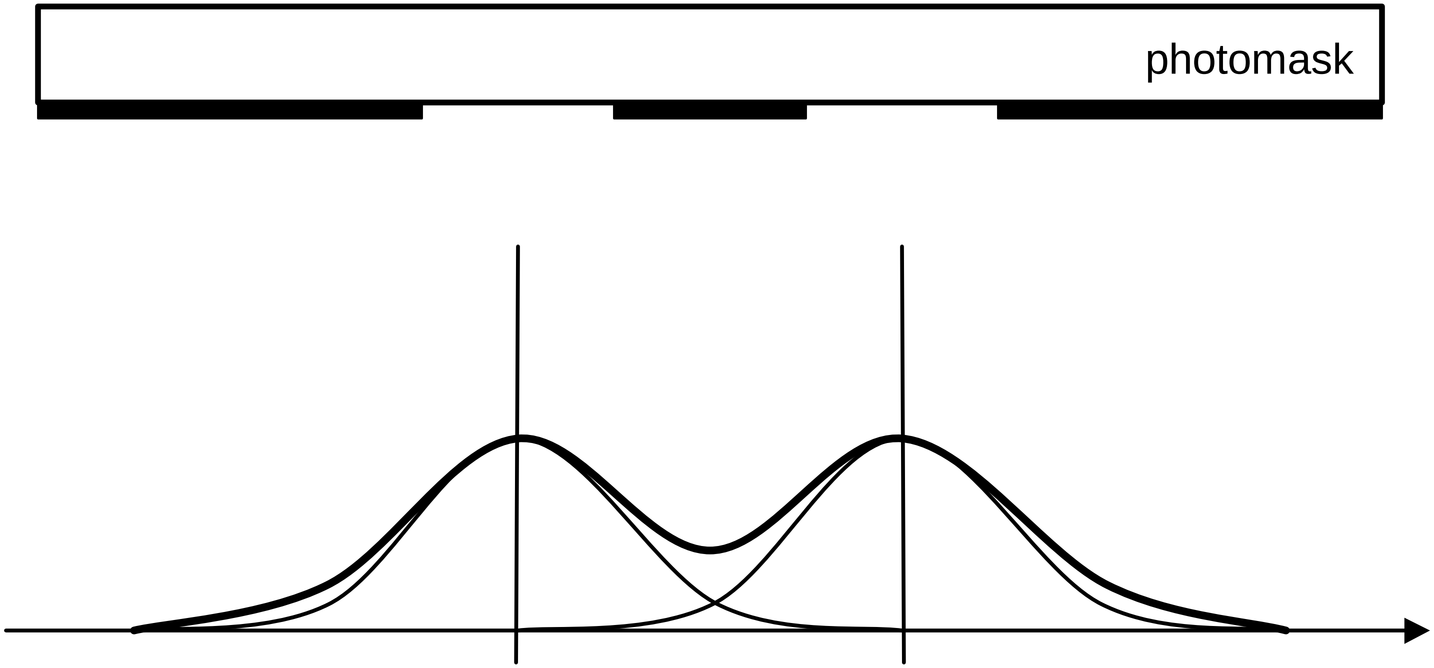
$$\text{MTF(system)} = \text{MTF(element}_1) \times \text{MTF(element}_2) \times \text{MTF(element}_3) \times \ldots$$

Modulation Transfer Function in Photolithography

MTF(system) = MTF(mask) × MTF(optics) × MTF(resist)



Proximity Exposure Effect - 2



Phase Shifting Masks