Lithography Lecture #1

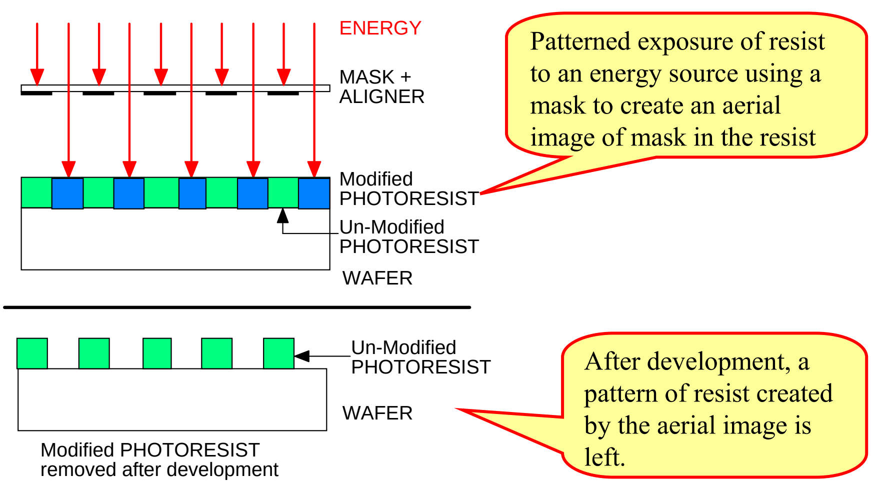
OUTLINE

- Overview of Lithography
- Optics of Lithography
  - –Metrics, Optics of Micro-Lithography, Aligners, Photomasks
- Photoresists
  - –Components of Photoresist, Metrics, Photoresist processing, Multi-layer resist
- Advanced Lithography
  - –E-beam Lithography, Soft Lithography

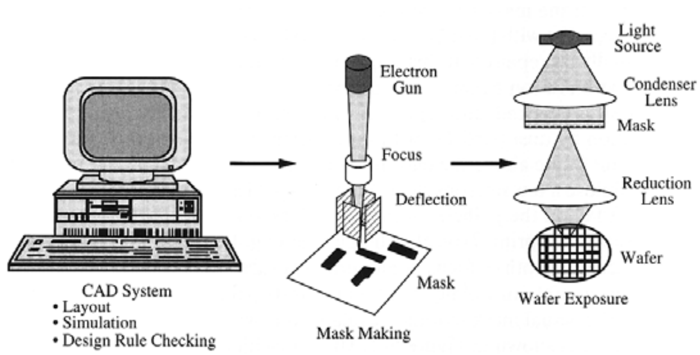
Reading Assignment: Plummer, Chapter 5
Reference: Campbell, Chapters 7, 8 & 9

Overview of Lithography

- **Lithography is the process by which circuit or device patterns are transferred from layout to Si wafers**



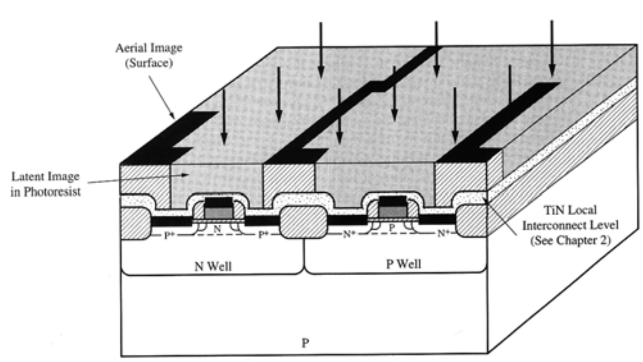
Typical Lithography Process I



Plummer Fig. 5-1

- Layout functional blocks (or use previous designs) and use software tools help route or wire connections between functional blocks
- Tools check for design rule violations
- Circuit and system level simulation tools predict performance
- Information from design transferred to mask making machine and pattern written on a **mask blank** using scanning electron or laser beam

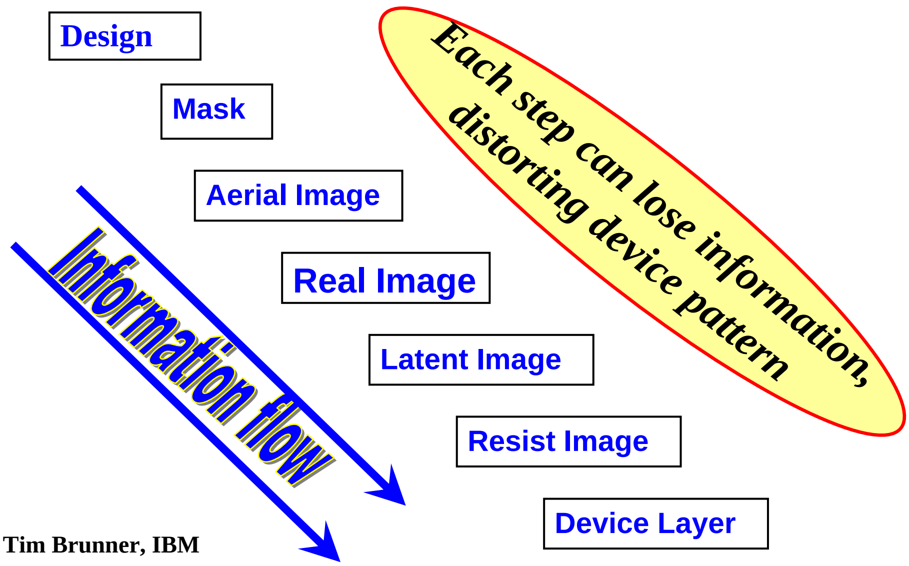
Typical Lithography Process II



Plummer Fig. 5-2

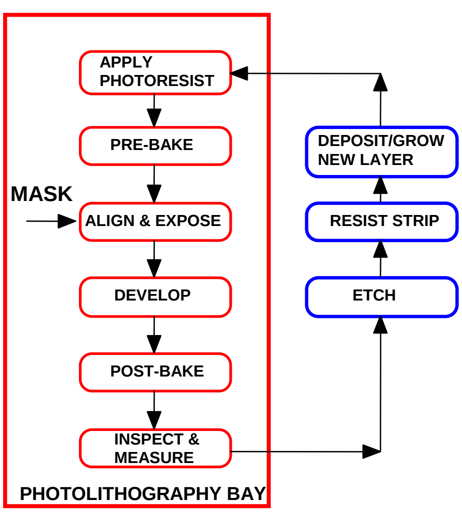
- Use mask to expose the resist using a photo aligner
  - Creates an aerial image of mask pattern on the resist
- Resist is then developed removing (exposed or exposed regions)
- Resist is used to transfer mask pattern onto wafer
  - Ion implantation, oxide tech, metal etch, silicon etch, etc

Lithography as Information Flow

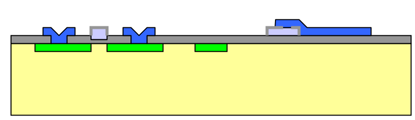


Tim Brunner, IBM

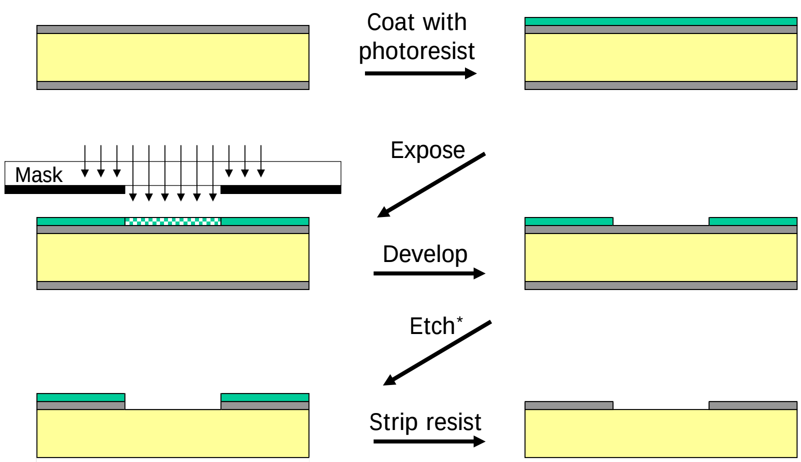
Typical Lithography Process Sequence



- Wafers spend about 40-50% of the time in photo bay
- Majority of the steps in any process sequence are followed by lithography and etch/implant



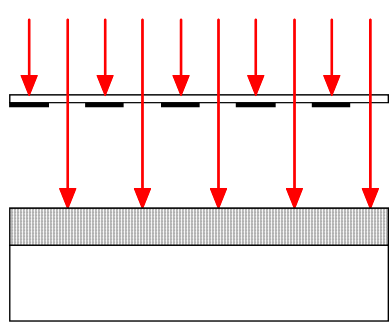
Typical Pattern Transfer Steps



*Wet etch

Schmidt

Functional Components of Lithography



- **Energy** —cause (photo)chemical reactions that modify resist dissolution rate
- **Mask** —Pattern (or direct) energy to create an aerial image of mask in resist
- **Aligner** —Align mask to previous patterns on wafer (to a tolerance level)
- **Resist** —Transfer image from mask to wafer, After development Positive resist reproduces the mask pattern, Negative resist reproduces inverse mask pattern
- **Substrate** —Has previous mask patterns

Energy Sources

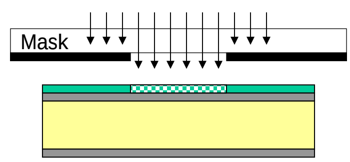
Waves or Particles

- Energy sources are required to modify the photoresist.
- The energy source is aerial imaged on the photoresist.
- The imaging can be done by scanning the energy beam or by masking the energy beam.
- Bright sources are usually required for high throughput.

		Wavelength	Energy
Light	UV	400 nm	3.1 eV
	Deep UV	250 nm	4.96 eV
	X-Ray	0.5 nm	2480 eV
Particles	Electrons	0.62 Å	20 keV
	Ions	0.12 Å	100 keV

$$\mathbf{E} = \mathbf{h}\nu = \frac{\mathbf{hc}}{\lambda}$$

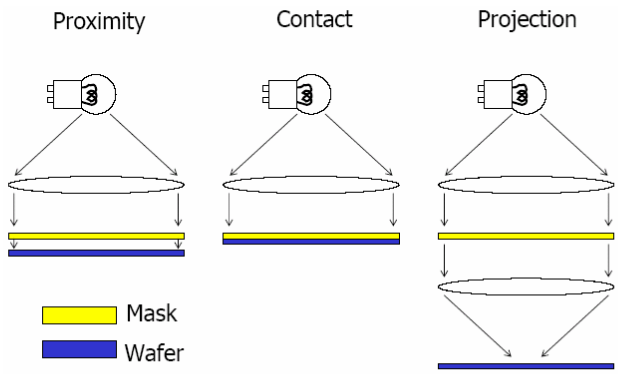
Mask



Schmidt

- Block radiation where it is not wanted i.e. absorb radiation
  - Need opaque material at the desired wavelength
- Transmit radiation where it is needed
  - Need material with high transmission at the desired wavelength
- For Optical lithography, mask is
  - Quartz glass (transparent) + Cr (opaque)

Aligner



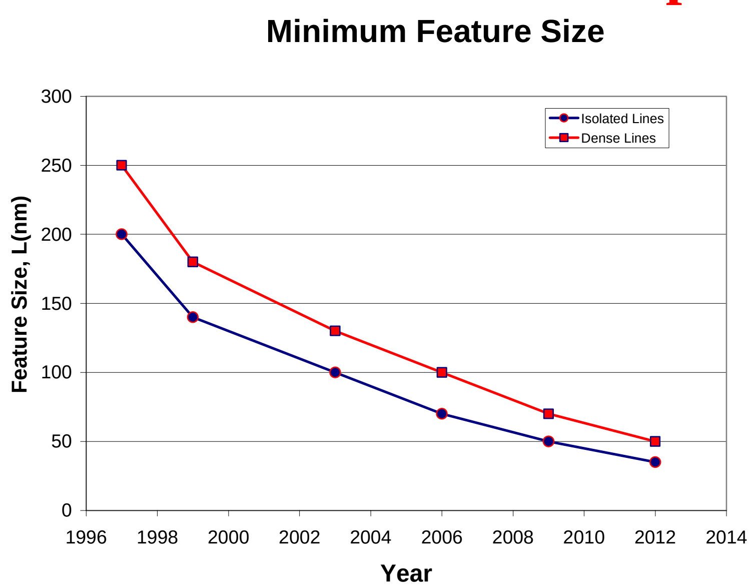
Schmidt

- Align pattern on mask to previous patterns on the wafer
- Exposure of photoresist to radiation pattern which is an aerial image of mask
- **Types of aligners**
  - Contact, Proximity & Projection

Resist

- Viscous liquid which has a “solid” form when solvents are driven out
- Spin coated on coated on surface to be patterned
- Exposure of resist to energy/radiation leads to (photo) chemical reactions and changes the resist dissolution rate in the developer
- Remaining resist is “rugged” enough to protect (mask) underlying substrate during subsequent processing

Semiconductor Roadmap



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Metrics of Lithography Systems

- Resolution(smallest dimension that can be printed)
  - Determined by optical system, resist, etch process
  - Critical Dimension (CD) control **(3σ = 10% of mean)**
- Registration (alignment 3σ=1/3 resolution)
  - Determined by optical system and aligner
- Dimensional Control (device, die, wafer, lot uniformity)
  - Determined by optical system, mask, resist, etch process
- Throughput (how many wafers/hour)
  - Determined by optical system, resist

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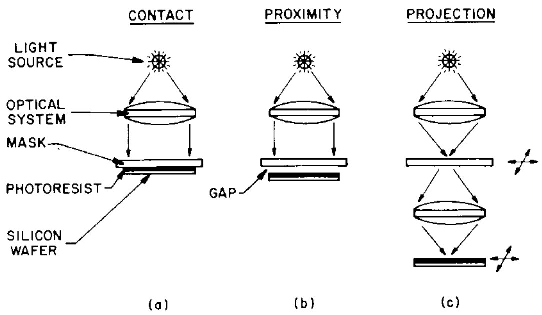
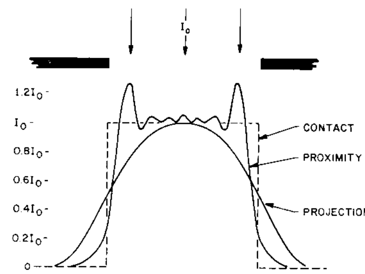
Optical Aligners
Exposure Systems

Comparison of three exposure systems



Light intensity profile for three exposure systems

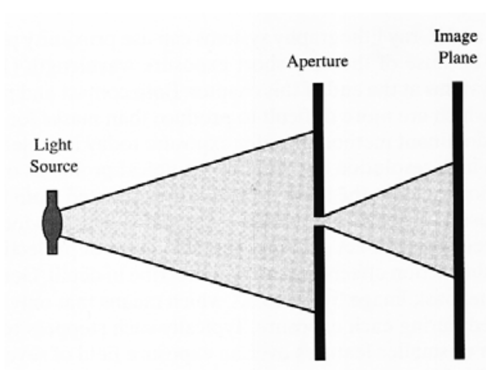


Contact Aligner: photoresist is in intimate contact with the chrome-side of the mask at the time of exposure. Mask image:Resist image is 1:1, not limited by diffraction

Proximity Aligner: photoresist is not in intimate contact with mask—separated by a few microns. Mask image:Resist image is 1:1. Limited by near field (Fresnel diffraction) diffraction

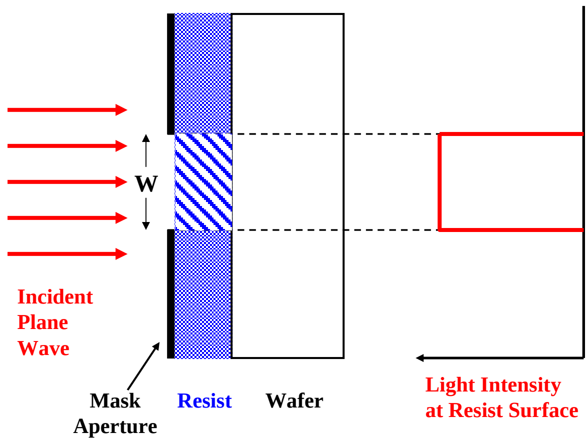
Projection Aligner: photoresist is not in intimate contact with mask —mask image is projected onto resist by lenses. Limited by far field (Fraunoffer diffraction) diffraction

Optics Review
What is Diffraction?



- Diffraction is the spread of radiation into un-exposed regions
  - Near-field diffraction (Fresnel Diffraction)
  - Far-field diffraction (Frauhoffer Diffraction)

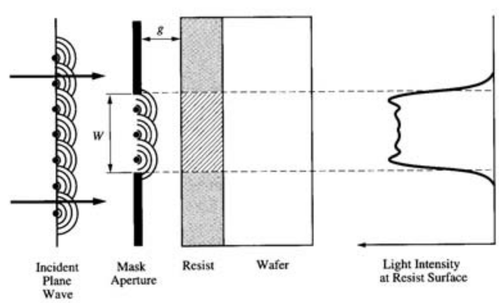
Contact Printing



- **Contact Aligner**—mask is in hard contact with resist
- not diffraction limited

Proximity Printing

Near Field (Fresnel) Diffraction



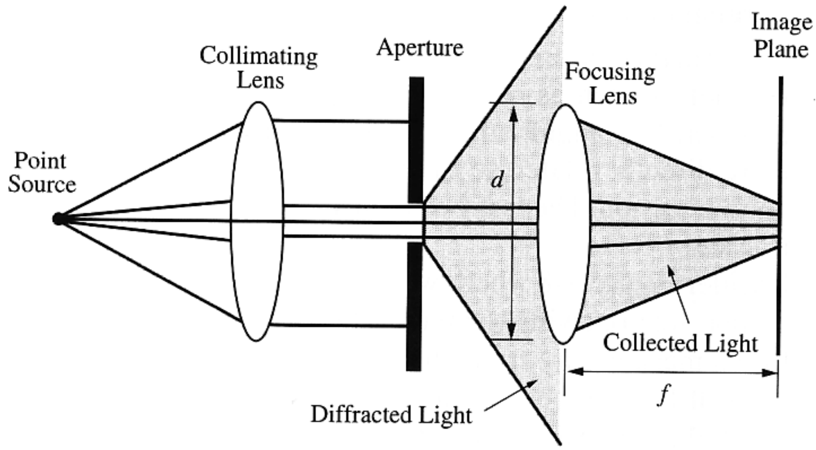
$$\lambda < \mathbf{g} < \frac{\mathbf{W}^2}{\lambda}$$

$\mathbf{W}$ = mask feature size

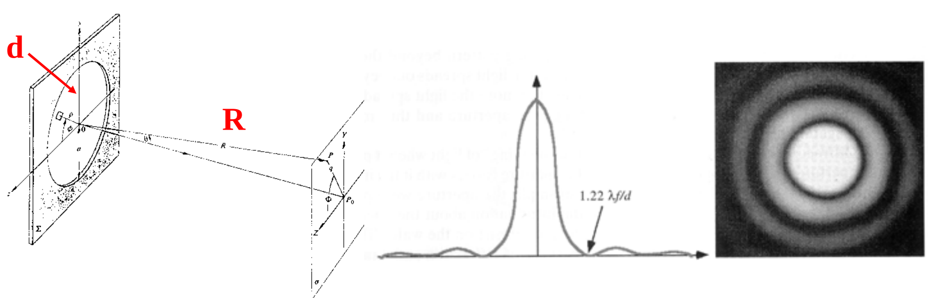
$$\mathbf{W}_{\text{min}} \approx \sqrt{\lambda \mathbf{g}}$$

- Mask and wafer are separated by a small gap of 2-20 μm
- The resulting diffraction pattern has several features
  - Intensity rises gradually near the edges producing some resist exposure outside the mask edge
  - Ringing in intensity distribution within the aperture
- As mask separation g increases, quality of image degrades

Projection Printing



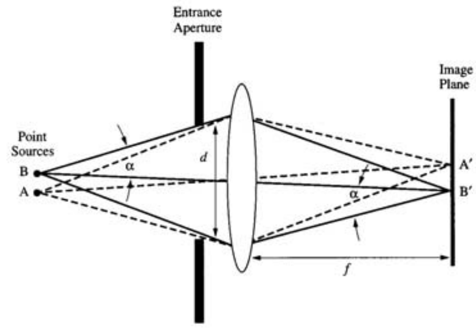
Far Field (Frauhoffer) Diffraction



First minimum $q_1 = 1.22\frac{R\lambda}{2a} = 1.22\frac{f\lambda}{d}$

- The analysis is for circular apertures with radius a, diameter d=2a.
- Observation of the light intensity at a distance R (usually at the focal length f) shows the above circular diffraction pattern.
- The diffraction pattern has a diameter (of central maximum) equal to q_1.

Resolution of Point Images



- Consider two close point sources that we are trying to image as shown in figure
- Images produced will be "Airy" disks
- The Rayleigh's criteria for resolution of the images occur when the center of one "Airy" disc is at the first minimum of the other "Airy" disk
- Resolution (minimum distance between the two sources) is given by

$$\mathbf{R} = 1.22\frac{\lambda \mathbf{f}}{\mathbf{d}}$$

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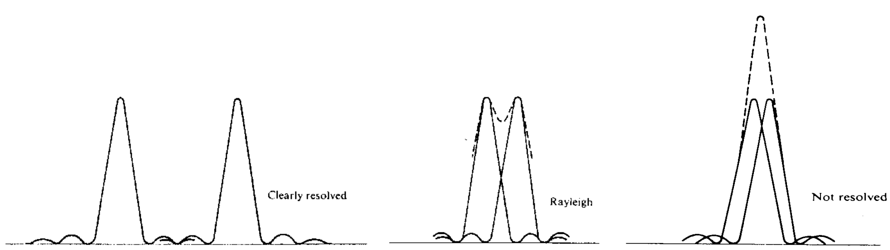
Resolution of Point Images



$$(\Delta \mathbf{l})_{min} = 1.22\frac{\mathbf{R}\lambda}{2\mathbf{a}} = 1.22\frac{\mathbf{f}\lambda}{\mathbf{d}}$$

Rayleigh's criteria occurs when the center of one disc is at the first minimum of the other disc

R = f = focal length of lens
d=2a=aperture diameter

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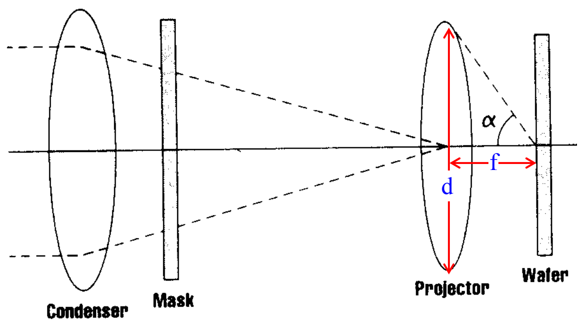
What is Numerical Aperture (NA)?

- Numerical aperture of an optical system is a measure of the ability of the collect light
- NA^2 is a measure of the light gathering power



Define

$$NA = n_o \sin\alpha$$

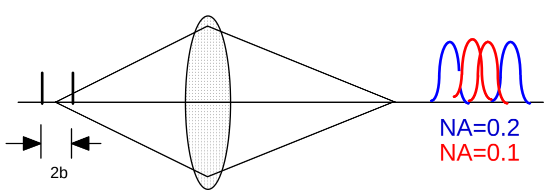
$$\mathbf{n}_0 = 1$$

$$\sin\alpha \approx \frac{\mathbf{d}/2}{\mathbf{f}} = \frac{\mathbf{d}}{2\mathbf{f}}$$

$$\mathbf{NA} = \frac{\mathbf{d}}{2\mathbf{f}}$$

α is maximum acceptance angle that can be focused by the optical system

Resolution
(Grating)



$$(\Delta\mathbf{l})_{min} = 2\mathbf{b} = 1.22\frac{\mathbf{f}\lambda}{\mathbf{d}} = 0.61\frac{\lambda}{\mathbf{NA}}$$

$$\mathbf{NA} = \frac{\mathbf{d}}{2\mathbf{f}}$$

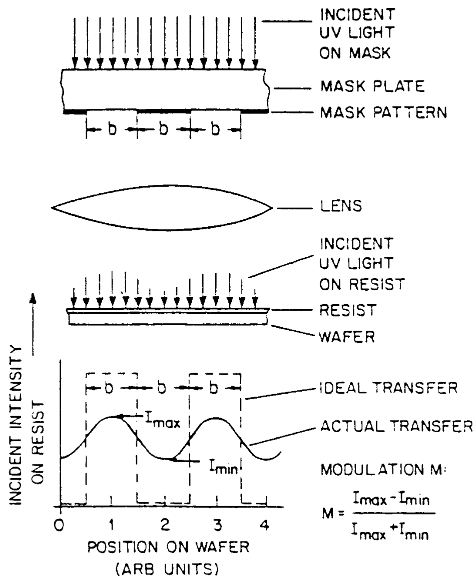
In general

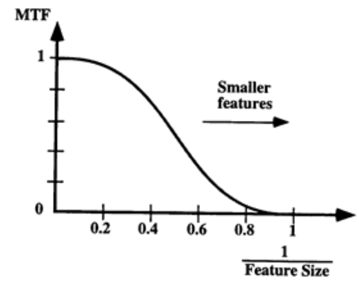
$$\text{Min. Line Width} = \mathbf{k}_1 \frac{\lambda}{\mathbf{NA}}$$

$$\mathbf{k}_1 = 0.6 - 0.8$$

- Let 2b be the period of a grating (equally spaced lines and spaces)
- 2b is separation between two images, b is minimum linewidth
- Raleigh's criterion corresponds to situation when the two images being resolved have intensity reduced to 80% at minimum

Modulation Transfer Function





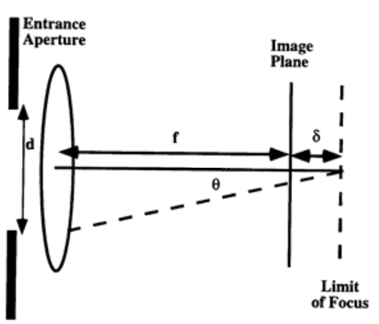
$$Modulation = M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$M_{mask} = 1 \qquad M_{image} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$MTF = \frac{M_{image}}{M_{mask}} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Depth of Focus

- Depth of Focus (DOF) decreases as the numerical aperture increases
- If δ is the on-axis path length difference at the limit of focus, then path length difference is δcosθ.
- Raleigh criteria for depth of focus (DOF) is that the two path lengths do not differ by more than λ/4



$$\frac{\lambda}{4} = \delta - \delta \cos\theta$$

Assuming θ is small

$$\frac{\lambda}{4} = \delta\left[1 - \left(1 - \frac{\theta^2}{2}\right)\right] \cong \delta\frac{\theta^2}{2}$$

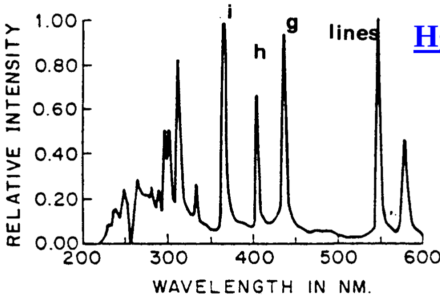
$$\theta \cong \sin\theta = \frac{\mathbf{d}}{2\mathbf{f}} = \mathbf{NA}$$

$$\therefore \mathbf{DOF} = \delta = \pm\frac{\lambda}{2(\mathbf{NA})^2} = \pm\mathbf{k}_2\frac{\lambda}{(\mathbf{NA})^2}$$

$$\delta = \frac{\lambda}{(\mathbf{NA})^2}$$

$$\mathbf{DOF} = \mathbf{k}_2\frac{\lambda}{(\mathbf{NA})^2}$$

Optical Sources



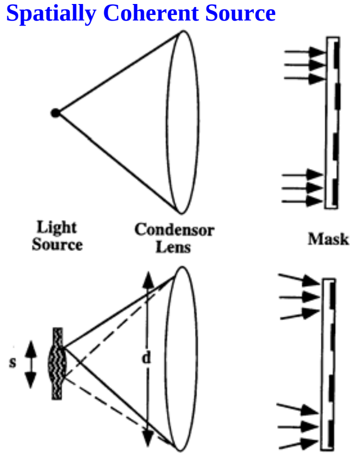
Hg Lamp Spectrum

- Current lithography systems use the **high pressure Hg lamp** which has several lines with high intensity.
  - g-line (436 nm)
  - h-line (405 nm)
  - i-line (365 nm)
- The optical source being contemplated for future lithographic systems use **Excimer Lasers**
  - deep UV (308 nm -157 nm)
    - KrF (248 nm) - current generation
    - ArF (193 nm) - next generation

Spatial Coherence

- Spatial coherence S is an indication of the angular range of light waves incident on mask or degree to which light from source are in phase

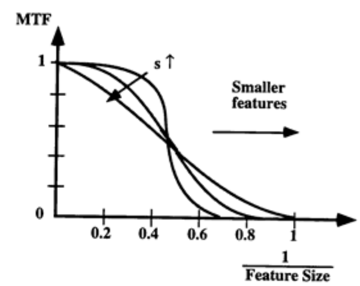
Spatially Coherent Source



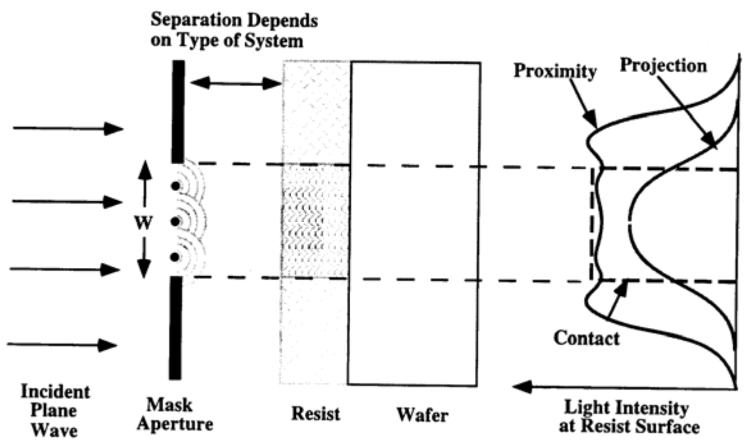
Partially Coherent Source

$$s = \frac{\text{source diameter}}{\text{aperture diameter}}$$

$$s = \frac{NA_{\text{condenser optics}}}{NA_{\text{projection optics}}}$$



Comparison of Aligners



- **Contact Aligner**—mask is in hard contact with resist; not diffraction limited
- **Proximity Aligner**—mask is separated from resist by a gap of 2-10 µm; limited by near-field (Fresnel) diffraction
- **Projection Aligner**—mask is very far from resist; aerial image focused on resist by lens; limited by far-field (Faunhofer) diffraction

Comparison of Aligners

Contact Printing

- Mask is brought into physical contact with wafer

Issues

- Contact implies gap < than a few λ due to surface features ≥ 1 µm, wafer warpage & dust particules
- Direct contact to mask results in mask damage, particulates and defects

Proximity Printing

- Small gap (2-20 µm) between mask and wafer (mask damage eliminated)

Issues

- Near-field (Fresnel) diffraction effects⇒ loss of exact mask reproduction for small L
- Shadowing may occur if light source is not collimated

Projection Printing

- Similar to photography
- Project mask image on to wafer at either 1:1, 5:1 or 10:1 reduction

Issues

- Need of good lenses need image size
- Usually print small area, then step and repeat
- Trade-off resolution with speed

Photo-Masks

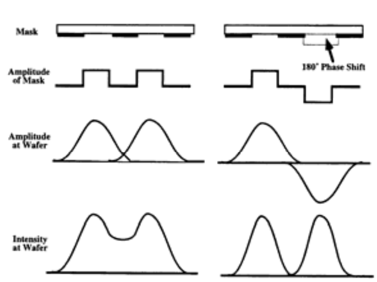
- Fabricated by e-beam direct write using a electronic database generated by the CAD tools
  - There are several substrate (transparent) types
    - Quartz, low expansion glass, sodalime glass
  - There are also several Opaque materials used to block light
    - Chrome, emulsion, iron oxide
- Often, a master is made on quartz; then the the pattern is transferred to less expensive L.E. glass where it is step and repeated to create several dies
- Two polarities of masks are common
  - Light field, **LF** (mostly clear)
  - Dark field, **DF** (mostly dark)

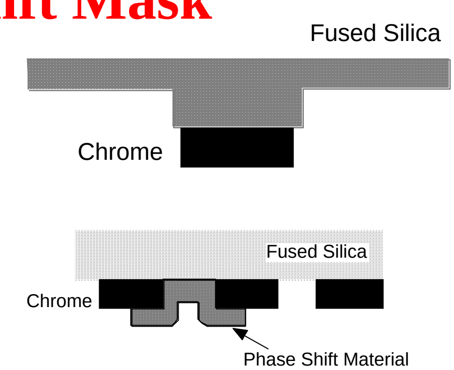
Pop Quiz!!!

What is the field of the of the following masks from the lab?

Mask #1 ____________ Mask#2 _____________

Phase Shift Mask





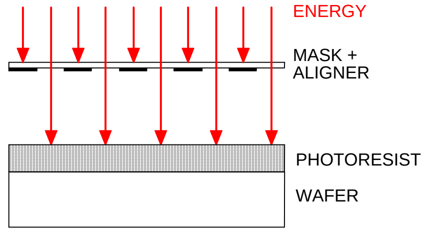
$$\mathbf{E} = \bar{\mathbf{E}}(\bar{\mathbf{r}},\mathbf{t}) = \bar{\mathbf{A}}\cos(\omega\mathbf{t} - \bar{\mathbf{k}} \bullet \bar{\mathbf{r}})$$

$$\mathbf{E} = \mathrm{Re}\{\bar{\mathbf{A}}\exp[\mathbf{i}(\omega\mathbf{t} - \bar{\mathbf{k}} \bullet \bar{\mathbf{r}})]\}$$

$$\varphi = \omega\mathbf{t} - \bar{\mathbf{k}} \bullet \bar{\mathbf{r}} \quad \text{phase}$$

- Extends resolution capability of current optical lithography
- Takes advantage of the wave nature of light
- PSM changes the phase of light by 180° in adjacent patterns leading to destructive interference rather than constructive interference
- Improves MTF of aerial image on wafer

Summary



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  - Energy— Modify resist dissolution rate
  - Mask—Pattern (or direct) energy to resist
  - Aligner—Align mask to previous patterns on wafer
  - Resist—Transfer image from mask to wafer
- Aligners
  - Resolution limited by diffraction
  - MTF, DOF, coherence
  - Contact Printing, Proximity Printing, Projection Printing
  - Photomasks, Phase Shift Mask
  - Hg lamp, g-line, h-line, i-line

Three Ways to Improve Resolution

Reduce λ

$$W_{min} = k_1 \bullet \frac{\lambda}{NA}$$

Reduce k_1

Increase NA