ME 141B: The MEMS Class
Introduction to MEMS and MEMS Design

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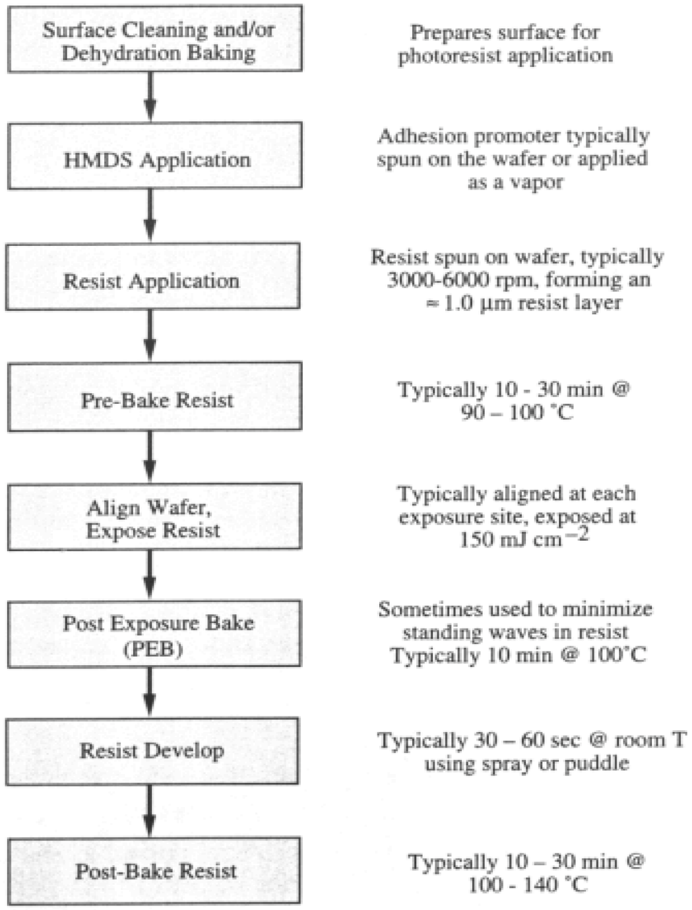
Outline

- Class odds and ends
- Lithography I
  - Photolithography
  - Ebeam lithography
  - Nanoimprint
  - Dip-pen
  - Soft

Photolithography

- Photo-litho-graphy… from Latin: light-stone-writing
- Photolithography is an optical means for transferring patterns onto a substrate. It is essentially the same process that is used in lithographic printing
- Patterns are first transferred to an imagable photoresist layer
- Photoresist is a liquid film that can be spread out onto a substrate, exposed with a desired pattern, and developed into a selectively placed layer from subsequent processing
- Photolithography is a binary pattern transfer: there is no gray-scale, color, not depth to the image

Photolithography Processing Steps



Surface Cleaning and/or Dehydration Baking	Prepares surface for photoresist application
HMDS Application	Adhesion promoter typically spun on the wafer or applied as a vapor
Resist Application	Resist spun on wafer, typically 3000-6000 rpm, forming an ≈ 1.0 μm resist layer
Pre-Bake Resist	Typically 10 - 30 min @ 90 – 100 °C
Align Wafer, Expose Resist	Typically aligned at each exposure site, exposed at 150 mJ cm^{-2}
Post Exposure Bake (PEB)	Sometimes used to minimize standing waves in resist Typically 10 min @ 100°C
Resist Develop	Typically 30 – 60 sec @ room T using spray or puddle
Post-Bake Resist	Typically 10 – 30 min @ 100 - 140 °C

Figure 5-31 Typical photoresist process flow for DNQ g-line and i-line positive resists.

(Plummer et al)

Photolithography Processing Steps

- **Clean wafer:** to remove particles on the surface as well as any traces of organic, ionic, and metal impurities
- **Dehydration bake:** to drive off the absorbed water on the surface to promote the adhesion of PR
- **Coating:**
  - Coat wafer with adhesion promoting form (e.g. HMDS)
  - Coat with photoresist
- **Soft bake:** to drive off excess solvent and to promote adhesion
- **Exposure**
- **Post-exposure bake:** (optional): to supress standing wave-effect
- **Develop**
- **Clean, Dry**
- **Hard Bake:** to harden the PR and improve adhesion to the substrate

Photoresist Spin Coating

- Wafer is held on a spinner chuck by vacuum and resis it coated to uniform thickness by spin coating
- Typically 3000-6000 rpm for 15-30 seconds
- Resist thickness is set by:
  - Primarily resist viscosity
  - Secondarily spinner rotational speed
- Resist thickness is given by t = kp^2/w^(1/2), where
  - k = spinner constant, typically 80-100
  - p = resist solids content in percent
  - w = spinner rotational speed in rpm/1000
- Most resist thickesses are 1-2 um for commercial processes

Photoresist Spin Coating

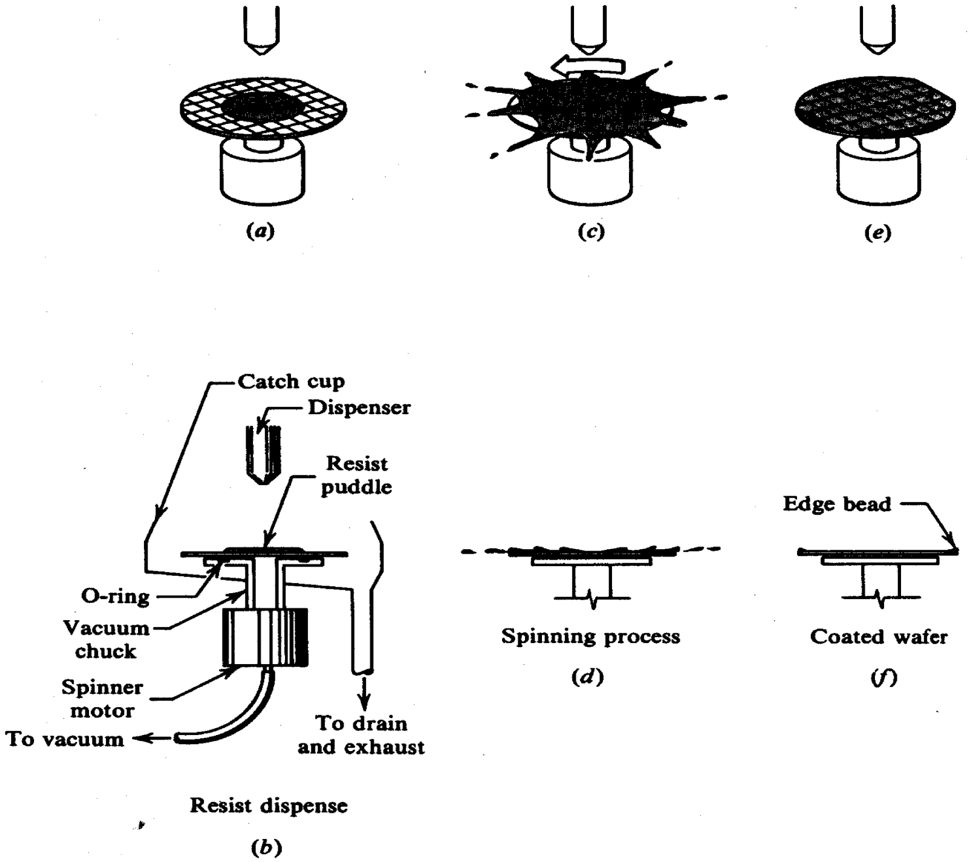


Figure 4-11 Spin coating of resist. (*a*) Resist puddle applied to substrate. (*b*) Profile view of this step, showing some details of the spin coating equipment. (*c*) Spinning begins, throwing off most of resist. (*d*) Profile view of this step, showing waves in resist and function of catch cup. (*e*) Spinning complete, substrate coated. (*f*) Profile view of coated substrate, showing edge bead. Resist thickness is greatly exaggerated.

(Ruska)

Spinning Artifacts

- Striations
  - ~30 nm variations in resist thickness due to nonuniform drying of solvent during spin coating
  - ~80 – 100 um periodicity, radially out from center of wafer
- Edge Bead
  - Residual ridge in resist at edge of wafer
  - Can be up to 20-30 times the nominal thickness of the resist
  - Radius on wafer edge greatly reduces the edge bead height
  - Non-circular wafers greatly increase the edge bead height
  - Edge bead removers are solvents that are spun on after resist coating and which partially dissolve away the edge bead
- Streaks
  - Radial patterns caused by hard particulates whose diameter are greater than the resist thickness

Automated Resist

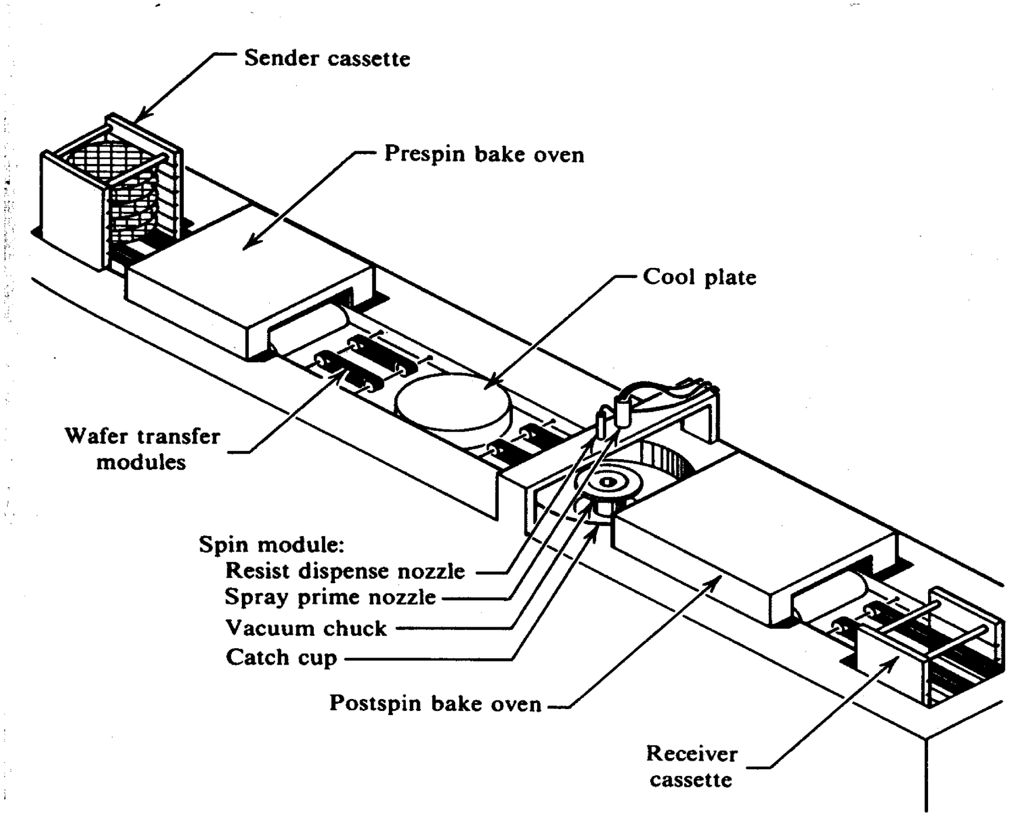


Figure 4-16 An automated spin-coater for photoresist. This sketch is conceptual in nature and is not meant to accurately represent any specific piece of equipment; in fact, it combines features from several different manufacturers.

(Ruska)

Spray Development

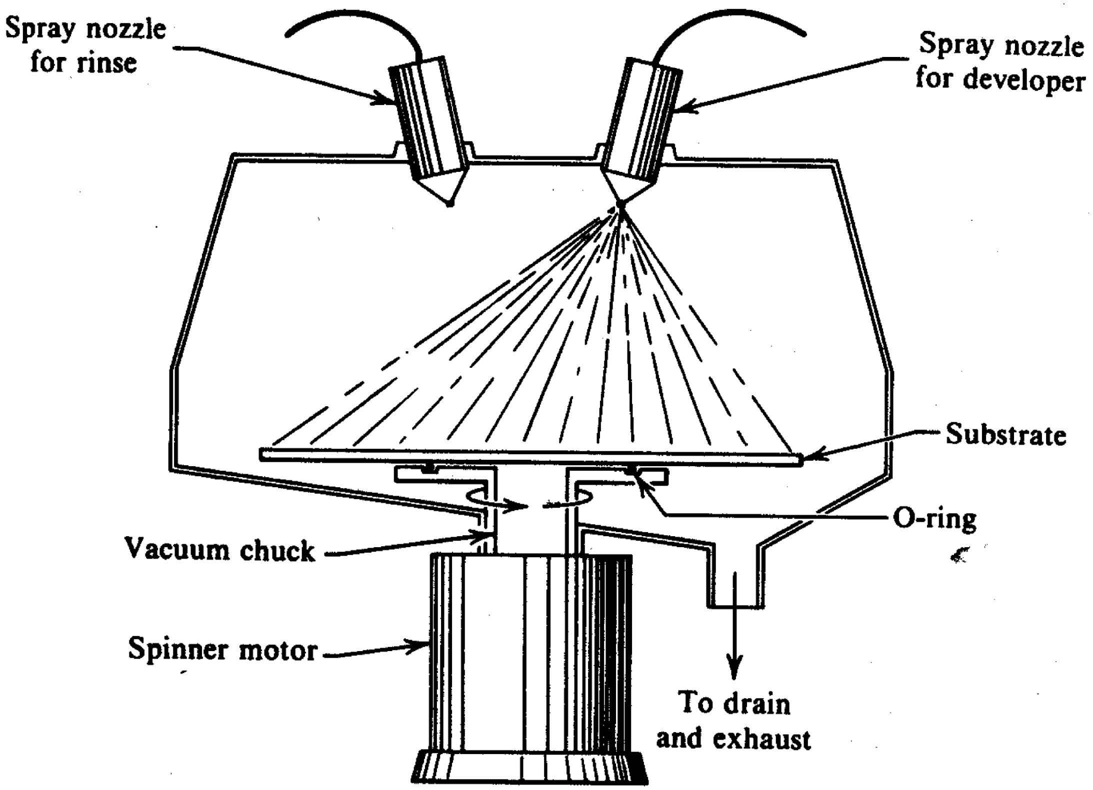


Figure 4-19 Spray developing of resist.

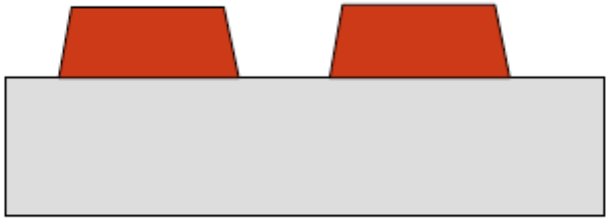
(Ruska)

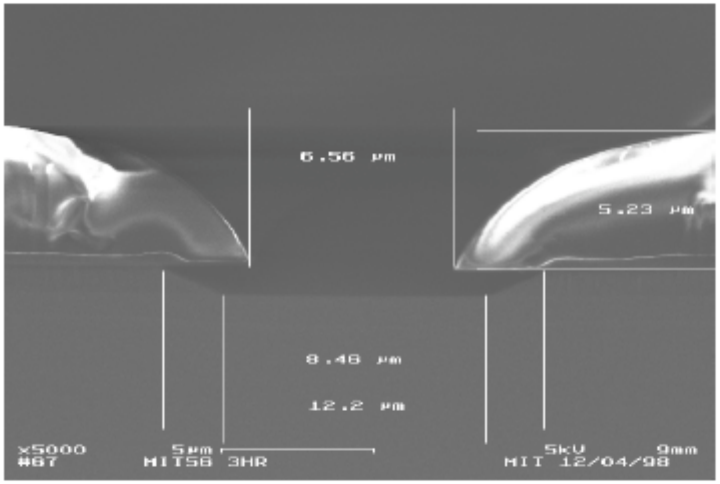
More about resist

- Resist thickness (0.6-1 um) is a function of
  - Spin speed
  - Resist viscosity
  - Spin time
- Positive resists are mostly used
  - Negative resists swell and are more toxic
- G-line and i-line resists have three components
  - Inactive resin (that resists etching and ion implantation/milling)
  - PAC- Photoactive Compound
  - PAG – Photo-acid generator (acts as a chemical amplified or catalyst)
- PAC is a diazonaphthoquinones (inhibits dissolution unless exposed to light)

Positive Thick Photoresist

- Spin cast
- Thicknesses of order 10 microns
- Sloped profiles
  - Slope somewhat controllable through process conditions
- Some planarizing capability
- Typical Applications:
  - Prolonged or low selectivity dry etch
  - Deep reactive ion etch
  - Masking any etch over topography
- Not a standard front end material, but not inherently incompatible with it

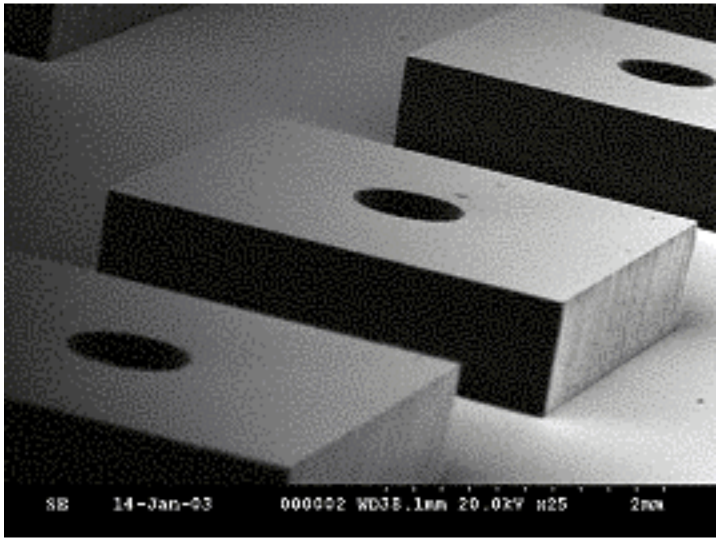


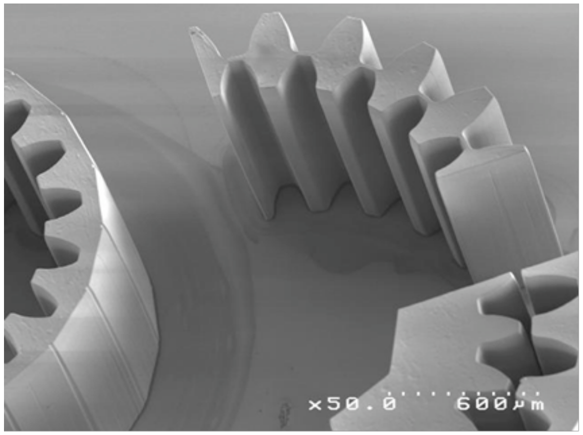


Courtesy of Reza Ghodssi. Used with permission.

Very Thick Photoresists

- SU-8 epoxy
  - Spin cast
  - Negative resist, optical exposure
  - Can planarize extreme topographies
  - Can be structural, not easily dissolved
- Poyimide
  - Spin cast
  - Can planarize topographies
  - Humidity sensitive



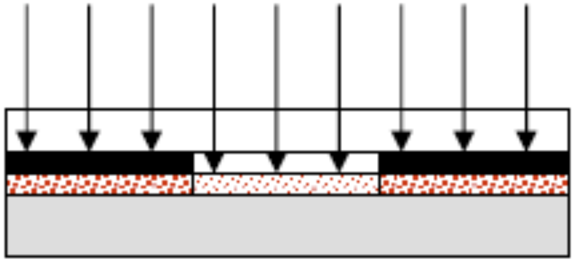


Photomasks

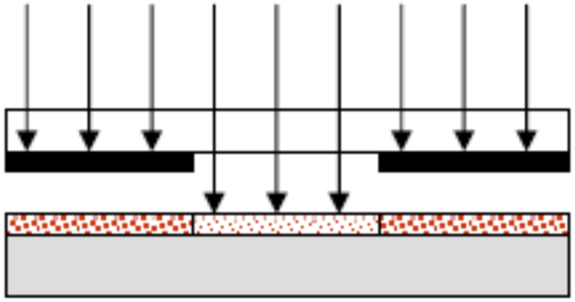
- Master patterns which are transferred to wafers
- Types:
  - Transparency mask (cheapest)
  - Photographic emulsion on soda lime glass
  - Fe_2O_3 on soda lime glass
  - Cr on soda lime glass
- Dimensions:
  - 4” x 4” x 0.060” for 3-inch wafers
  - 5” x 5” x 0.060” for 4-inch wafers
- Polarity:
  - “light-field” = mostly clean, drawn feature = opaque
  - “dark-field” = mostly opaque, drawn feature = clear

Methods of optical lithography I

- Contact
  - Mask touches wafer
  - Inexpensive
  - Contact degrades mask
  - No die size limit
  - Resolution: down to 1 micron nervously; down to several microns comfortably



- Proximity
  - Mask of order 10 microns from wafer
  - Inexpensive
  - Less mask damage
  - Diffraction means lower resolution
  - No die size limit
  - Resolution: down to several microns nervously, somewhat larger comfortably



Exposure Systems

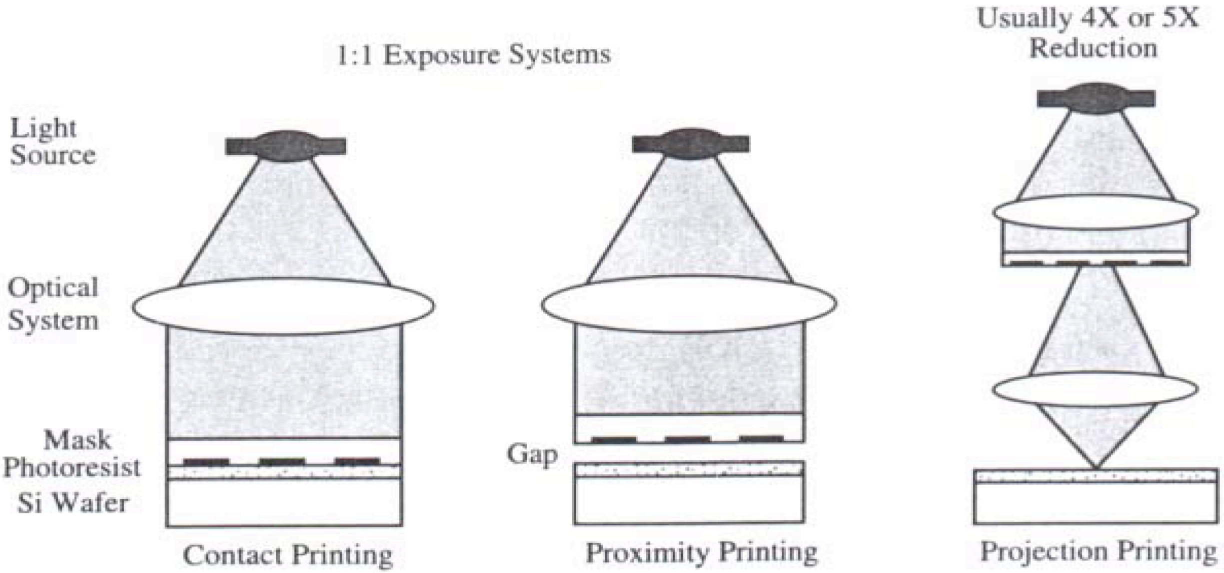


Figure 5–3 Three basic methods of wafer exposure.

← resolution ↑

Alignment and Exposure Hardware

- For simple contact, proximity, and projection systems, the mask is the same size and scale as the printed wafer patter. Ie. the reproduction ratio is 1:1
- Projection systems give the ability to change the reproduction ratio. Going to 10:1 reduction allows larger size patterns on the mask, which is more robust to mask defect.
- Mask size can get unwieldy for large wafers.
- Most wafers contain an array of the same pattern, so only one cell of the array is needed on the mask. The system is called Direct Step on Wafer – “Steppers”
  - ➢ Advantage: only ne cell of wafer needed
    - The one cell must be PERFECT, since it is used for all die

Projection Lithography

- Projection lithography, especially when combined with an optical imaging system that reduces the image size, is used for high-resolution patterning (submicron to very submicron)
- Larger mask features, no contact with mask
- Wafer steppers expose one die at a time, assuring good focus and registration
- Something to consider: if your device needs a fine features, a stepper may be required. But steppers have limits on dies size of about 1 cm.

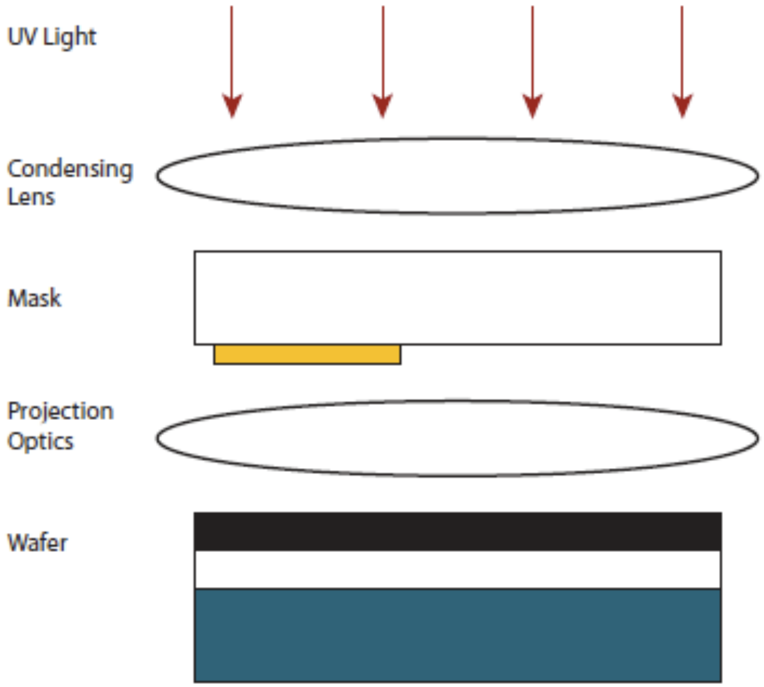


Image by MIT OpenCourseWare.
Adapted from Figure 3.15 in: Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 53.
ISBN: 9780792372462.

Stepper system

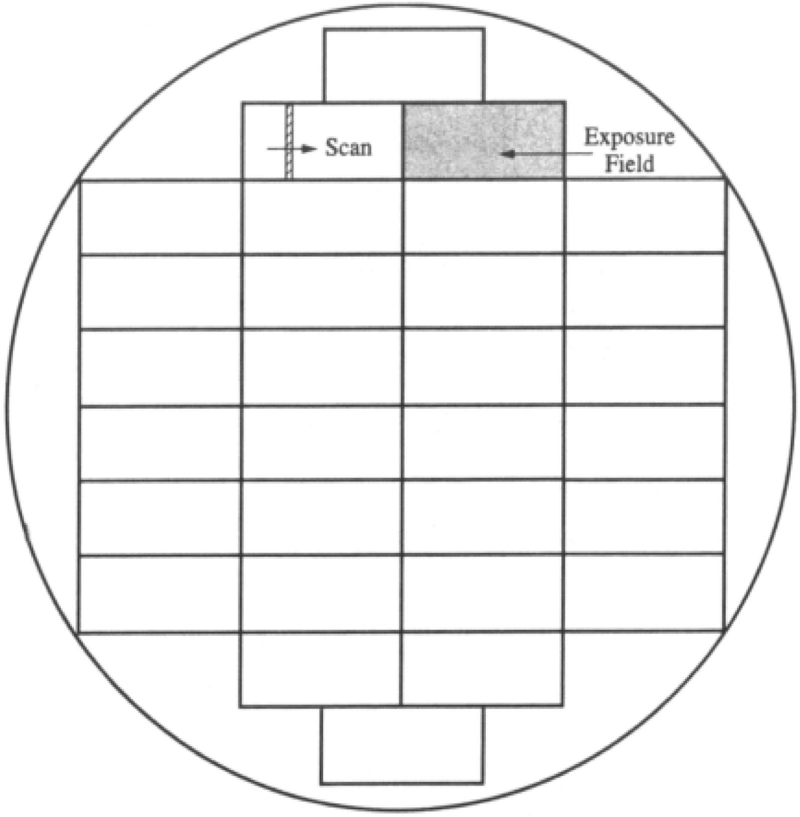


Figure 5–30 Step and scan system. Stepping accomplishes the major moves from one exposure field to another. Within each exposure field, the mask pattern is scanned across the field.

(Plummer et al)

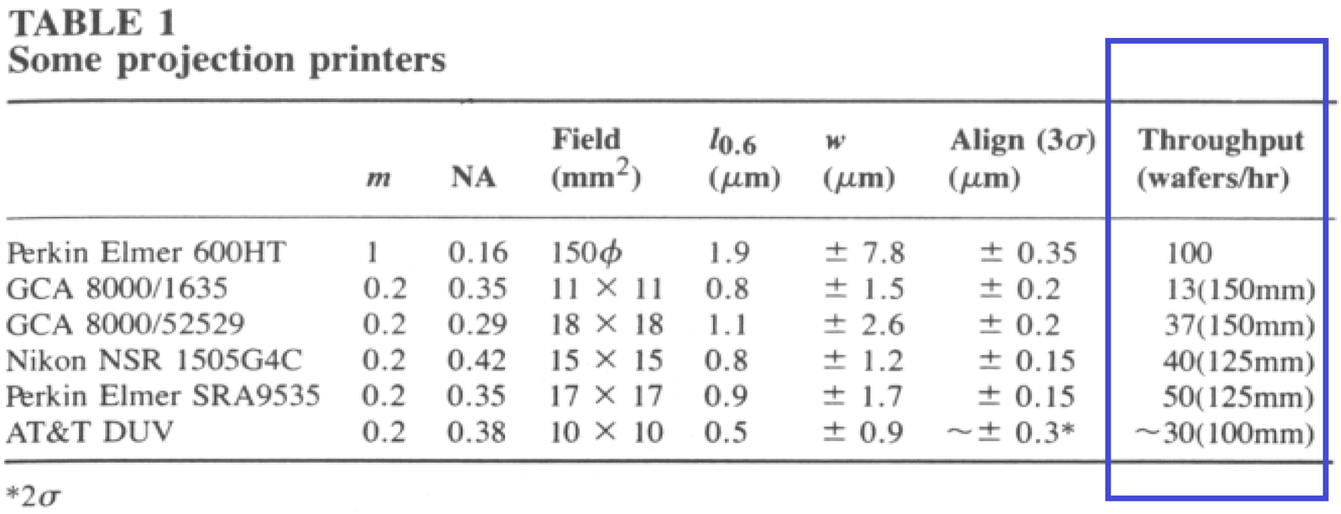


TABLE 1
Some projection printers

	m	NA	Field (mm^2)	$l_{0.6}$ (μm)	w (μm)	Align (3σ) (μm)	Throughput (wafers/hr)
Perkin Elmer 600HT	1	0.16	150ϕ	1.9	± 7.8	± 0.35	100
GCA 8000/1635	0.2	0.35	11 × 11	0.8	± 1.5	± 0.2	13(150mm)
GCA 8000/52529	0.2	0.29	18 × 18	1.1	± 2.6	± 0.2	37(150mm)
Nikon NSR 1505G4C	0.2	0.42	15 × 15	0.8	± 1.2	± 0.15	40(125mm)
Perkin Elmer SRA9535	0.2	0.35	17 × 17	0.9	± 1.7	± 0.15	50(125mm)
AT&T DUV	0.2	0.38	10 × 10	0.5	± 0.9	~± 0.3*	~30(100mm)

*2σ

(Plummer et al)

Mask Aligner – MA6

Optical Train

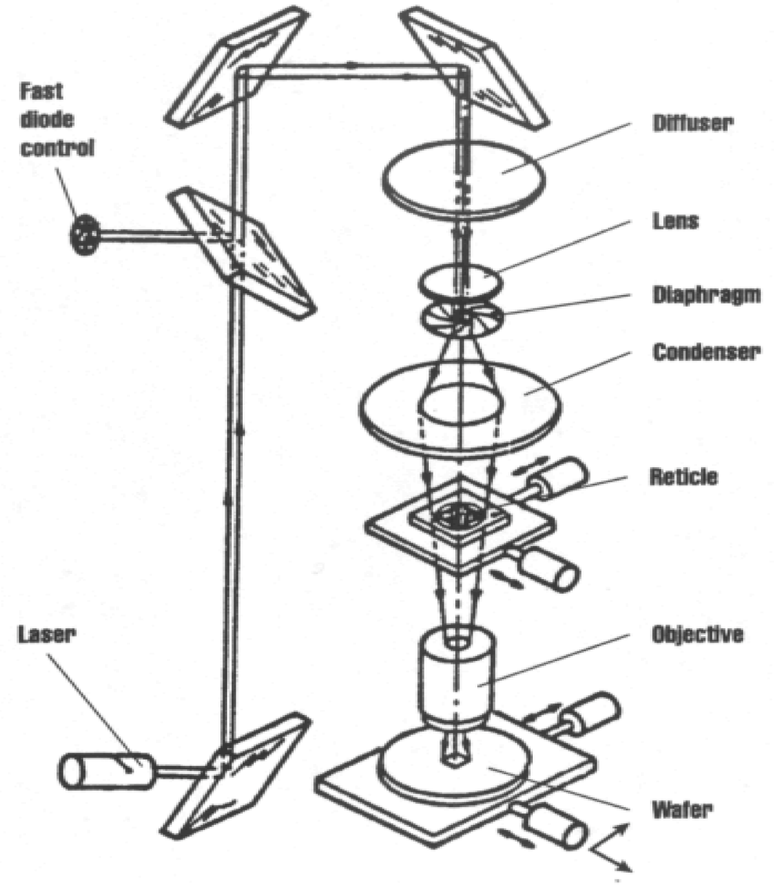


Figure 7-14 Optical train for an excimer laser stepper *(after Jain).*

Exposure Systems

- Four important characteristics:
  - Resolution
  - Depth of Focus
  - Modulation Transfer Function
  - Spatial Coherence of Light Source
- Light source
  - Hg g-line 436 nm, i-line 365nm,
  - KrF 248 nm
  - ArF 193 nm
- First: Short discussion of diffraction of light

Simple Diffraction

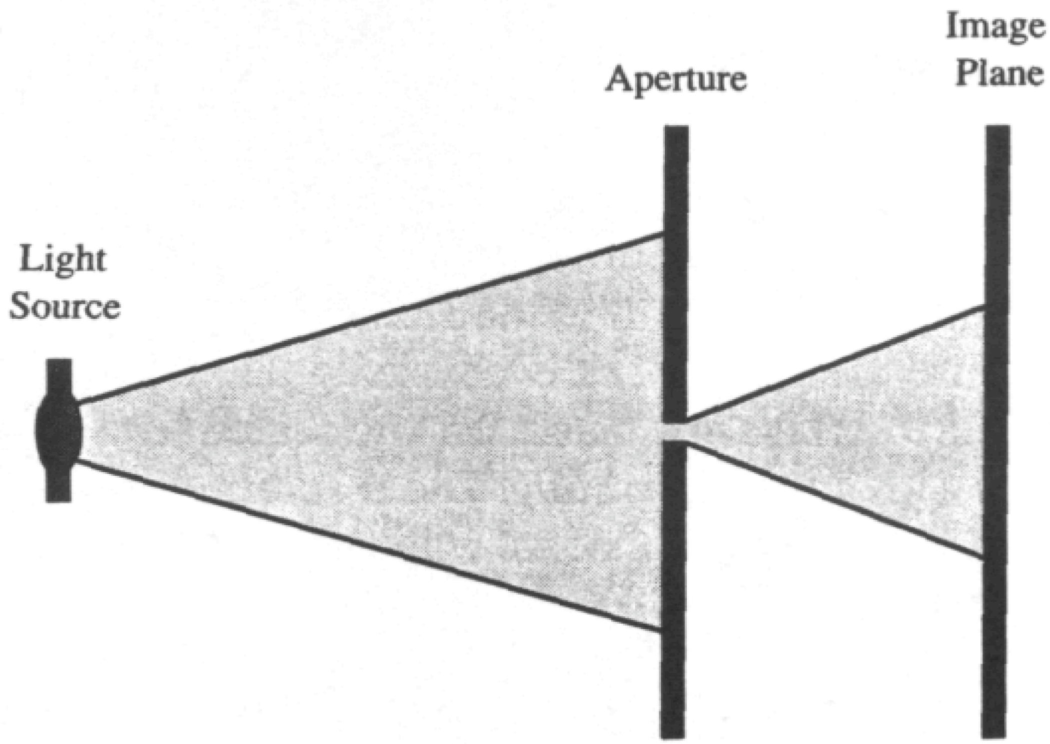


Figure 5–4 Simple example of diffraction effects. Light passes through a narrow aperture. The image formed covers a much larger area than can be explained based on simple straight line ray tracing.

(Plummer et al)

Huygens-Fresnel principle

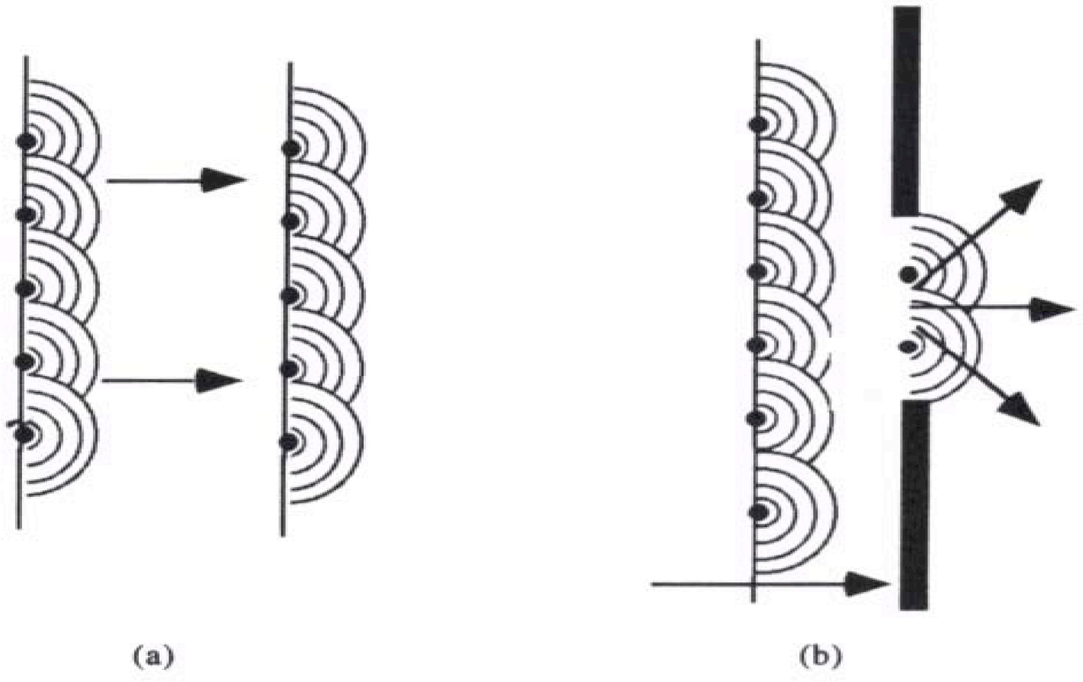


Figure 5–5 Propagation of a plane wave in (a) free space and (b) through a small aperture, illustrating the use of the Huygens-Fresnel principle to construct the wavefront as it propagates.

(Plummer et al)

Diffraction optics

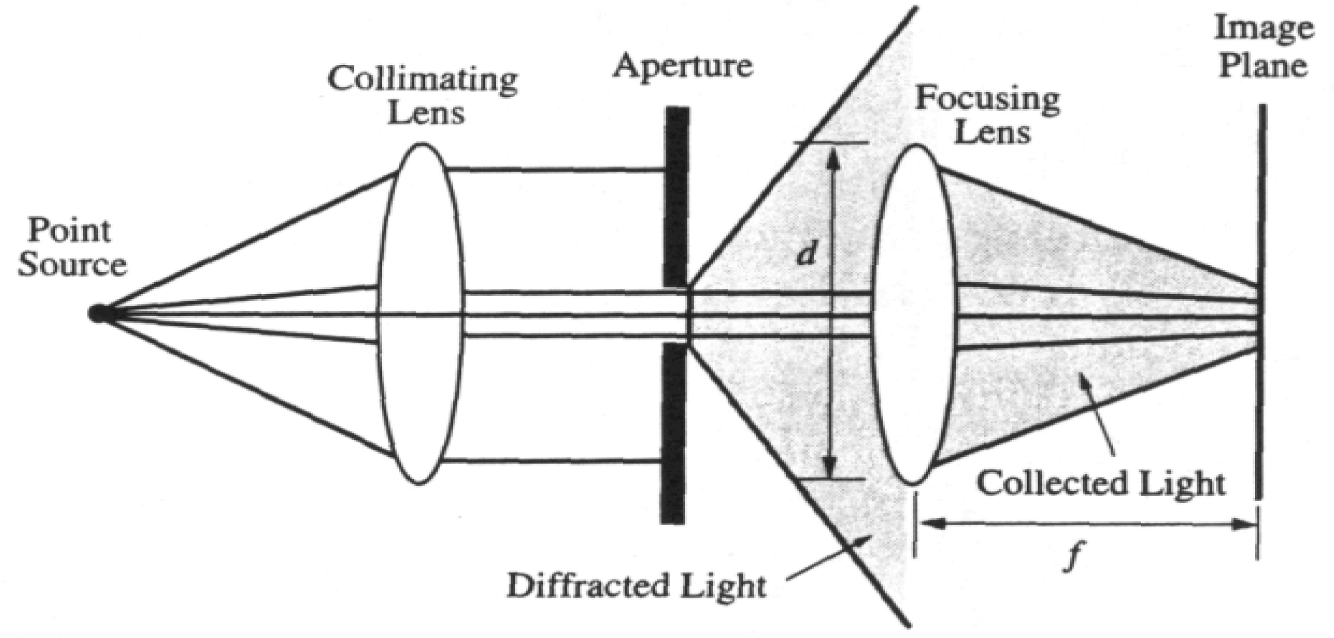


Figure 5–6 Qualitative example of a small aperture being imaged.

(Plummer et al)

Fraunhofer Diffraction

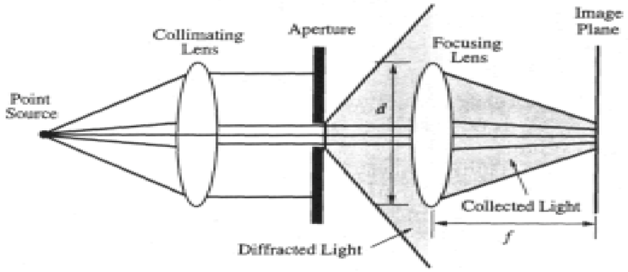


Figure 5–6 Qualitative example of a small aperture being imaged.

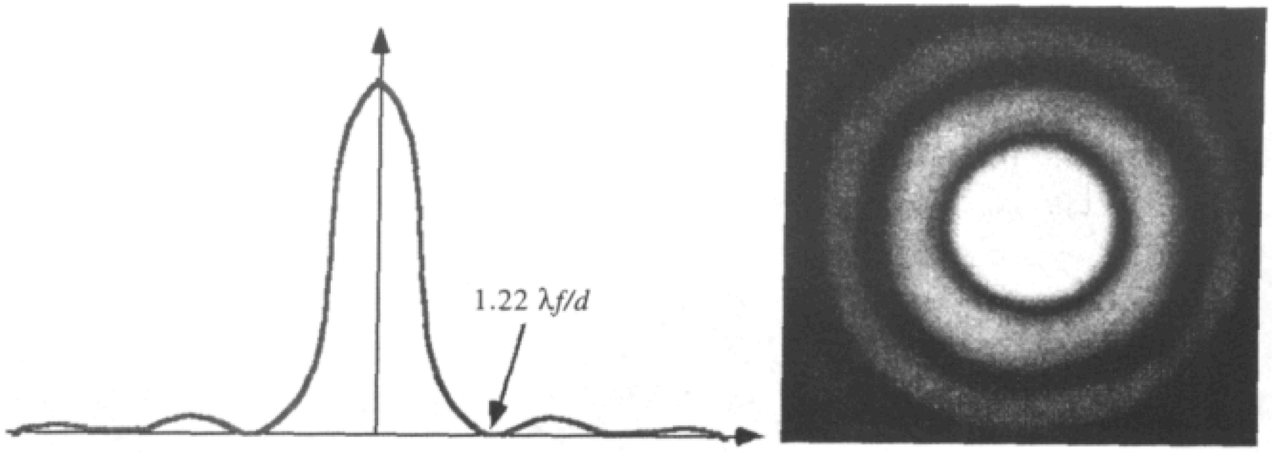
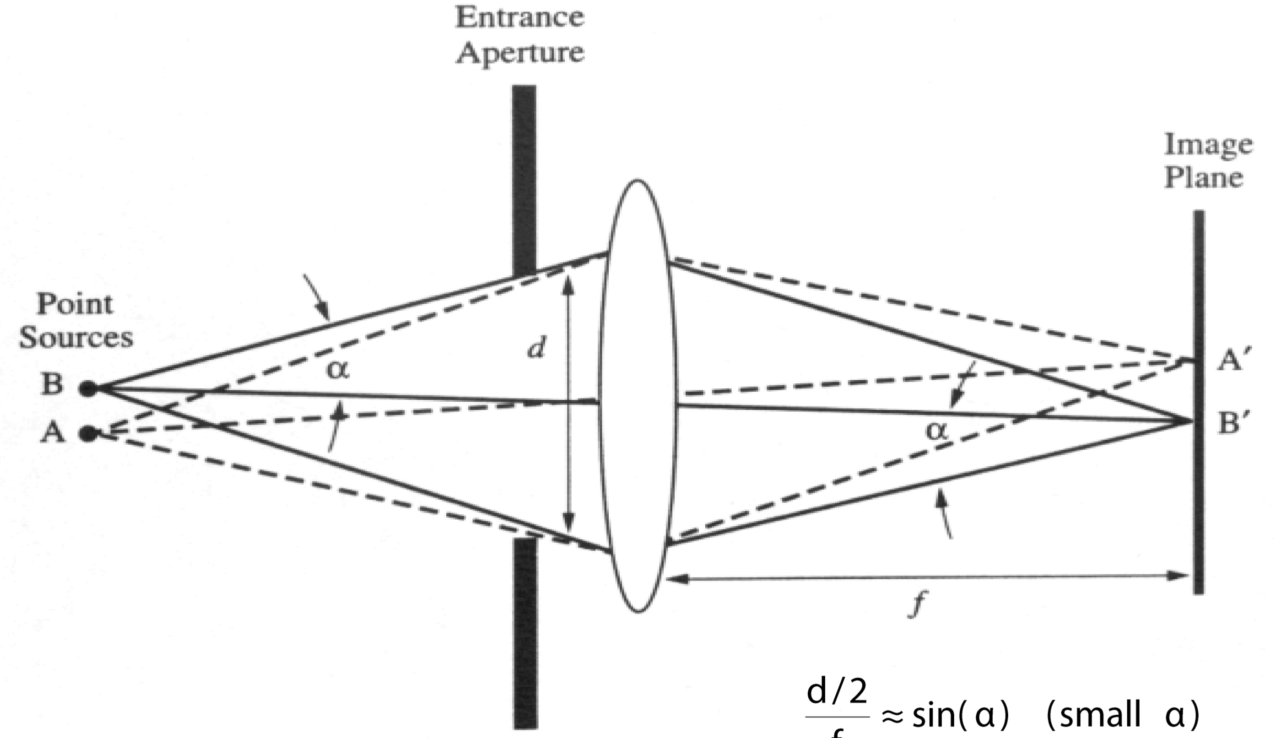


Figure 5–7 Image intensity of a circular aperture in the image plane (Fraunhofer diffraction pattern). The intensity is sketched along any diameter on the left. The pattern on the right illustrates the 2D image. Photo courtesy of J. Goodman. Reprinted with permission of McGraw-Hill [5.2].

(Plummer et al)

Resolution



$$\frac{d/2}{f} \approx \sin(\alpha) \quad (\text{small } \alpha)$$

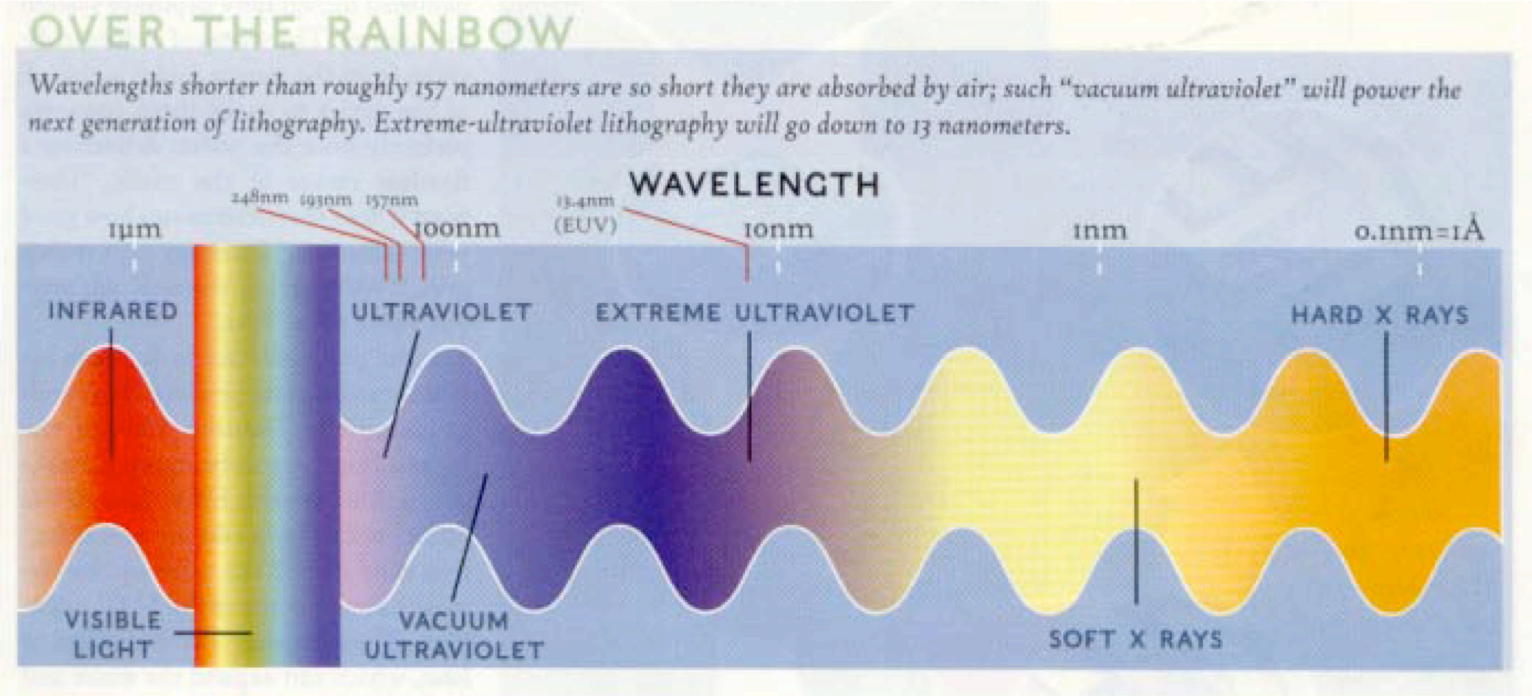
Figure 5–8 Illustration of the resolving power of a lens when two point sources are to be separated in the image.

(Plummer et al)

Resolution

- Assuming maximum resolution occurs when centers lie at Intensity minima
  - Minimum spacing = 1.22 λ f/d
- R = resolution = $\dfrac{1.22\lambda f}{d} = \dfrac{1.22\lambda f}{n[2f\sin(\alpha)]} = \dfrac{0.61\lambda}{n\sin(\alpha)} = \dfrac{0.61\lambda}{NA} = k_1\dfrac{\lambda}{NA}$
- Where *n* = index of refraction of the material between lens and focal plane (~ 1 for air)
- NA = numerical aperture = *n* sin (α)
- k_1 depends on resist properties and ranges from 0.6 to 0.6

Wavelengths

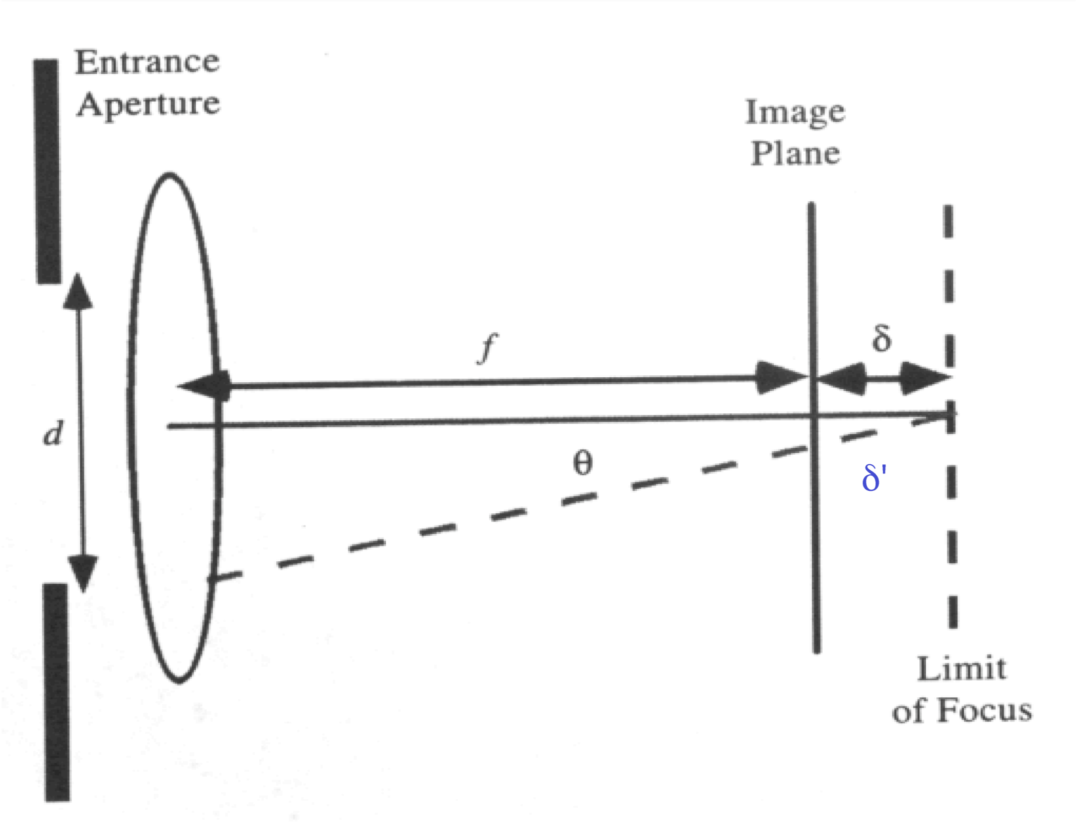


OVER THE RAINBOW

Wavelengths shorter than roughly 157 nanometers are so short they are absorbed by air; such "vacuum ultraviolet" will power the next generation of lithography. Extreme-ultraviolet lithography will go down to 13 nanometers.

(Red Herring, 2000)

Depth of Focus



(Plummer et al)

Depth of Focus

- δ = extra path length along on-axis path at limit to focus ~ δ' cos (θ) where δ' = then the extra path length from edge of lens
- Therefore, we can define DEPTH OF FOCUS such that

$$\lambda/4 = \delta' - \delta'\cos(\theta)$$

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

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

Iff n~1, as it is for air

- Depth of Focus = DOF = $\delta = \pm\frac{\lambda}{2(NA)^2}$

Modulation Transfer Function (MTF)

$$MTF \quad \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$$

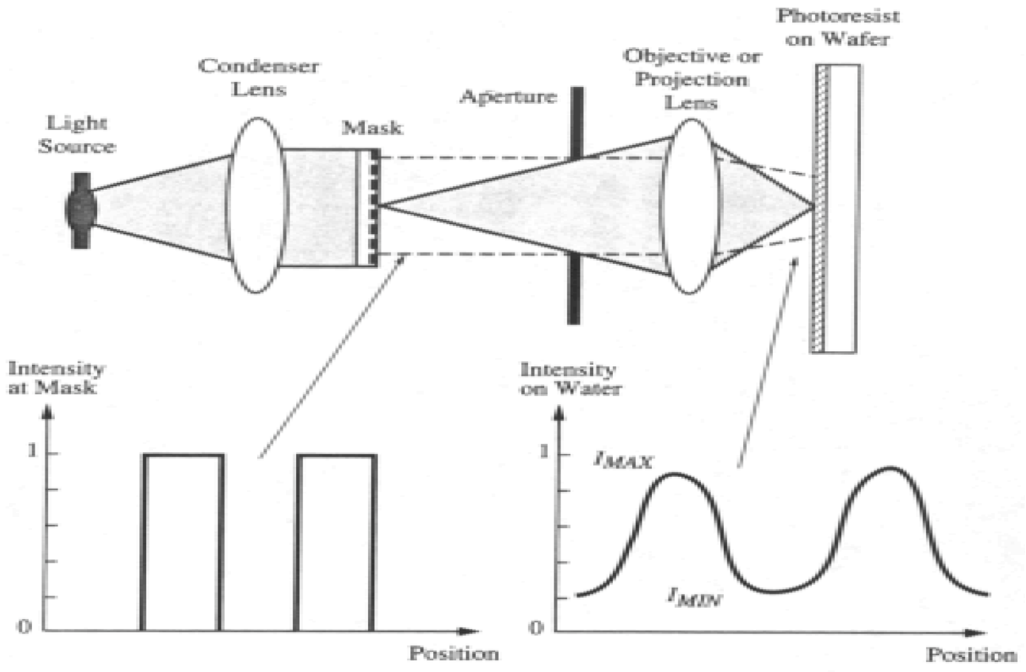


Figure 5–10 Modulation Transfer Function (*MTF*) concept. A generic lithography system is shown at the top with a mask being imaged on photoresist on a wafer. The mask *MTF* is almost ideal (*MTF* = 1) since the feature sizes are 4 – 5 X larger than those imaged in the resist and diffraction effects are minimal. The aerial image *MTF* is much lower (*MTF* ≈ 0.6) because of diffraction effects in the optical system.

MTF vs. feature size

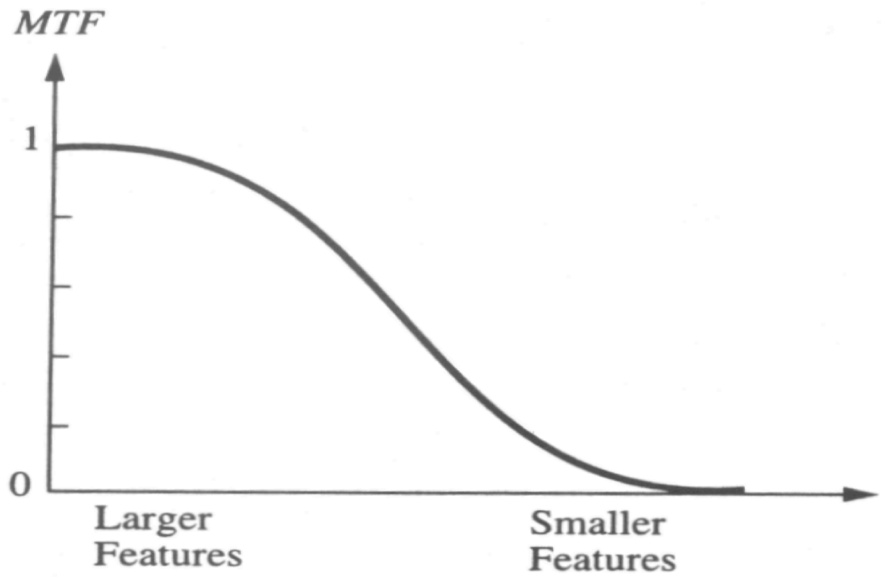


Figure 5–11 Modulation Transfer Function (*MTF*) versus feature size in the image.

(Plummer et al)

Coherent light

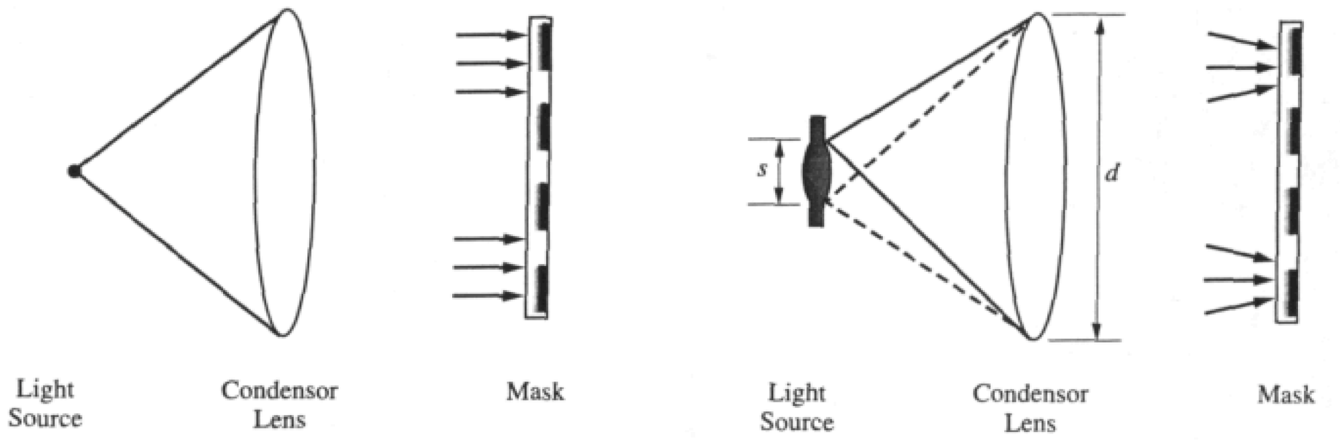


Figure 5–12 Examples of spatially coherent (left) and partially coherent (right) light sources.

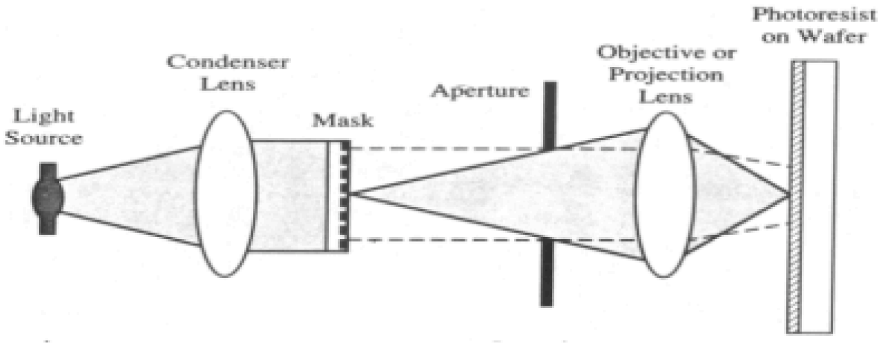
(Plummer et al)

Spatial Coherence

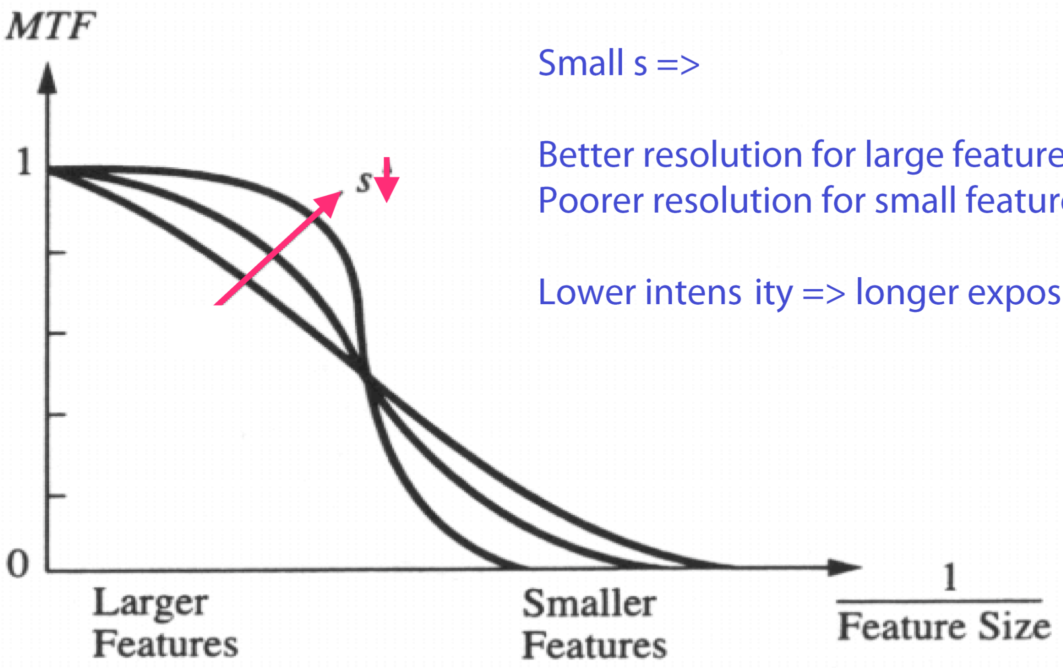
S = spatial coherence of light source

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

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



Feature size dependence



Small s =>

Better resolution for large features
Poorer resolution for small features

Lower intensity => longer exposure

Figure 5–13 Modulation Transfer Function (MTF) versus feature size in the image. As *s* increases (more incoherent source), the MTF degrades for larger features but improves for very small features.

(Plummer et al)

Fresnel Diffraction

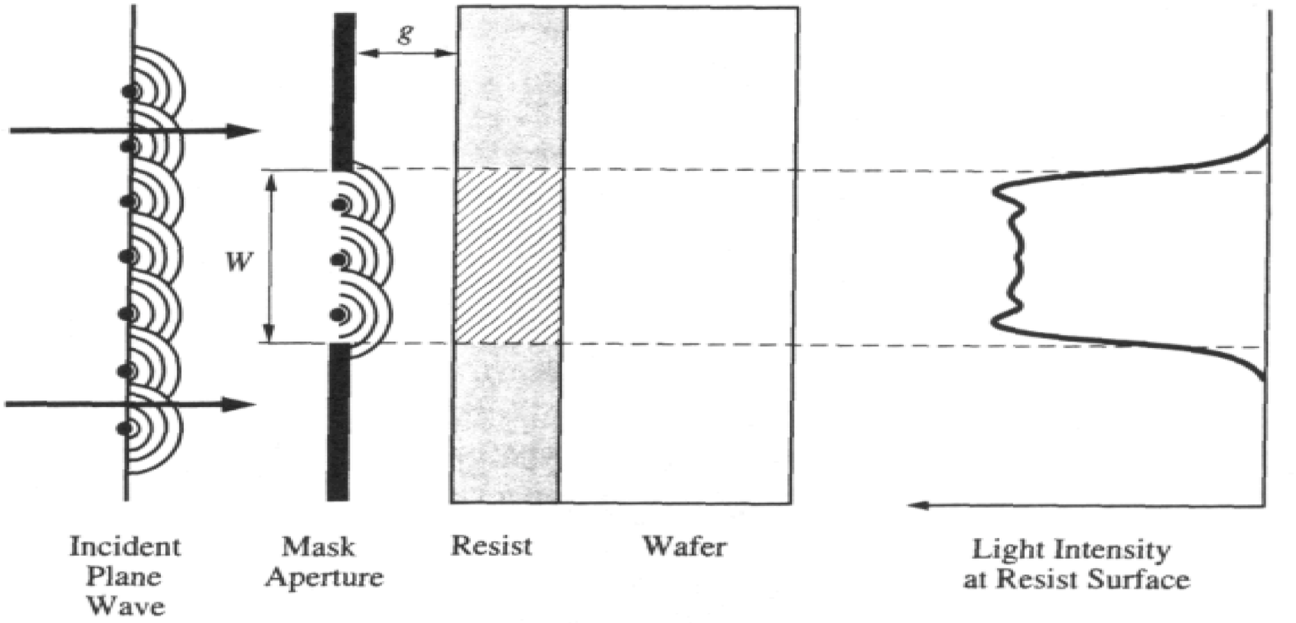


Figure 5–14 Basic contact or near field exposure system illustrating the use of Huygen's wavelets emanating from an aperture in the mask. A mask feature size of *W* is assumed, along with a mask to resist separation of *g*. The resulting light intensity distribution (aerial image) at the resist surface is shown on the right.

(Plummer et al)

Proximity feature size

- For proximity printing, within the fresnel diffraction range

$$\lambda < g < W^2 / \lambda$$

- Where λ = wavelength

  g = gap

  W = size of mask aperture == feature size

$$W \approx \sqrt{\lambda g}$$

Exposure Systems

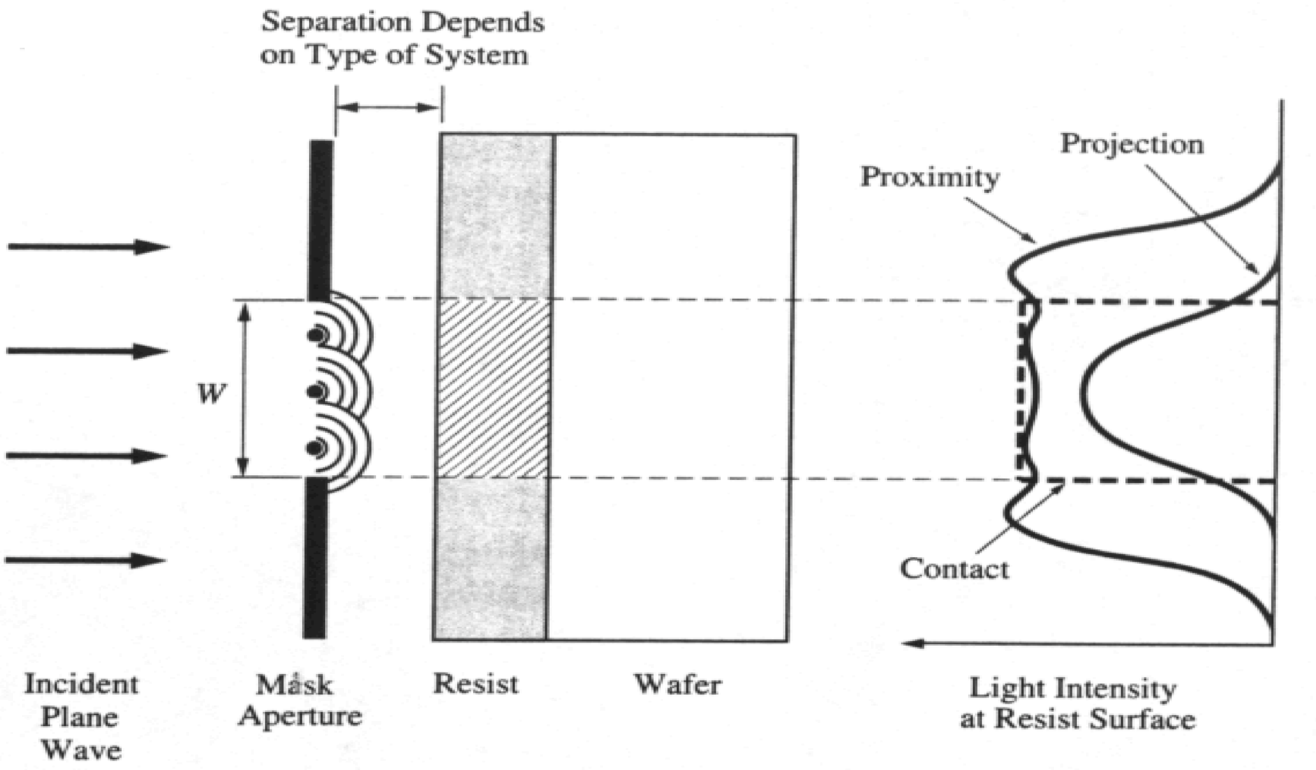


Figure 5–15 Aerial images produced by the three types of optical lithography tools. The mask and wafer would be in hard contact in a contact aligner, separated by a gap *g* in a proximity aligner, and far apart with an intervening focusing lens in a projection system.

(Plummer et al)

Developer

- Basic Developer
  - TMAH (Tetramethyl ammounium hydroxide
  - KOH, or NaOH in H_2O

- Development rate: 100-200 nm/s

- Basic Properties
  - Contrast γ
  - Critical Modulation Transfer Function

Contrast

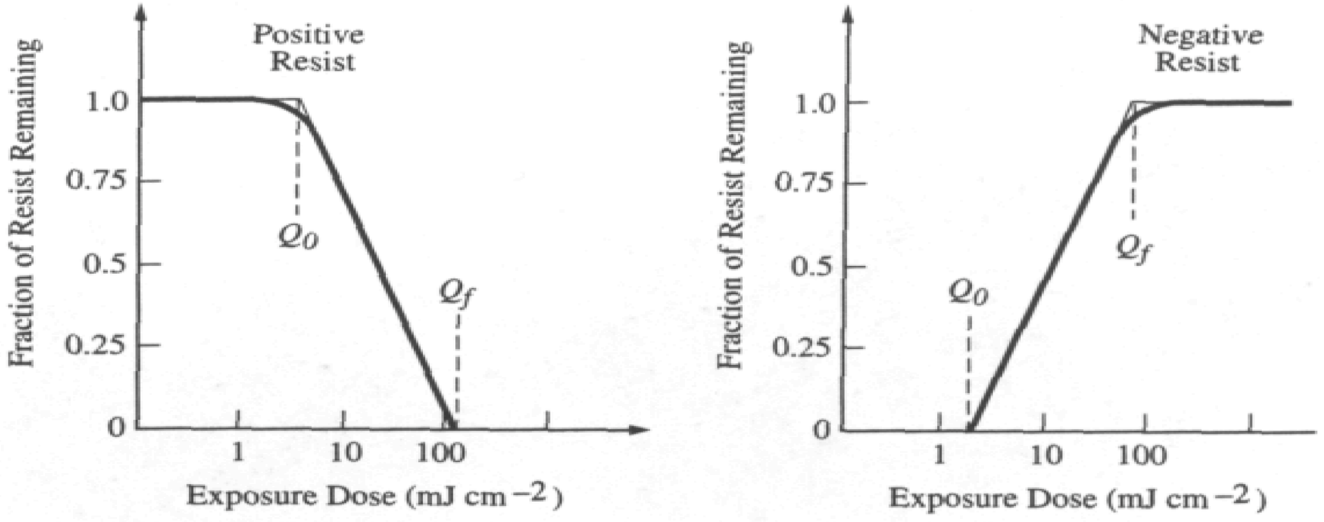


Figure 5–20 Idealized contrast curves for positive and negative resists.

$$\text{contrast}\ \gamma \quad \frac{1}{\log_{10}\frac{Q_f}{Q_o}}$$

g-line and i-line resists: γ~2 to 3 Q_f~100mJ/cm^2

(Plummer et al)

Critical MTF

Critical MTF = CMTF ~ minimum optical transfer function to resolve pattern in resist

$$\text{CMTF} = \frac{Q_f - Q_o}{Q_f + Q_o} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1}$$

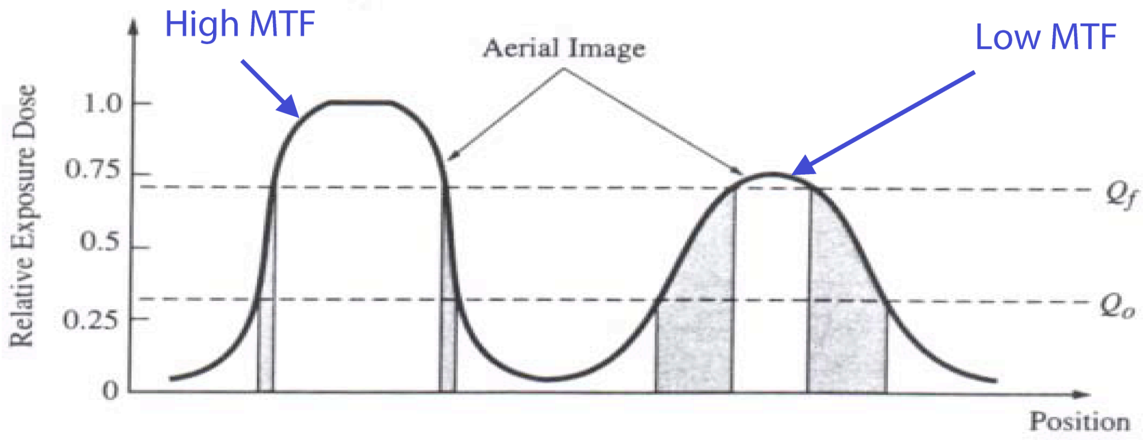


Figure 5–21 Example of how the quality of the aerial image and the resist contrast combine to produce the resist edge profile. The left side shows a sharp aerial image and steep resist edges (gray area). The example on the right shows a poorer aerial image and the resulting gradual edges on the resist profile.

Higher contrast leads to sharpening, and allows imaging of poorer aerial images

(Plummer et al)

Loss of Resolution

topography and reflection causes loss of resolution
hence CMP and anti-reflection coatings

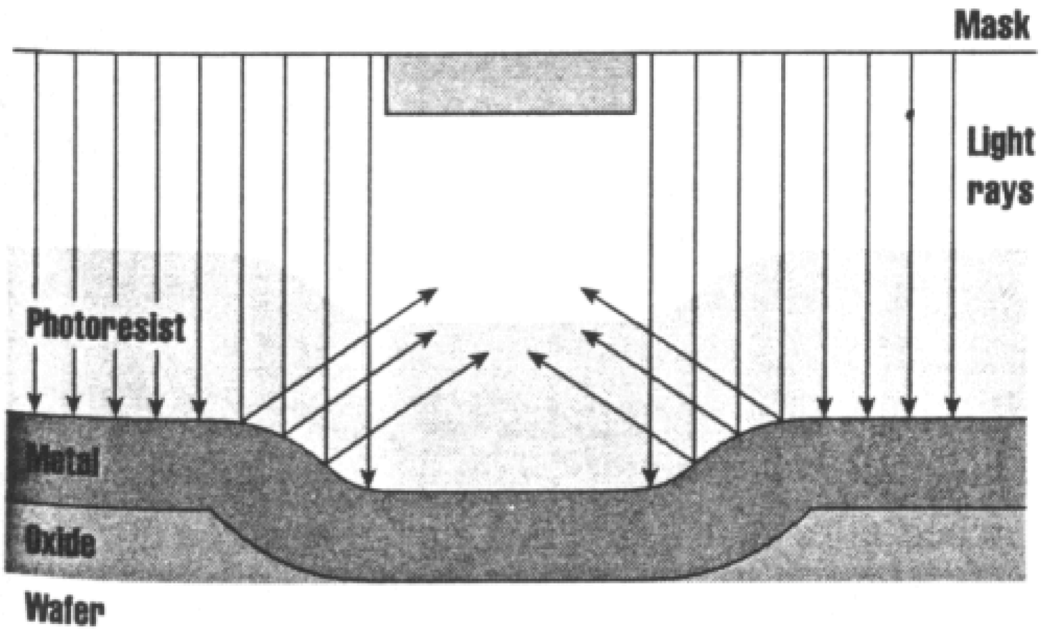


Figure 7-24 Light from the exposed regions can be reflected by wafer topology and be absorbed in the resist in nominally unexposed regions.

Optical Proximity Correction

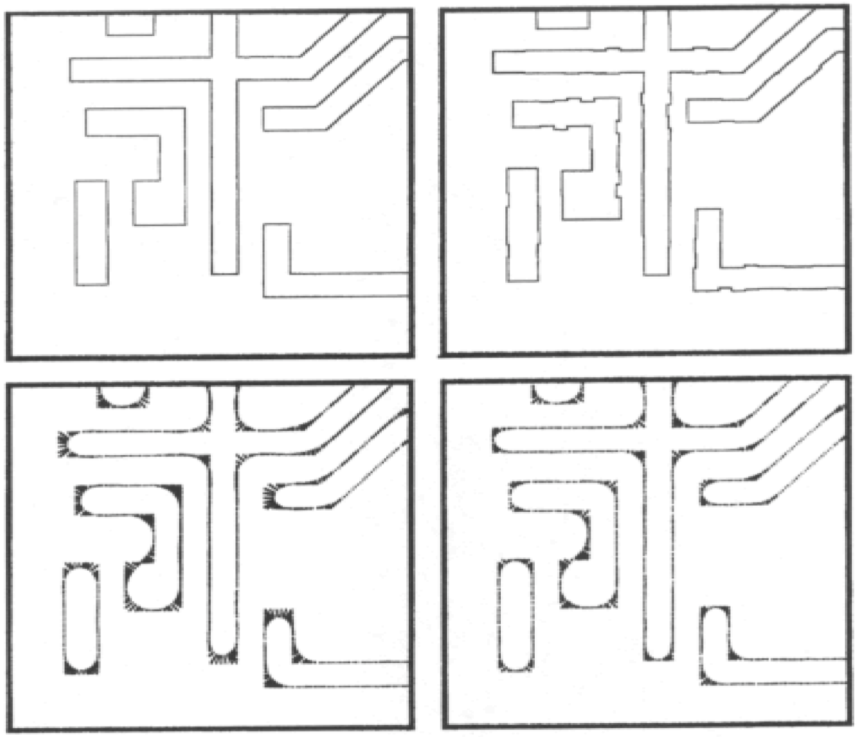


Figure 5–25 Mask patterns with (right) and without (left) OPC are shown on the top. The corresponding aerial images (calculated) are shown on the bottom. Note the improvement in the quality of the aerial image when OPC is used. The dark lines in the bottom patterns indicate the difference between the mask and aerial image in each case [5.13]. Reprinted with permission of SPIE.

(Plummer et al)

Other Patterning Techniques

- Imprinting and Hot embossing
- Laser Photoablation
- Nanoimprint Lithography
- Soft Lithography
- E-beam Lithography
- X-ray Lithography (LIGA)

E-beam lithography

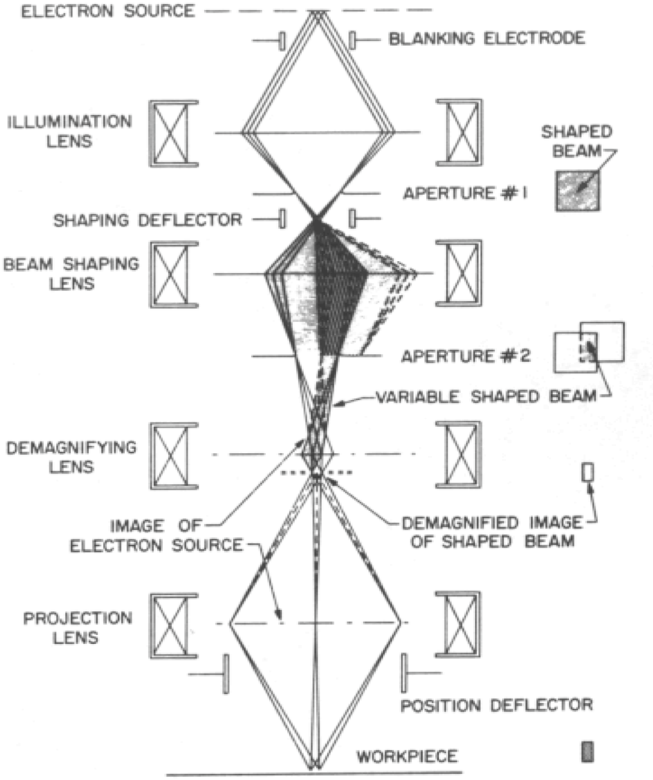


FIGURE 19
JEOL JBX6A3 electron optical system.

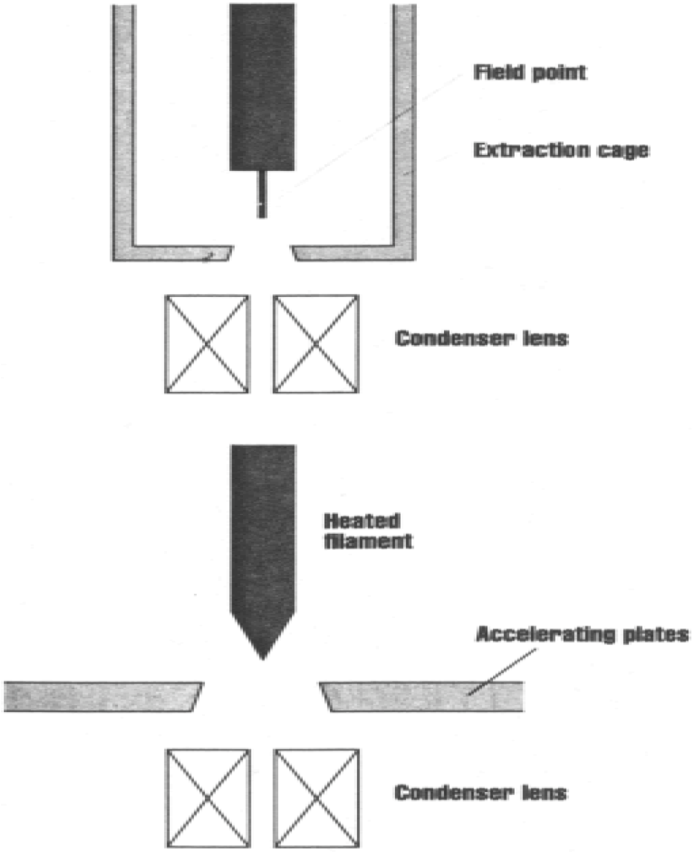


Figure 9-4 Simplified cross section schematics of field emission and thermionic emission electron guns.

E-beam lithography

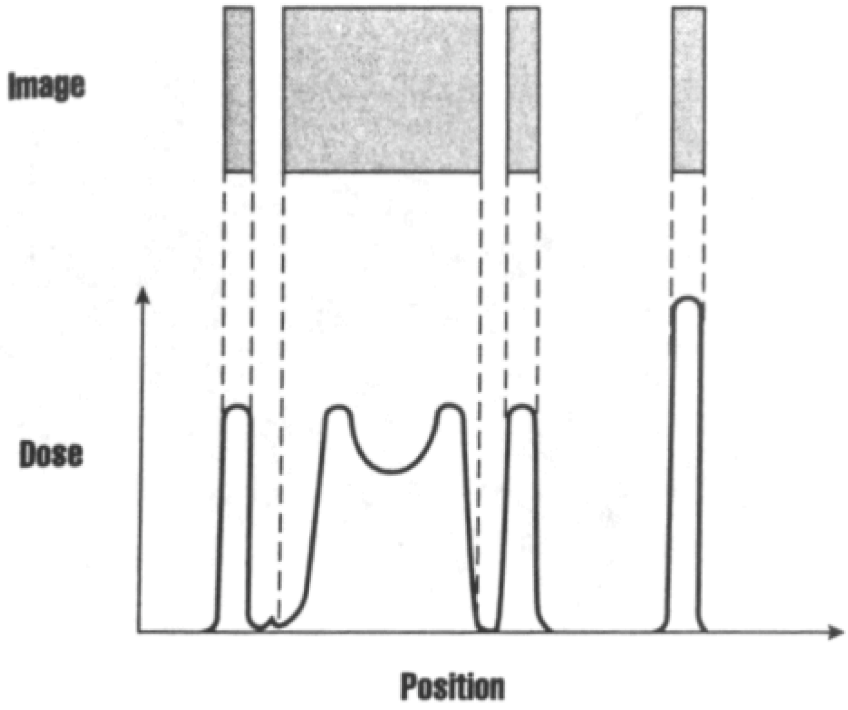
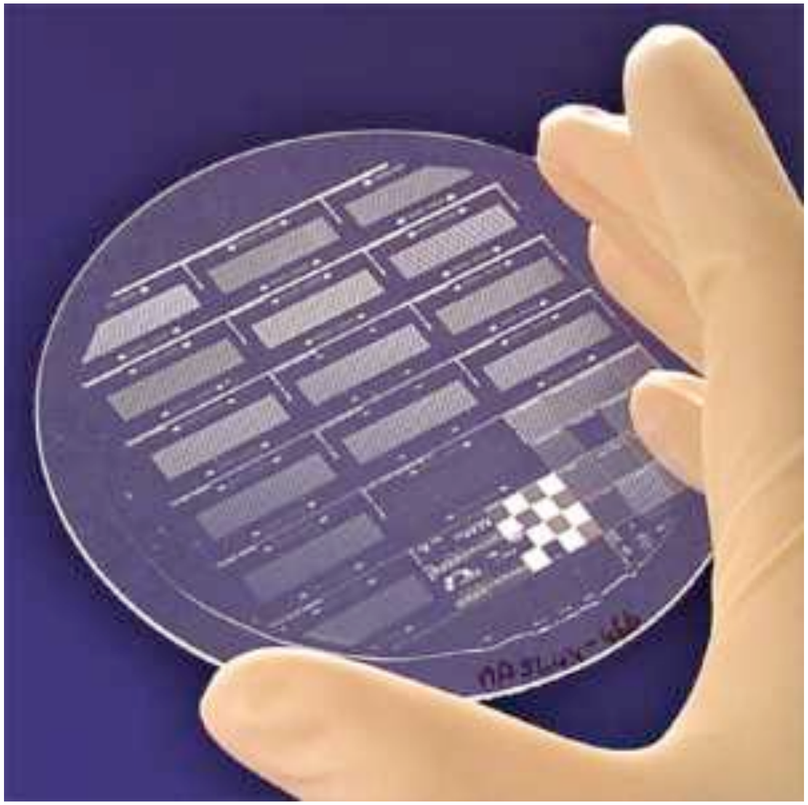


Figure 9-11 Small and large figures to be patterned with EBL requires position dependent dosage to compensate for proximity effects.

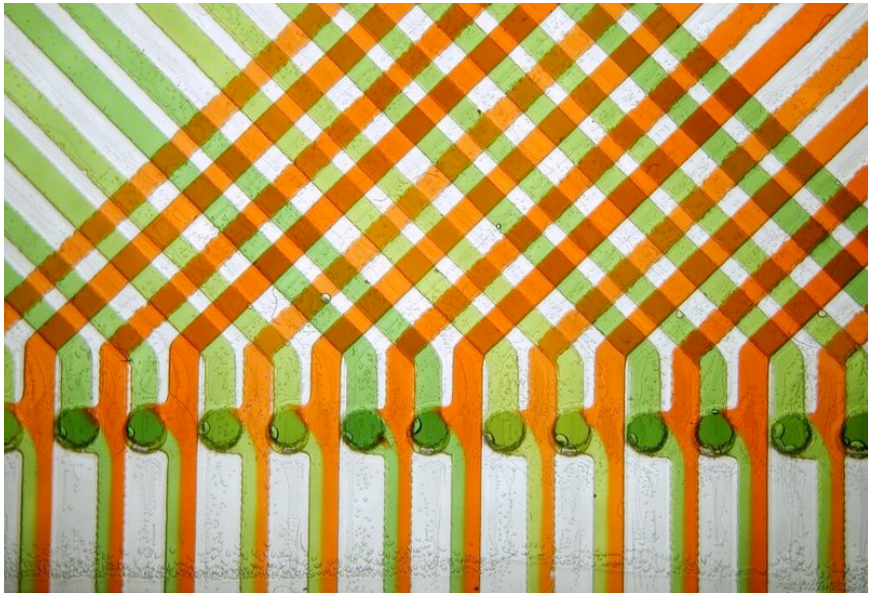
Imprinting/Embossing

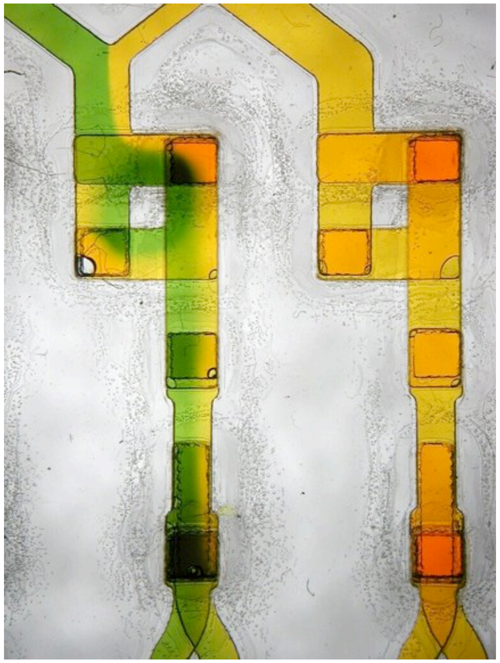
- Stamp made in Si or metal
- Stamp pressed on plastic to form microfluidic channels
- Many common plastics successfully imprinted



Soft Lithography

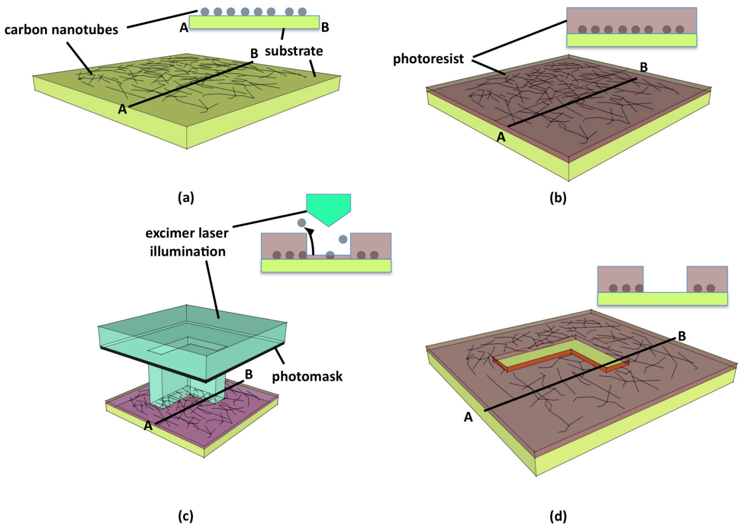
- Elastomeric polymer (PDMS) cast in a Si stamp and cured
- Polymer is peeled off
- Channel architecture thus transferred to the polymer
- PDMS technology is becoming popular

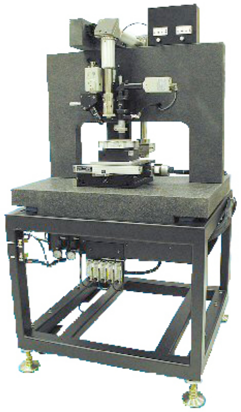




Laser Photoablation

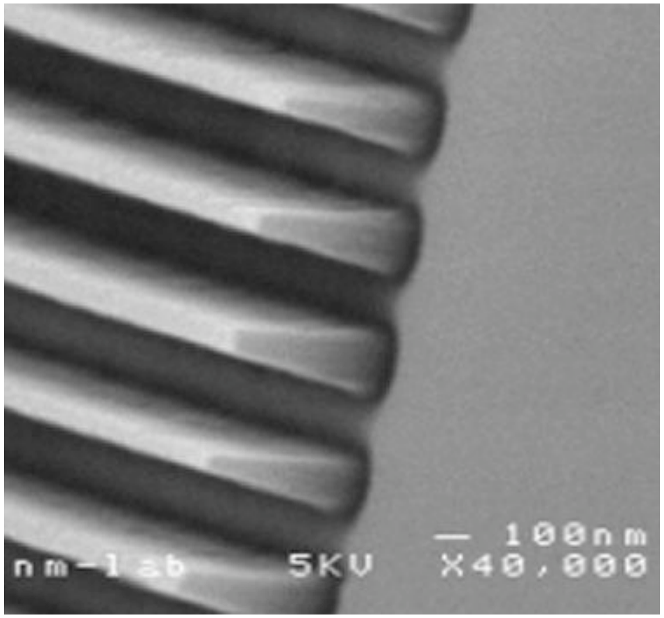
- High aspect ratio channels achievable
- Laser pulses in the UV region used
- Sealing by thermal lamination with a PET/PE film at 125C
- Depth controllable

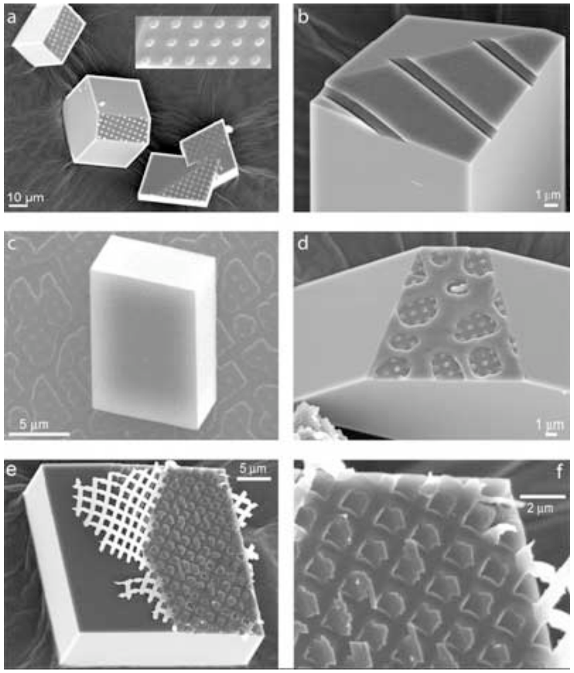




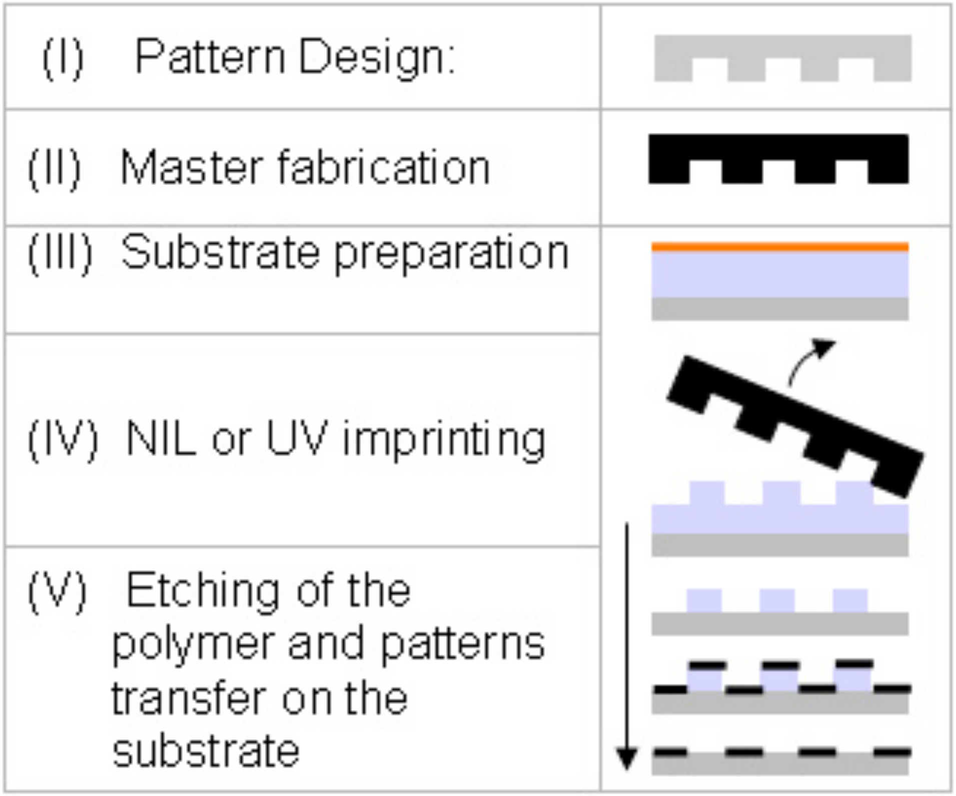
Nanoimprint Lithography

- Creates patterns by mechanical deformation of imprint resist
  - Resist is monomer of polymer that is cured by heat or UV during the imprinting
  - Adhesion between resist and template carefully controlled

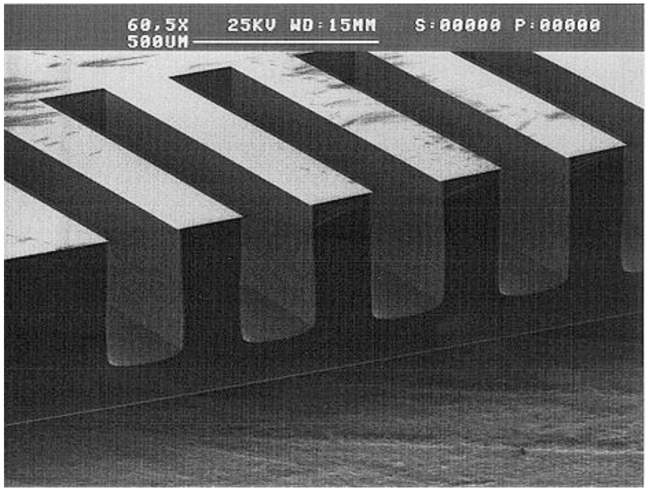


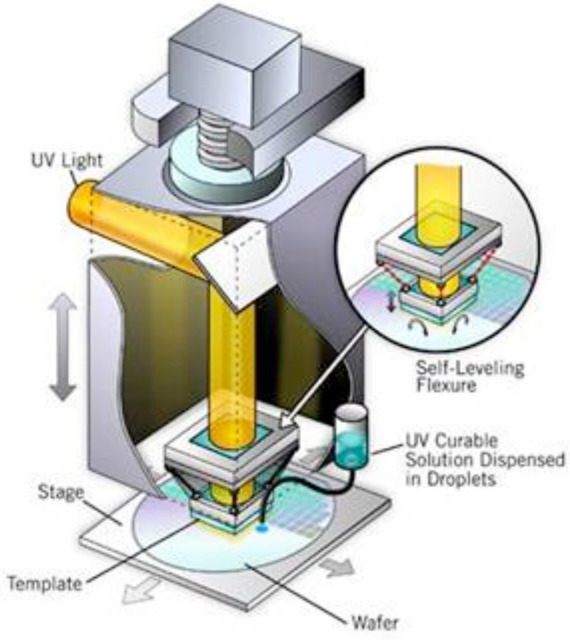


Nanoimprint Lithography



- (I) Pattern Design:
- (II) Master fabrication
- (III) Substrate preparation
- (IV) NIL or UV imprinting
- (V) Etching of the polymer and patterns transfer on the substrate

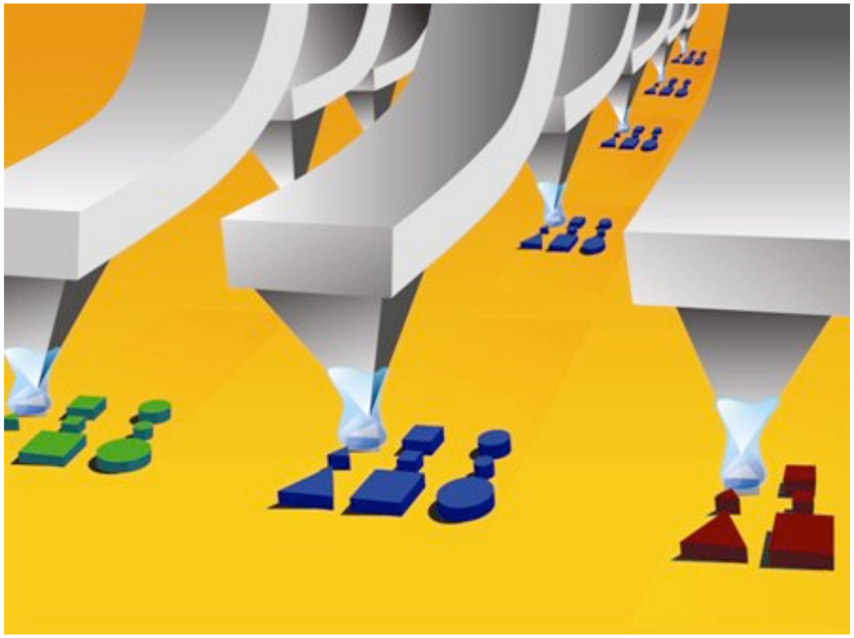




Double-sided aligned lithography

- Goal: align features on the back of the wafer to features on the front
  - Common requirement in bulk micromachining
  - Not a standard IC capability
  - Functionality more common as market grows
- What you need:
  - Double side polished wafer
  - Double sided alignment tool
    - IR alignment, registration to global fiducials in the tool, through holes, etc.

Dip-Pen Lithography

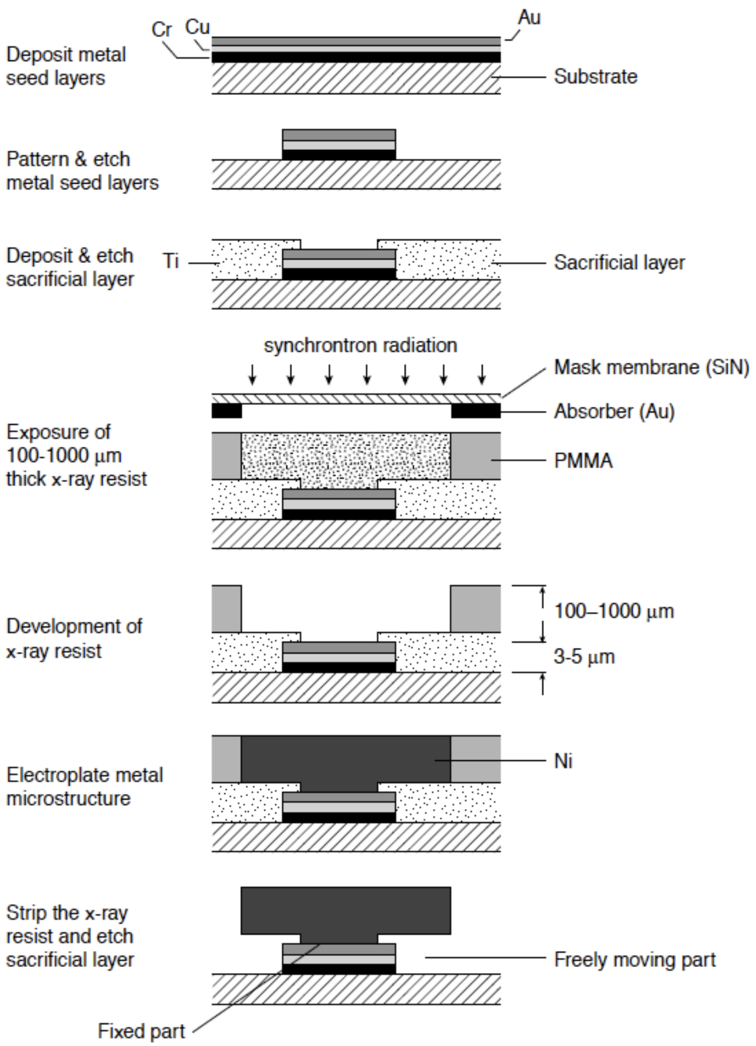


- Scanning Probe lithography where AFM tip transfers molecules to surface
- Uses meniscus from solvent
- Cantilever = pen
- Allows direct deposition

X-Ray lithography

- Mask generation using e-beam lithography
- Au instead of Cr as absorber requires different mask processing
- Poor depth of focus requires contact printing
  - Mask heating and radiation damage leads to distortion
  - Mask wear is an issue
- X-ray litho allows for LIGA – Lithographie, Galvanoformung, Abformtechnik – lithography, electrodeposition and molding – high aspect ratios, deep trenches in polymer masks
- Subsequently fill with electrodeposited metals

LIGA Process Flow



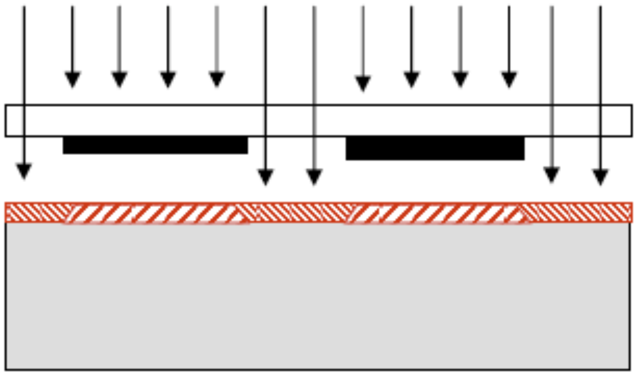
- Need electrically conductive sbstrate
- Good adhesion for resist (typically PMMA)
- Metal plates (SS, Cu/Ni, Au or Ti)
- Si wafer with Ti or Ag/Cr conductive top layer

Details that matter for lithographic processing

- Existing topography: if your existing feature heights are comparable to or greater than the thickness of the resist that you are putting down, you will not have good coverage
  - Incompletely covered sidewalls, holds full of resist, resist that never enters a hole at all
  - Solutions: eliminate the topography, thicker resist, alternate coating technology (spray on, electrophoretic resist?), use of a previously patterned hard mask instead of a resist mask
- Patterned resist does not have a square profile – can affect the topography of whatever you pattern with the resist
- Resist adhesion
  - If the surface of the wafer is hydrophilic (like SiO2), the resist might peel during subsequent wet processing steps.
  - Surface preparation is key (e.g. dehydration bake and HMDS coating to render surface hydrophobic)

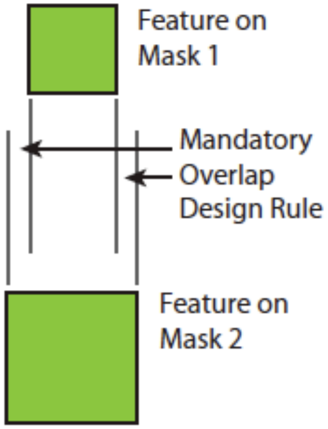
Another important detail: process bias

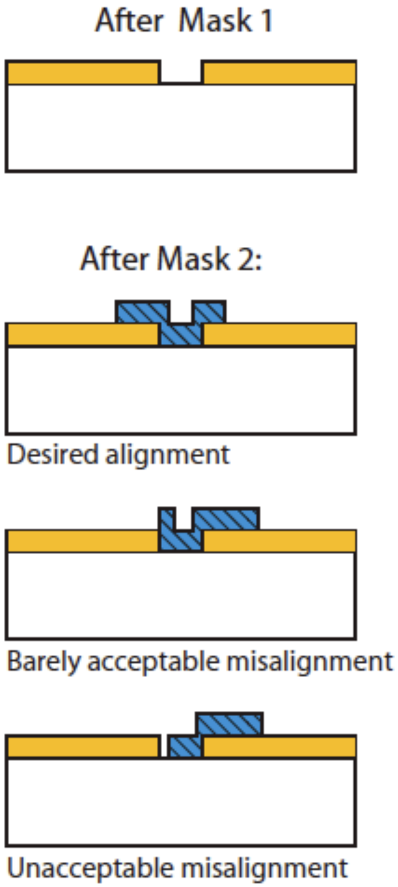
- The feature drawn on the mask is NOT the same size as the feature produced on the wafer
- Exposed area usually extends beyond clear area on mask
- Resist selection impacts process bias
  - ➢ Resist thickness
  - ➢ Resist Tone



Design Rules

- Alignment of one pattern to the next is critical to device fabrication
- Design rules are created to assure that fabrication tolerances do not destroy devices





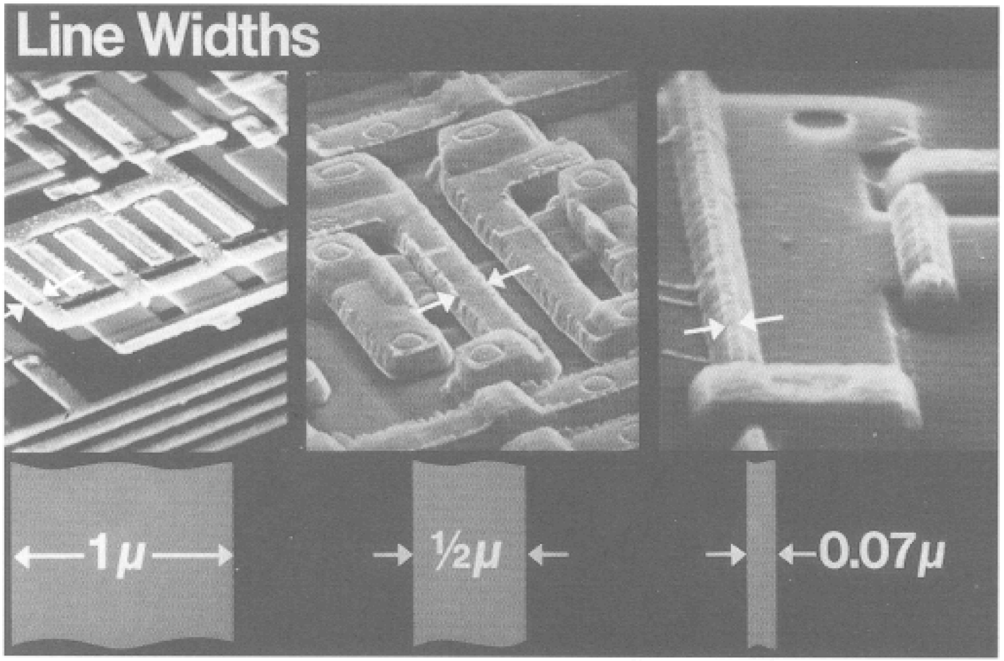
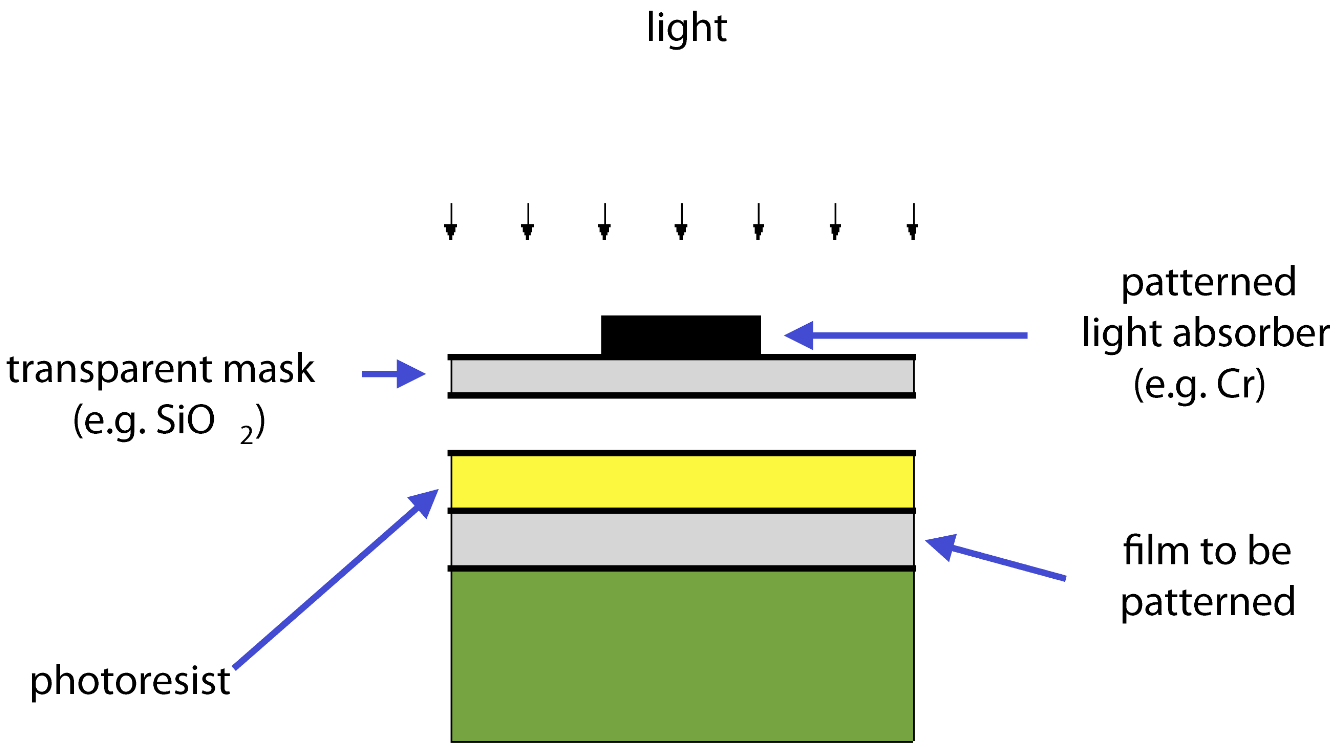


Fig. 1-6 Shrinkage in the aluminum interconnection linewidth in high device density IC chips. Courtesy of P. Chaudhari, IBM Corp.



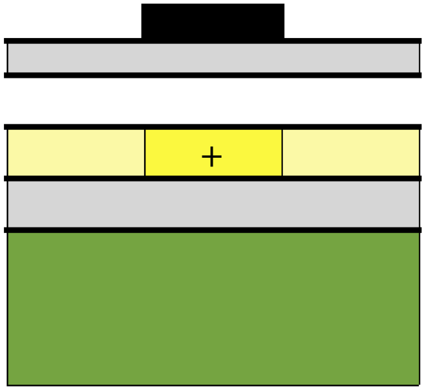
light

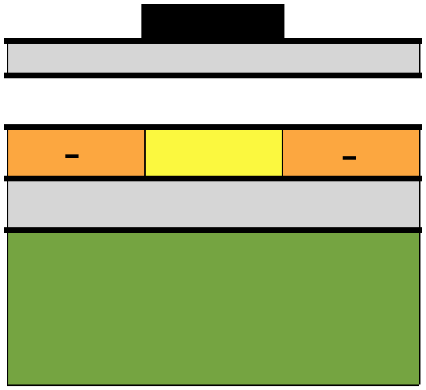
transparent mask
(e.g. SiO_2)

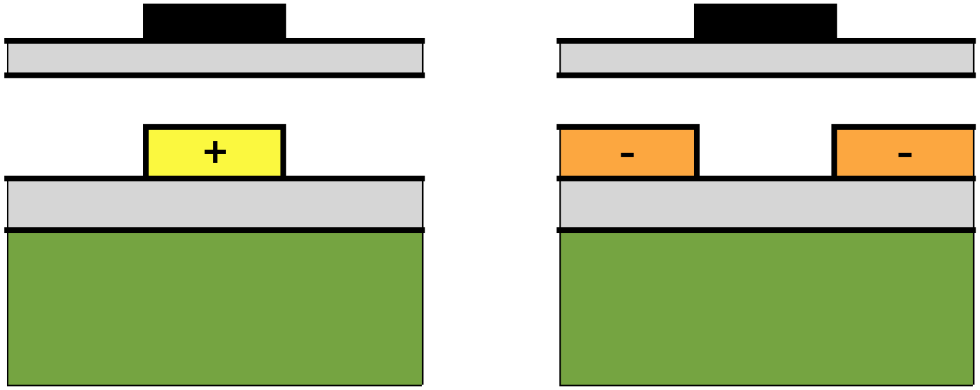
patterned
light absorber
(e.g. Cr)

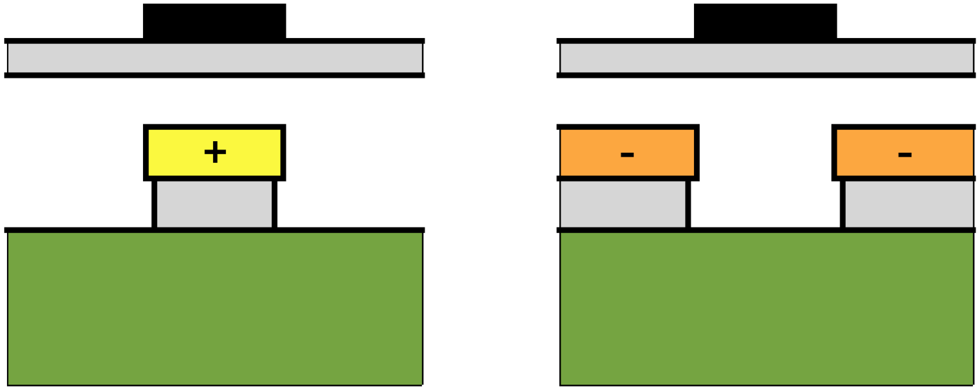
photoresist

film to be
patterned

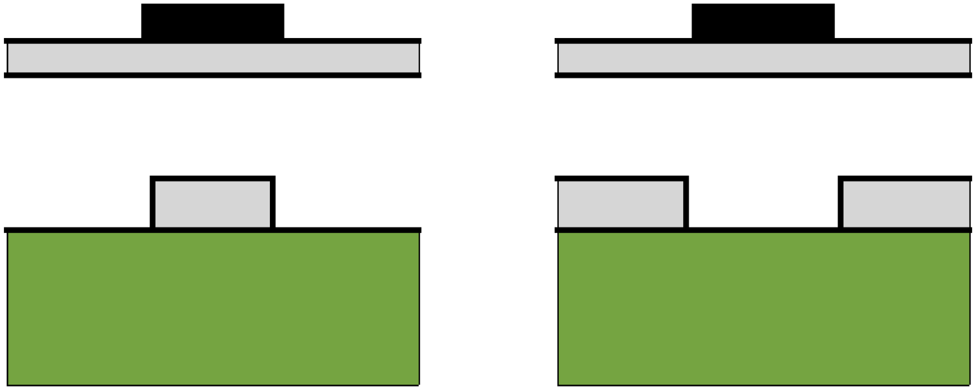








subtractive patterning



Special purpose lithographic techniques 2

- Shadow masking
  - ➢ Direct evaporation or sputtering through physical holes in a shadow mask (think stencils)
  - ➢ Back end/everything else process
  - ➢ "Last ditch" technique for patterning surfaces that cannot be coated with resist (large topography, fragile features)
- "Soft lithography"
  - ➢ Using PDMS as a physical mold to replicate structures
  - ➢ Advantages:
    - Patterning curved surfaces
    - Rapid, inexpensive fabrication