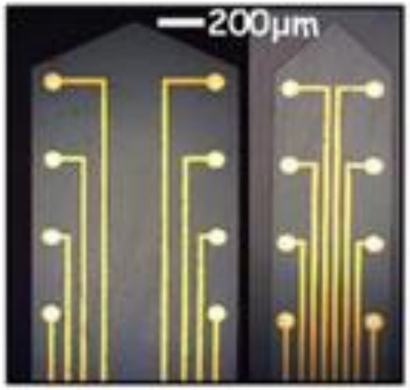
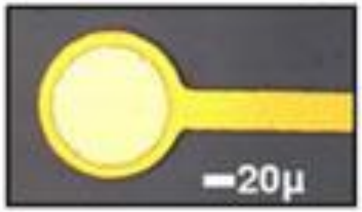
Current Microfabrication and Nanofabrication Technologies

One of the microfabricated devices shown next to a US penny for size comparison.



Photomicrographs of two different electrode arrays and a <u>recording electrode</u>

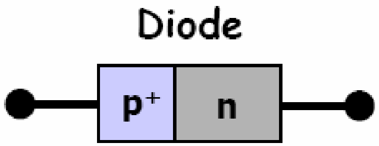


🟧 parylene-insulated
🟨 exposed gold

A Brief History of Microfabrication

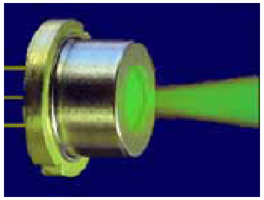
Microfabrication: creation of structures on the micrometer scale
Nanofabrication: creation of structures on the nanometer scale

Electronic Devices (1960 – Present)



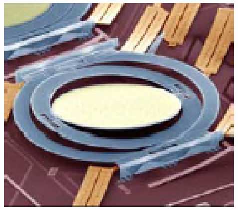
- 1960: single or <10 elements on one 1-2mm chip
- Today: billions (10^9) of elements on one 20x20mm chip
- Germanium (Ge) to Silicon (Si)

  Advantages: easy growth of insulating oxide layers; excellent barrier to diffusive processes.



Optical Devices (1970 – Present)

- Active devices: detectors (PIN), sources (LED, LD), modulators
- Passive Devices: Lenses, waveguides, diffractive optics



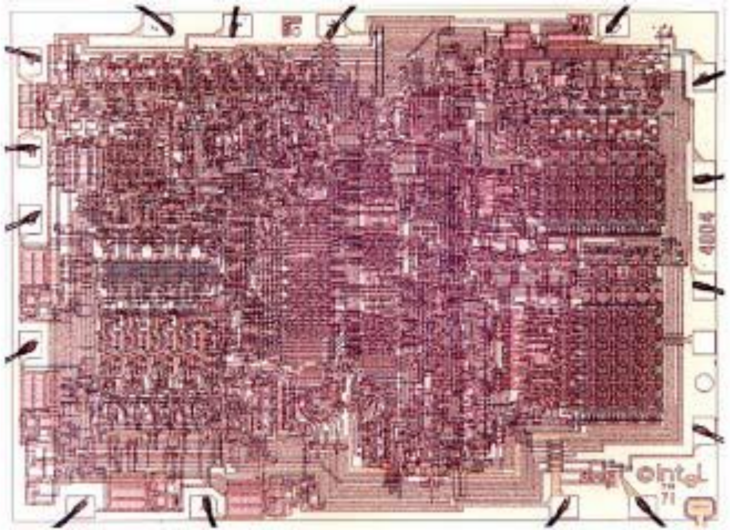
MST News, No. 3/00, pp. 6-9, June 2000

Microelectromechanical Devices (MEMS) (1980 – present)

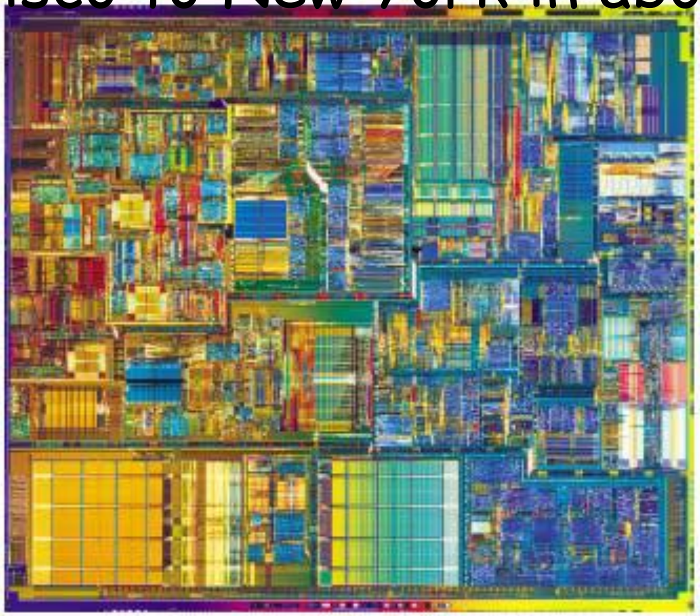
- Multiple types of actuation: rotational, torsional, lateral, vertical
- n be combined with other technologies: optics, fluidics, etc.

A Brief History of Microfabrication

Intel's first microprocessor, the 4004, ran at 108 kilohertz (108,000 hertz), compared to the Intel® Pentium® 4 processor's initial speed of 1.5 gigahertz (1.5 billion hertz). If automobile speed had increased similarly over the same period, you could now drive from San Francisco to New York in about 13 seconds.



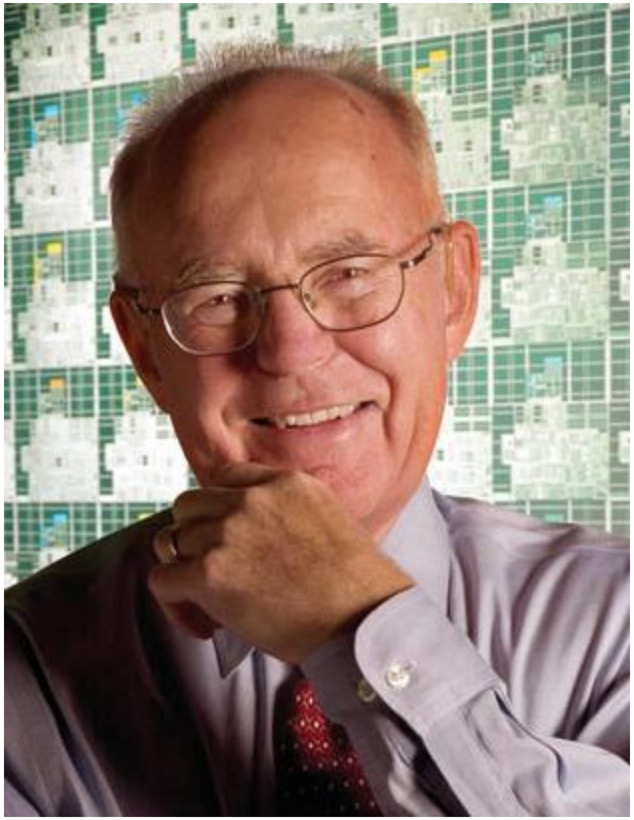
1971: The 4004

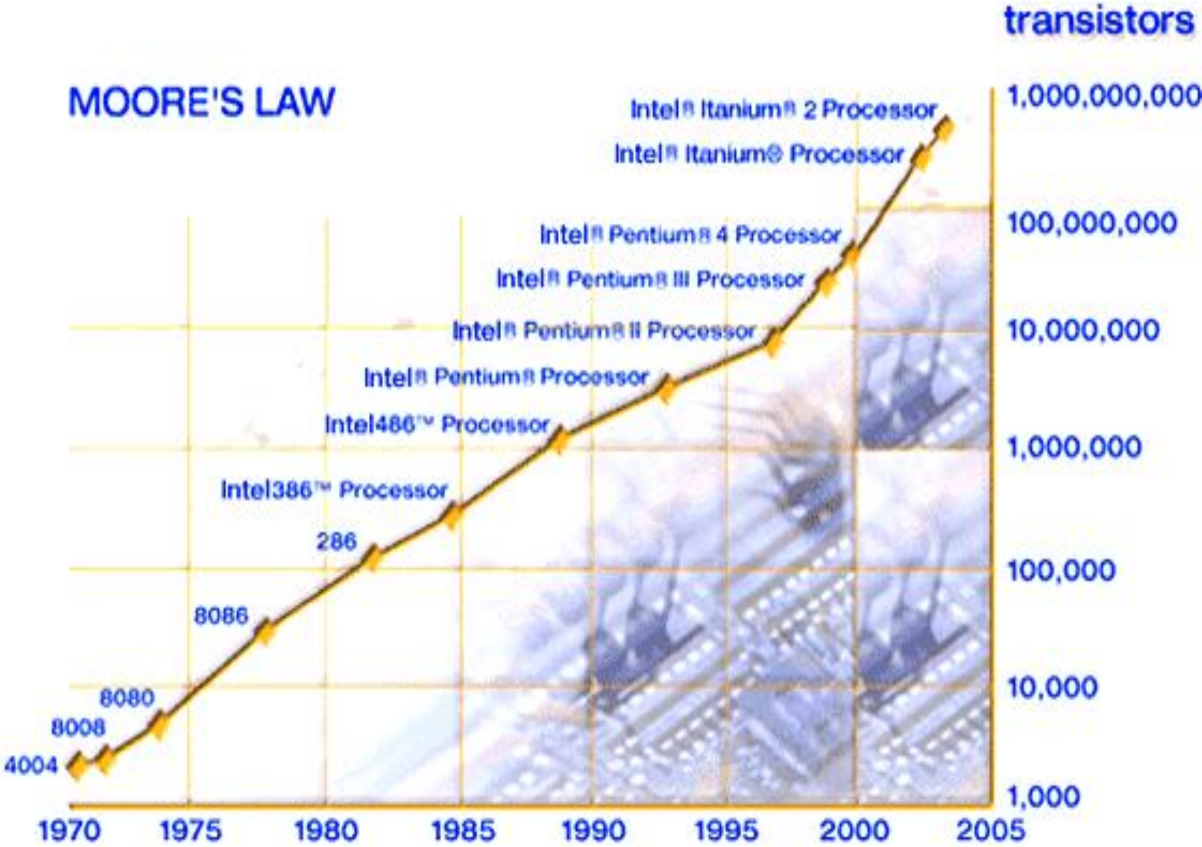


2000: The P4

(Courtesy http://www.intel.com/intel/intelis/museum/online/hist_micro/hof/)

Moore's Law



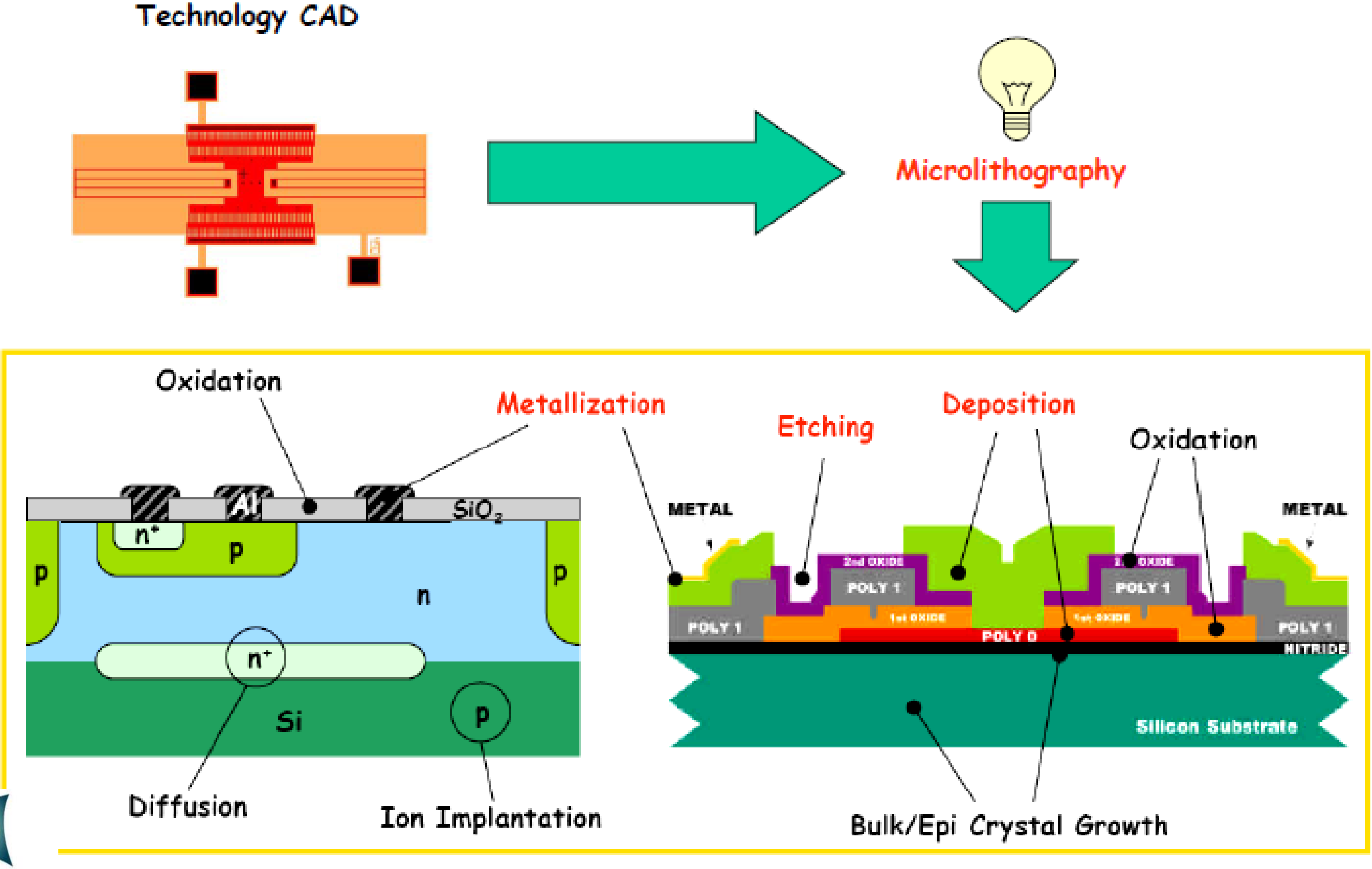


Gordon Earle Moore (1929~)

The number of transistors on a chip doubles about every 2 years.

(Courtesy http://www.intel.com/technology/silicon/mooreslaw/index.htm)

The Big Picture



Photolithography

Microlithography: transfer and registration of micron scale patterns to a common substrate from a master mask pattern.

- Allows selective application of additive and subtractive processes, as well as 3D structures within device layers.
- MOST CRITICAL STEP! Pattern transferred, even if incorrect, is replicated into underlying layer.
- Performed using an optical aligner.
- Aligner performance measures:
  - ♦ Resolution: minimum feature size that can be transferred.
  - ♦ Registration: overlay accuracy from layer to layer.
  - ♦ Throughput: wafers per hour; a trade off btw throughput and high resolution/registration accuracy.

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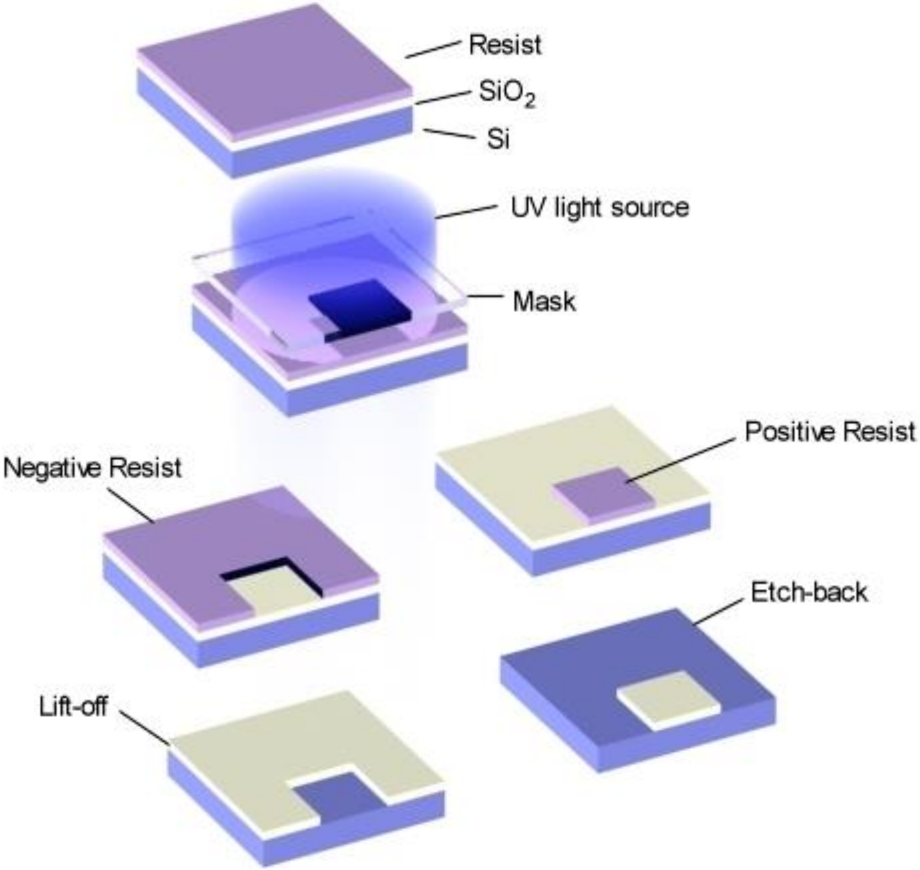
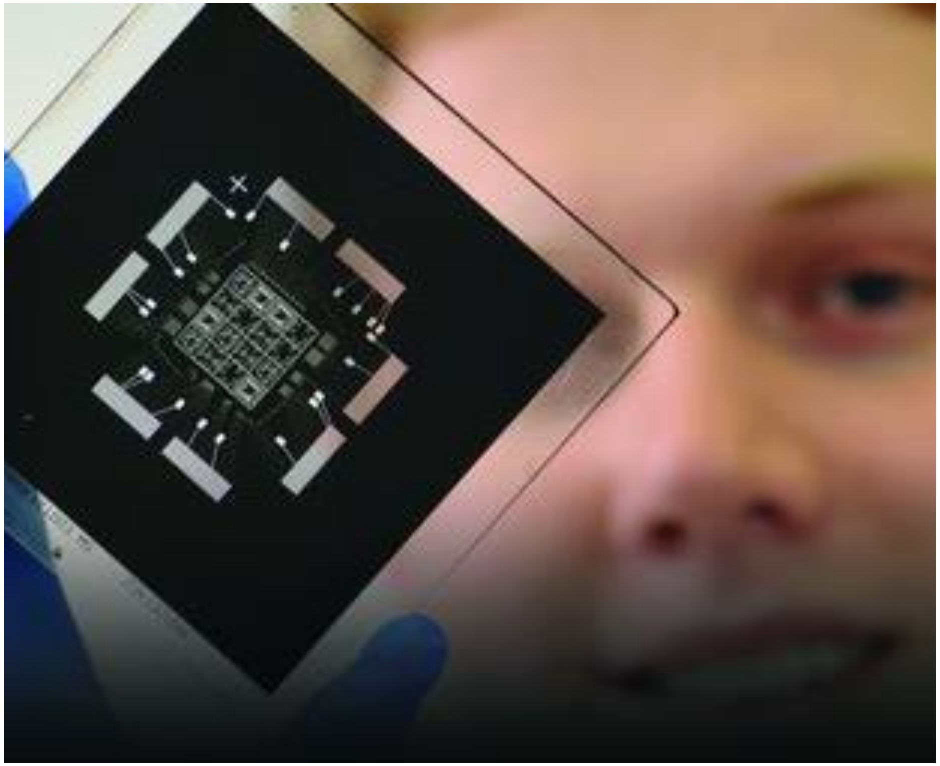
Photolithography





Photomask

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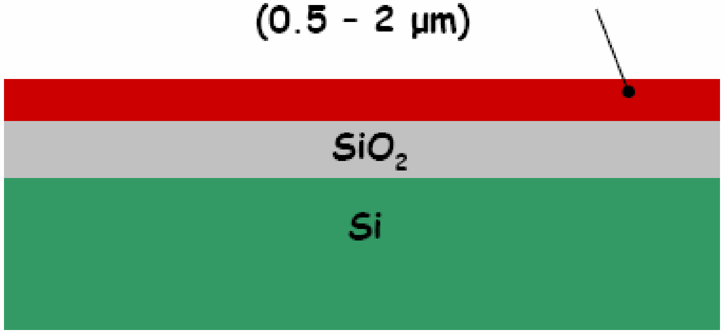
Photolithography –Process Overview (1)

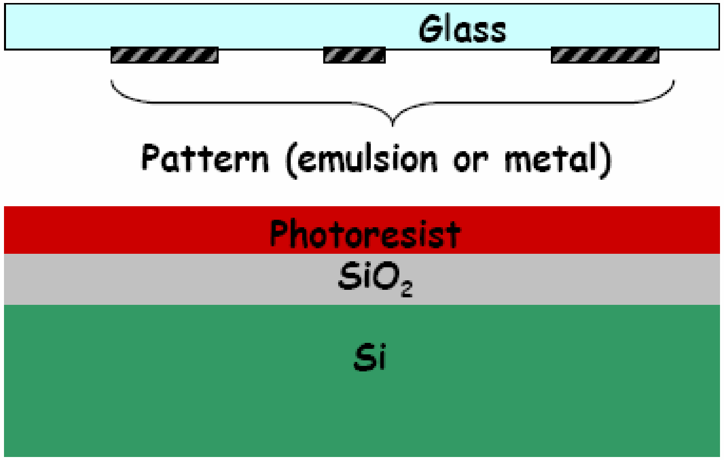
Clean substrate to promote adhesion
(multi-step chemical clean & bake)
Possibly add adhesion promoter

Spin/spray application of photoresist
(0.5 - 2 μm)



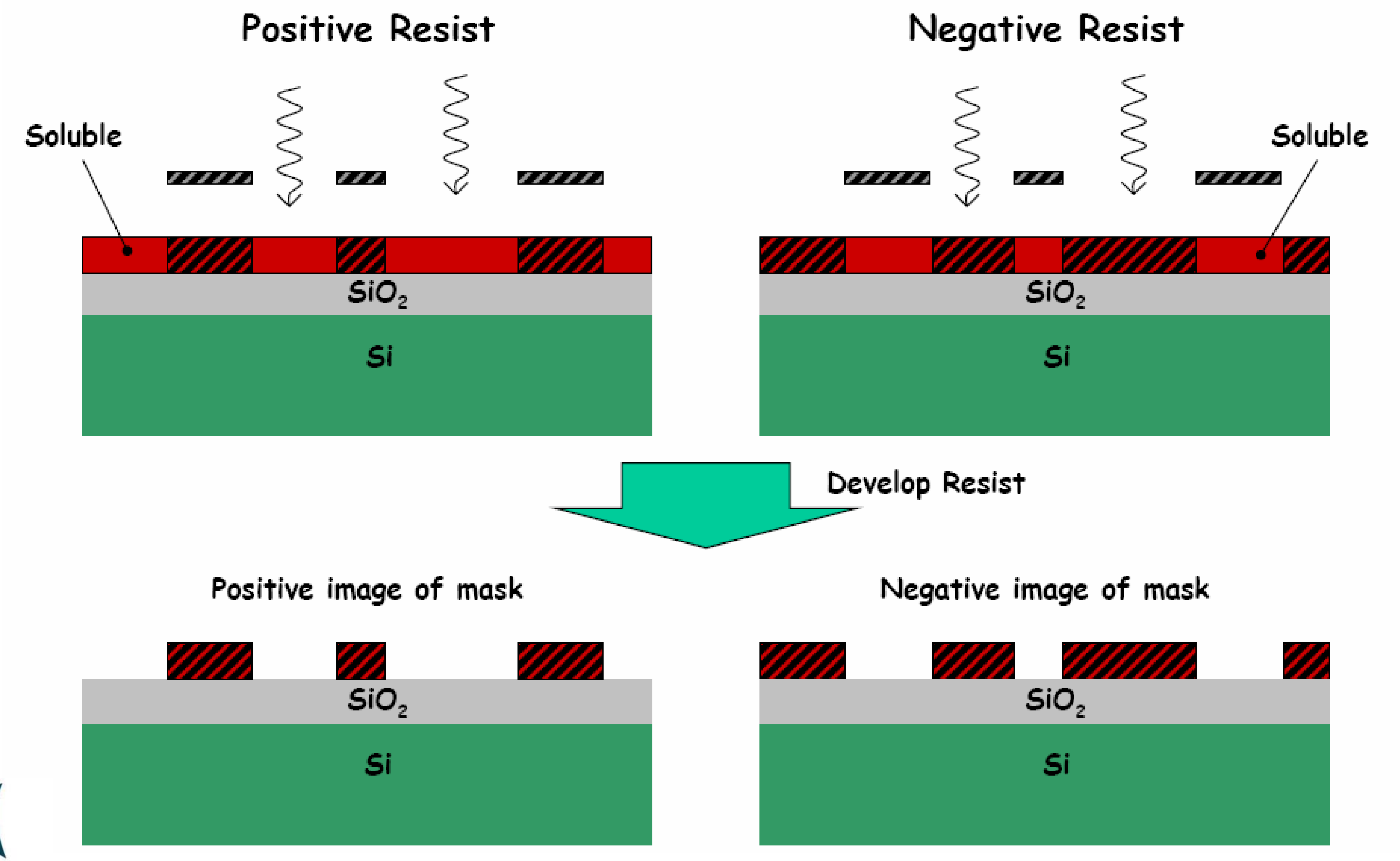
Pre-exposure bake
(1 min. on ~90° C hotplate)

Position mask over substrate using
mask aligner



Expose to UV source

Photolithography -Process Overview (2)

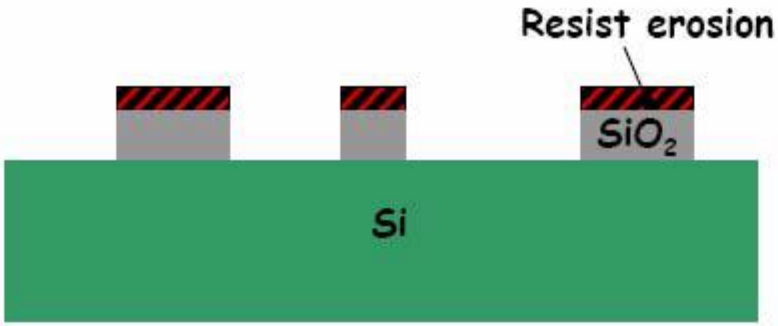


Photolithography -Process Overview (3)

Post-exposure bake
(30 min. in ~130°C oven)

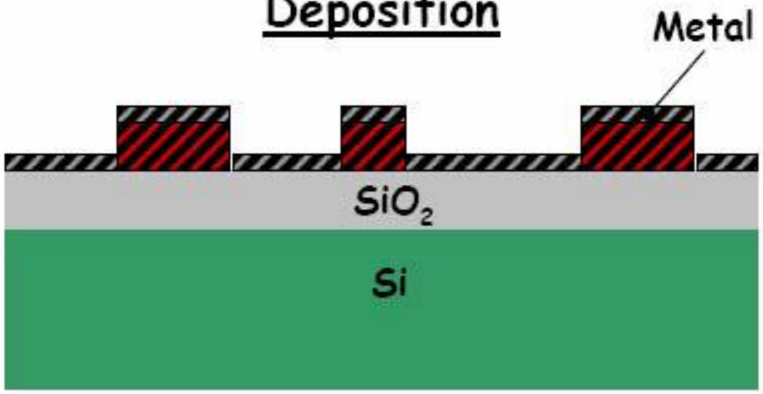
Use resist as a physical mask

Etching



- Resist must adhere
- Resist must withstand etch

Deposition

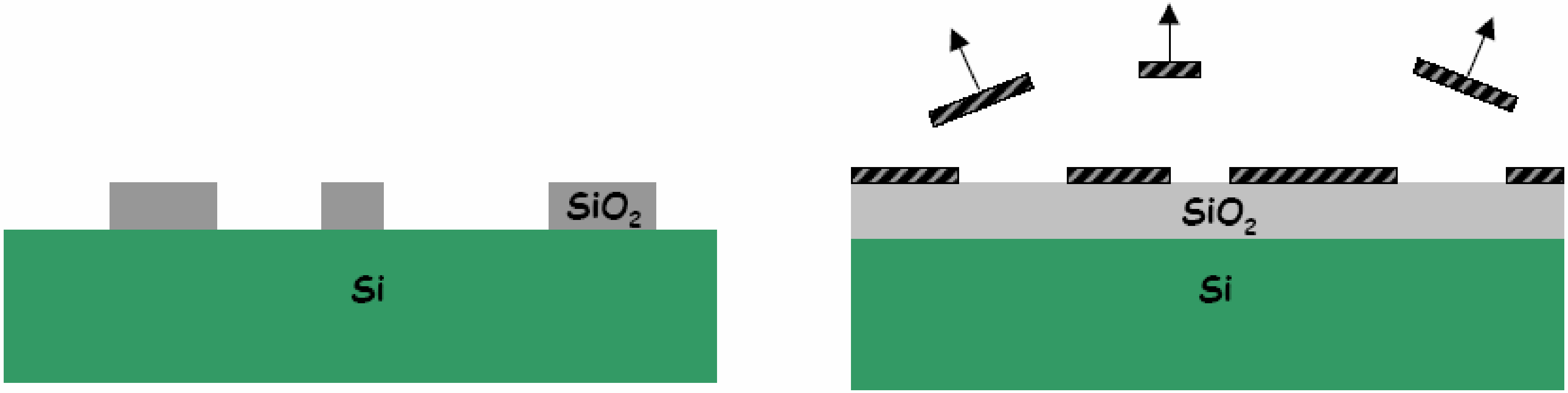


- Allows for **liftoff**

Photolithography -Process Overview (4)

Strip Resist

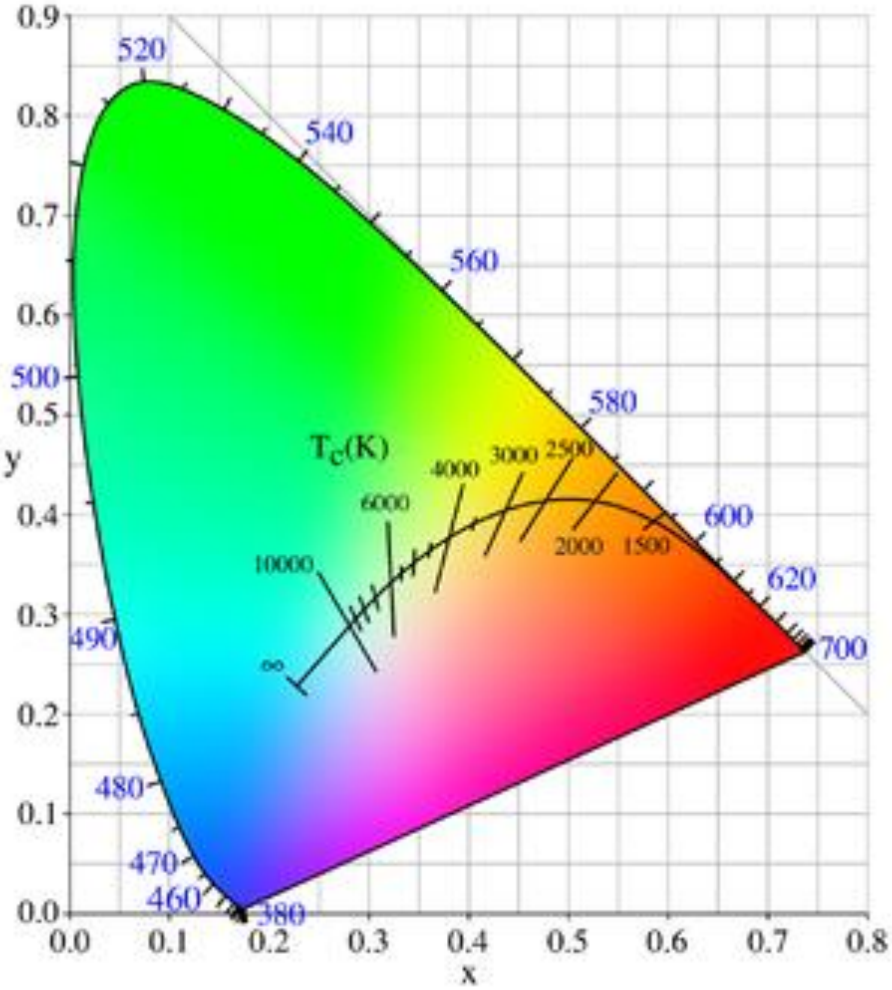
(dissolve using acetone or O_2 plasma)



- Anisotropic (unidirectional) etch

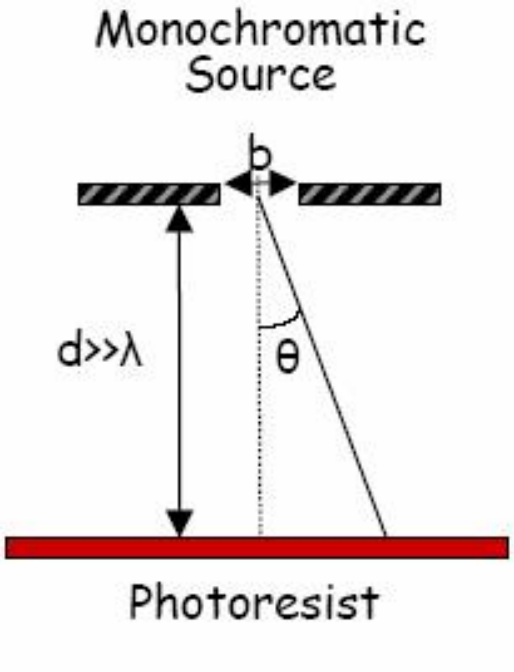
- Negative image of mask as metallization (liftoff metallization)

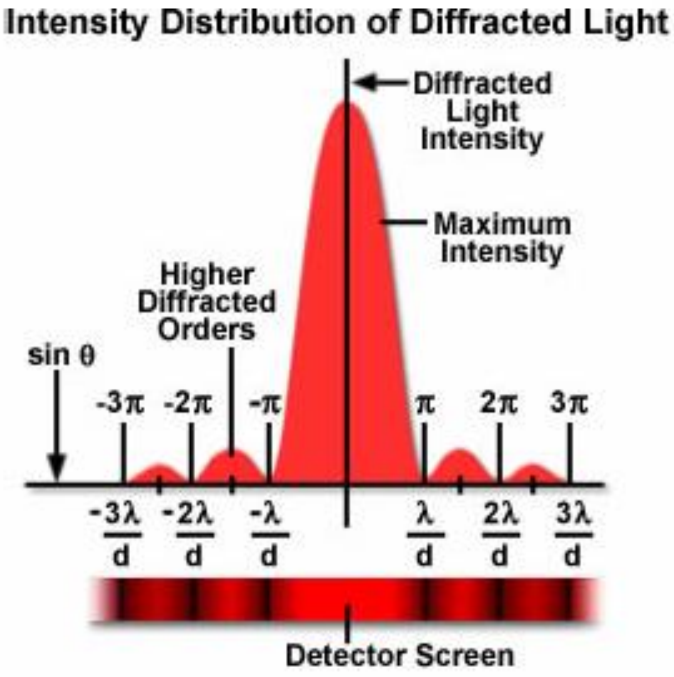
The Wave Form of Light



Diffraction Limitation of Photolithography

- Ideally, we want the exposure light source to create an exact masking shadow on the photoresist but the wave-like nature of light creates significant challenges at the scale of microlithography.
- Diffraction phenomena must be considered when feature size and spacing approaches λ, the wavelength of the exposure light. These considerations have driven the evolution of lithography exposure systems.
- Long mask features are essentially slits or apertures:



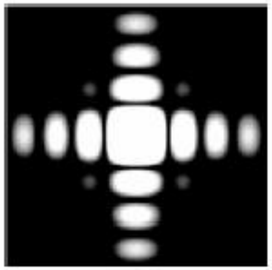


One Dimension:

$$I(\theta) = I(0)\left(\frac{\sin\beta}{\beta}\right)^2$$

$$\beta = \frac{\pi b}{2\lambda}\sin\theta$$

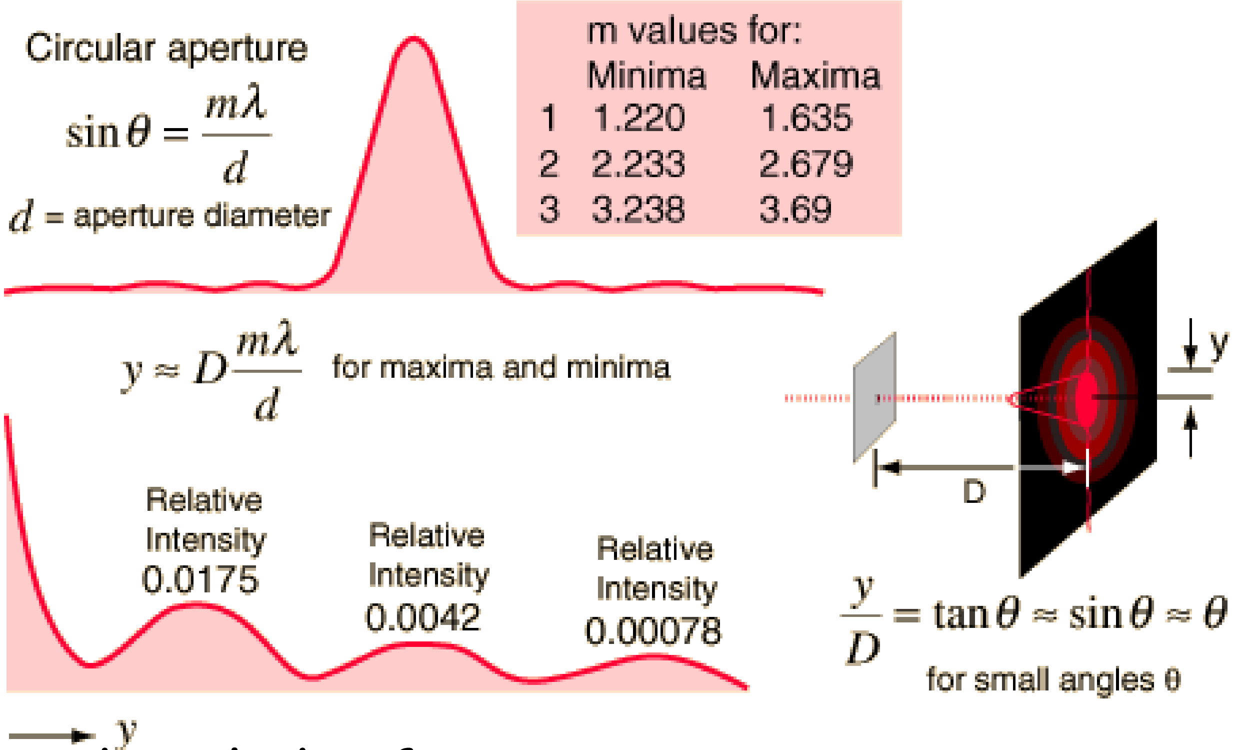
Two Dimensions:



Square Aperture

Circular Aperture

Circular Aperture Diffraction



Circular aperture

$$\sin\theta = \frac{m\lambda}{d}$$

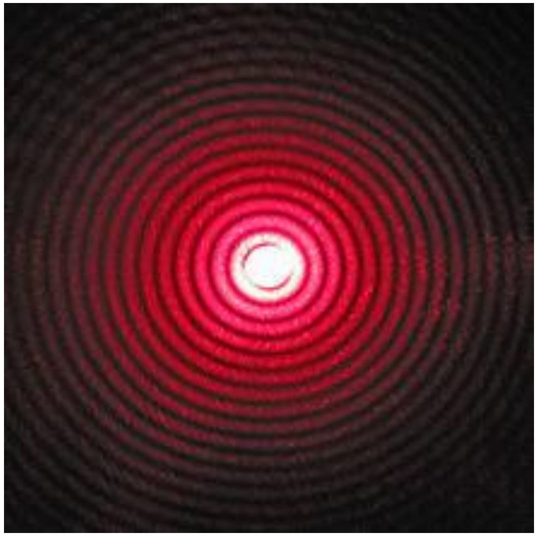
d = aperture diameter

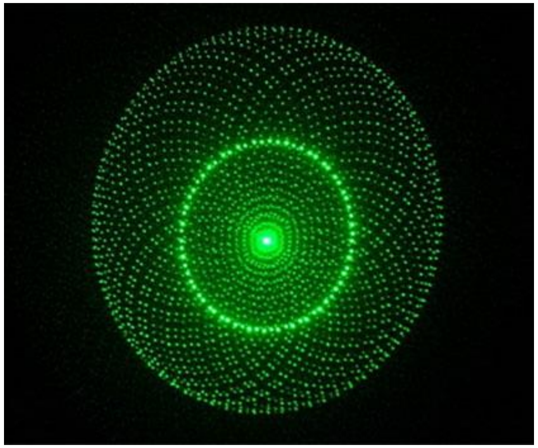
	m values for: Minima	Maxima
1	1.220	1.635
2	2.233	2.679
3	3.238	3.69

$$y \approx D\frac{m\lambda}{d}$$ for maxima and minima

$$\frac{y}{D} = \tan\theta \approx \sin\theta \approx \theta$$

for small angles θ





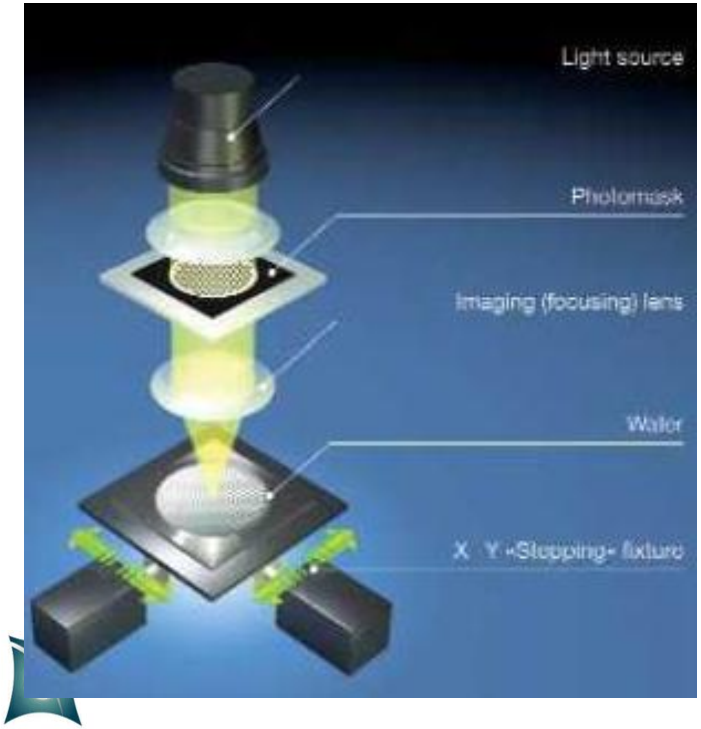
Airy's Disc

When light from a point source passes through a small circular aperture, a diffuse circular disc surrounded by much fainter concentric circular rings.

(hyperphysics.phy-astr.gsu.edu/hbase/phyopt/cirapp2.html#c2)

Types of Photolithography

1. Contact Lithography
2. Proximity Lithography
3. Projection Lithography

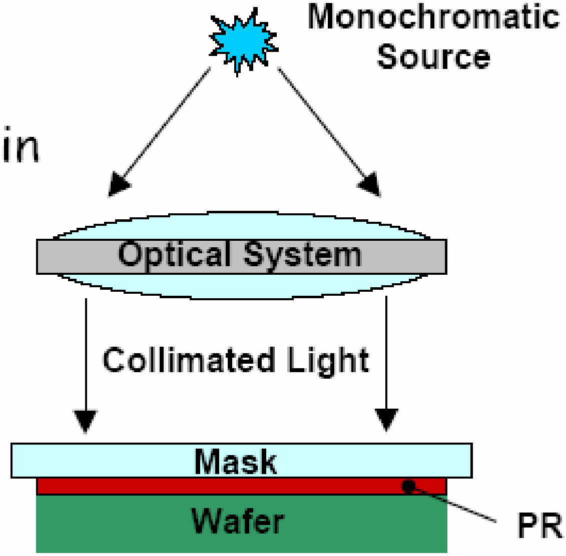


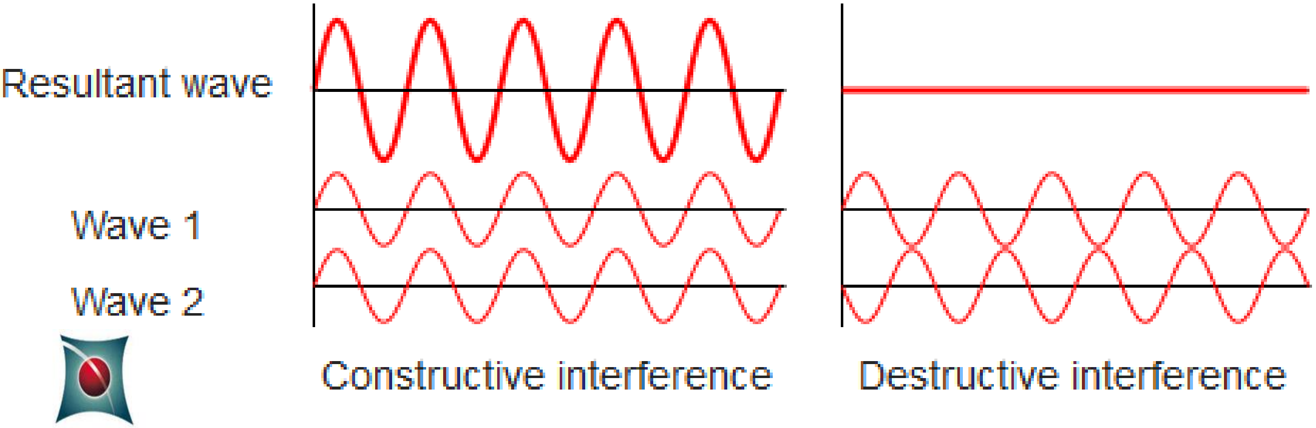
Mask Aligner

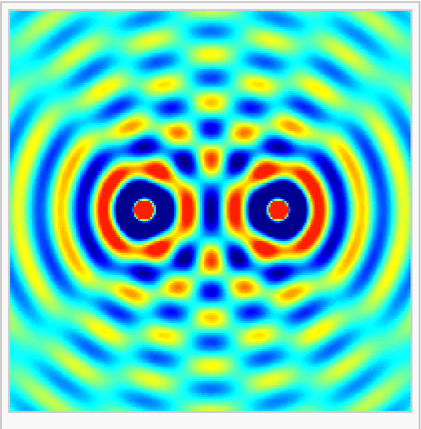
Types of Photolithography (1)

Contact Lithography

- Research workhorse; capable of submicrion (> 0.5μm) in localized areas.
- Shortcomings
  - Mask contact resist ⟹ mask demage
  - Non-planar surfaces cause interference effects

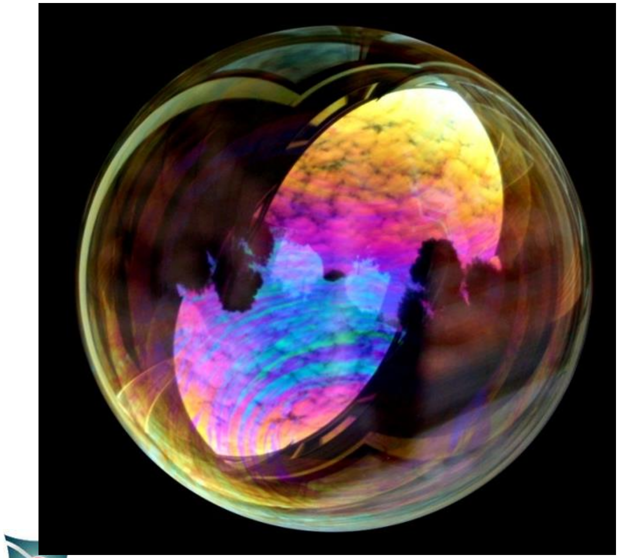




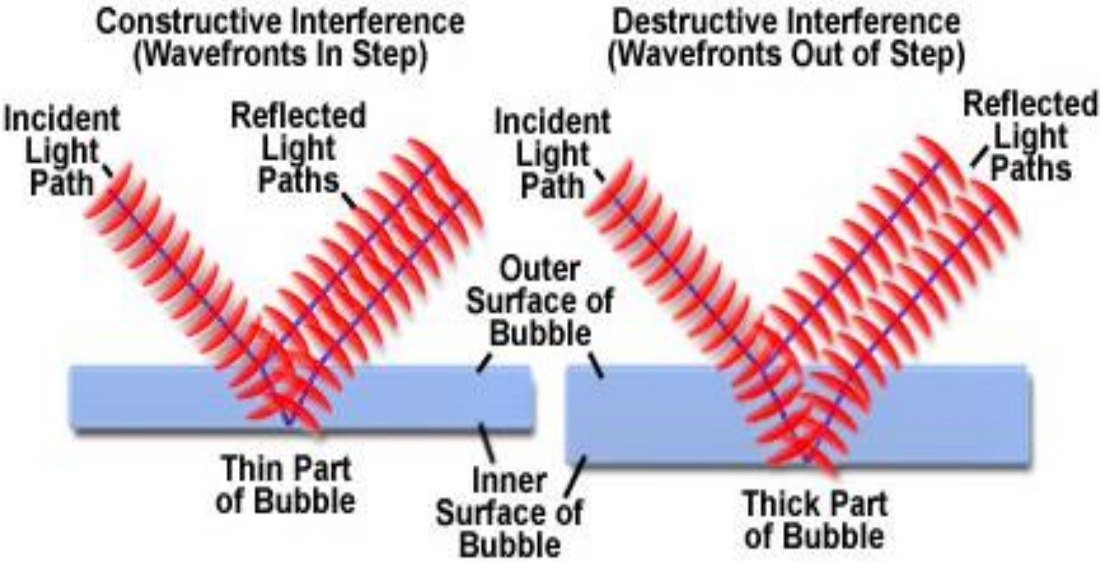


Interference Effects

Light Waves on Non-Planar Surface



Colorful Bubbles

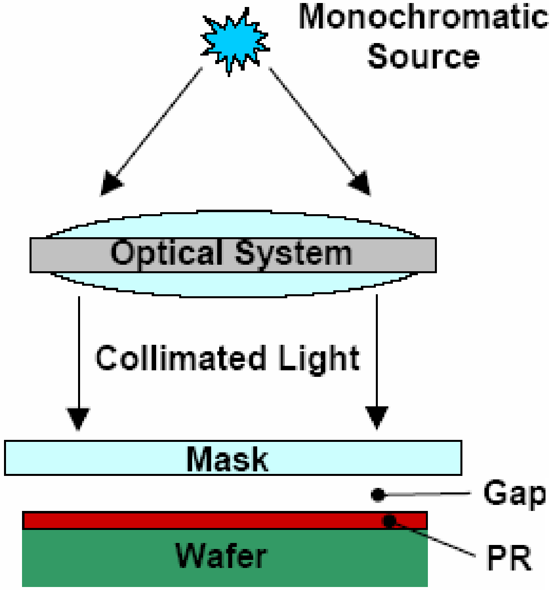


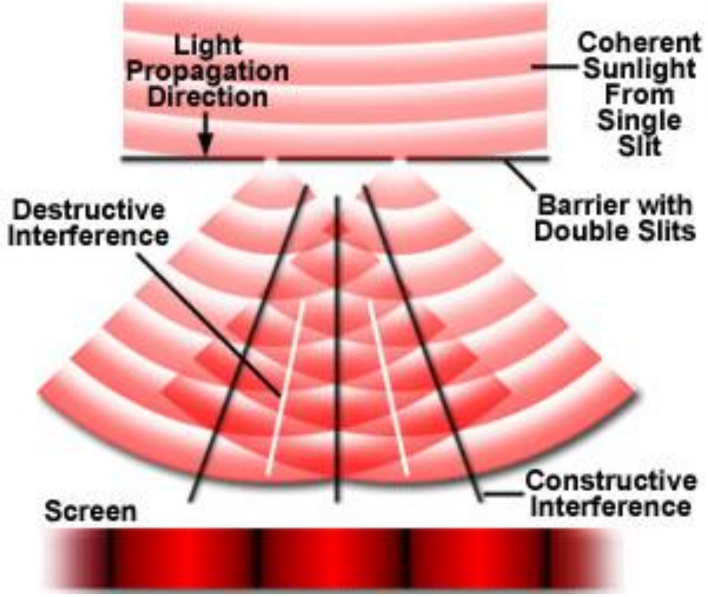
Interference Effect on Non-Planar Surface

Types of Photolithography (2)

Proximity Lithography

- No marring of resist or mask
- Small uniform gap between mask and resist
- Useful for lines and spaces (feature sizes) exceeding 5-10μm in width



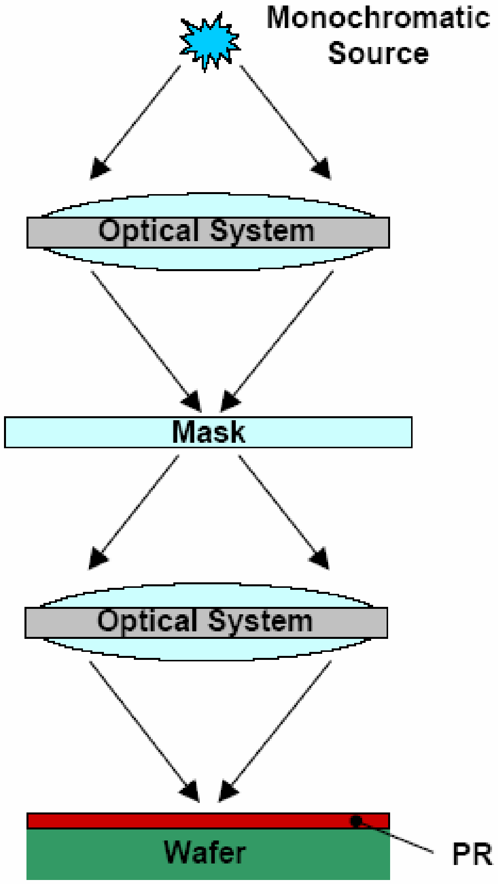


Young's Double Slit Experiment

Types of Photolithography (3)

Projection Lithography

- Resolution greatly improved by using optics to shape the wave phase fronts of the illumination source
  - Collimated or converging beam illuminates mask and projects a scaled image onto the photoresist
  - Currently used to produce features down to 0.4μm repeatedly



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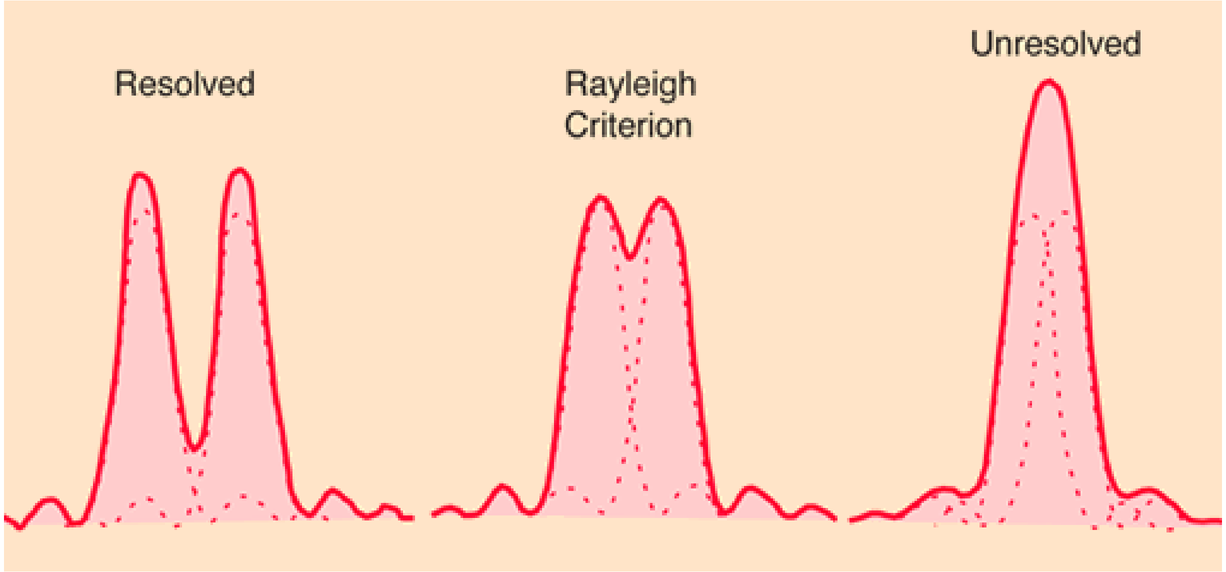
Resolution Limit -Rayleigh Criterion



The Rayleigh criterion is the generally accepted criterion for the minimum resolvable detail - the imaging process is said to be diffraction-limited.

Lord Rayleigh (1842 – 1919), British Nobel Prize winner

Critical Dimension (CD)

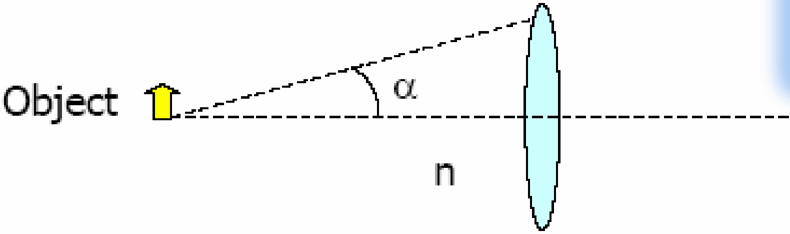
Minimum feature size (CD - critical dimension) is determined by a modified form of Rayleigh's criterion:

$$\boxed{CD_{\min} = K_1 \lambda / NA}$$

K_1 = empirical constant (typically 0.4 or less)

λ = wavelength

NA = numerical apeture



$$\boxed{NA = n \sin \alpha}$$

$$\alpha_{\max} = \frac{\pi}{2}$$

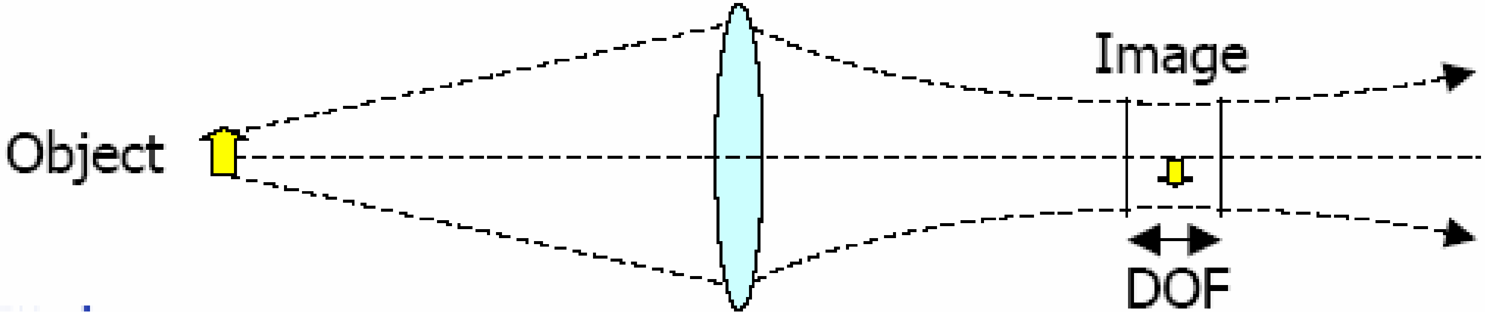
So for lens in air:
n=1, NA<1

Image Depth of Focus (DOF)

Resolution in the mask image

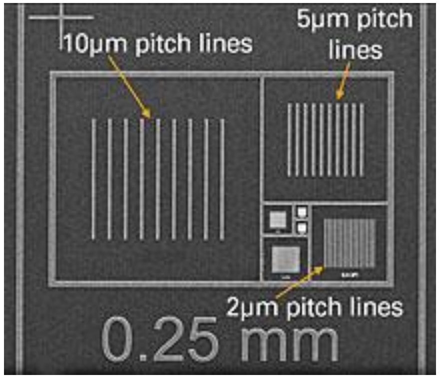
Image depth of focus (DOF)

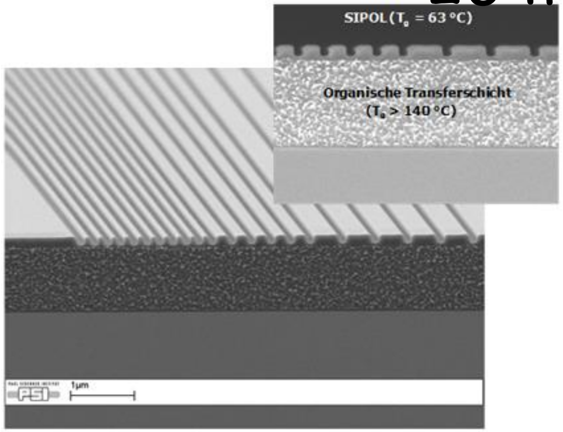
$$DOF = \frac{k_2 \lambda}{(NA)^2}$$



CD & DOF for Different Wavelengths

λ (nm)	NA	DOF/CDmin
436 (G line)	0.35	3559nm/620nm
365 (i line)	0.55	1206nm/331nm
248 (KrF)	0.68	536nm/182nm
193 (ArF)	0.85	264nm/113nm





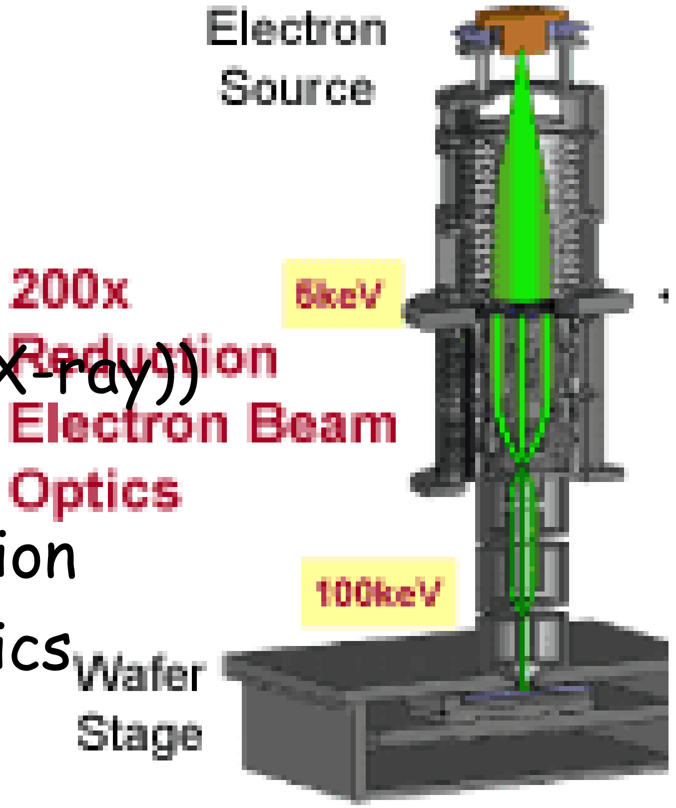
Future Directions

Optical Lithography

- Shorter wavelengths
- Ultra thin film (UTF) resists

X-Ray

- Short wavelength (1nm to 10nm (soft X-ray))
- Sources
  - ♦ Point sources cause pattern distortion
  - ♦ Collimated beams need complex optics



E-beam

- Special resists (PMMA, etc.)
- Danger of radiation damage to underlying layers
  - ♦ Sensitive oxides and oxide/semiconductor interfaces

Lithography Roadmap

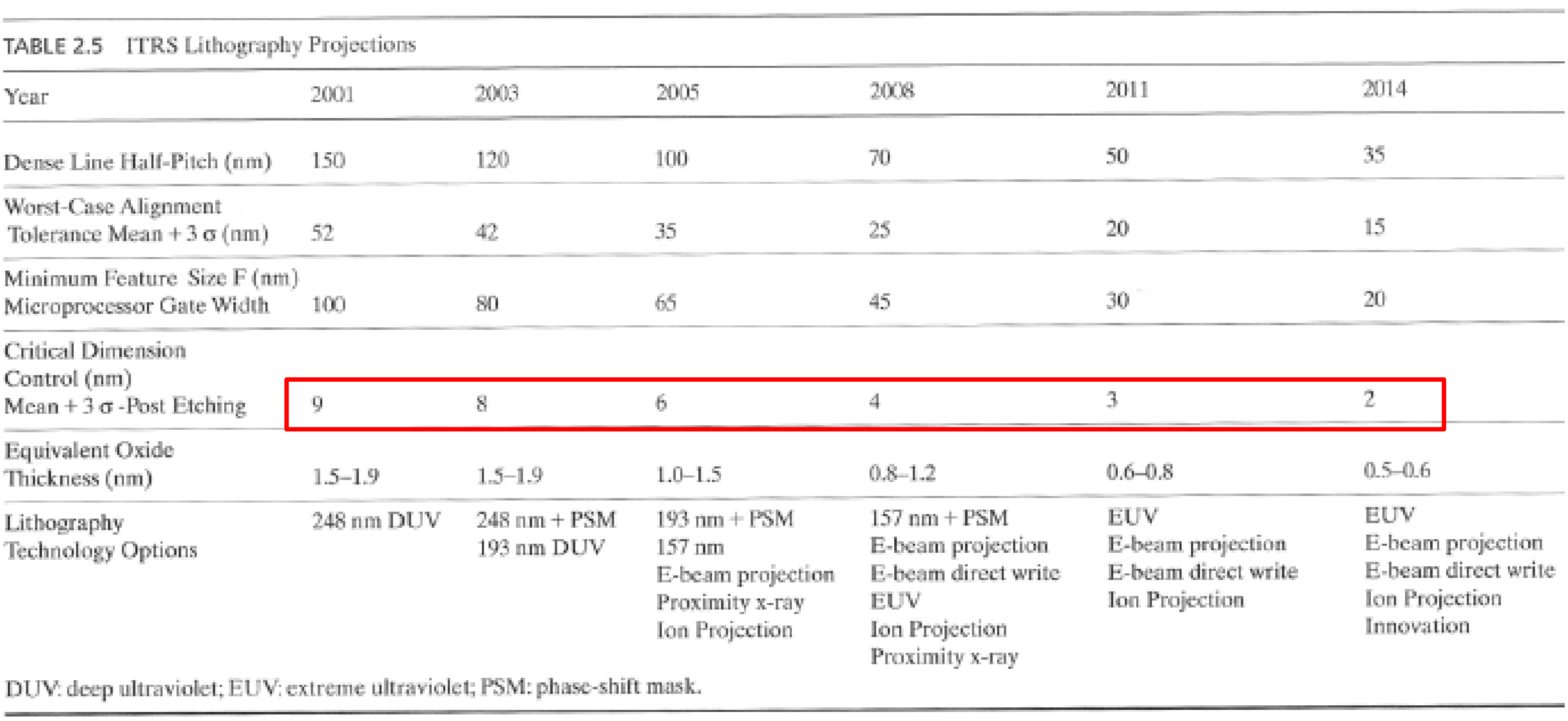


TABLE 2.5 ITRS Lithography Projections

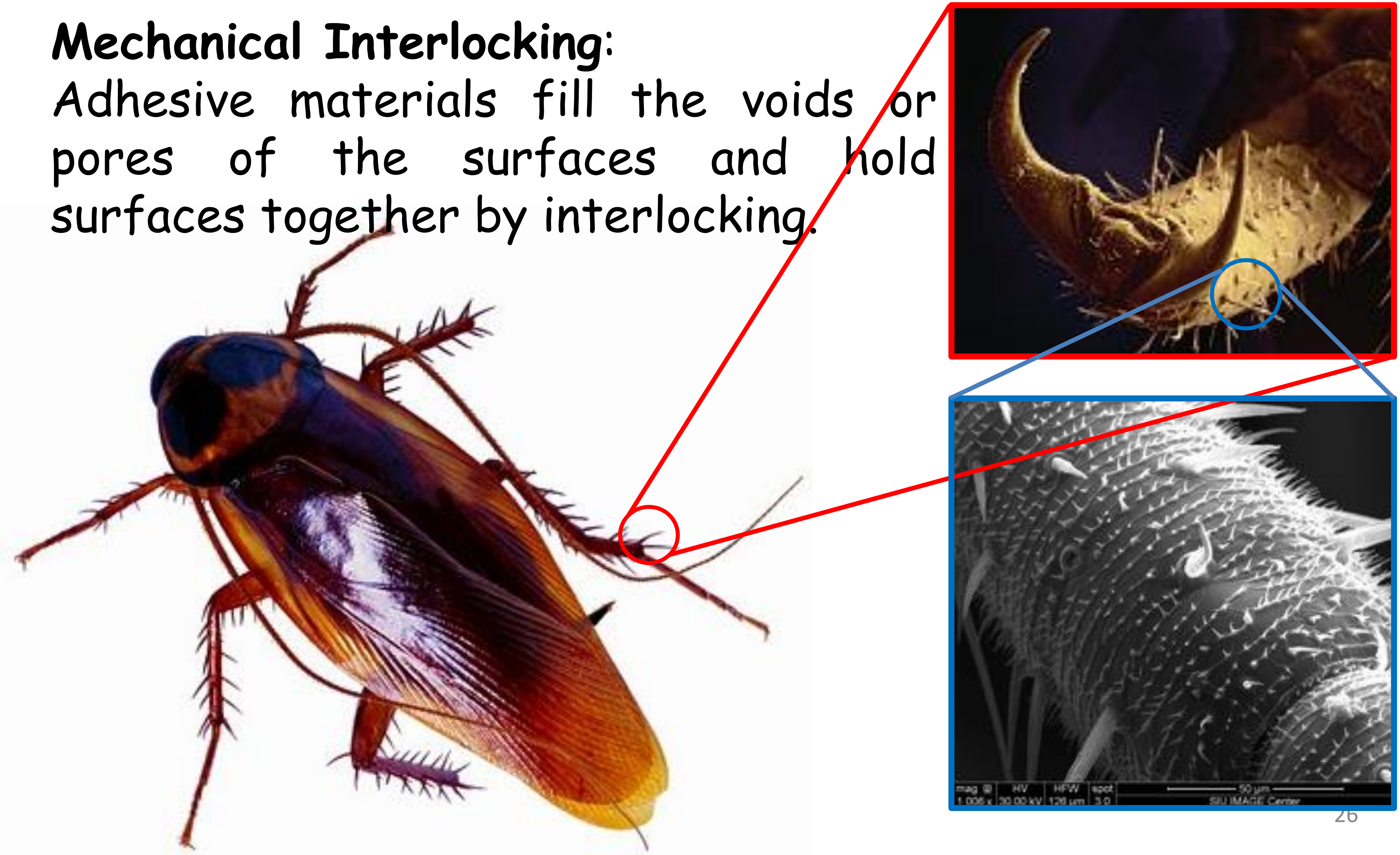
Year	2001	2003	2005	2008	2011	2014
Dense Line Half-Pitch (nm)	150	120	100	70	50	35
Worst-Case Alignment Tolerance Mean + 3 σ (nm)	52	42	35	25	20	15
Minimum Feature Size F (nm) Microprocessor Gate Width	100	80	65	45	30	20
Critical Dimension Control (nm) Mean + 3 σ -Post Etching	9	8	6	4	3	2
Equivalent Oxide Thickness (nm)	1.5–1.9	1.5–1.9	1.0–1.5	0.8–1.2	0.6–0.8	0.5–0.6
Lithography Technology Options	248 nm DUV	248 nm + PSM 193 nm DUV	193 nm + PSM 157 nm E-beam projection Proximity x-ray Ion Projection	157 nm + PSM E-beam projection E-beam direct write EUV Ion Projection Proximity x-ray	EUV E-beam projection E-beam direct write Ion Projection	EUV E-beam projection E-beam direct write Ion Projection Innovation

DUV: deep ultraviolet; EUV: extreme ultraviolet; PSM: phase-shift mask.

(Courtesy The Science and Engineering of Microelectronic Fabrication, S. Campbell, Oxford, 2nd edition, 2001.)

Adhesive Materials (Cockroaches)

Mechanical Interlocking:
Adhesive materials fill the voids or pores of the surfaces and hold surfaces together by interlocking.

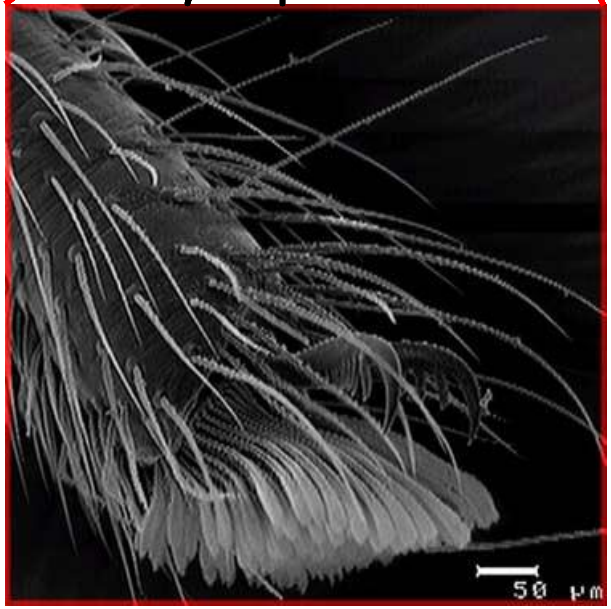


Mountain Climbing

Cockroach-Inspired Mountain Climbing Tools

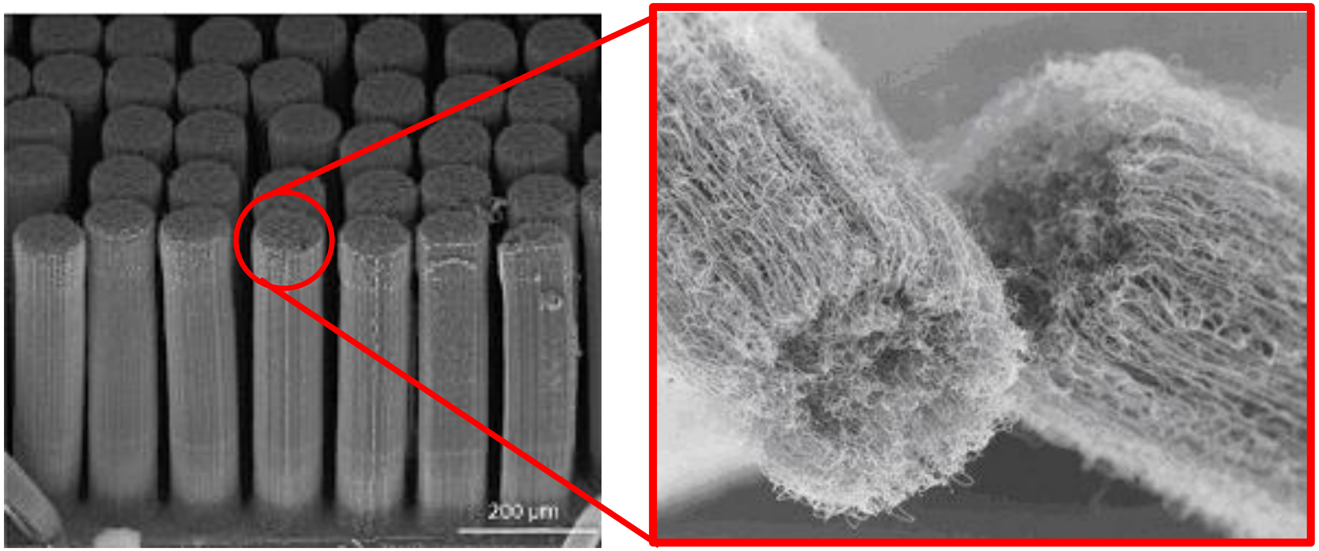
Adhesive Materials (Spiders)

Sticky Spider Feet



Proffitt, F. et al, *Science (2004)*

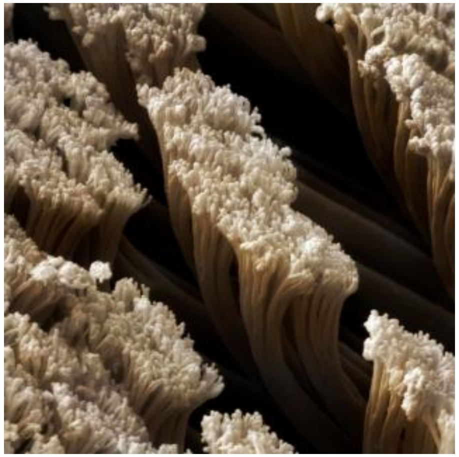
Mechanical Interlocking



Vertically Aligned Multiwalled CNT Arrays

CNT arrays can be directly grown on a solid surface. When the CNT array comes into contact with a target surface with certain roughness, the fine structures of CNTs ensure their capability of filling-in the cavities at interface, and make effective contact at mating surfaces.

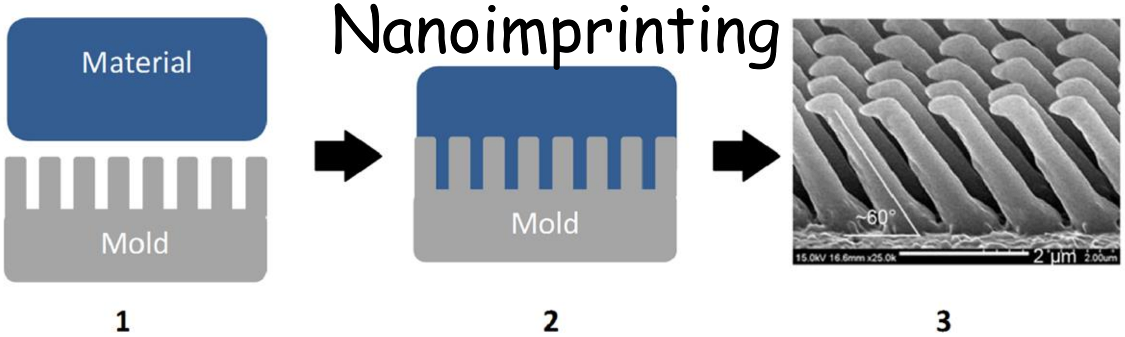
Adhesive Materials (Gecko)

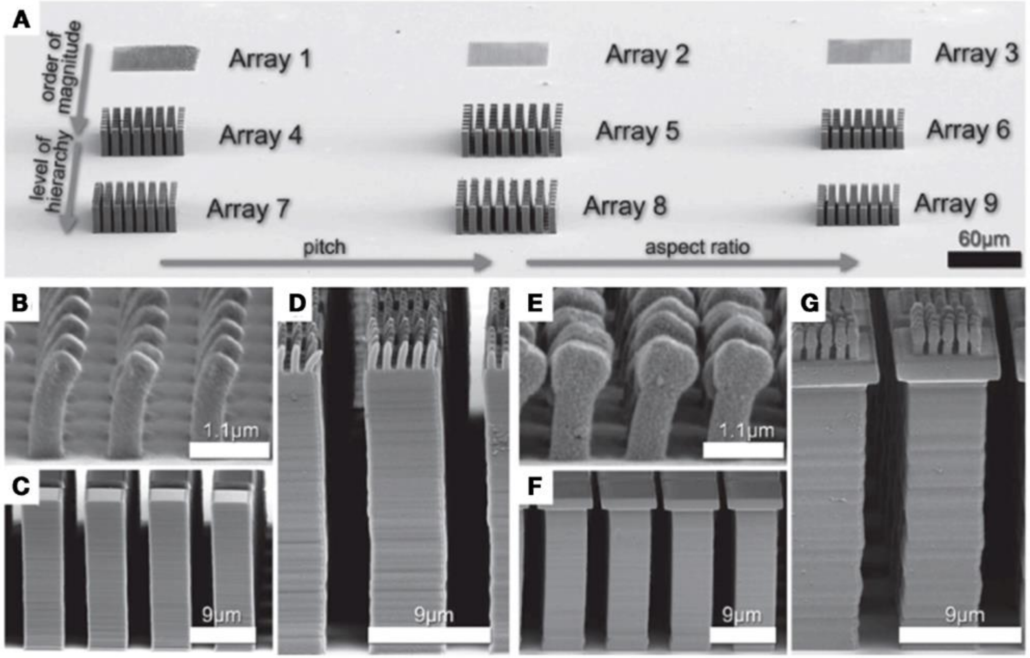


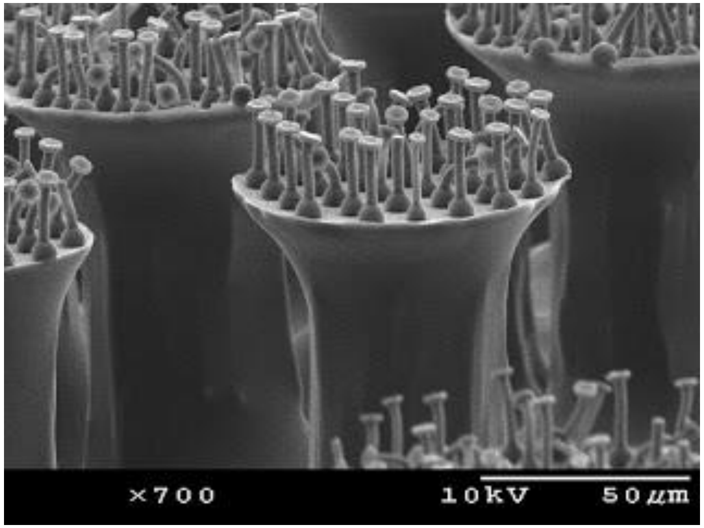
Dispersive Adhesion:
Van der Waals forces (anisotropic) include attractions and repulsions between atoms, molecules, and surfaces, as well as other intermolecular forces.

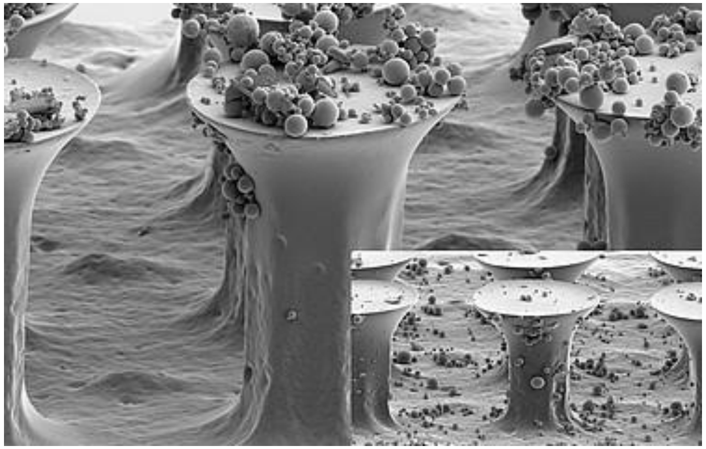
Dispersive Adhesion (Dry Adhesion) 1

Nanoimprinting





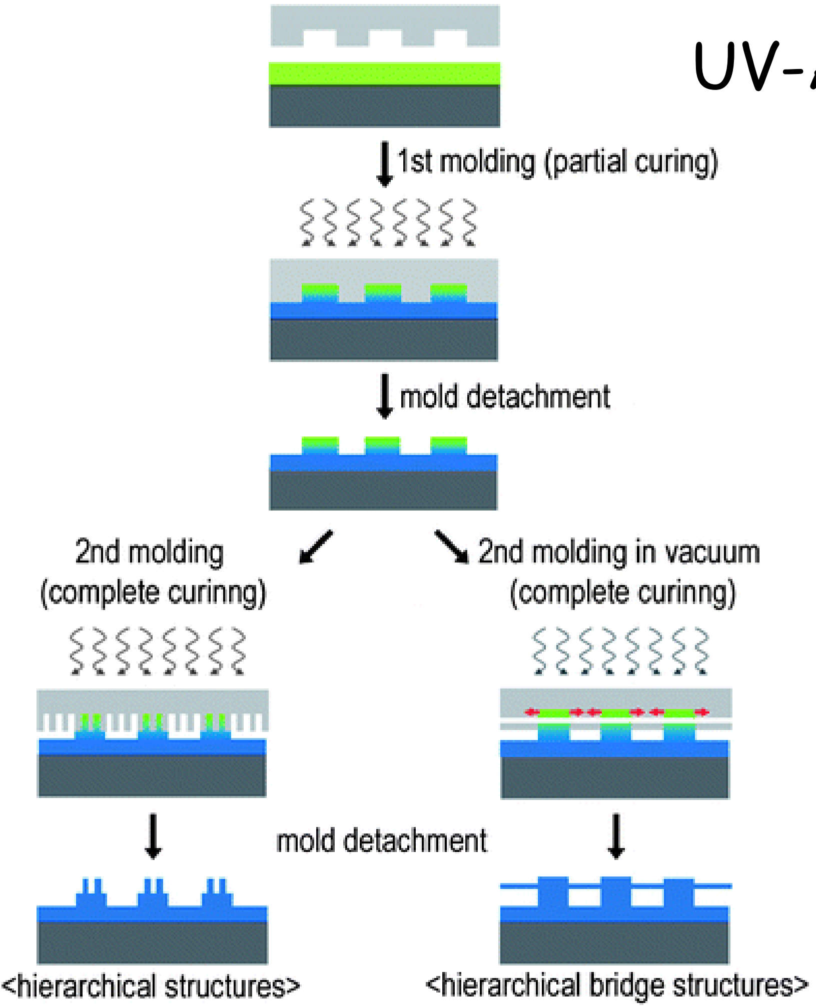




Andras, P.-A. et al, *Frontiers in Bioengineering and Biotechnology* (2013)

Dispersive Adhesion (Dry Adhesion) 2

UV-Assisted Capillary Force Lithography



1st molding (partial curing)

mold detachment

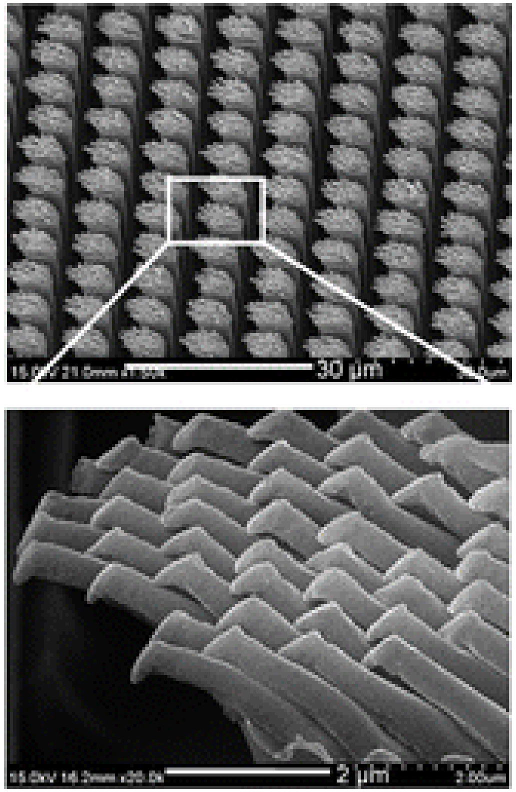
2nd molding
(complete curinng)

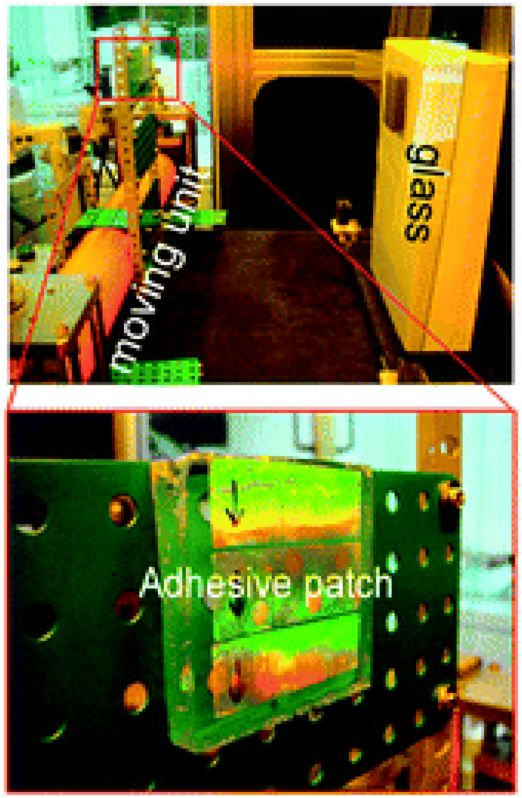
2nd molding in vacuum
(complete curinng)

mold detachment

<hierarchical structures>

<hierarchical bridge structures>

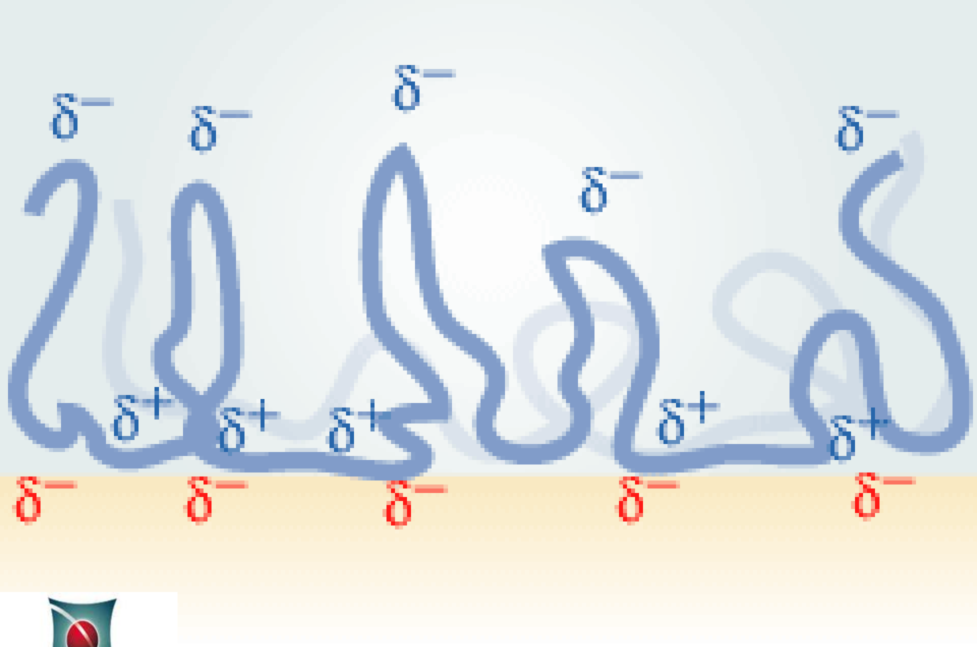




Jeong, H. E. et al, *Nanoscale (2009)*

Electrostatic Adhesion

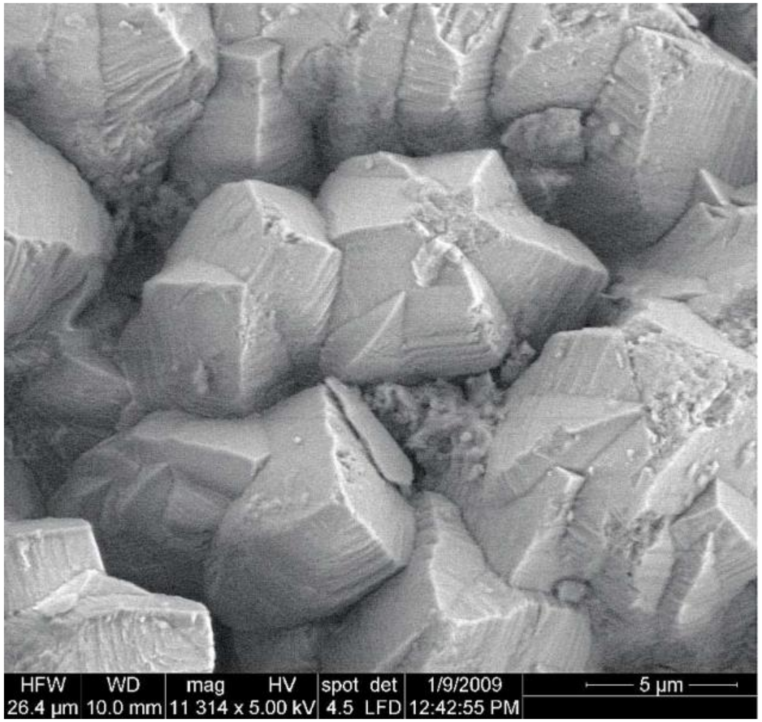
Electrostatic Adhesion:
Buildup of a charge on a surface caused by contact with other surfaces.



Electrostatic Self Adhesive Polyester Film.

Friction Resistance

Clam



Friction Resistance:
Force resisting the relative motion of solid surfaces, fluid layers, and material elements sliding against each other.

Chemical Adhesion (Wet Adhesion)

Shellfish (Mussel)

Catecholic Amino Acid 3,4-dihydroxyl-L-phenylalanine

Wet adhesion is used to describe two solids that are held together by a viscous mechanism—usually the presence of a liquid adhesive.

Waite, J. H., *Integrative and Comparative Biology* (2002)

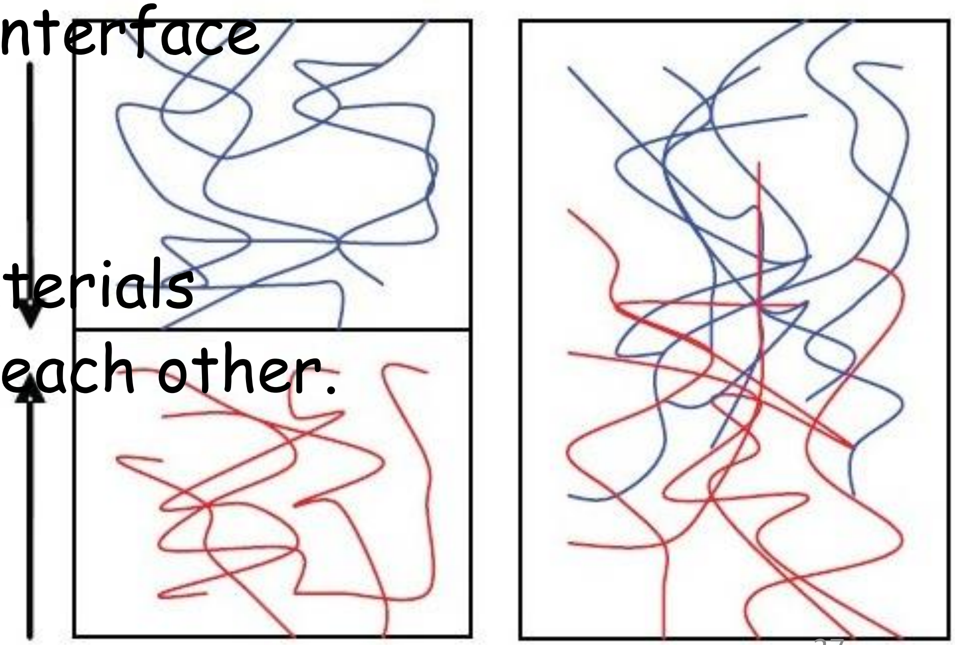
Chemical Adhesion

Chemical adhesion occurs when the surface atoms of two separate surfaces form ionic, covalent, or hydrogen bonds.

The attractive ionic and covalent forces are effective over only very small distances – less than a nanometer. This means not only that surfaces with the potential for chemical bonding need to be brought very close together, but also that these bonds are fairly brittle, since the surfaces then need to be kept close together.

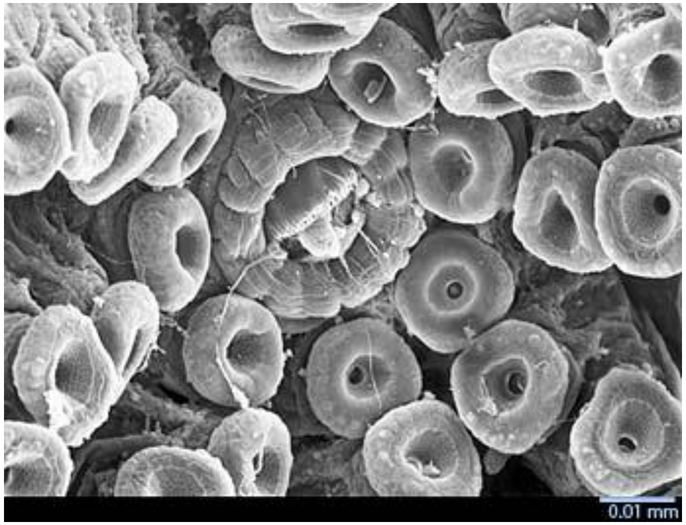
Diffusive Adhesion

- **Self-Diffusion**
  - Adhesive weaving into the adherent
  - Entanglement/coupling, chain reptation (Brownian motion), cooperative movement
- **Inter-Diffusion**
  - Both polymers cross the interface
- **Conditions**
  - Intimate contact
  - The molecules of both materials are mobile and soluble in each other.
  - Above T_g



Eastwood, E. A. et. al, *Macromolecules* (2002)

Adhesive Materials (Octopus)



Octopus Suckers

Vacuum Materials

Hook With Vacuum Suction Cup

Vacuum Lifter

Boston Ivy