Photolithography with a *Twist*

A workshop on gray scale and 3-D methods

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Outline

- Conventional photolithography
- Gray scale methods
- Gray scale masks
- Micro stereo lithography
- Two-photon lithography

Conventional photolithography

- Primary application
- Process
- Variations on the theme
- What can it do?
- What can’t it do?
- Exciting new applications of photolithography
- Successful extensions of conventional photolithography

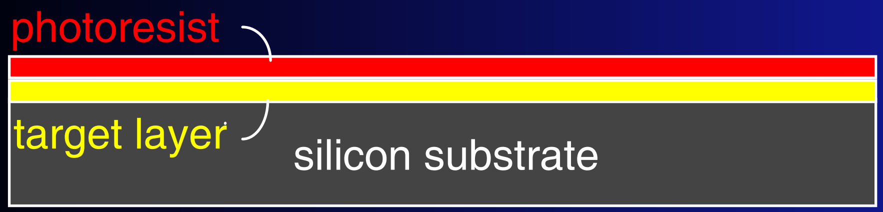
Conventional photolithography

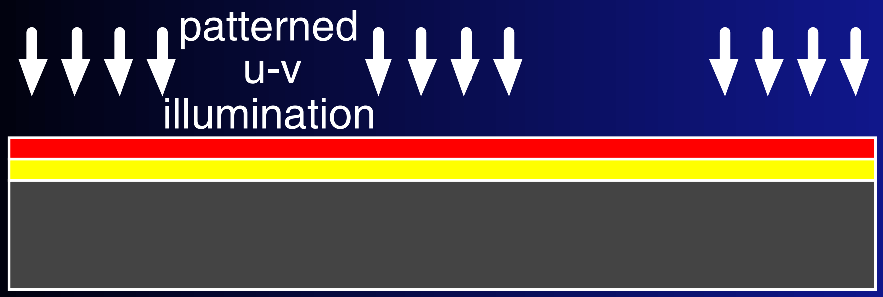
Primary application

- Integrated circuit processing
- Pattern photoresist to protect the wafer surface from etchant or ion implantation on a flat silicon substrate

Conventional photolithography

Planar processing of positive resist

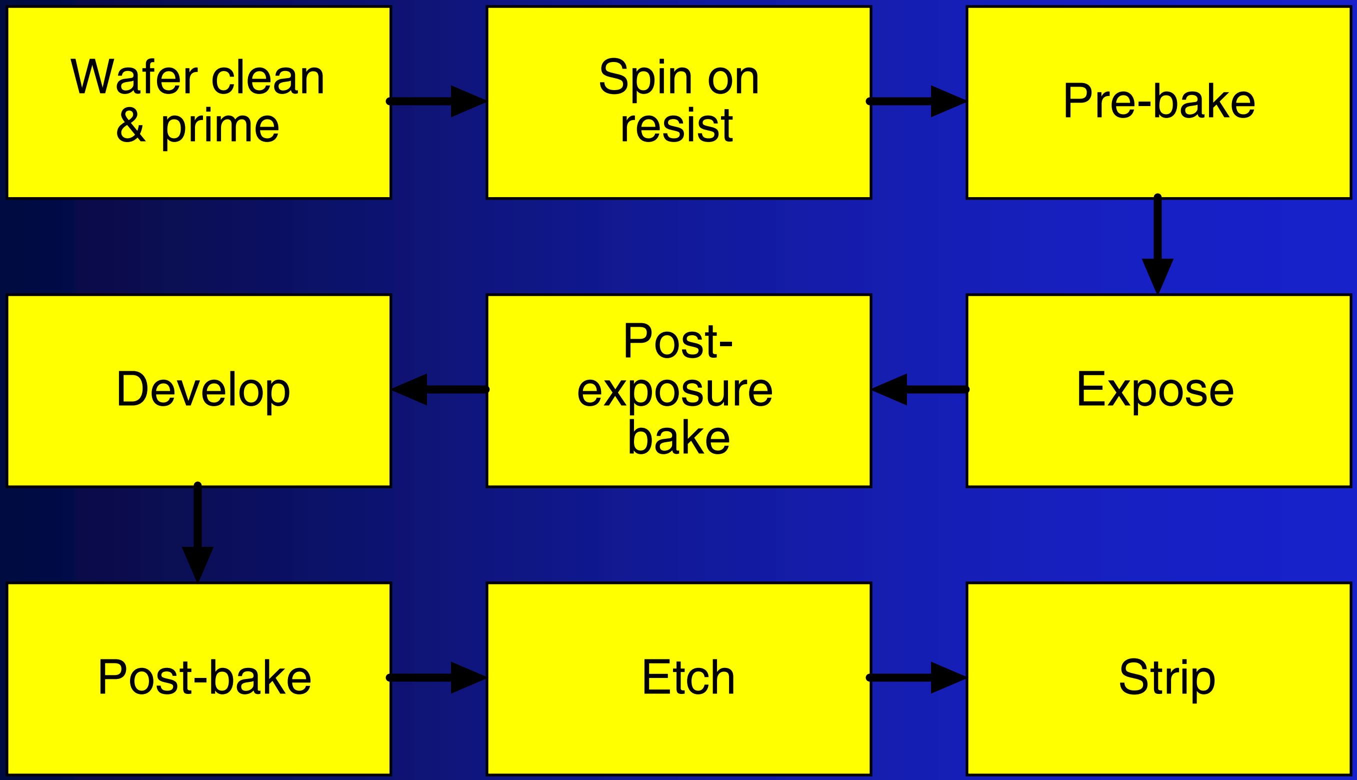




exposed photoresist is cleared (dissolved) by developer

target layer is etched and remaining photoresist is removed

Photoresist process flow



Wafer clean & prime

Spin on resist

Pre-bake

Expose

Post-exposure bake

Develop

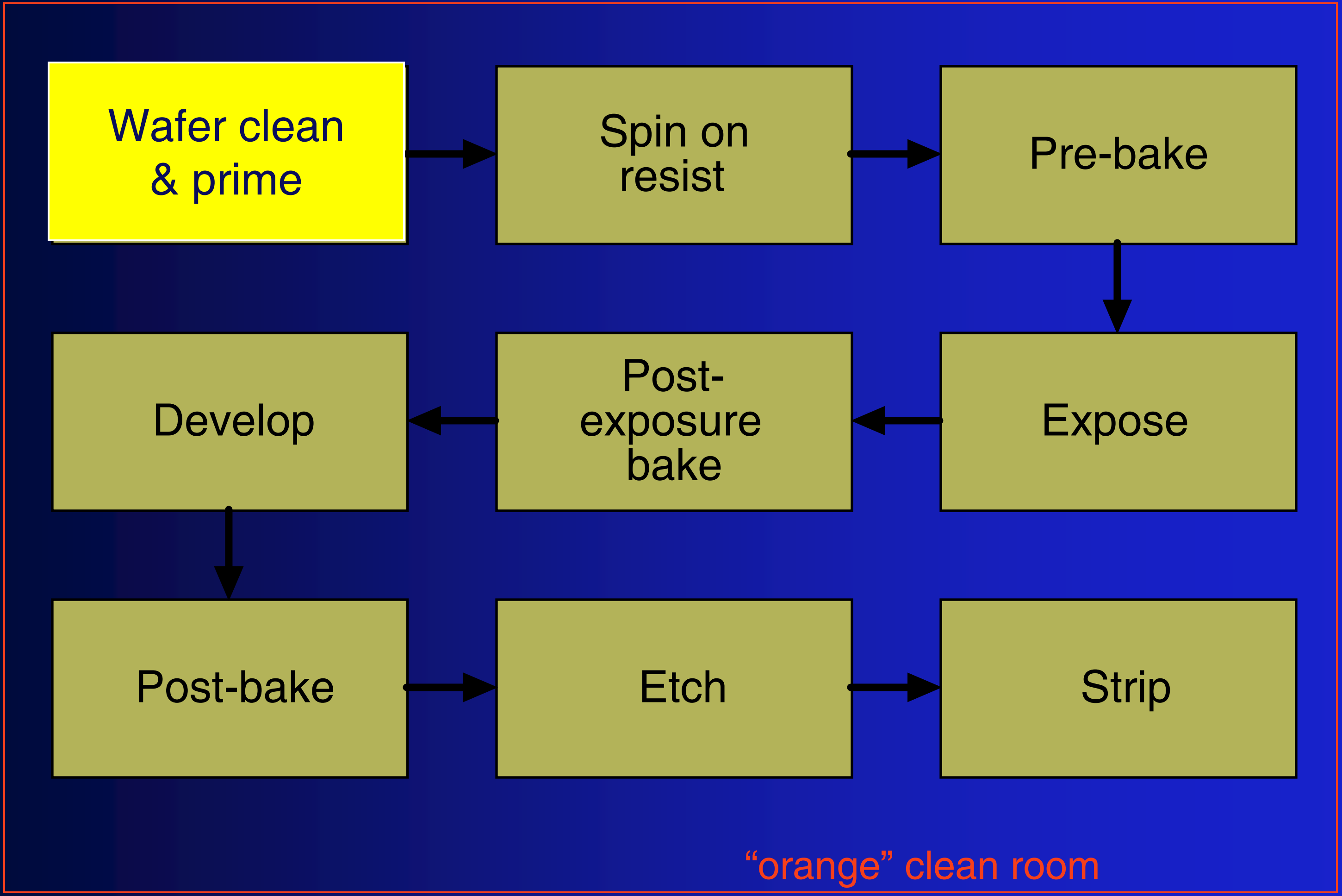
Post-bake

Etch

Strip

“orange” clean room

Photoresist process flow



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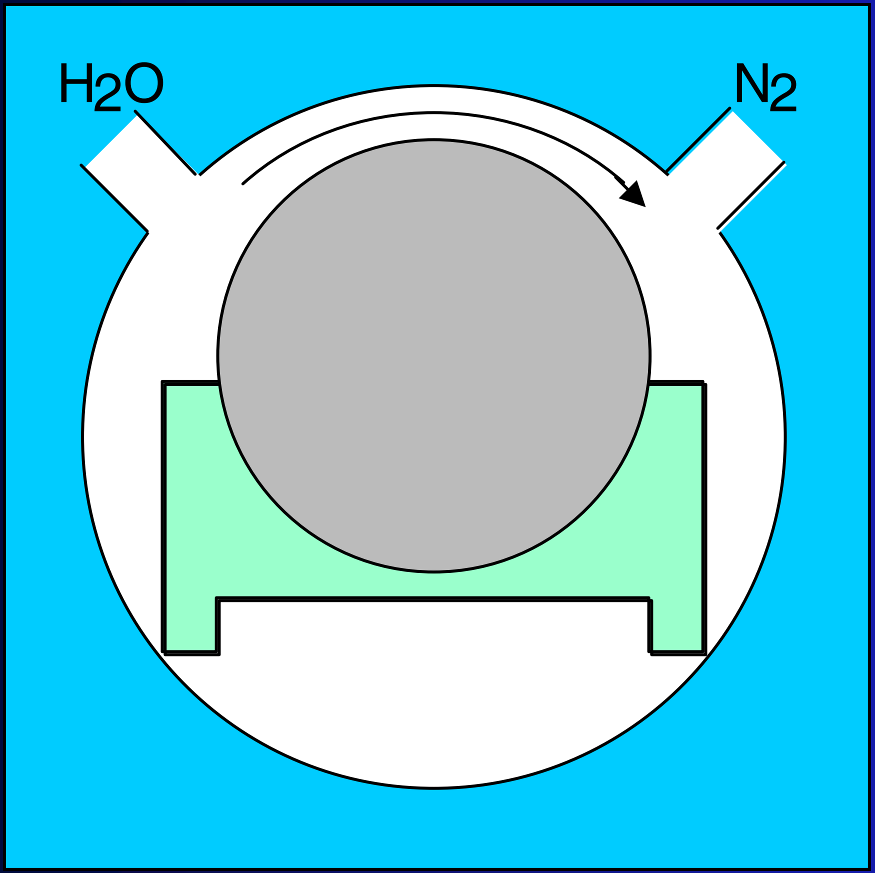
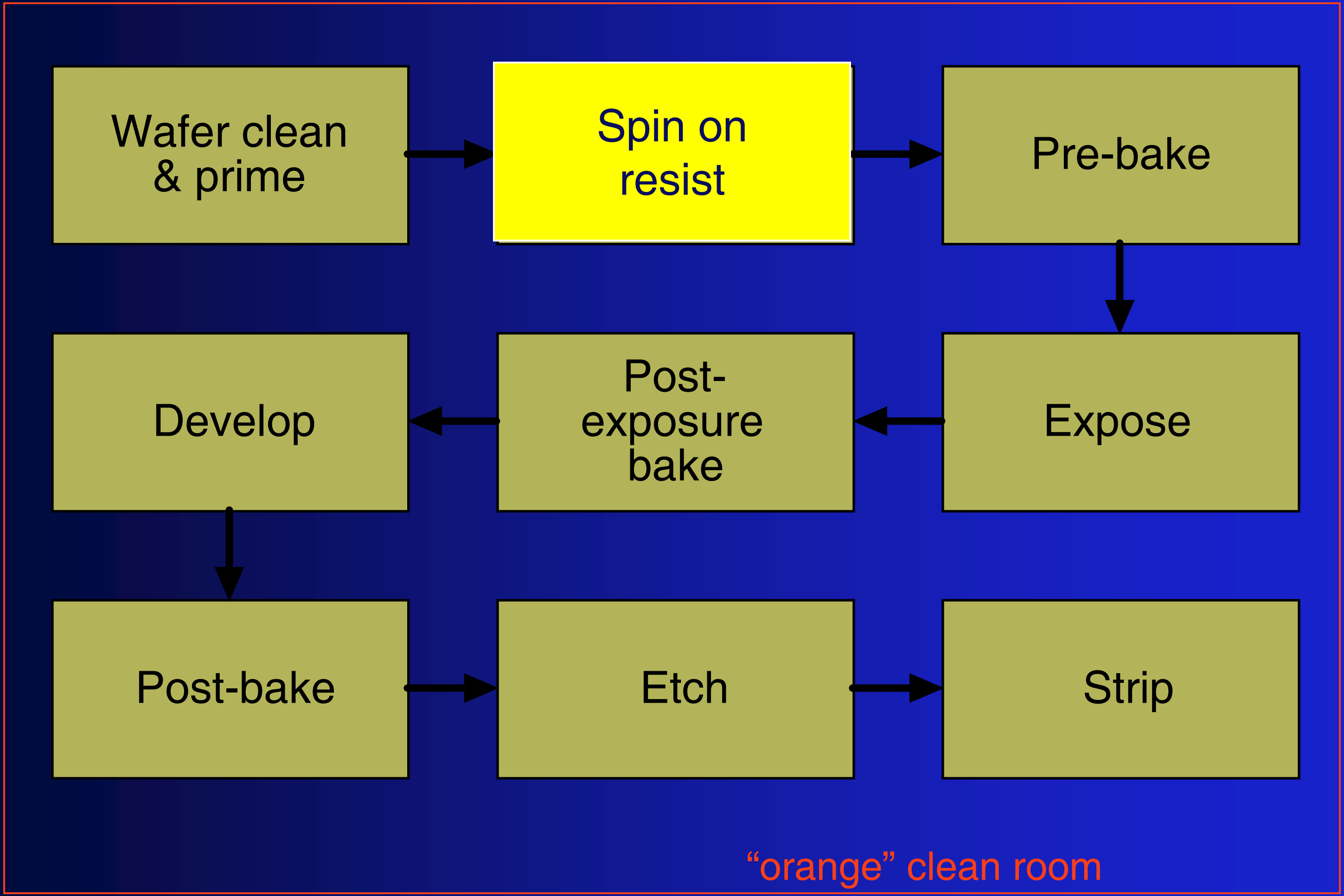
Wafer cleaning equipment

Spin-rinse dryer



Photoresist process flow



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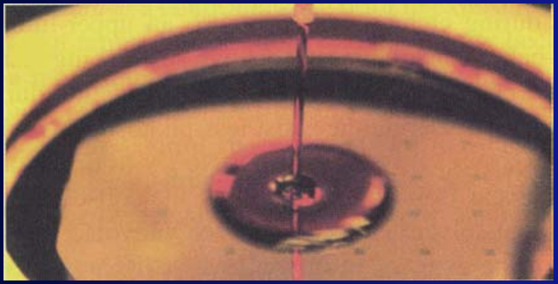
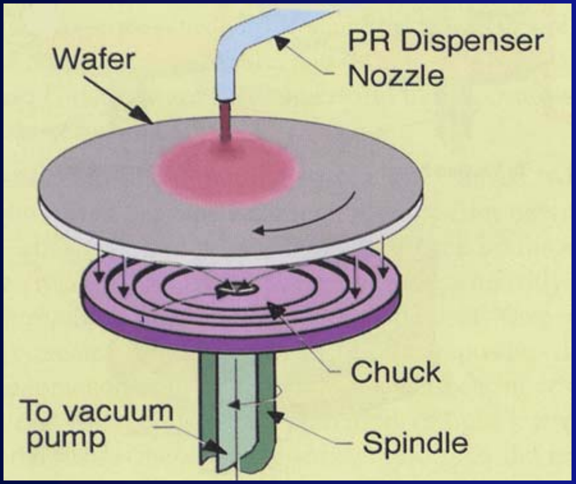
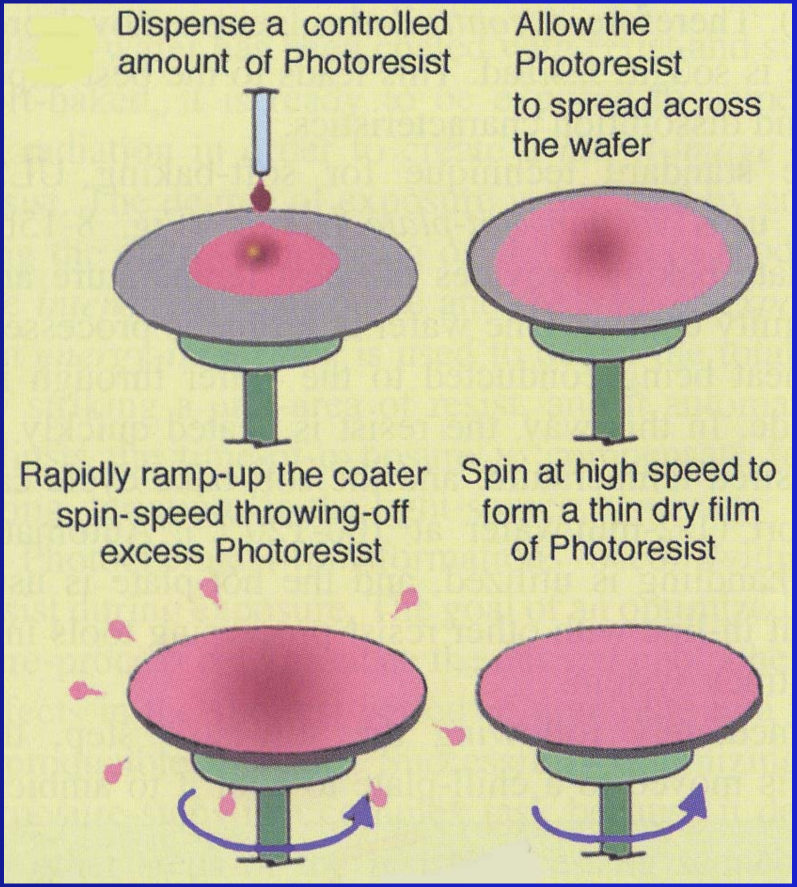
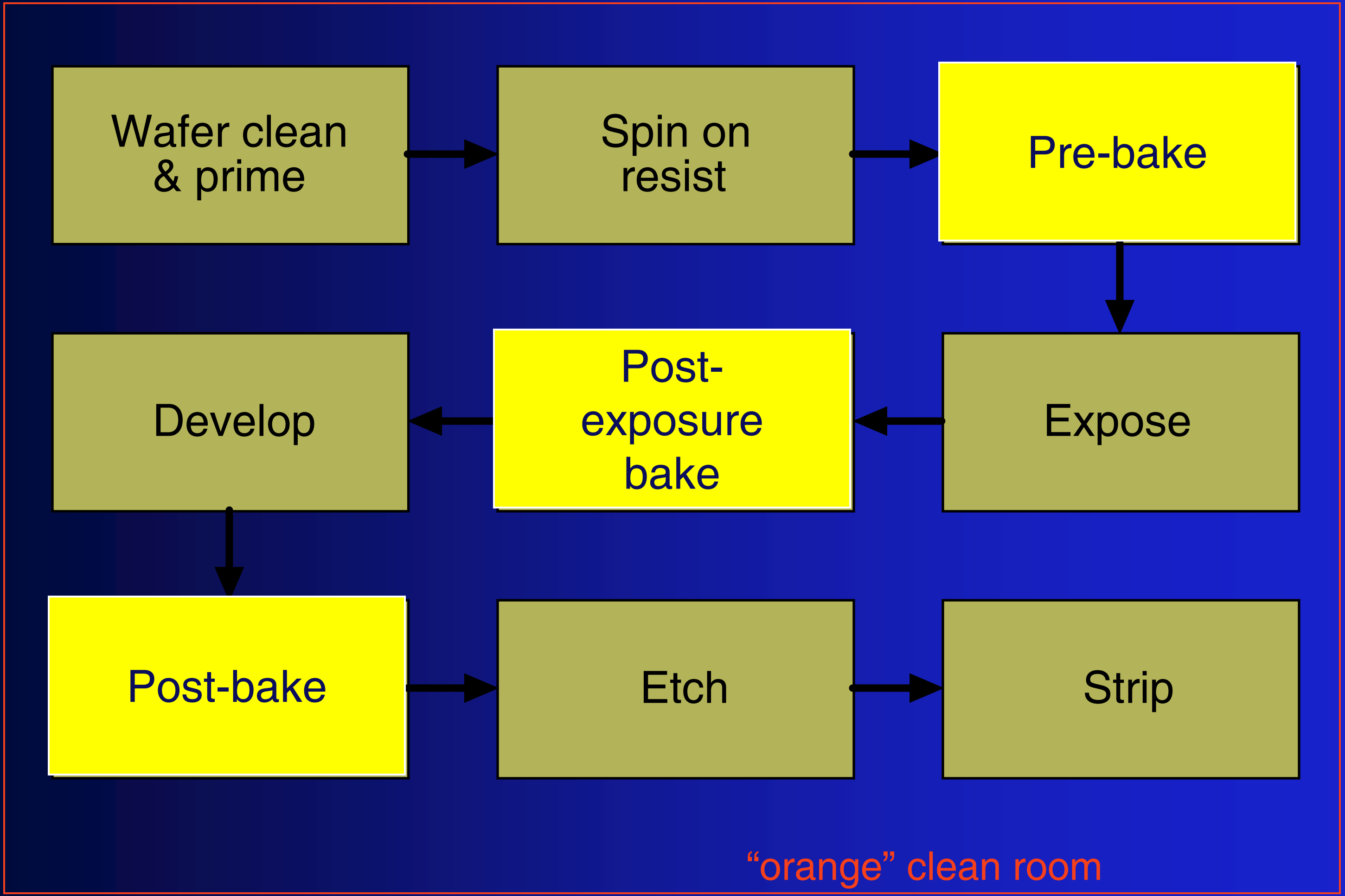
Spinner




Wafer
PR Dispenser Nozzle
Chuck
To vacuum pump
Spindle


Dispense a controlled amount of Photoresist
Allow the Photoresist to spread across the wafer
Rapidly ramp-up the coater spin-speed throwing-off excess Photoresist
Spin at high speed to form a thin dry film of Photoresist

Photoresist process flow



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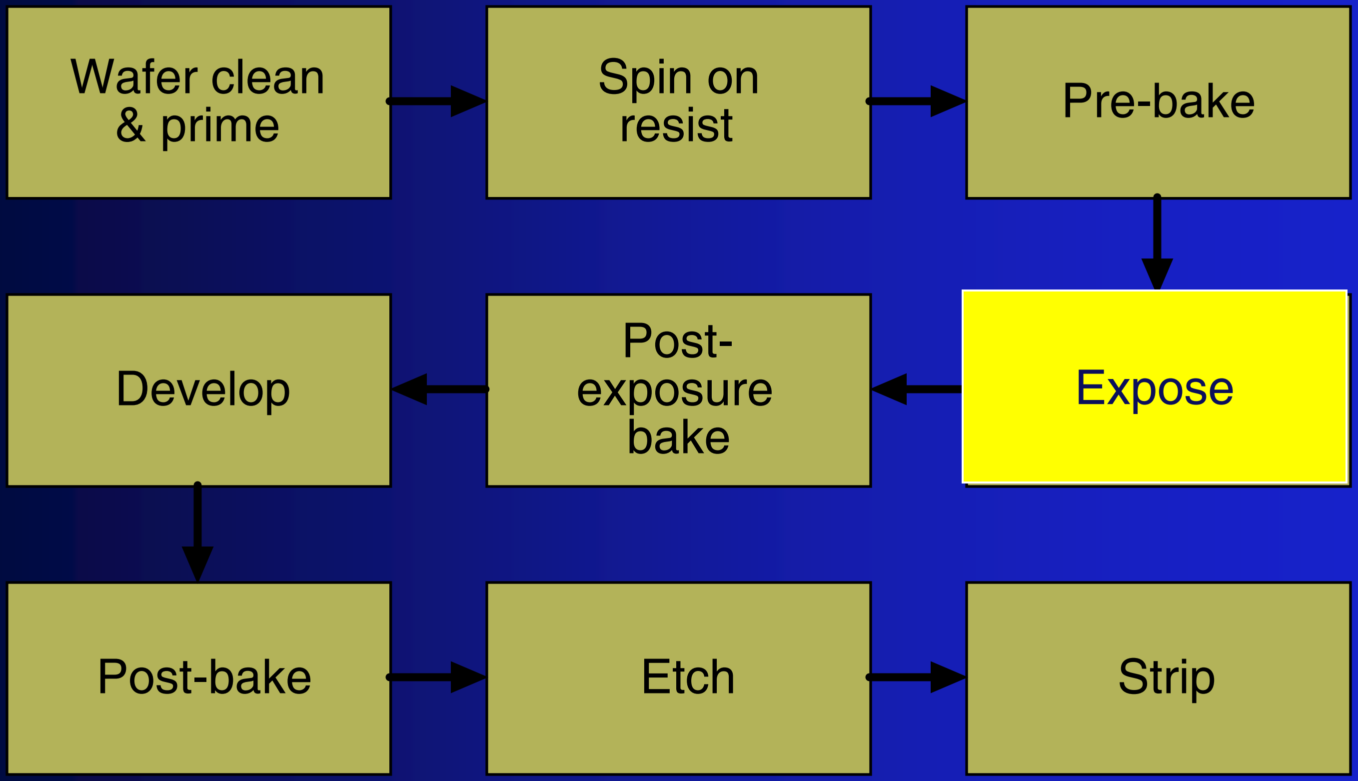

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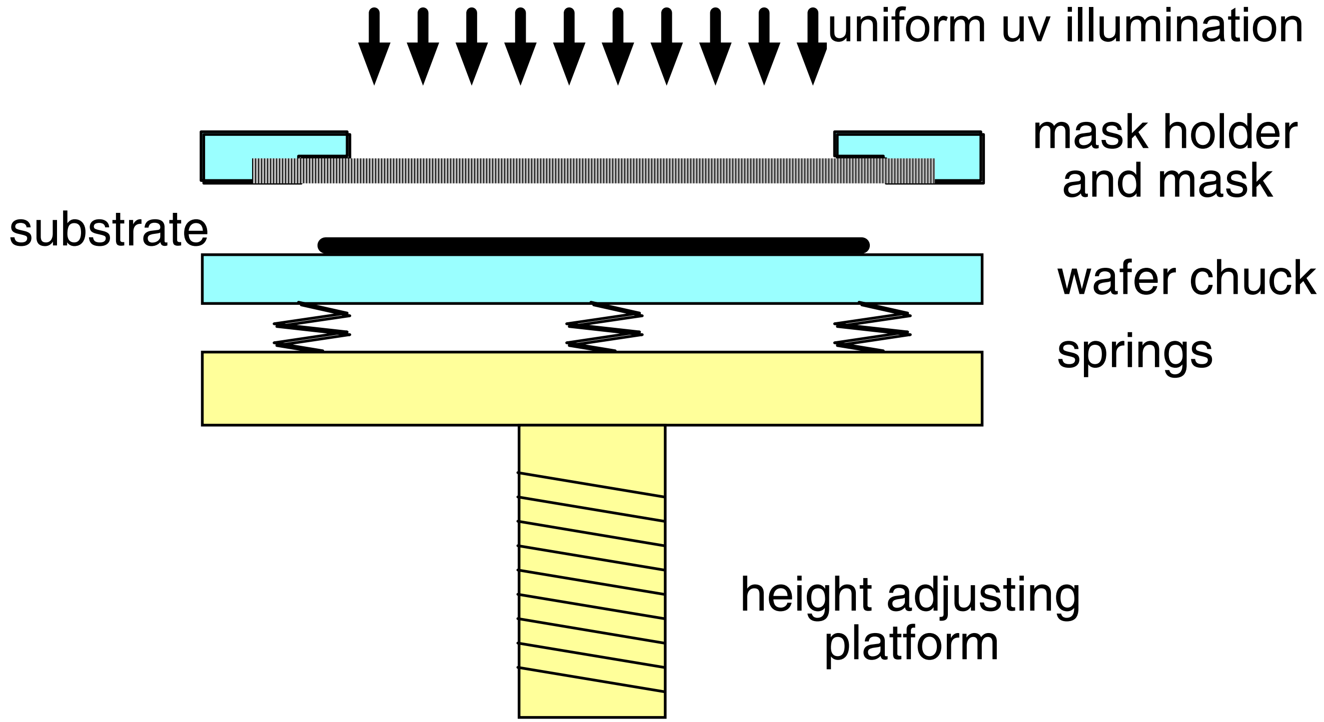
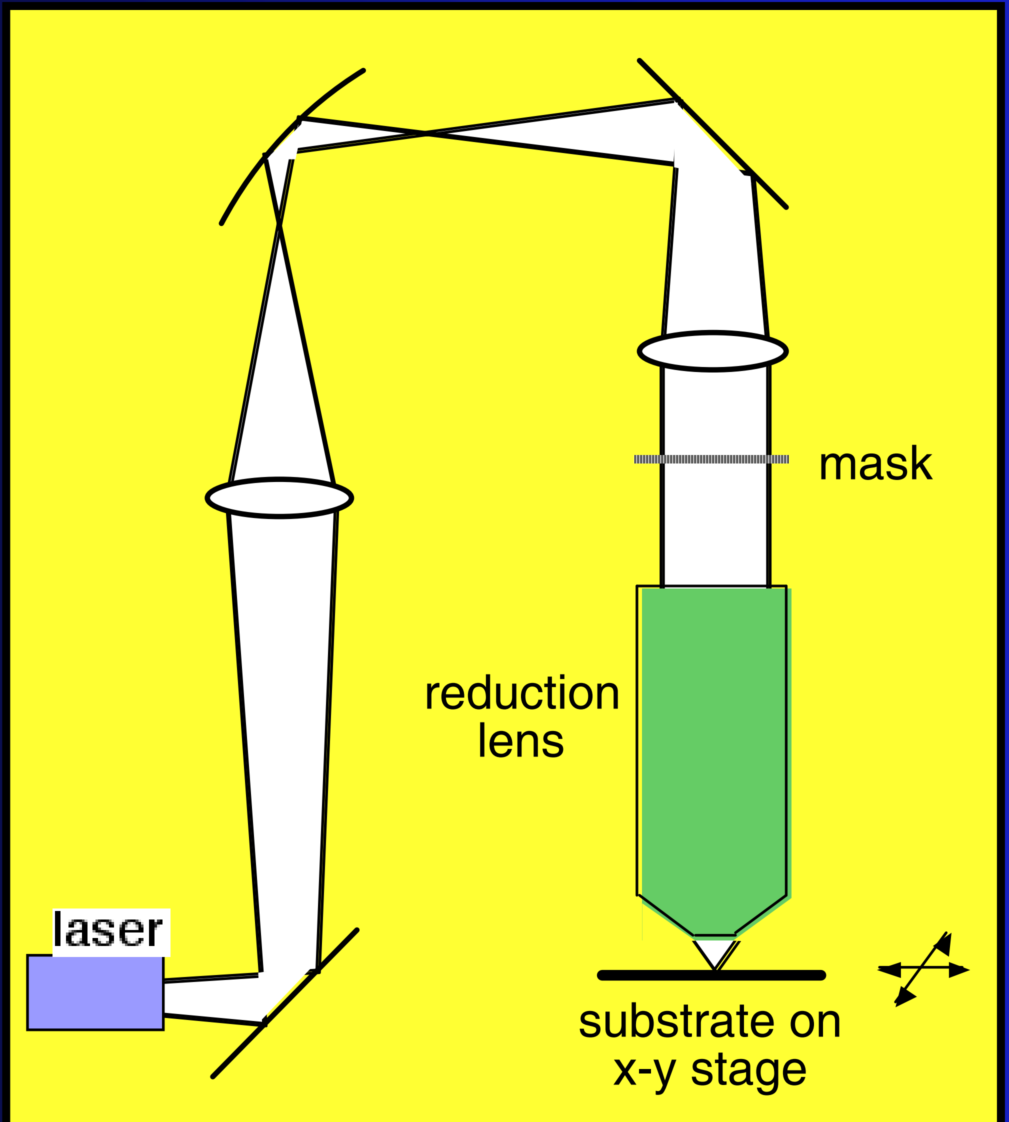
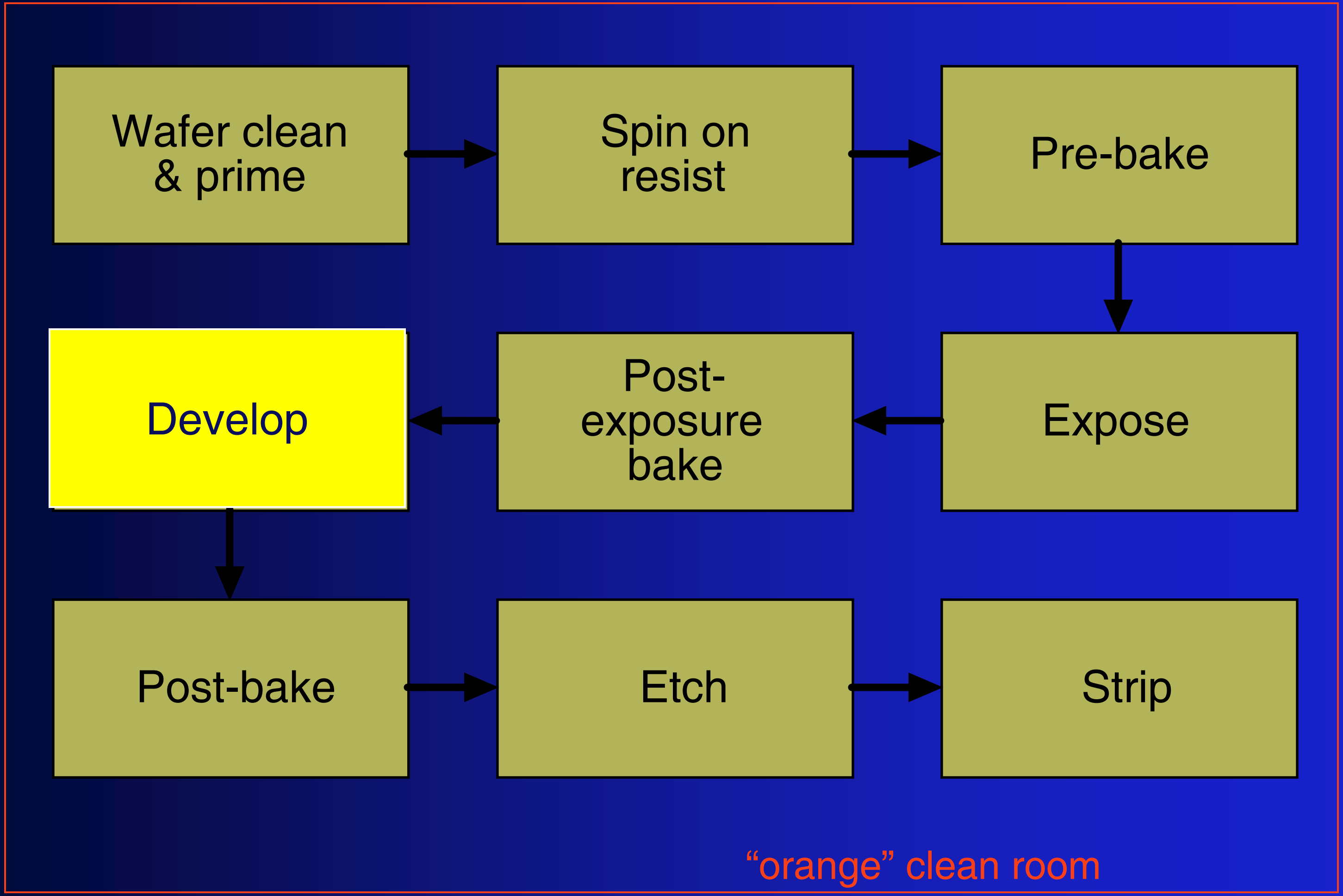
Contact mask aligner



Projection stepper



Photoresist process flow



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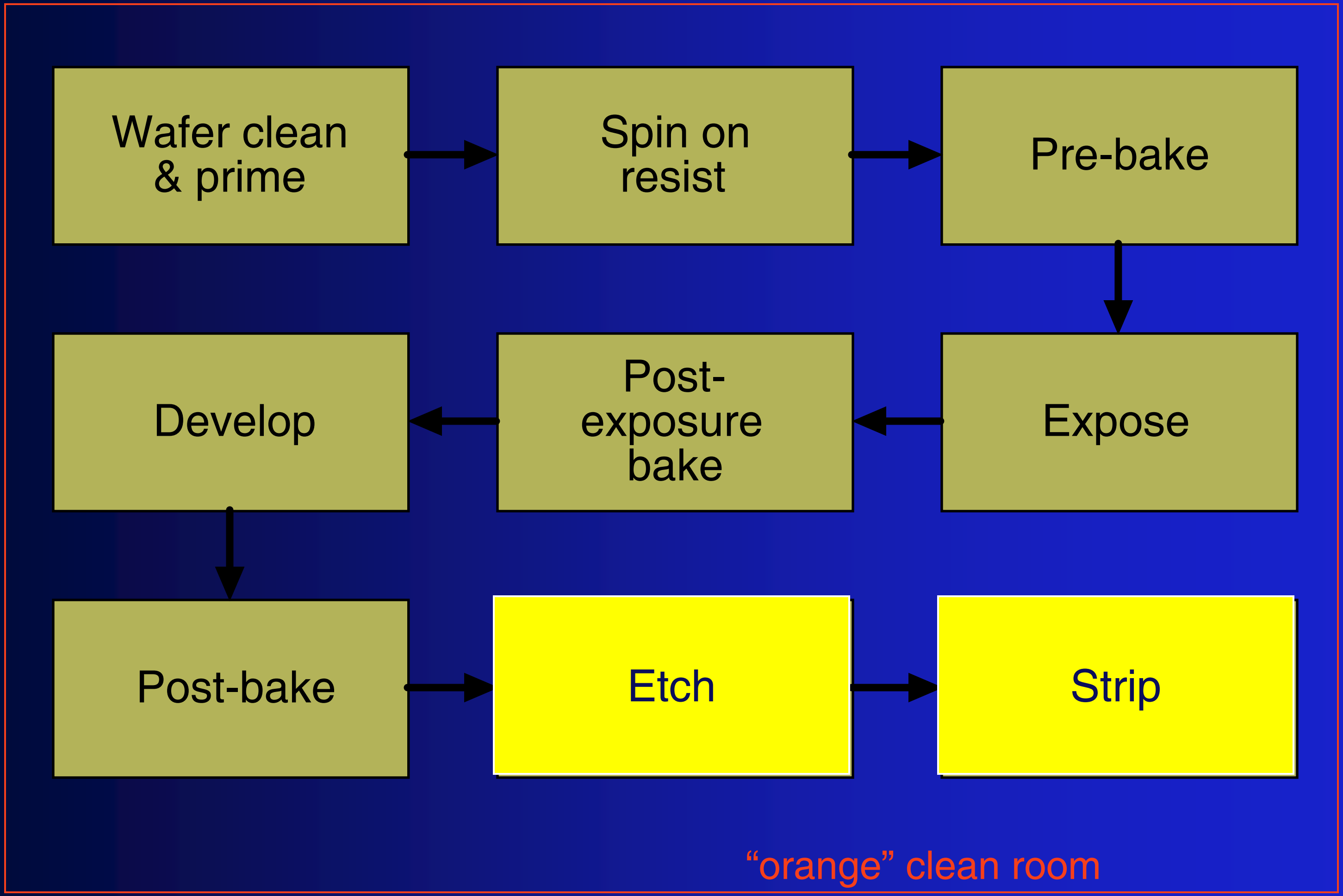

Wafer clean & prime

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Dry etch processes

- Plasma etching (back etching)

  ions in a glow discharge erode the wafer surface
- Reactive ion etching (RIE)

  plasma etching with Cl or F, which enhances etch rate of Si;
  plasma etching with O_2 enhances removal of photoresist
- Deep reactive ion etching (DRIE)

  Bosch process
  alternating reactive ion etch with deposition of teflon-like protective layers on vertical surfaces
- Ion beam etching

  beam of ions erodes most materials fairly uniformly

Conventional photolithography

Positive photoresist

- Exposure breaks polymer bonds
- Developer clears exposed photoresist

Negative photoresist

- Exposure polymerizes photoresist
- Developer dissolves unexposed regions

Conventional photolithography

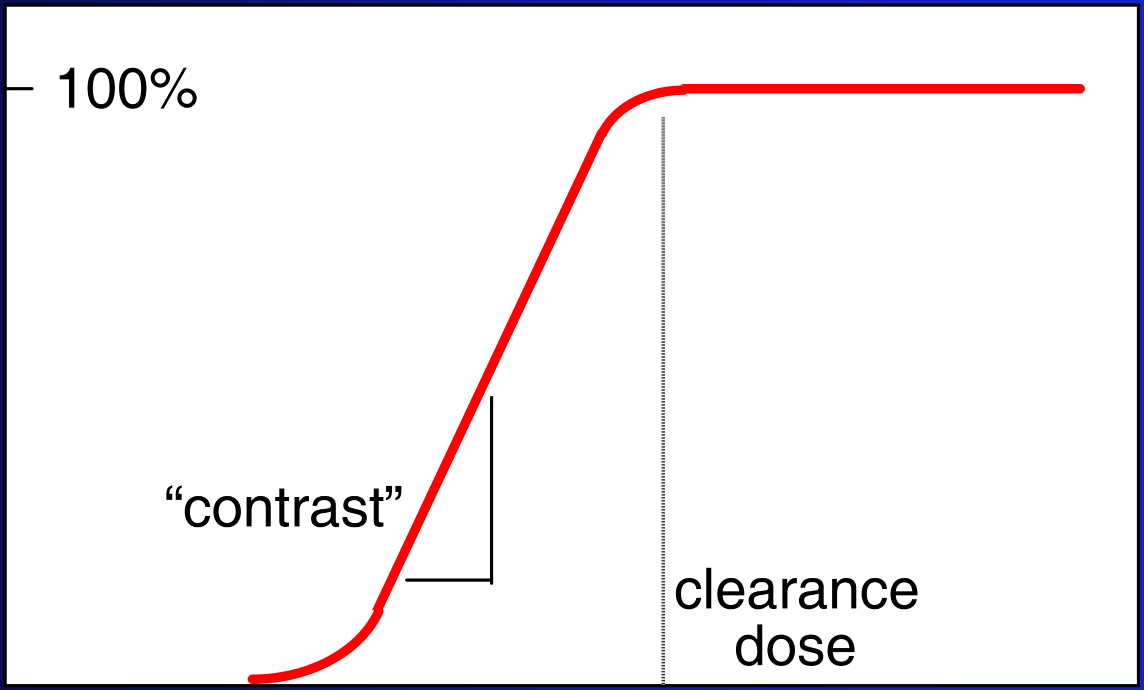
Positive photoresist

- novolac resin matrix + photo-active compound + solvent
- insoluble polymer matrix + photo-acid generator + solvent

Negative photoresist

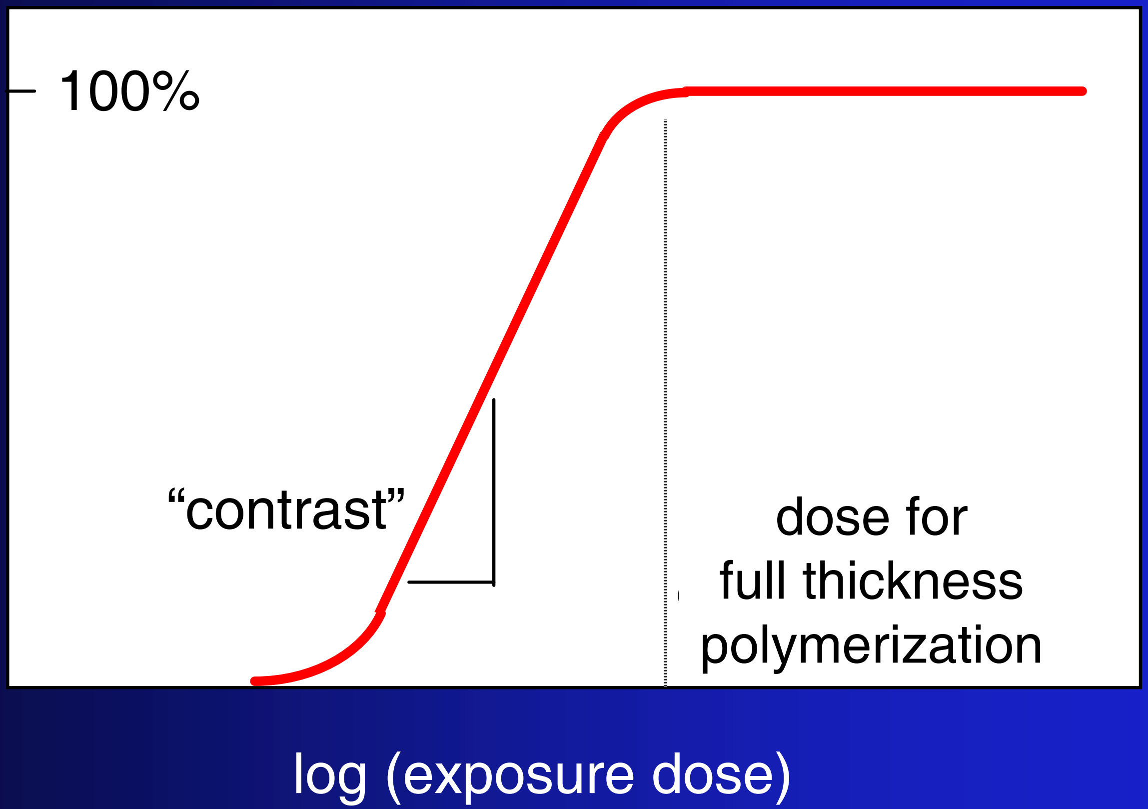
- synthetic rubber matrix + photo-acid generator + solvent
- epoxy resin matrix + photo-acid generator + solvent

Clearance of positive resist



log (exposure dose)

Polymerization of negative resist



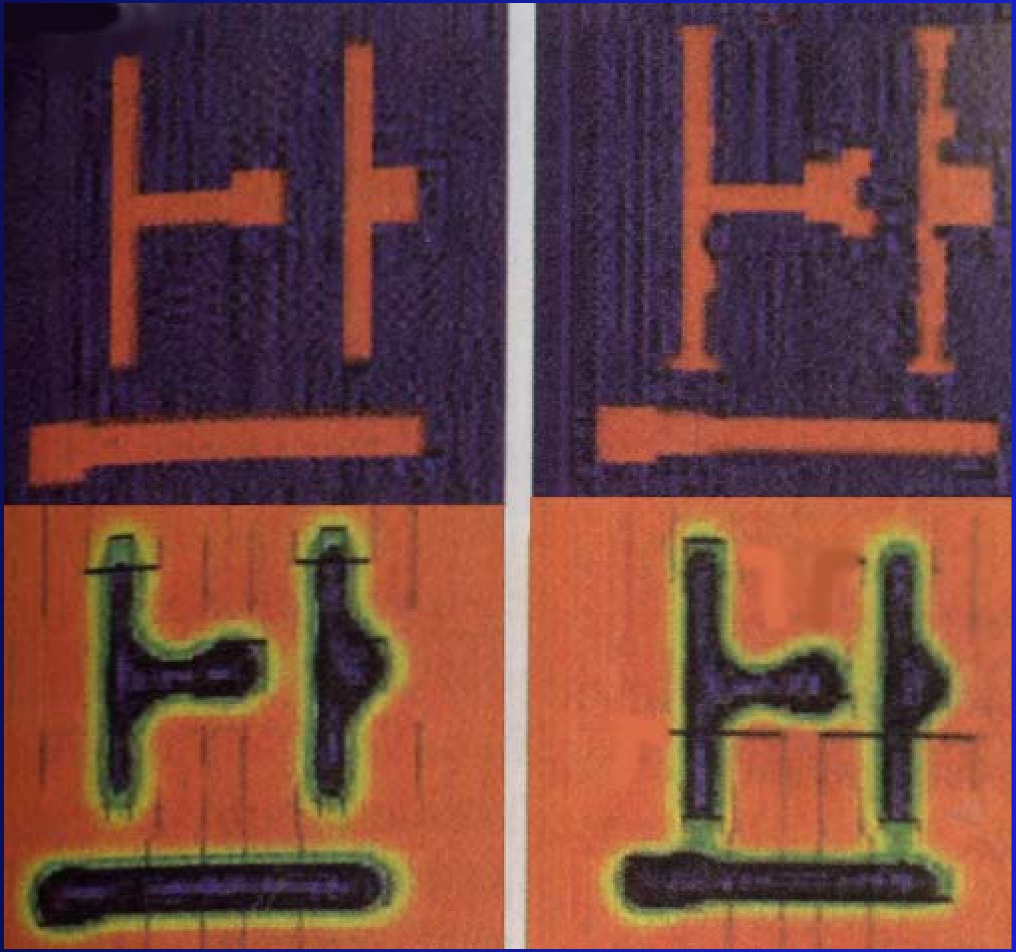
Conventional photolithography

- Contact aligners use 365nm (Hg)
- Present stepper wavelengths:

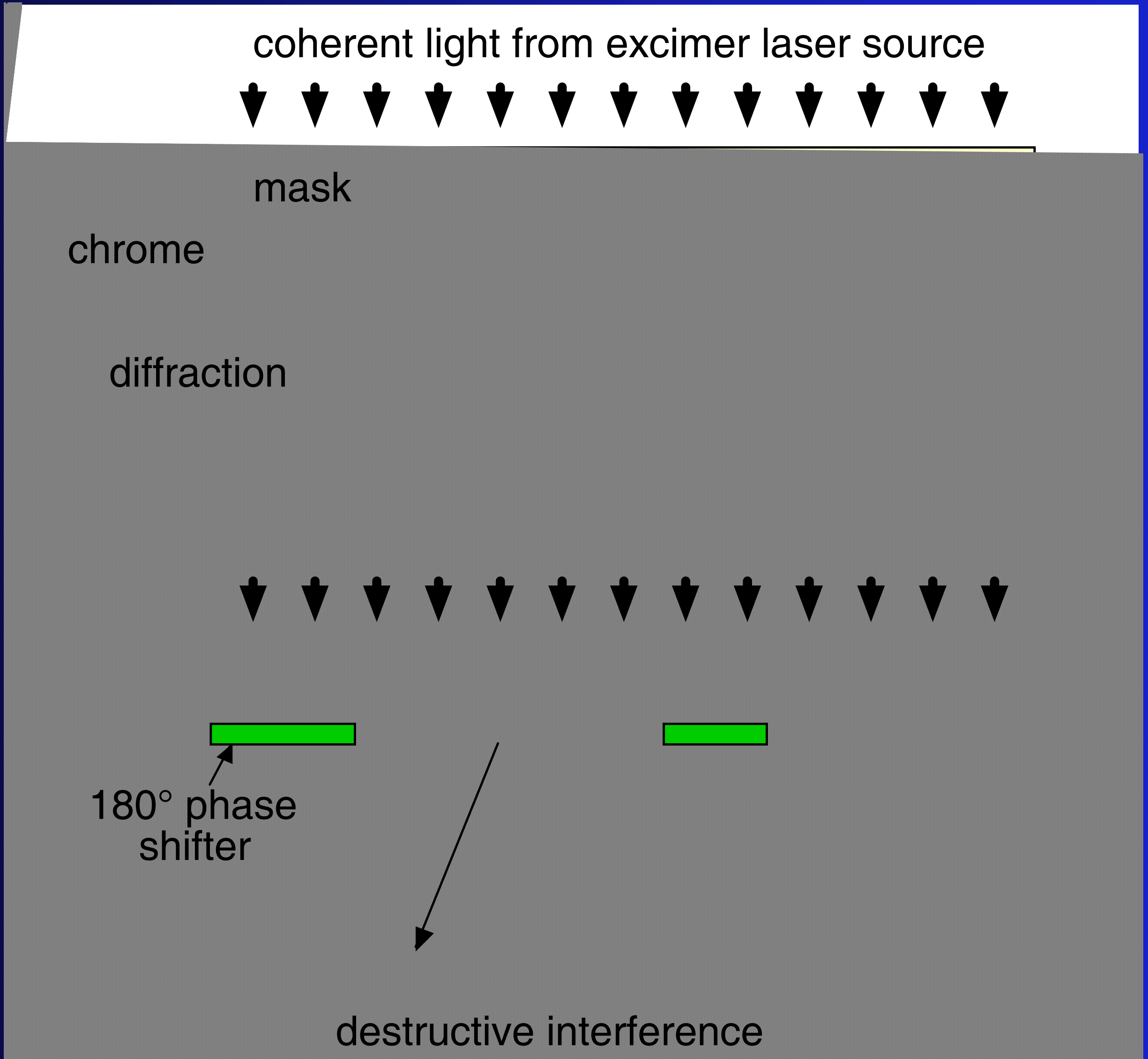
  365nm (Hg), 248nm (KrF-excimer), 193nm (ArF-excimer)
- Coming soon: 157nm (F_2-excimer)
- Feature size: 0.5λ to 0.7λ using phase-shift masks and optical proximity correction
- Electron-beam lithography: Direct write on wafer (DWW); one at a time…
- Extreme UV (λ ~ 11 – 14 nm) }
- X-ray lithography }

Research ongoing

Optical proximity correction



Phase shift masking



coherent light from excimer laser source

mask

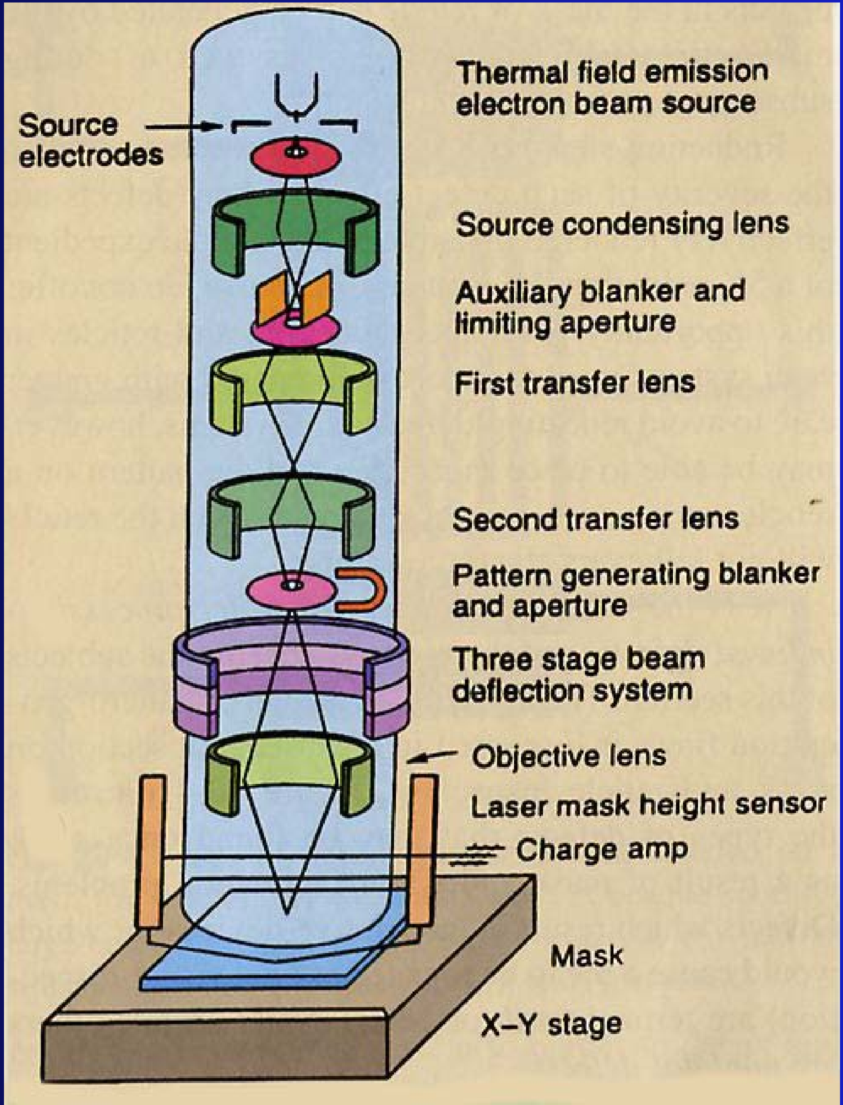
chrome

diffraction

180° phase
shifter

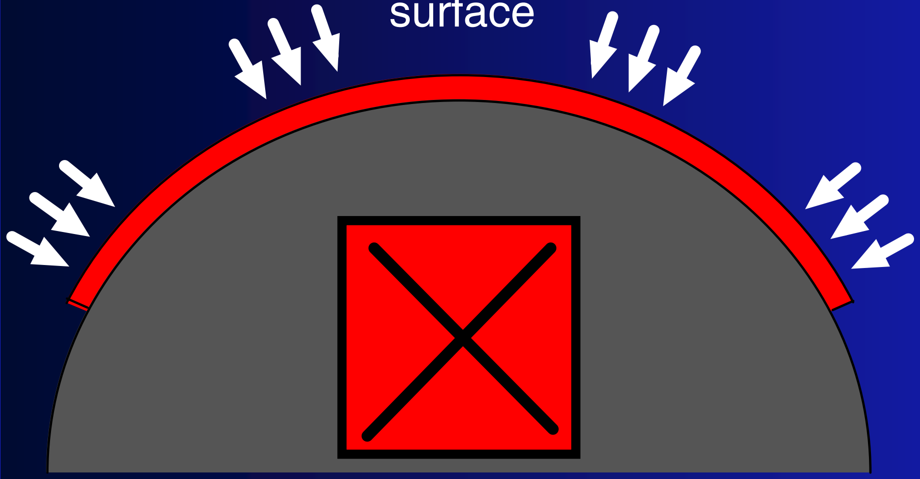
destructive interference

E-beam exposure system

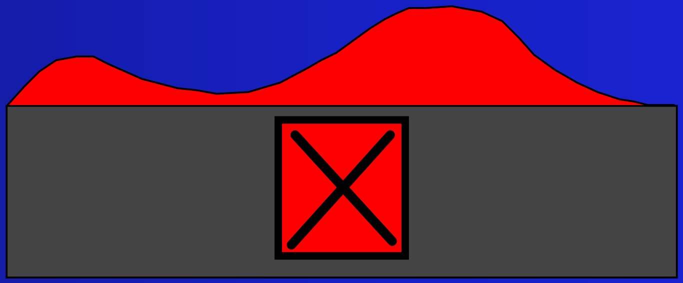


Conventional photolithography

- Cannot use non-planar substrates
- Cannot produce arbitrary non-planar shapes



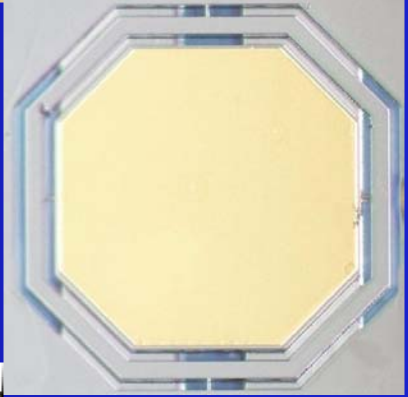
patterned u-v exposure on non-planar surface



Produce photoresist layer of varying thickness

Exciting new applications

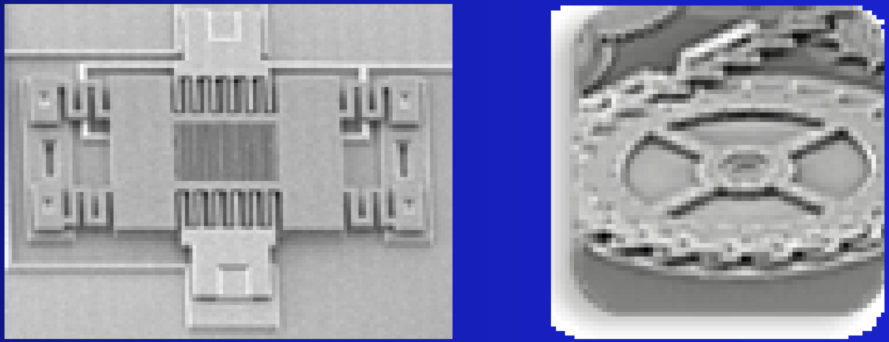
- Micro-optics
  - lens arrays
  - integrated optics
  - micro-opto-electro-mechanical systems on a chip (MOEMS)
  - grayscale diffractive elements
  - beam shaping
  - wavefront analysis



Exciting new applications

- Micro-fluidics
  - “lab-on-a-chip”
  - medical diagnostics
  - drug screening
  - genome research

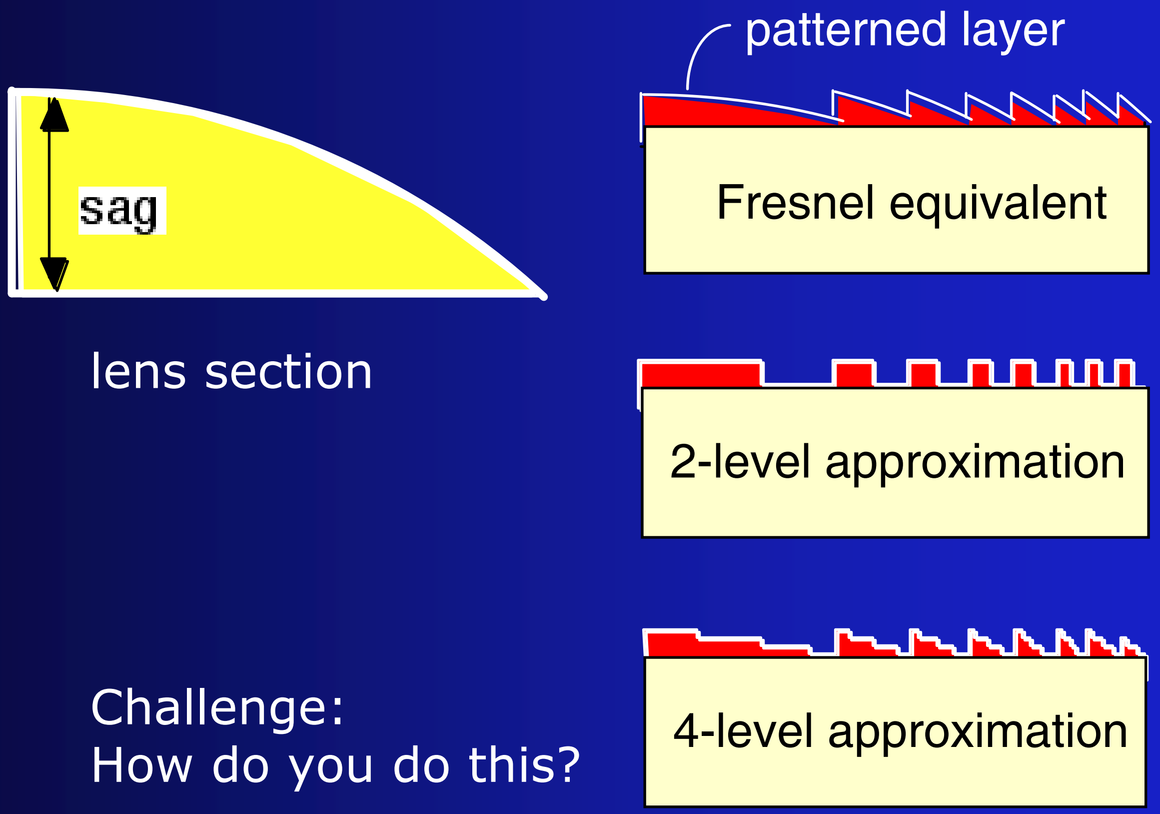
- Micro-mechanics
  - micro-sensors
  - micro-actuators
  - micro-robotics
  - micro-electro-mechanical systems on a chip (MEMS)



Successful extensions of conventional photolithography

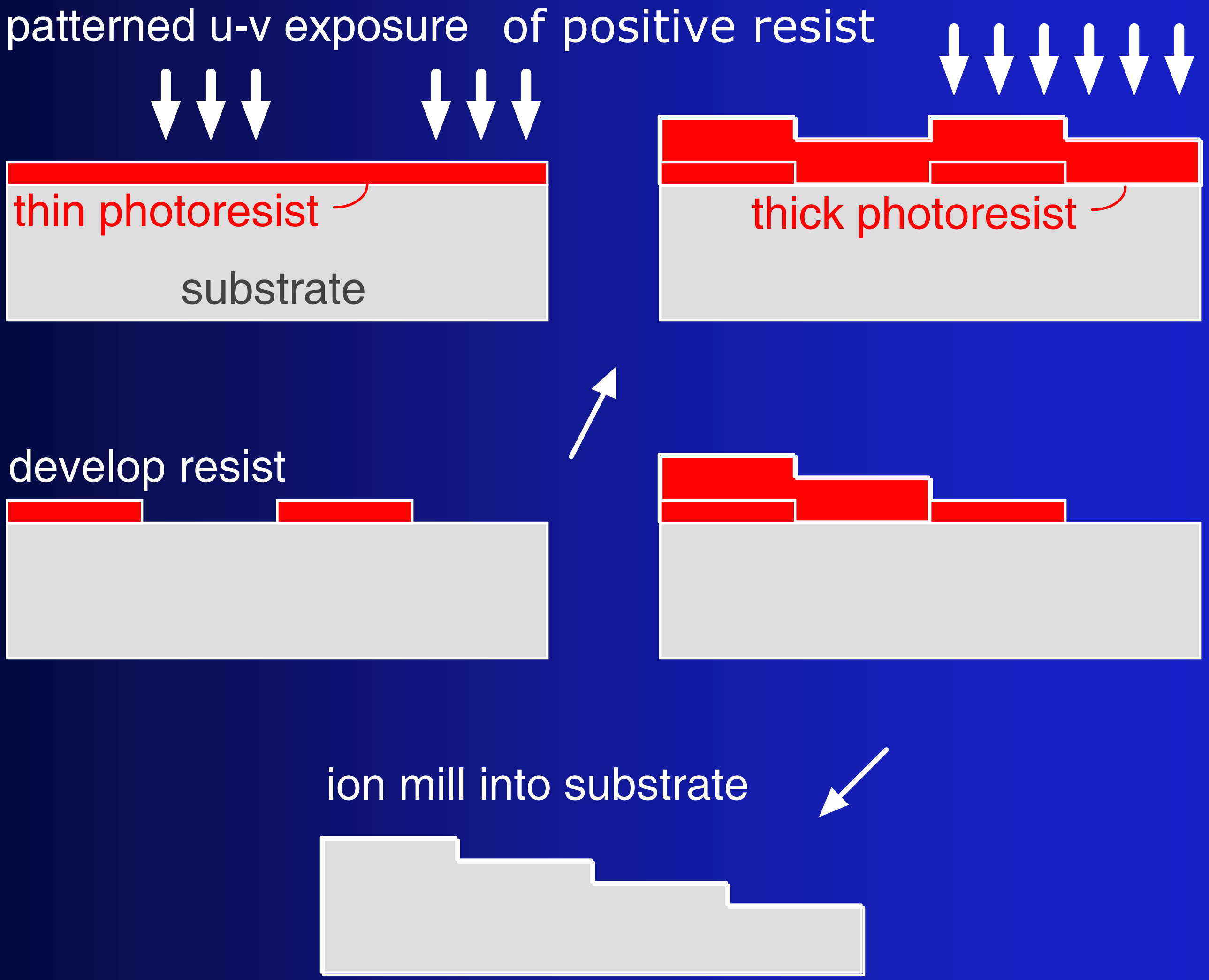
Micro-optics

- Multiple binary-masked photolithography



Challenge:
How do you do this?

Multiple binary-masking



patterned u-v exposure of positive resist

thin photoresist

substrate

thick photoresist

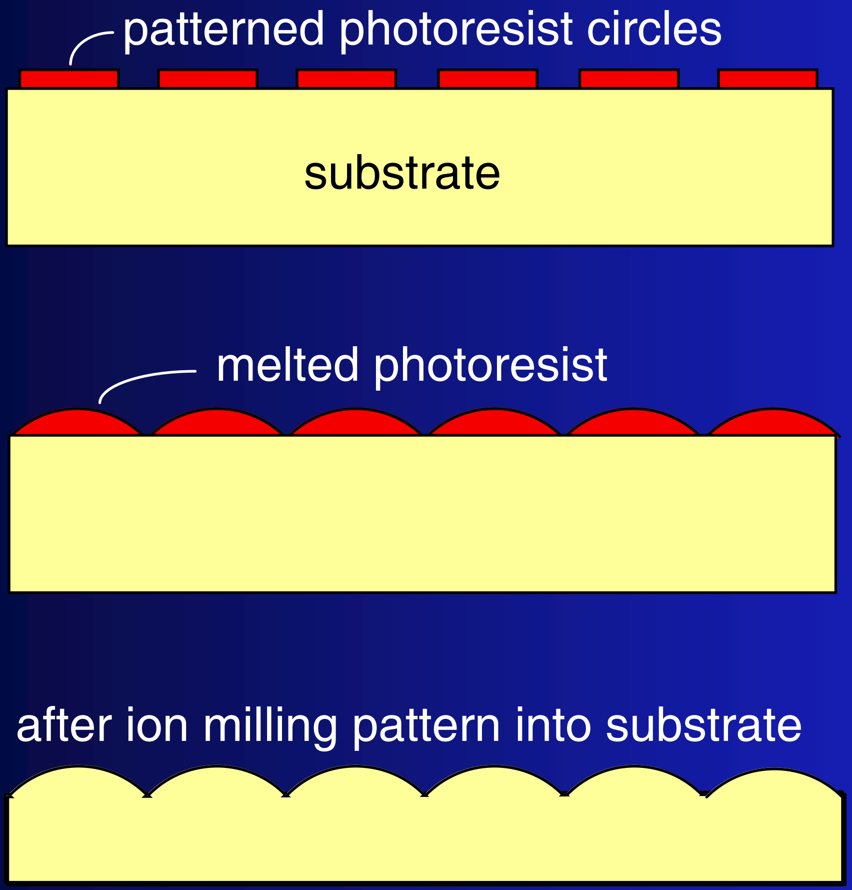
develop resist

ion mill into substrate

Successful extensions of conventional photolithography

Micro-optics

- Thermal reflow lenses



patterned photoresist circles

substrate

melted photoresist

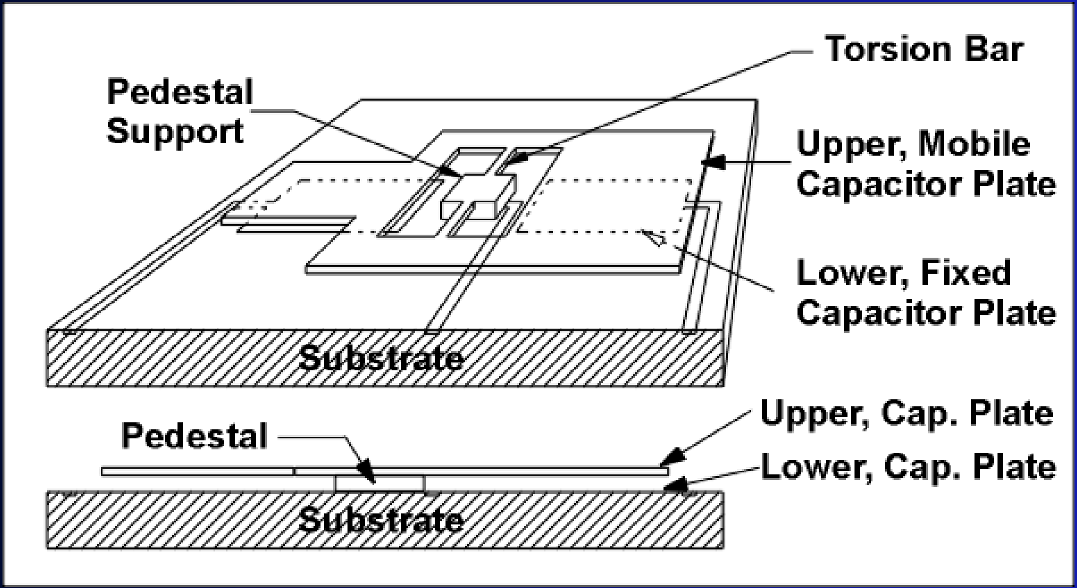
after ion milling pattern into substrate

Successful extensions of conventional photolithography

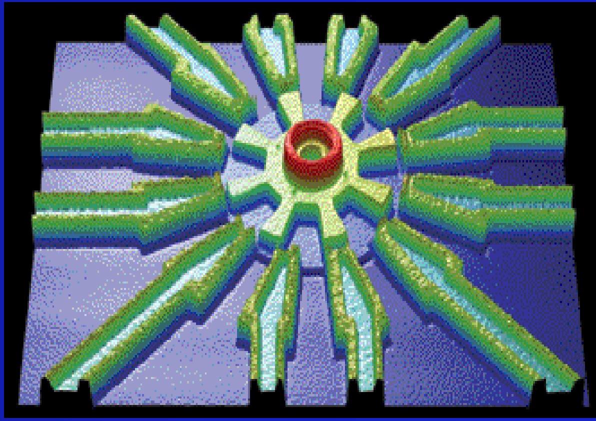
Micro-electro-mechanical systems

Patterned metal layers released from the substrate using sacrificial layers.

accelerometer



micromotor



Gray scale lithography with positive photoresist

- Advantages of gray scale
- Photoresist clearance *vs* dose
- Process flow
- Examples of current applications

Gray scale lithography with positive photoresist

Advantages

- Standard photolithographic processing, but grayscale mask is required

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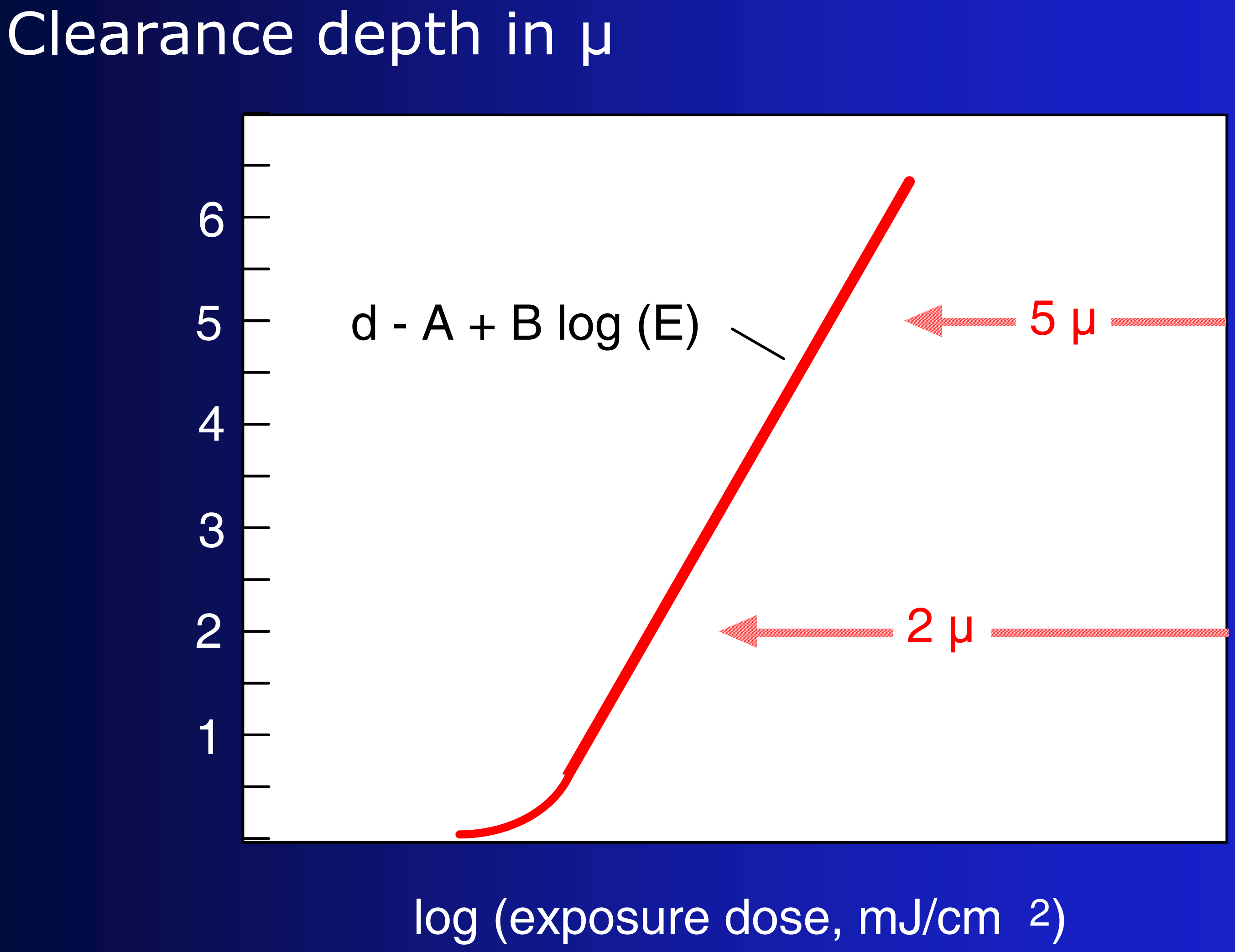
- Accurate 3-D shaping of the upper surface of the photoresist (with very tight process control)
- Resist thickness < 20 μ (typically), but topography transferred into substrate can be enhanced by manipulation of RIE parameters

Clearance depth of positive resist



Clearance depth: theory

Exposure Dose = E = I_0 t (mJ/cm^2)

I_0 = Incident light flux (mW/cm^2)
t = Exposure time (sec)

Energy needed/cm^3 to clear = W_0 (mJ/cm^3)

Energy absorbed per cm^3 at depth x = W(x)

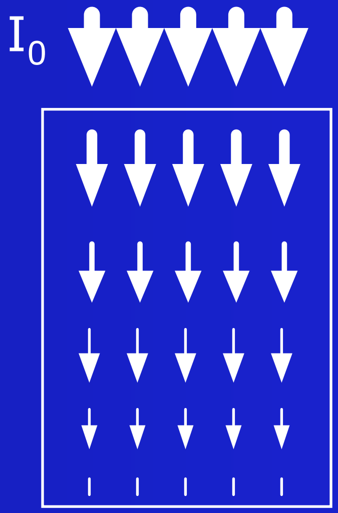
$W(x) = \alpha I(x) t$

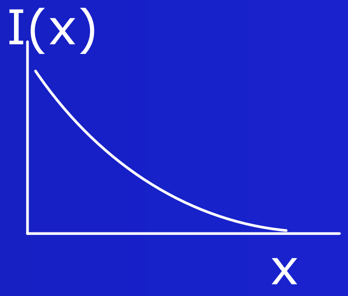
α = absorption coef (cm^{-1})
fractional loss of intensity per cm

$I(x) = (1-R) I_0 \exp(-\alpha x)$

R = reflectivity

$W(x) = \alpha (1-R) I_0 t \exp(-\alpha x)$





Clearance depth: theory

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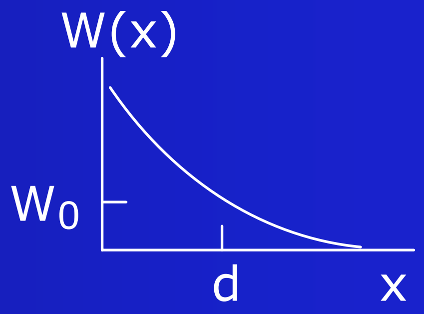


Resist at x will clear if $W(x) > W_0$

Maximum x that will clear = d (cm)

$W(d) = W_0 = \alpha\ (1-R)\ I_0\ t\ \exp(-\alpha\ d)$

$d = (-1/\alpha) \ln(W_0 / \alpha\ (1-R)\ I_0\ t)$

$= (1/\alpha) \ln(\alpha\ (1-R)/W_0) + (1/\alpha) \ln(I_0\ t)$

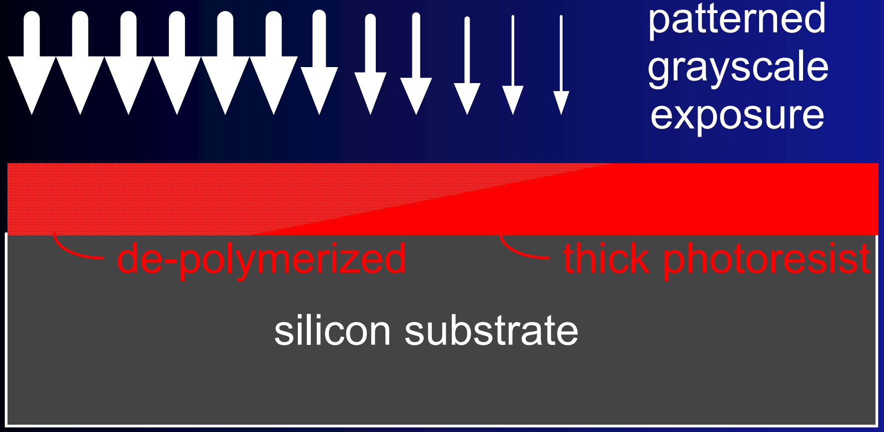
Therefore $d = A + B \log(E)$

Where $A = (1/\alpha) \ln(\alpha\ (1-R)/W_0)$
$B = 2.303/\alpha$

Therefore, by varying the incident dose, E, as a function of position on the wafer, we can clear to different depths.

Gray scale lithography with positive photoresist

Process flow


patterned grayscale exposure


development

after ion milling ; (equal erosion of resist and substrate)


after RIE or DRIE ; (enhanced erosion of substrate)

Gray scale lithography with positive photoresist

Current applications

- Beam shaping micro-optical elements
  - —coupling laser diode output to waveguide mode
  - —creating uniform line intensity from l.d. output

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- Diffractive optical elements
    - —blazed gratings
    - —combined refractive and diffractive elements

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    - —Fresnel lenses
- Diffractive optical elements
    - —blazed gratings
    - —combined refractive and diffractive elements
- Shaped MEMS structures
    - —electrodes for electrostatic actuators
    - —micro-engine structures (turbines, compressors)
    - —microfluidics

Gray scale lithography with negative photoresist

- Advantages of SU-8 resist
- Disadvantage of negative resist
- Process flow
- Potential applications

Gray scale lithography with negative photoresist

Advantages of SU-8 resist

- SU-8 is a photocurable epoxy; it is durable and resistant to most chemicals and solvents

Gray scale lithography with negative photoresist

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- SU-8 is available with a variety of viscosities and it can be spun-on with thickness between 10 and 300 µ
- Multiple applications can bring SU-8 thickness to > 1 mm
- SU-8 can be exposed with contact mask aligners to a depth of > 1 mm.

Conventional SU-8 processing

- Clean and prime wafer
- Spin on SU-8
- Pre-bake to drive off solvent (level hot plate)

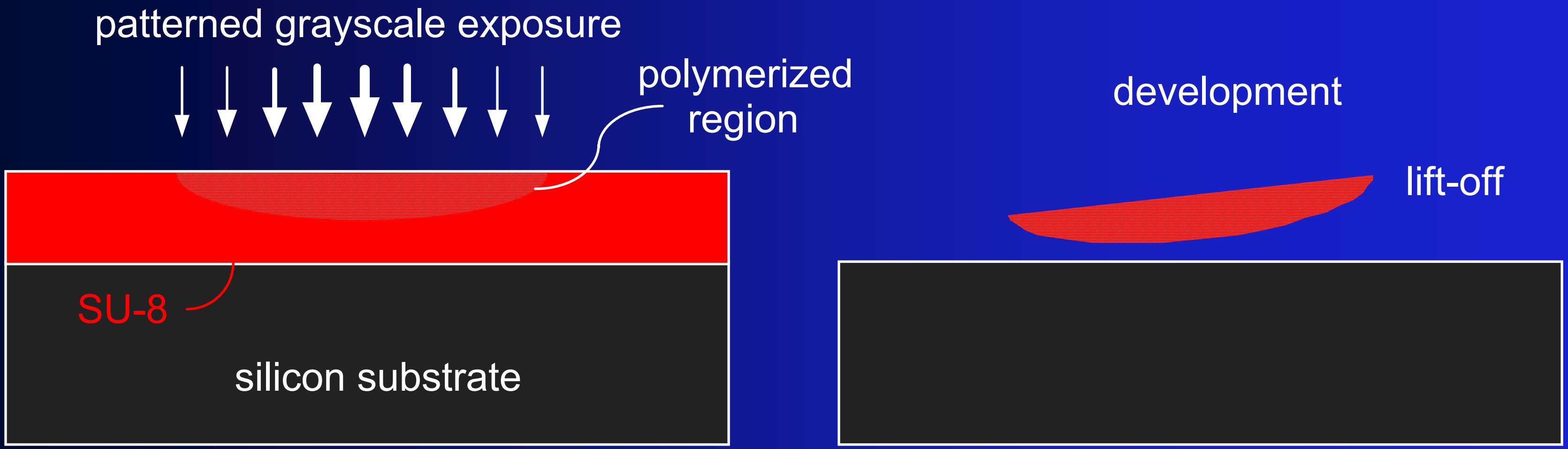
  SU-8 remains liquid after spin-on; after solvent is evaporated, layer is photopolymerizable, but pure SU-8 will melt at 55°C.
- Expose
- Post-bake (hot-plate)

  UV light releases photo-acid; at post-bake temperature (95°C) SU-8 will harden irreversibly
- Develop (dissolve unpolymerized SU-8)

Gray scale lithography with negative photoresist

Disadvantage of using SU-8

As with any negative resist, incomplete gray scale exposure in conventional process leads to hardening of surface, which "lifts off" the substrate if unattached!



Gray scale lithography with negative photoresist

Disadvantage of using SU-8

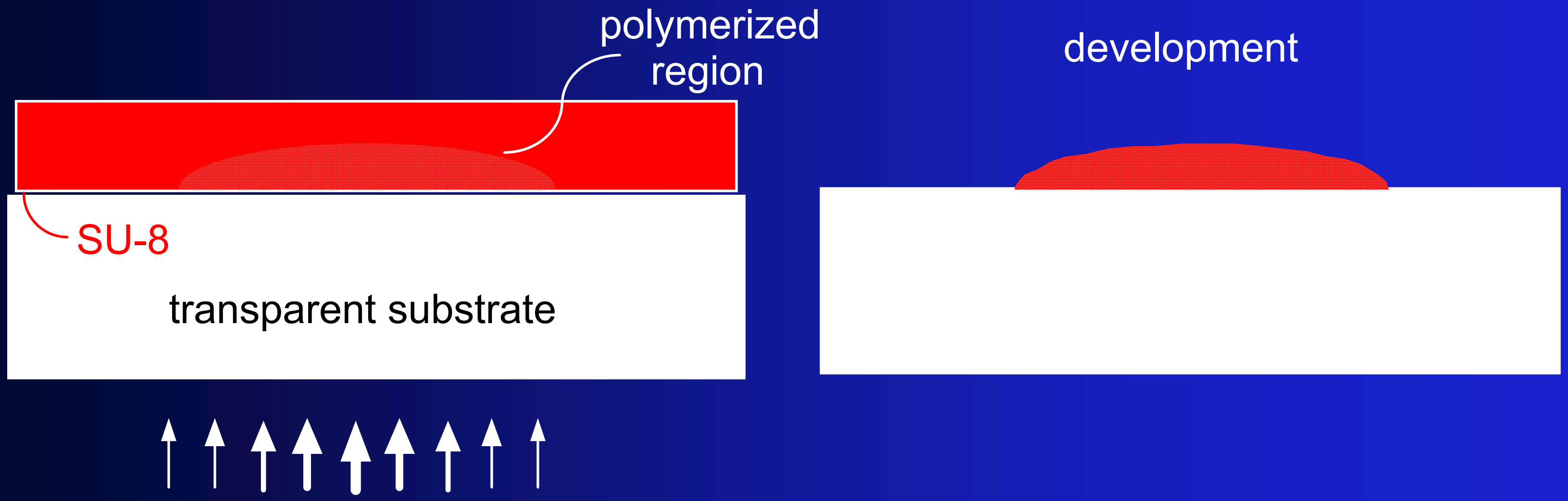
As with any negative resist, solvents are used to develop the image, and resist swelling occurs.

Resist swelling caused the IC industry to abandon negative photoresists when the feature size reduced to less than ~ 3µm.

In contrast, positive resists are developed in caustic aqueous solutions.

Gray scale lithography with negative photoresist

The process that works!



polymerized region

development

SU-8

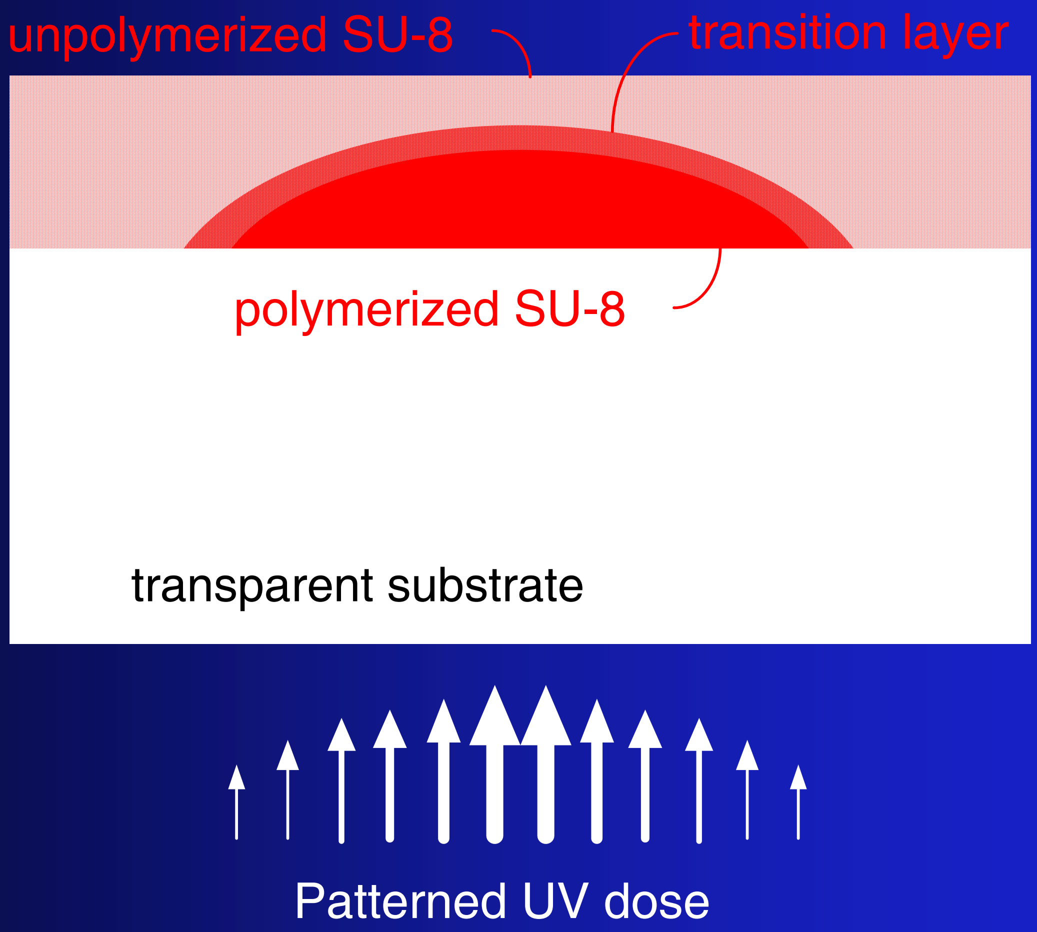
transparent substrate

patterned grayscale exposure
through the substrate

But it requires considerable modification of standard process flow…

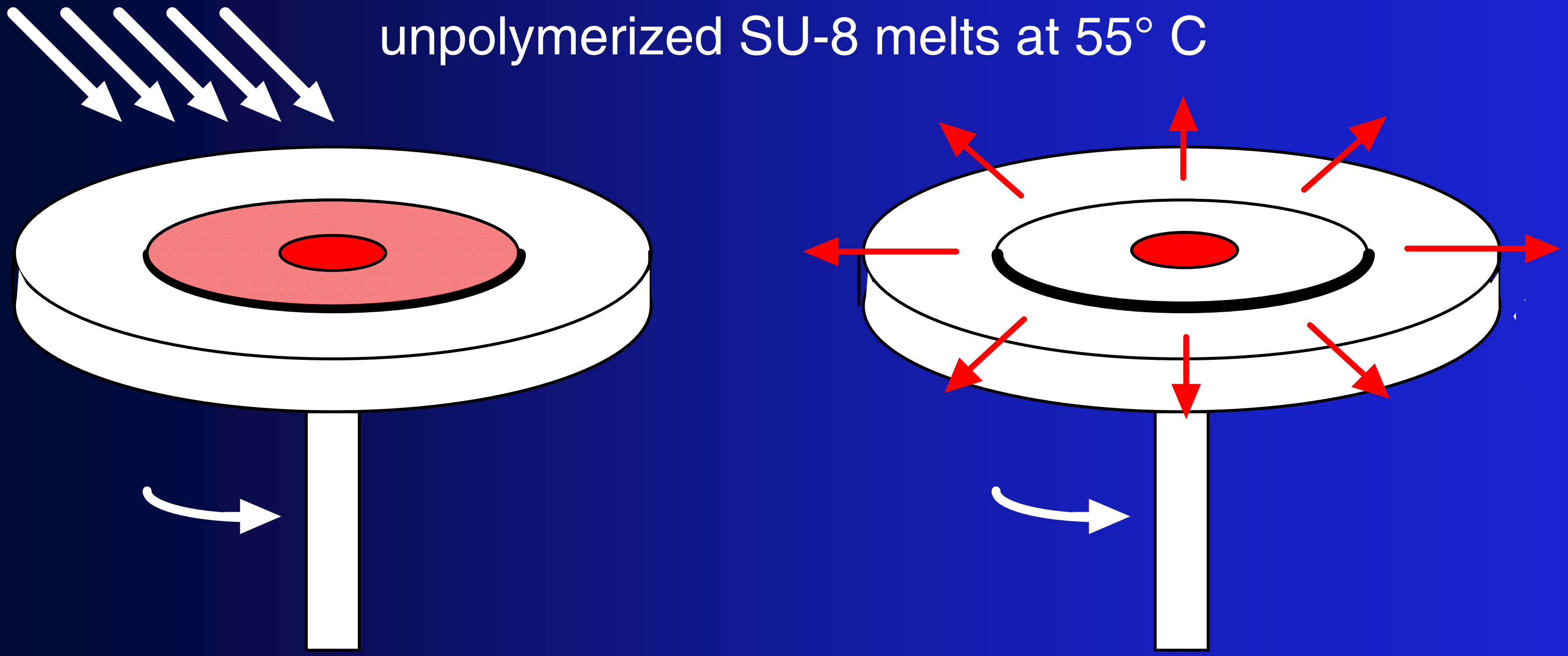
SU-8 development problems

Developer is aggressively taken up by the “barely polymerized” SU-8, swelling the layer by 30% in volume.



SU-8 development solution

Hot spin development

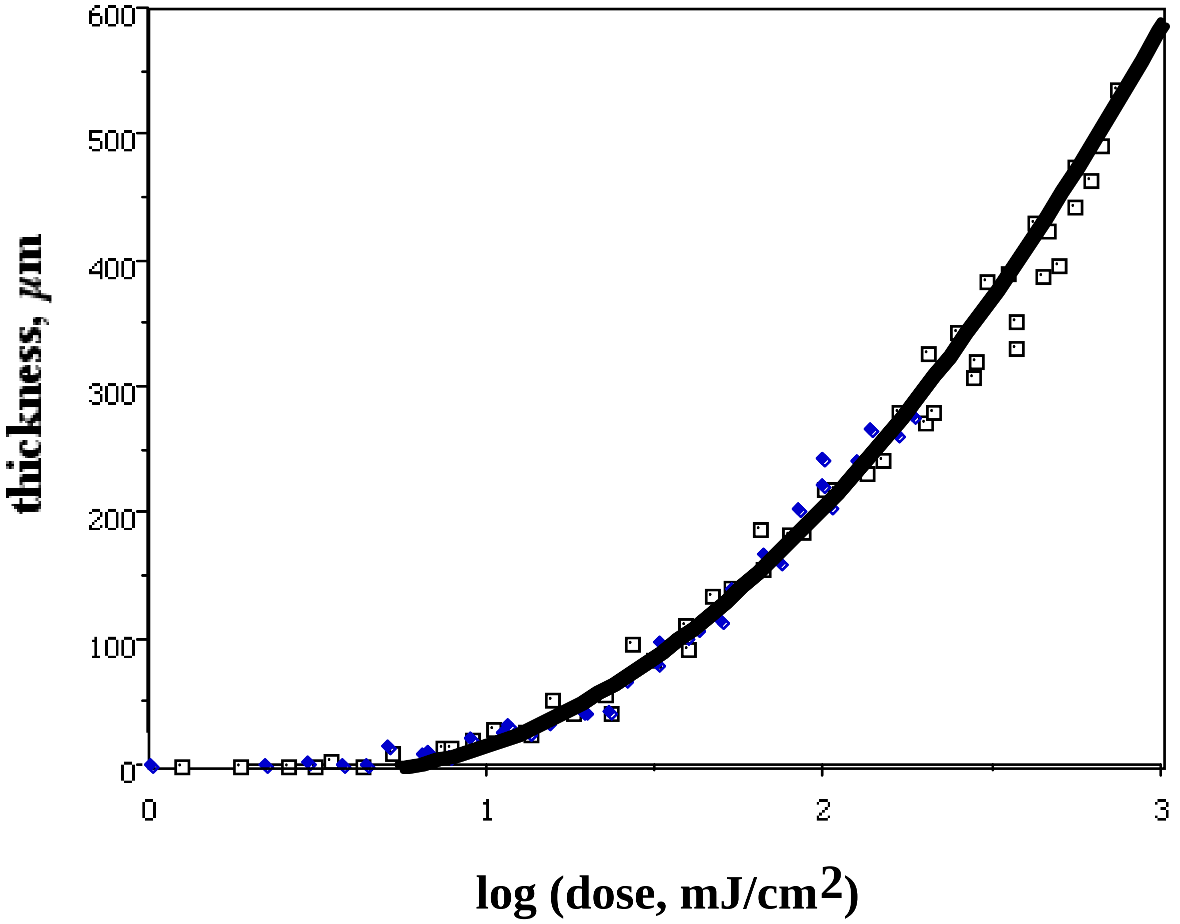


Heat

unpolymerized SU-8 melts at 55° C

polymerized SU-8 remains on substrate

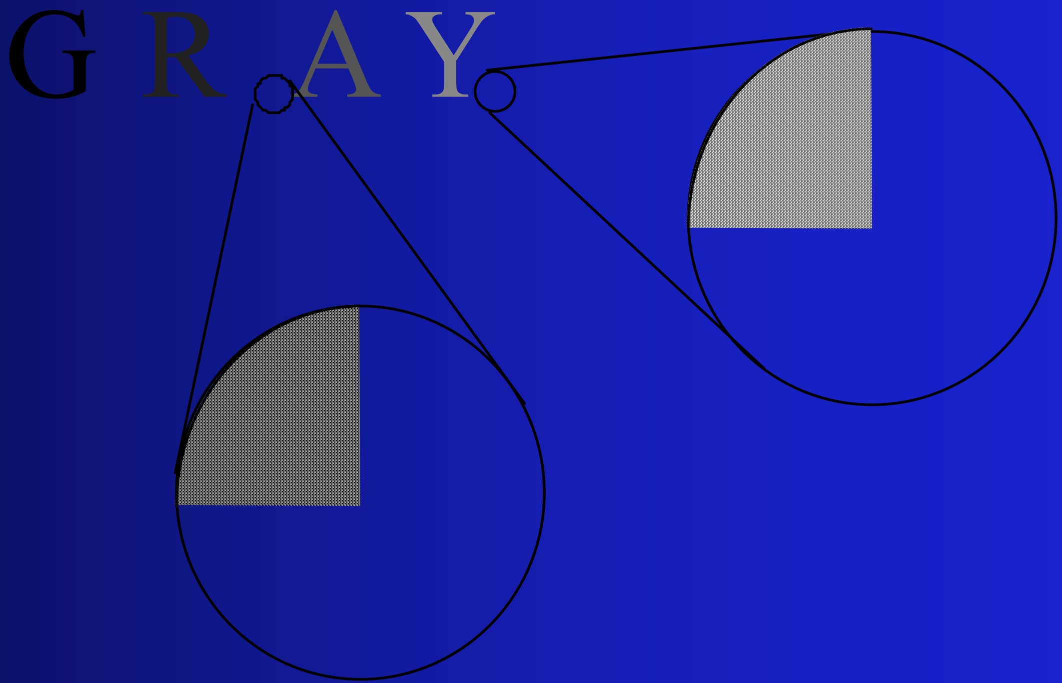
SU-8 thickness *vs* dose



Gray scale masks

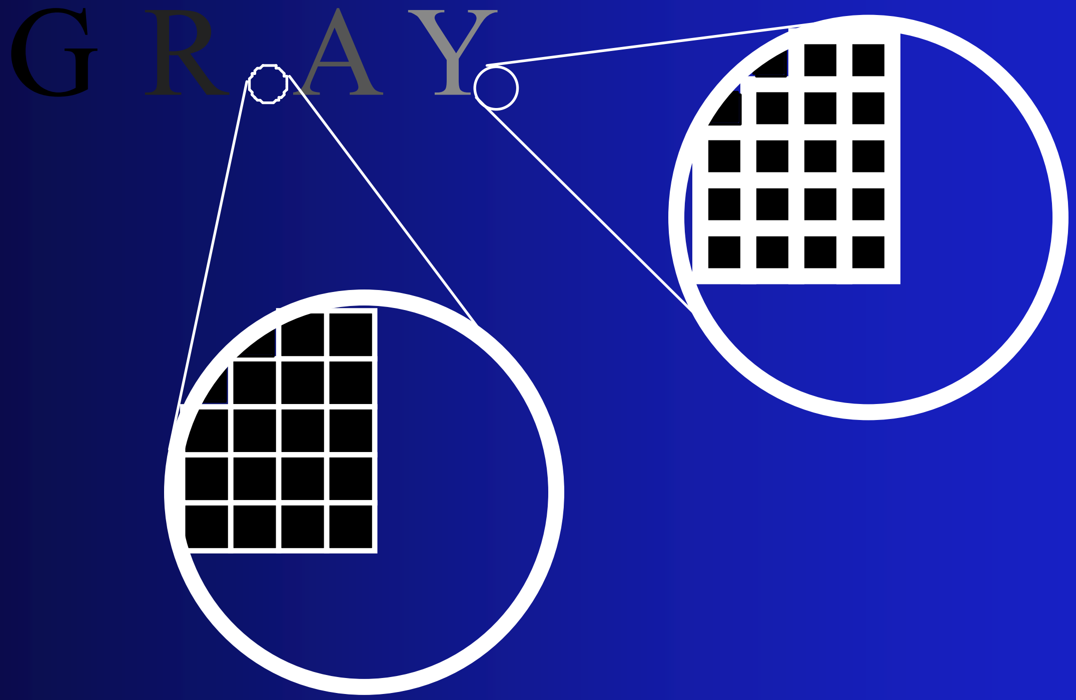
- Half tone masks—varying sized areas of full opacity
- “True” gray scale masks

Half tone print media



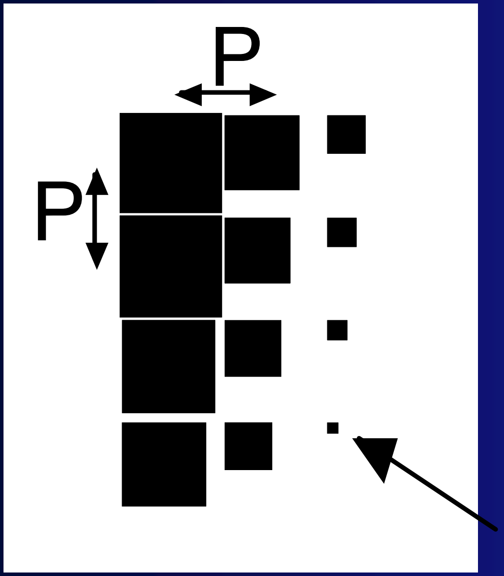
"Dots" are black, but sized to be below the resolution of the eye

Typical pseudo grayscale mask



Mask must be produced by e-beam exposure

Typical pseudo grayscale mask

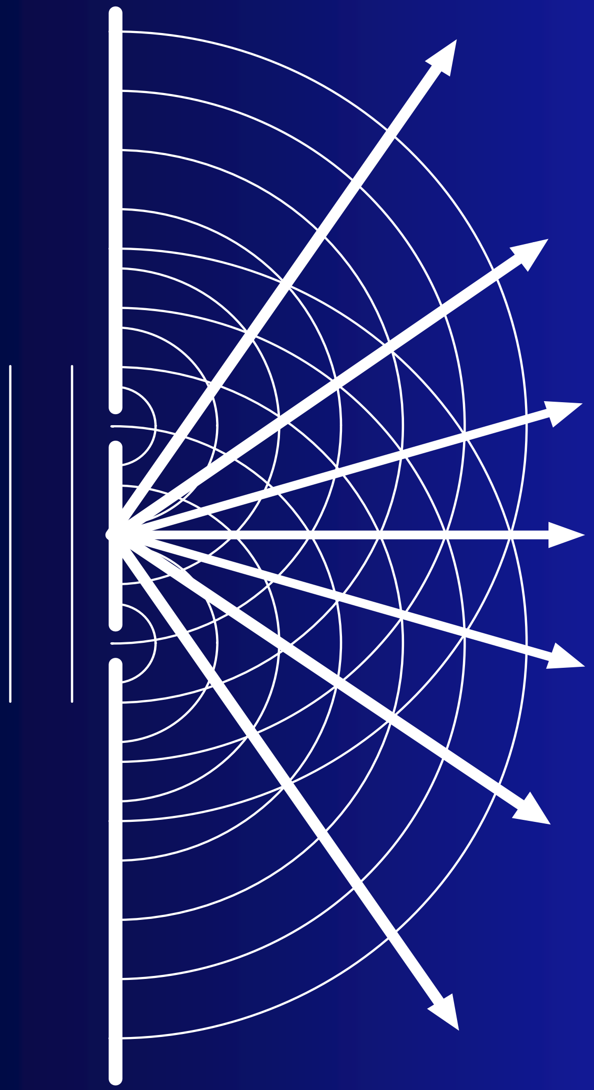


Design considerations

smallest possible feature size on mask, ε

P must be below resolution limit of mask aligner.
Range of gray tones: 0 —> 1, in steps of $(\varepsilon/P)^2$
Example: P = 1 μm, ε = 0.1 μm —> 100 grayscale steps

Physics of stepper resolution limit



Apertures in mask produce diffracted beams

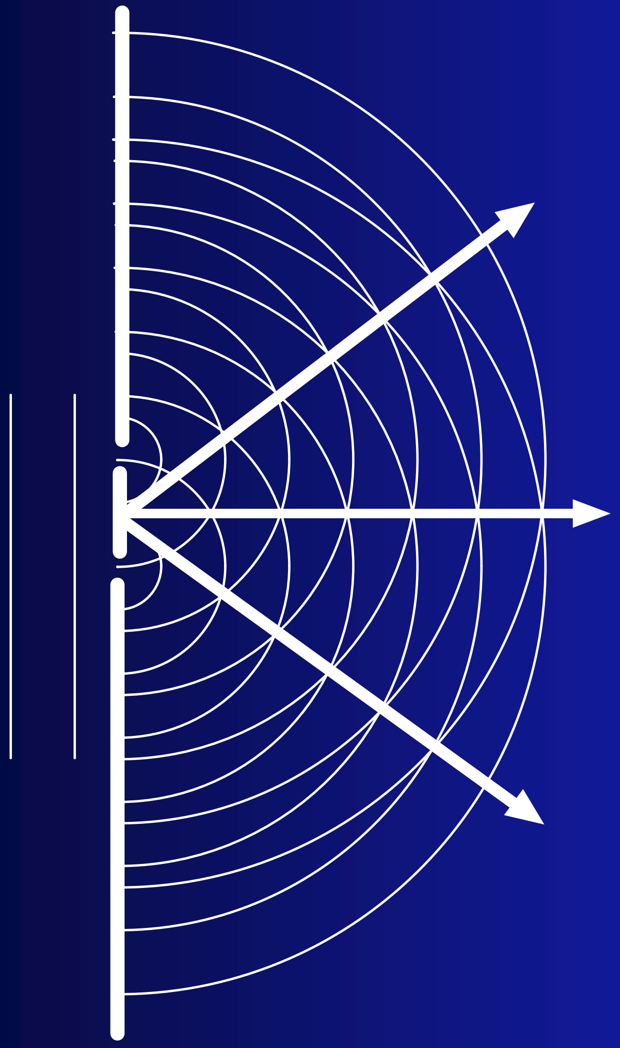
Sin θ = nλ/s

s=3.5 λ

θ = 0, 16.6°, 34.85°,59°

s = distance between slits
λ = wavelength
n = 0, ±1, ±2, …

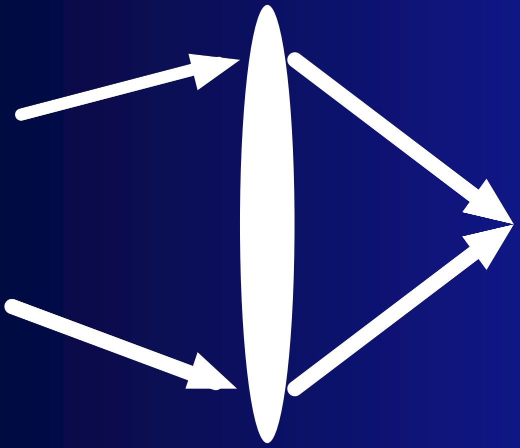
Physics of stepper resolution limit



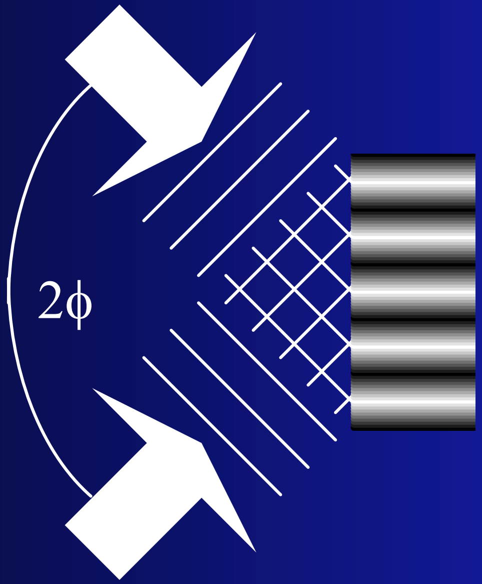
s=1.5 λ

θ = 0, 41.81°

Physics of stepper resolution limit

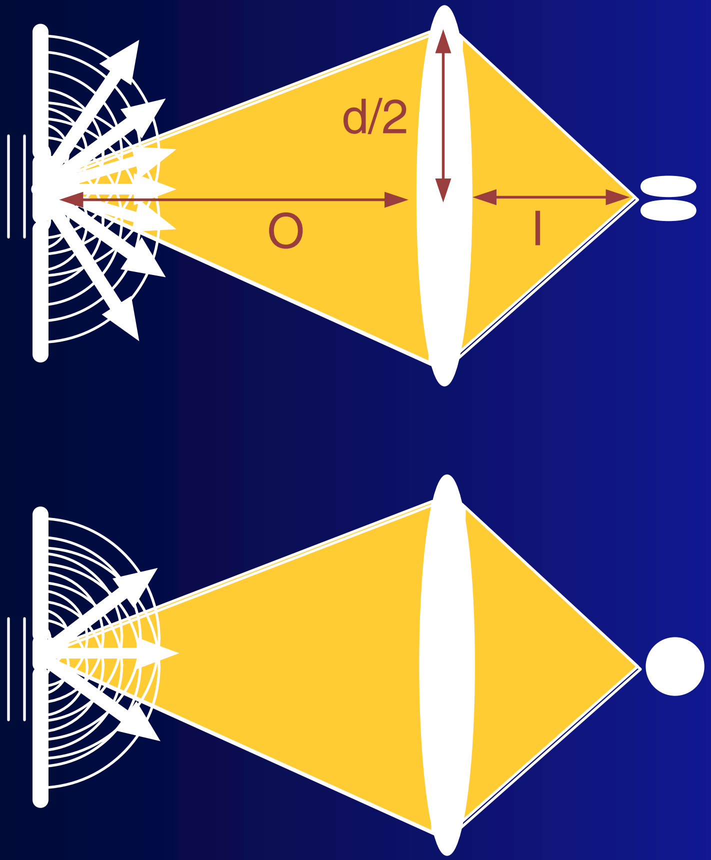


Converging rays produce diffraction patterns



$p = \lambda / \sin \phi$

Physics of stepper resolution limit



$$\frac{d/2}{I} = NA$$

$$\frac{d/2}{O} > \frac{\lambda}{s}$$

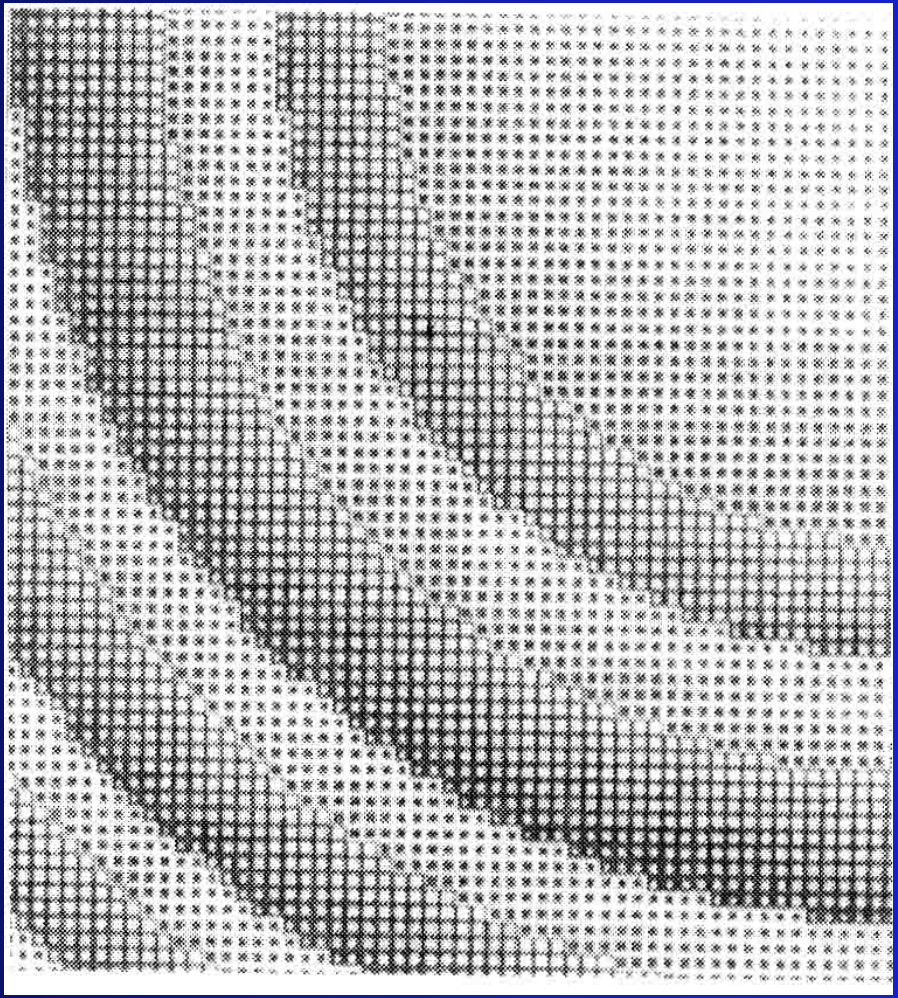
$$s > \frac{\lambda O}{d/2}$$

$$\frac{s}{M} > \frac{\lambda O/M}{d/2} = \frac{\lambda I}{d/2} = \frac{\lambda}{NA}$$

s=slit separation M=lens reduction factor

Typical pseudo grayscale mask

Detail of a Fresnel lens mask



Typical pseudo grayscale mask

Design considerations

- Not all thickness levels will “print”, due to non-linearity of photoresist clearance (or polymerization) *vs* dose

Typical pseudo grayscale mask

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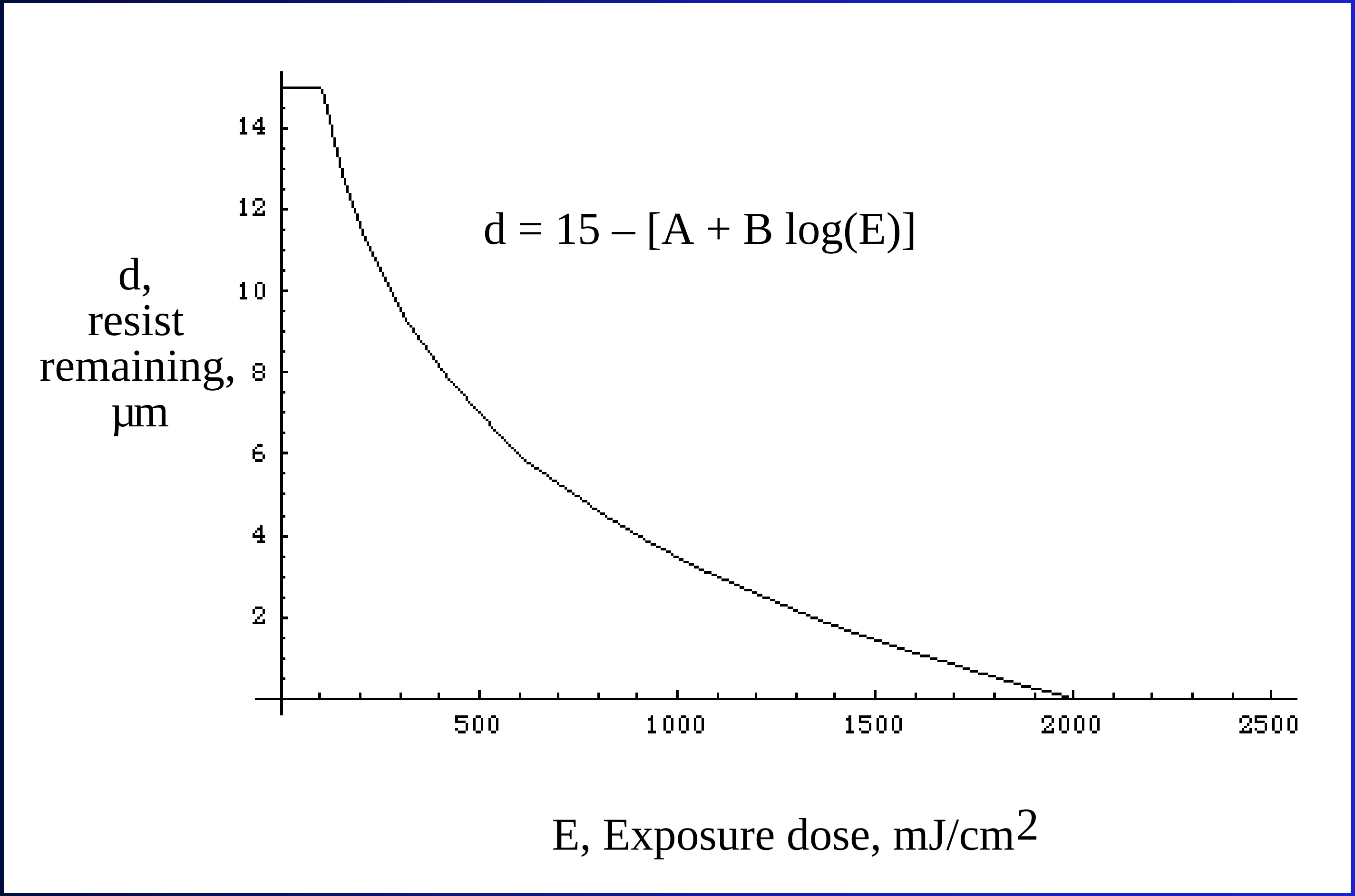
Typical pseudo grayscale mask

Design considerations

- Not all thickness levels will “print”, due to non-linearity of photoresist clearance (or polymerization) *vs* dose
- Mask design depends critically on a stable, consistent, reproducible lithographic process!
- Creation of a reliable depth *vs* gray-level calibration relationship is essential

Simulated calibration curve

Positive resist, 15 µm thick, $1/\alpha = 5\mu m$, $W_0 = 0.2\ nJ/\mu m^3$



Simulated calibration curve

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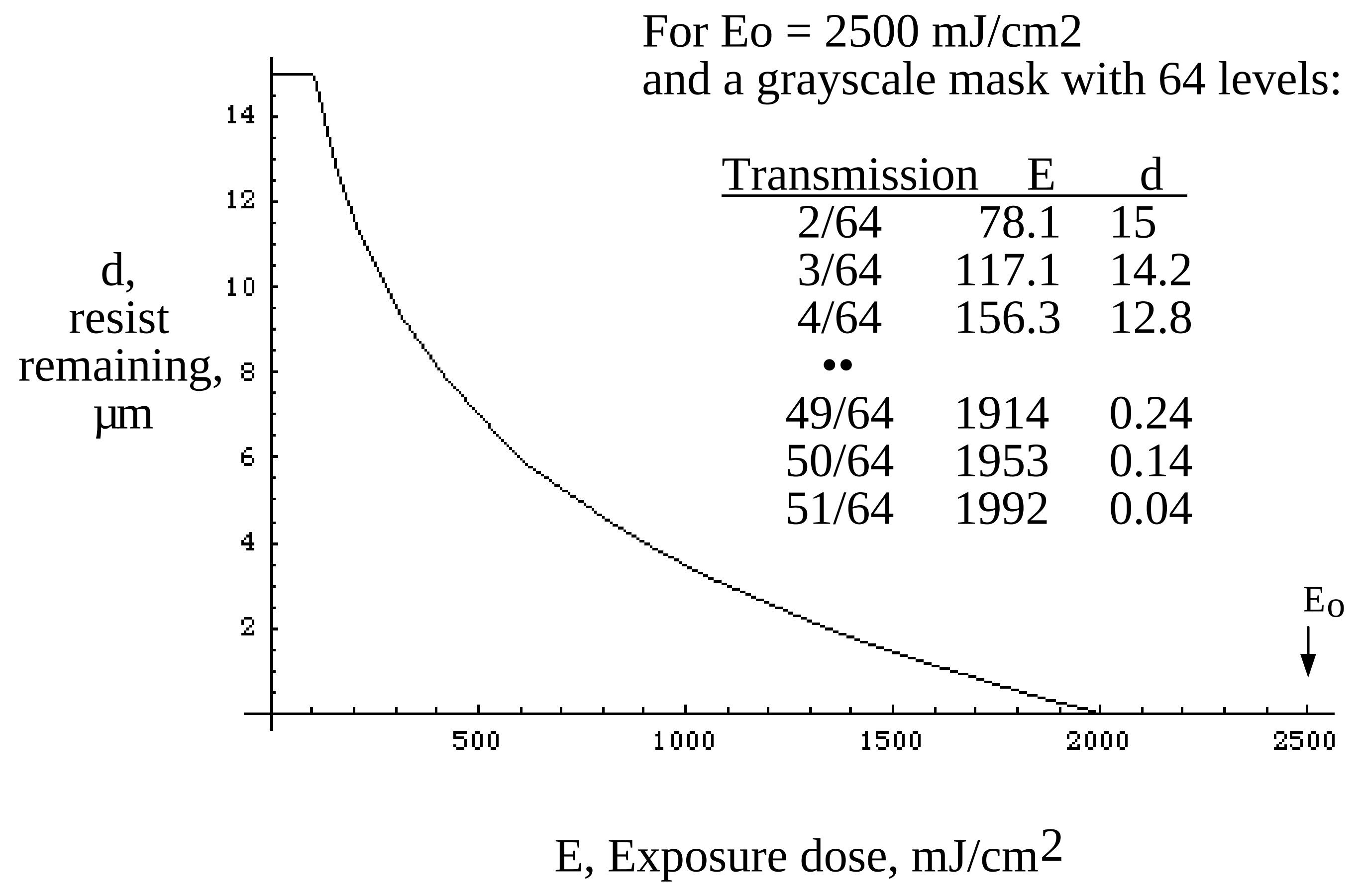


For Eo = 2500 mJ/cm2
and a grayscale mask with 64 levels:

Transmission	E	d
2/64	78.1	15
3/64	117.1	14.2
4/64	156.3	12.8
••		
49/64	1914	0.24
50/64	1953	0.14
51/64	1992	0.04

Calibration mask

Linearly stepped grayscale mask, 64 levels

Exposure using linearly stepped grayscale mask

Positive resist, AZ6420

True grayscale masks

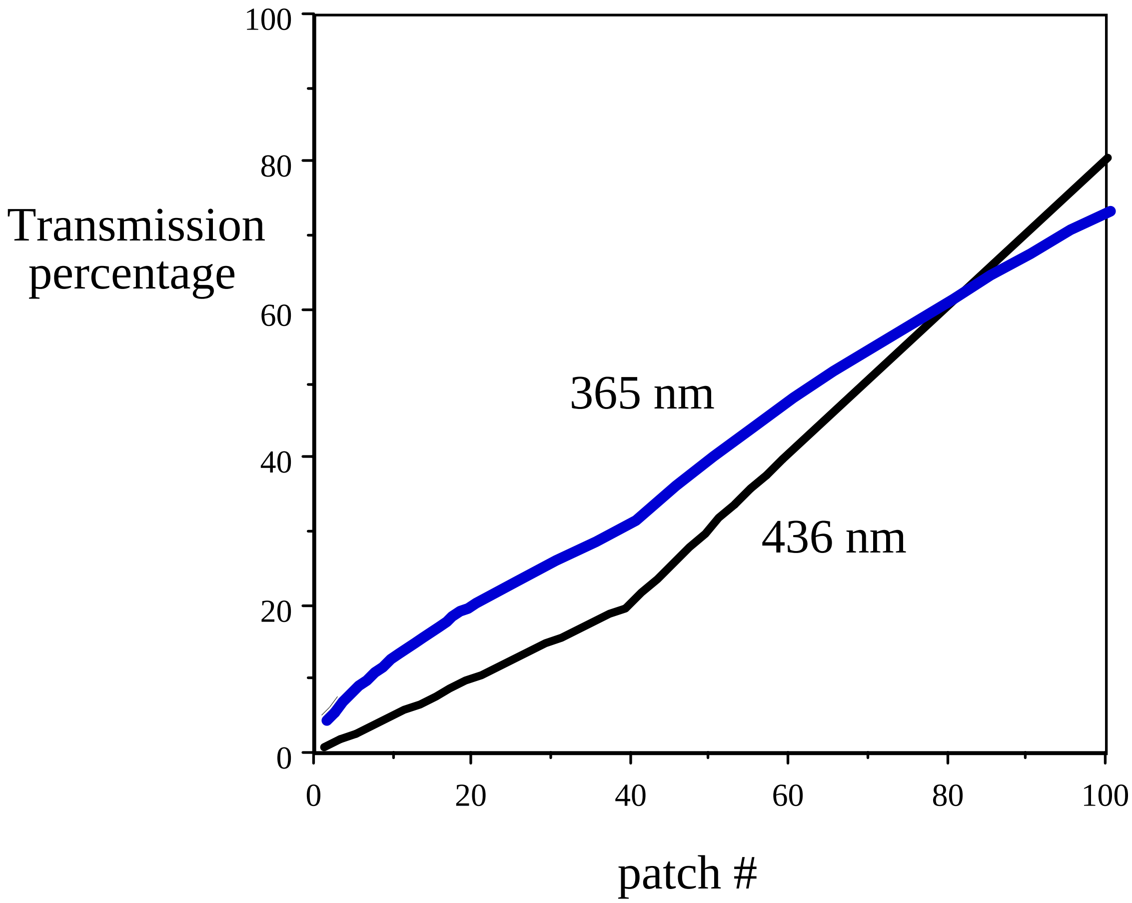
- HEBS glass
- Thermal bimetallic films
- Black & white photographic film

High energy beam sensitive glass

- Commercially available

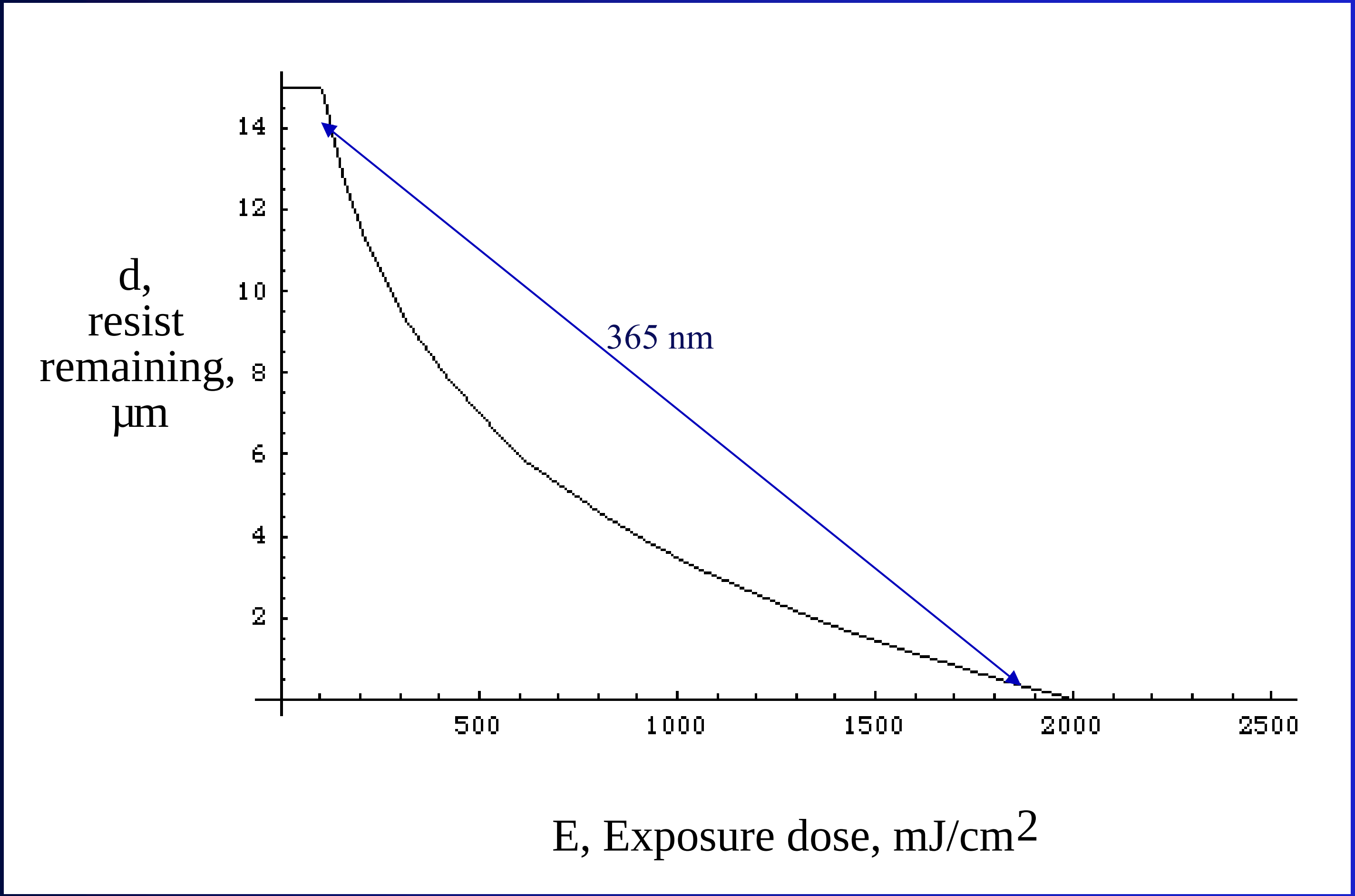
  (Canyon Materials, Inc., San Diego)
- Silver ions are diffused into top 3 µm of glass, forming silver-alkali-halide nanocrystals (generally transparent)
- Electron beam (>10 keV) exposure reduces crystals to metallic silver, which is generally opaque; silver density increases with electron dose
- Optical density of mask depends on silver density, but also on the wavelength of light
- Spatial resolution is very good, limited only by diameter of e-beam

HEBS glass calibration mask

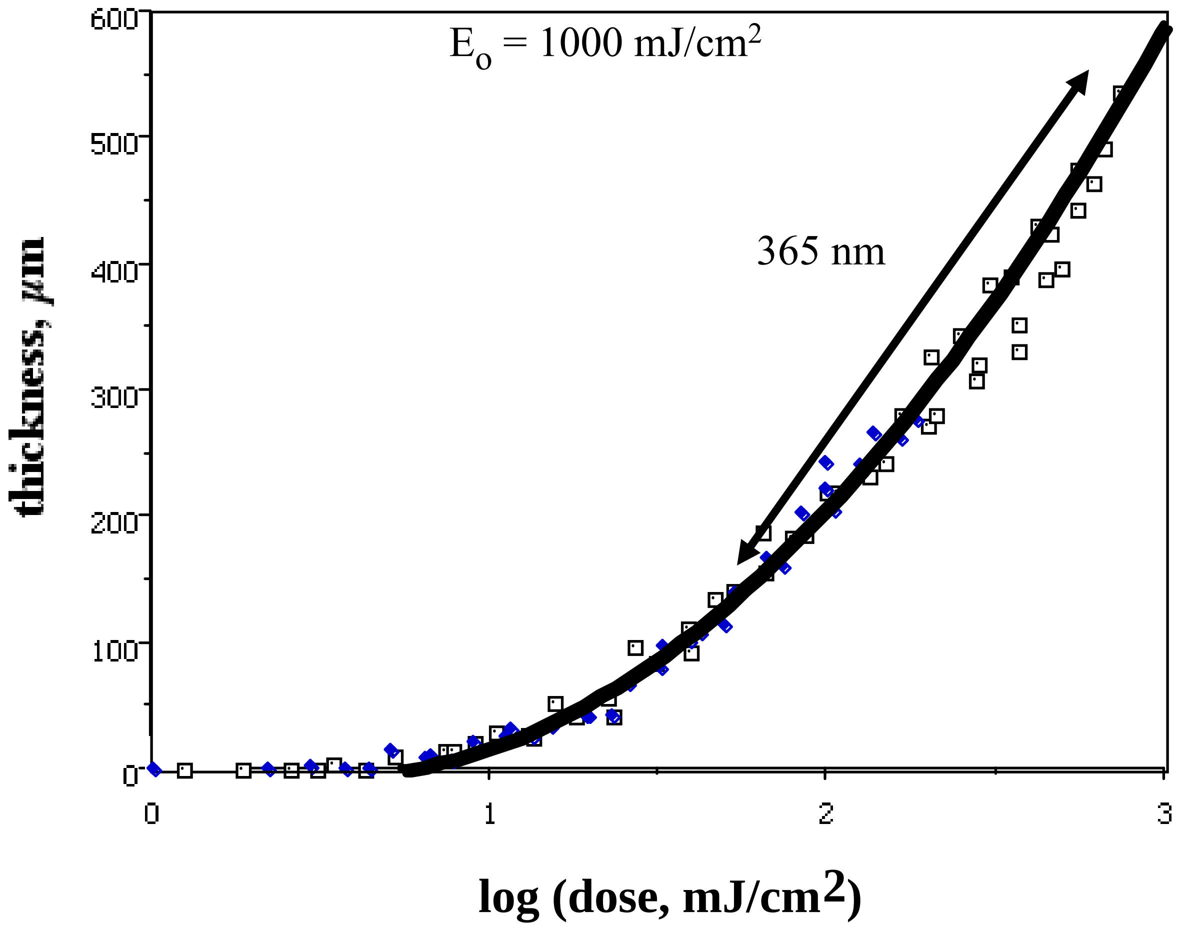


Photoresist thickness range for HEBS glass mask

15 µm positive resist; Eo = 2500 mJ/cm^2



SU-8 thickness range for HEBS glass mask

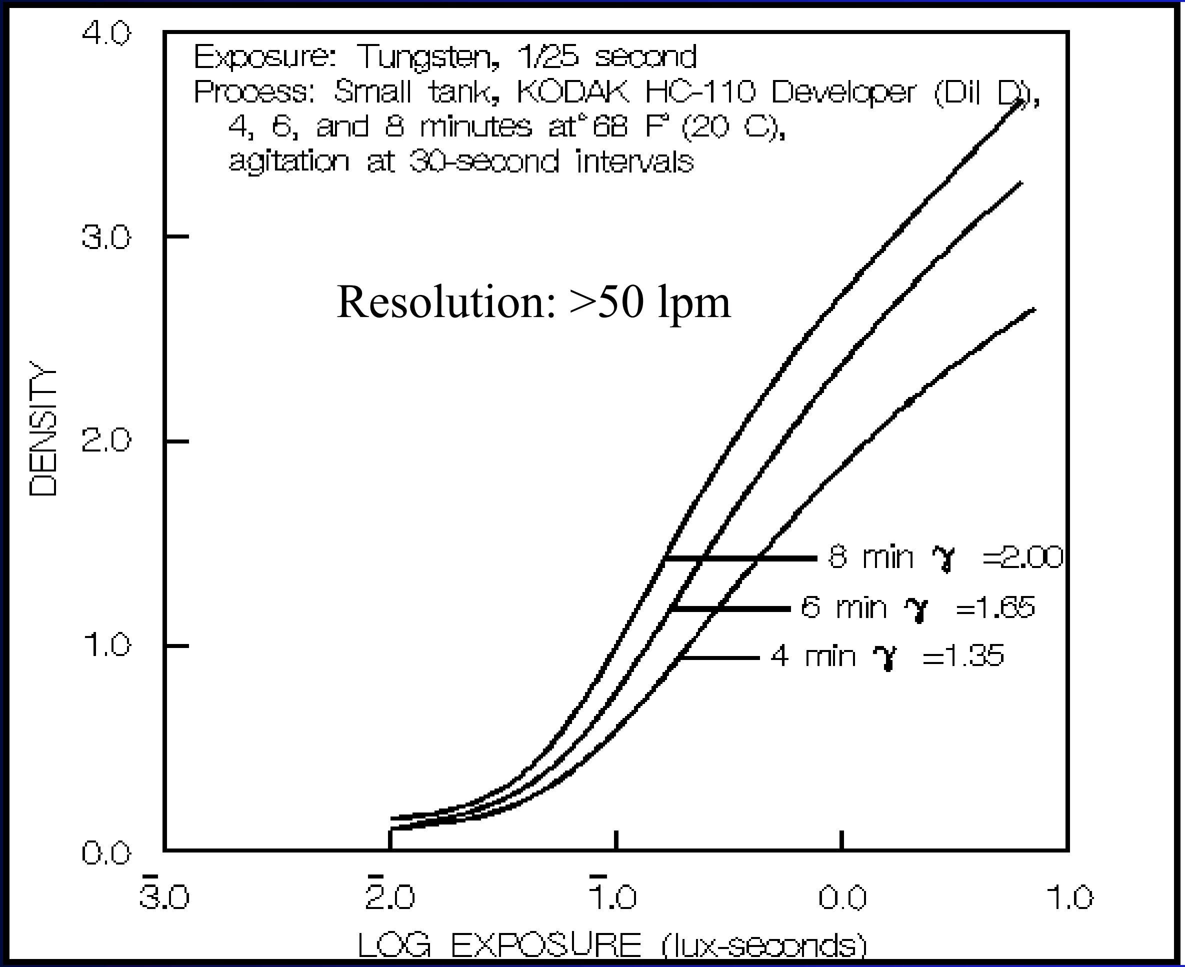


Proposed grayscale mask

- Bimetallic films on glass (Bi/In or Sn/In)
- Film thickness: 10 – 100 nm
- Laser exposure (heating) converts opaque metals to transparent mixed oxides
- Completeness of oxide conversion depends on time @ temperature
- OD range: 3.0 to 0.22 at 365 nm
- Spatial resolution: ~ 100 nm

The poor man’s grayscale mask

Black & white photographic film
Kodak Technical Pan



Exposure: Tungsten, 1/25 second
Process: Small tank, KODAK HC-110 Developer (Dil D),
4, 6, and 8 minutes at° 68 F° (20 C),
agitation at 30-second intervals

Resolution: >50 lpm

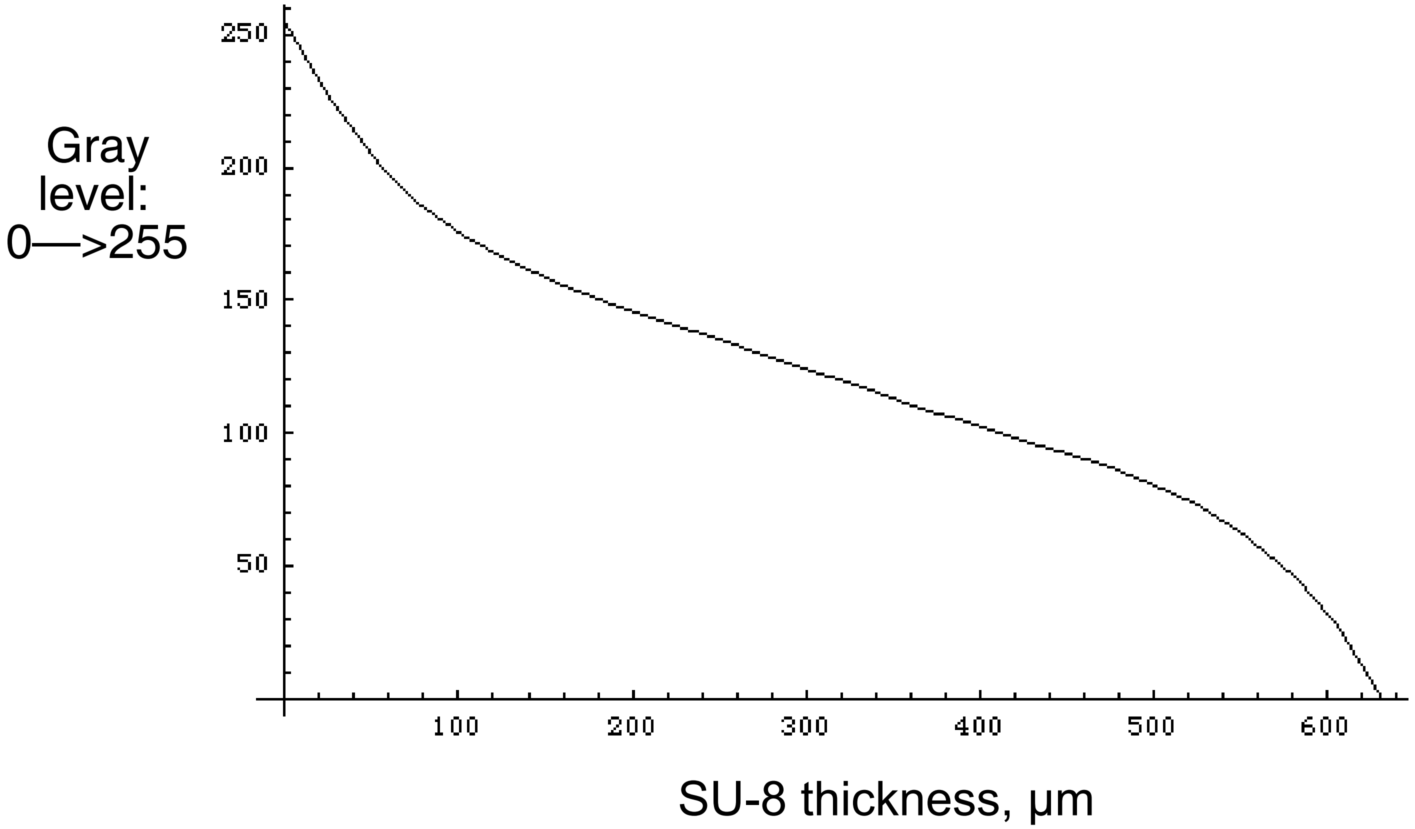
The poor man’s grayscale mask

My process:

- Create a grayscale calibration mask in Mathematica, and transfer to Photoshop to create a .tif file

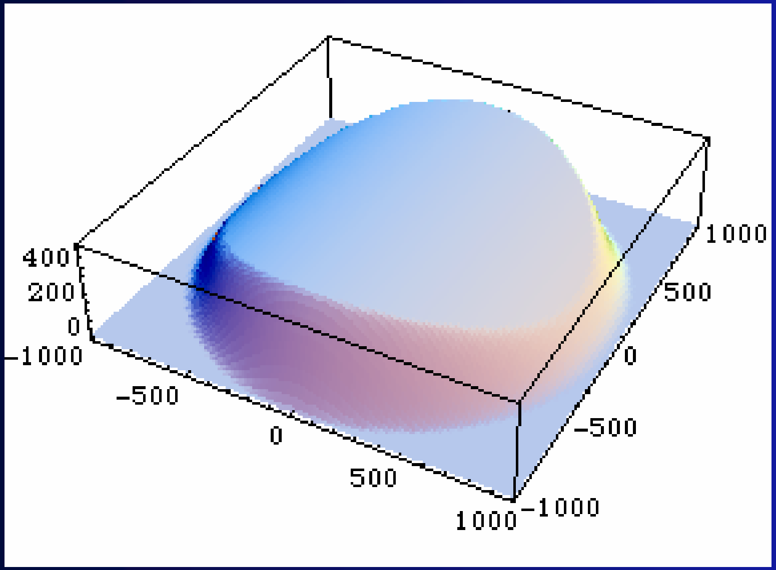
- Laser-expose Tech Pan film using .tif file
- Note all processing factors, so they can be reproduced exactly
- Use Tech Pan negative as your photolithography mask
- Process SU-8 with a stable process
- Measure heights of polymerized SU-8 cylinders
- Create a height *vs* gray-level calibration function

The poor man’s grayscale mask



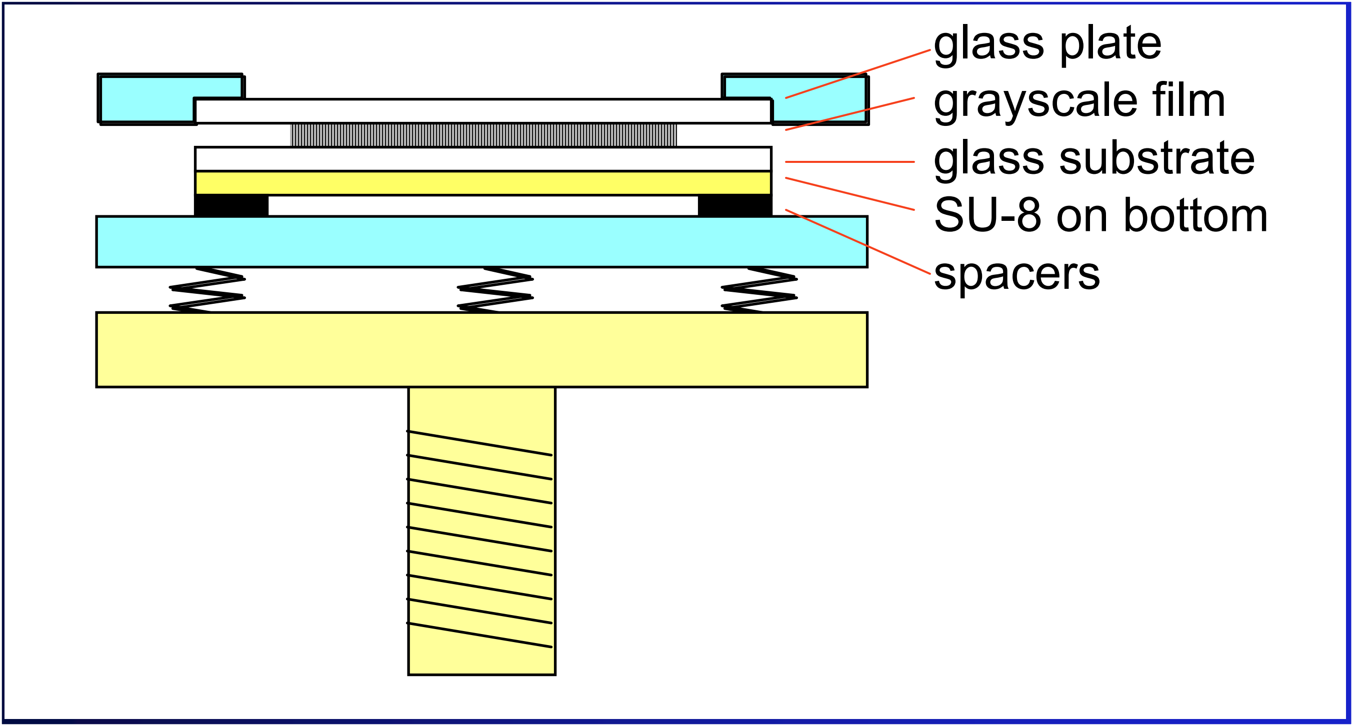
The poor man's grayscale mask

- Create structures in Mathematica, and plot heights in grayscale using the calibration function with "DensityPlot"

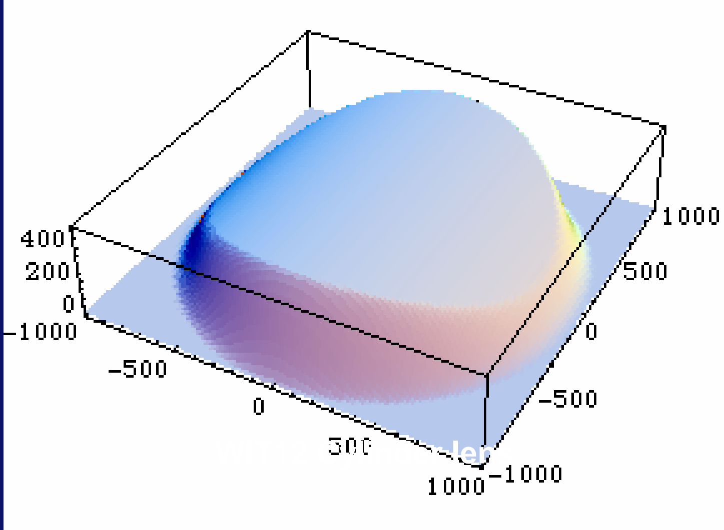


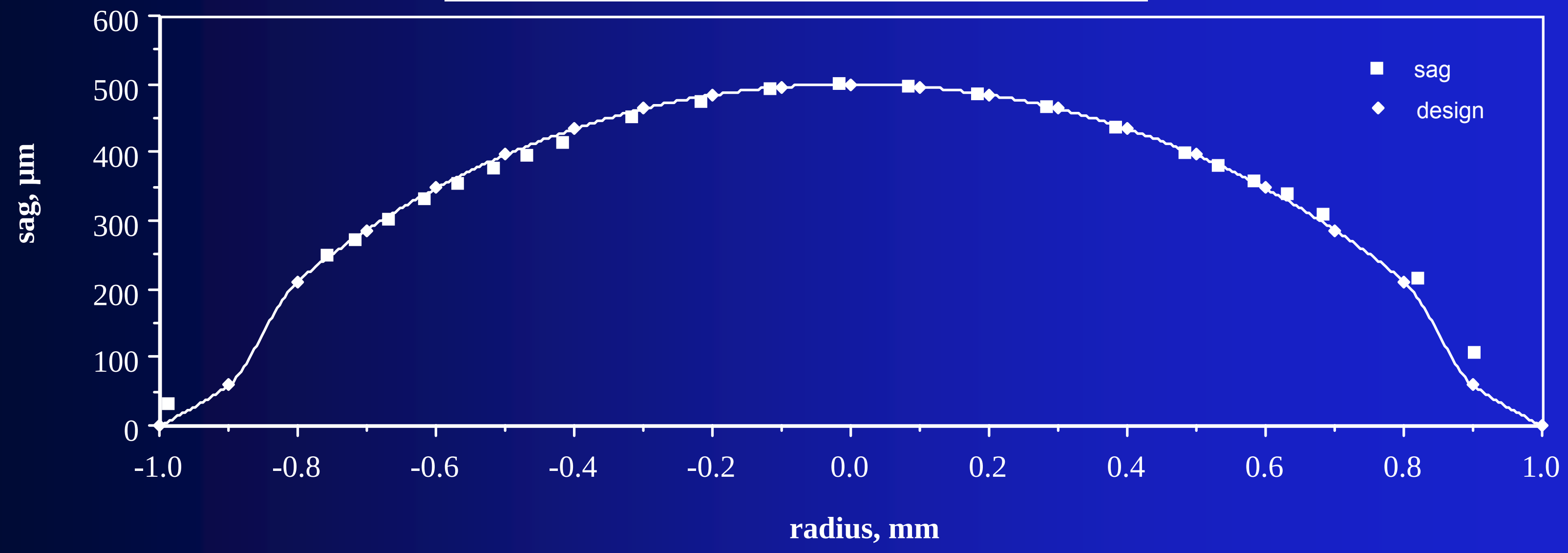
- Convert grayscale plot to .tif file
- Expose Tech Pan film from .tif file
- Expose SU-8 using Tech Pan negative as grayscale mask and process the SU-8

Contact printing with B & W film mask



The poor man's grayscale mask



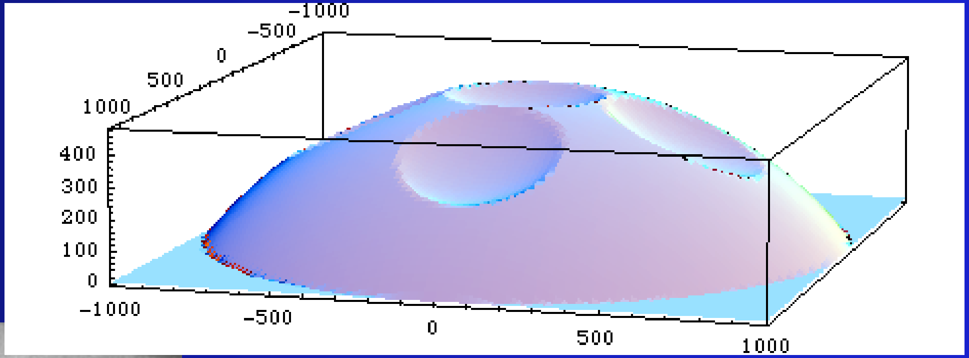


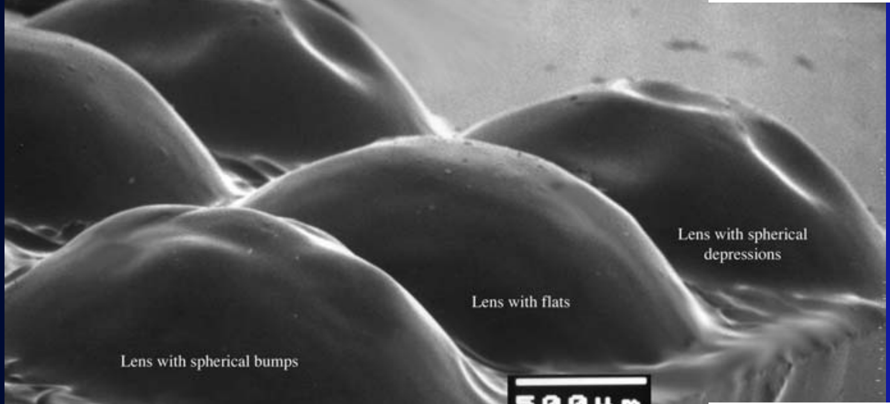
Grayscale calibration

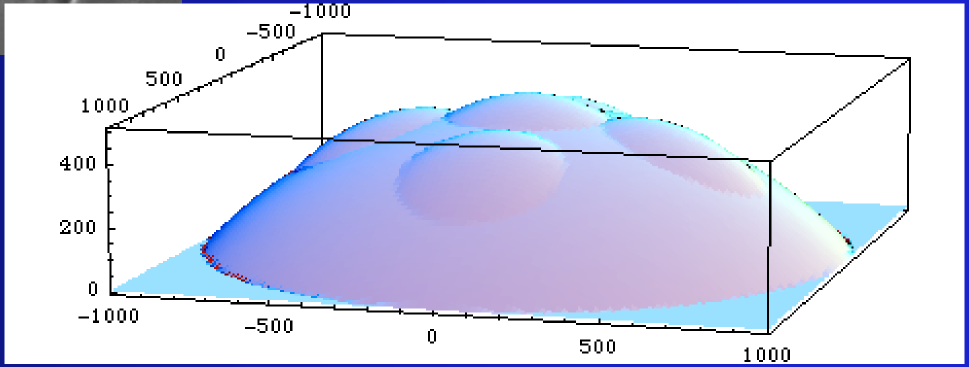
Process control issues

- Exposing beam must be uniform across the wafer
- Mask aligner intensity must remain constant from run to run
- Thickness of resist must be consistent
- Resist processing must be stable
- Aging of chemicals can be a problem

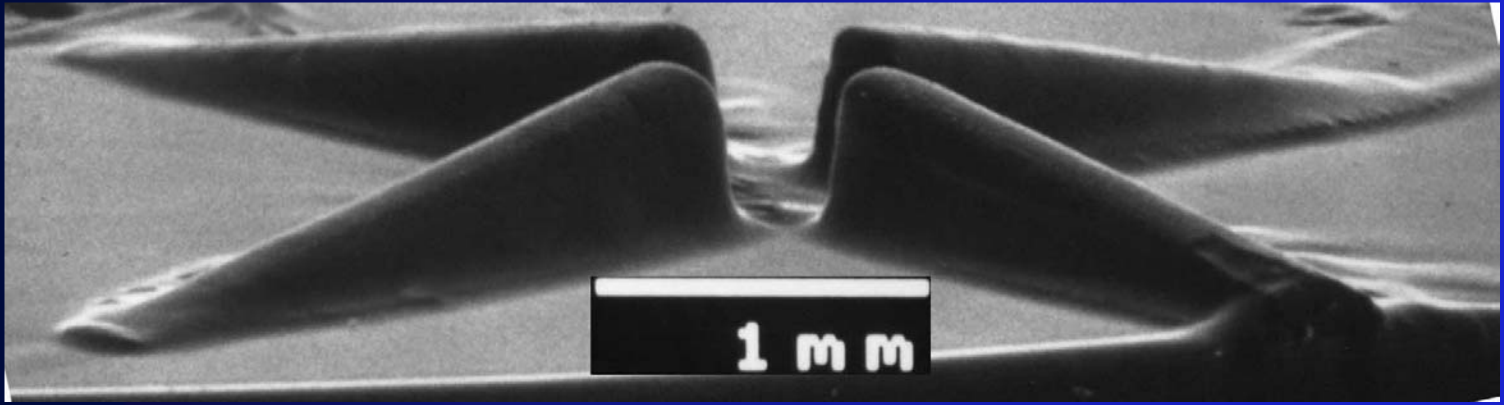
Some SU-8 grayscale structures

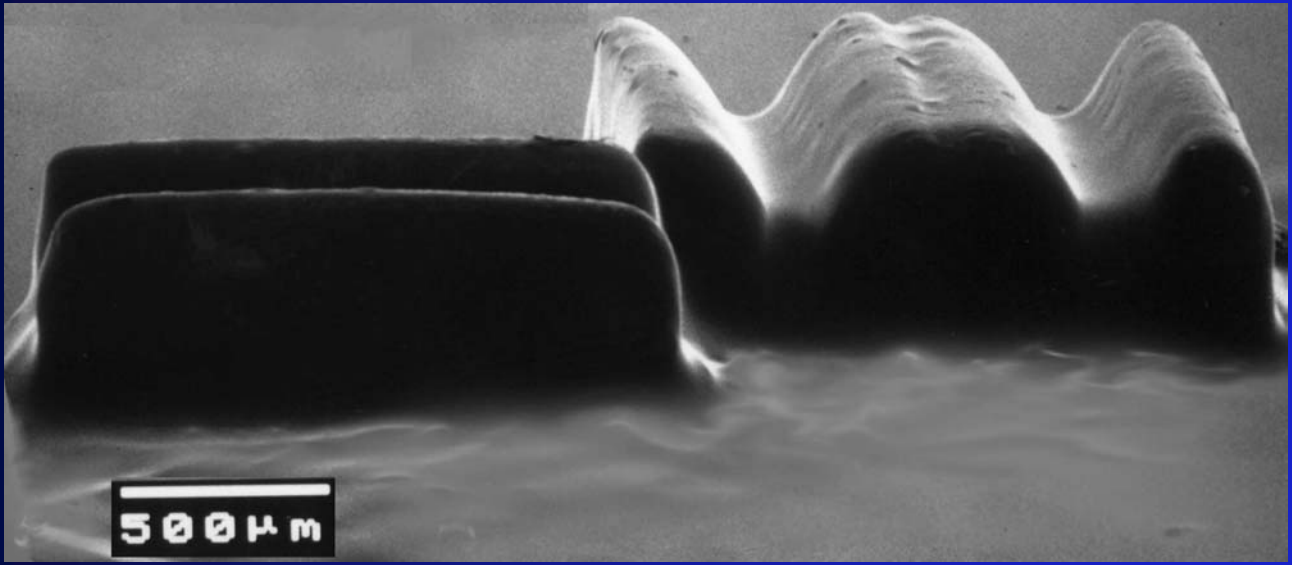






Some SU-8 grayscale structures





Micro stereo lithography

- Applications
- General methods
- Details
- New directions

Micro stereo lithography

Applications

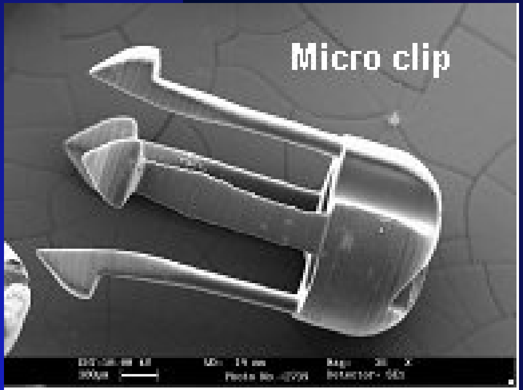
Generally used to build small complex 3-D structures using acrylic or epoxy.

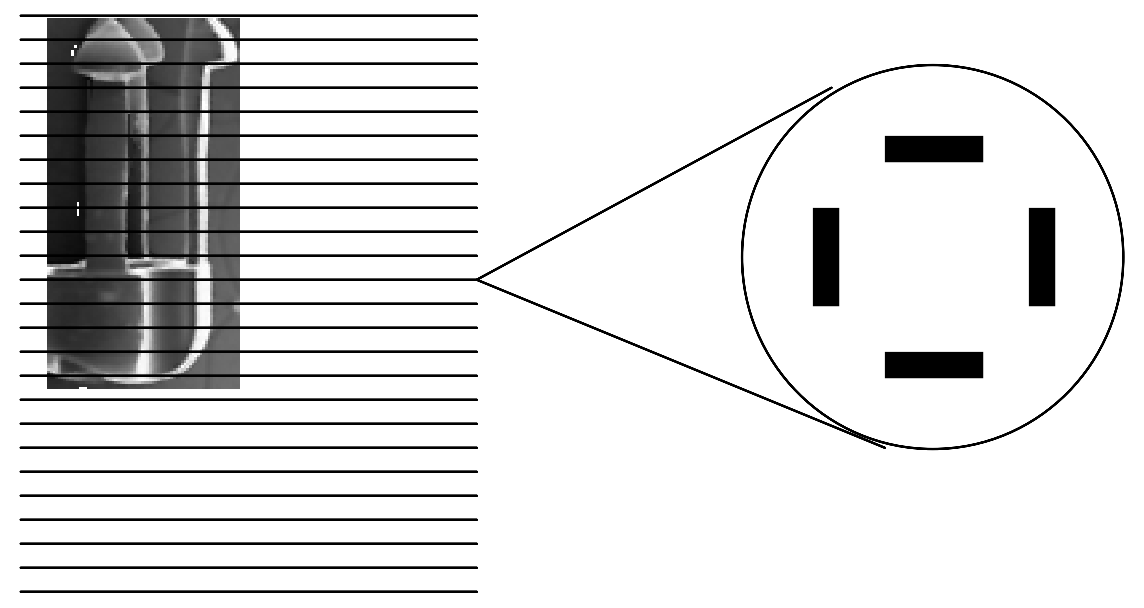
Can be used to build molds in which metals (Ni alloys, usually) can fill the voids by electroplating.

Micro stereo lithography

General methods

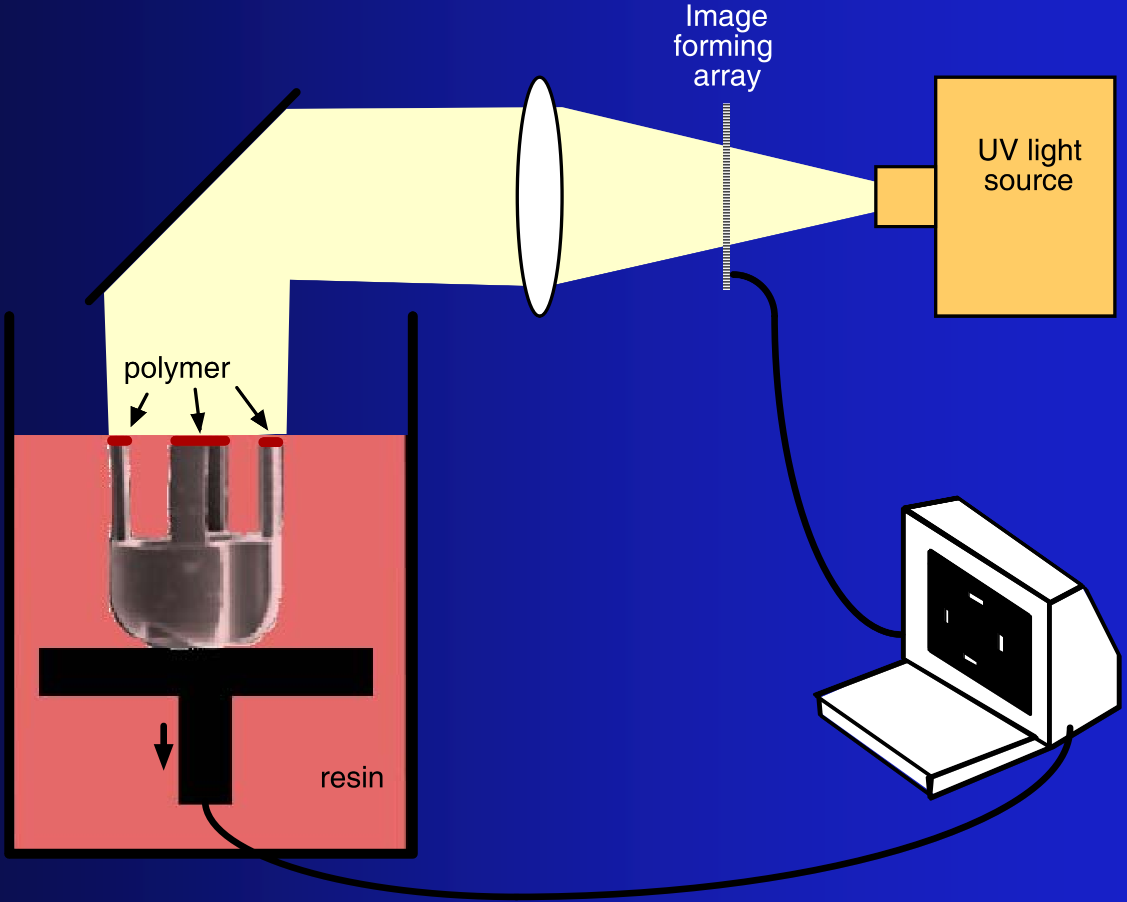
Create a digital file of 10 ~ 50 µm thick “slices” of a CAD drawing of the structure.





Micro stereo lithography

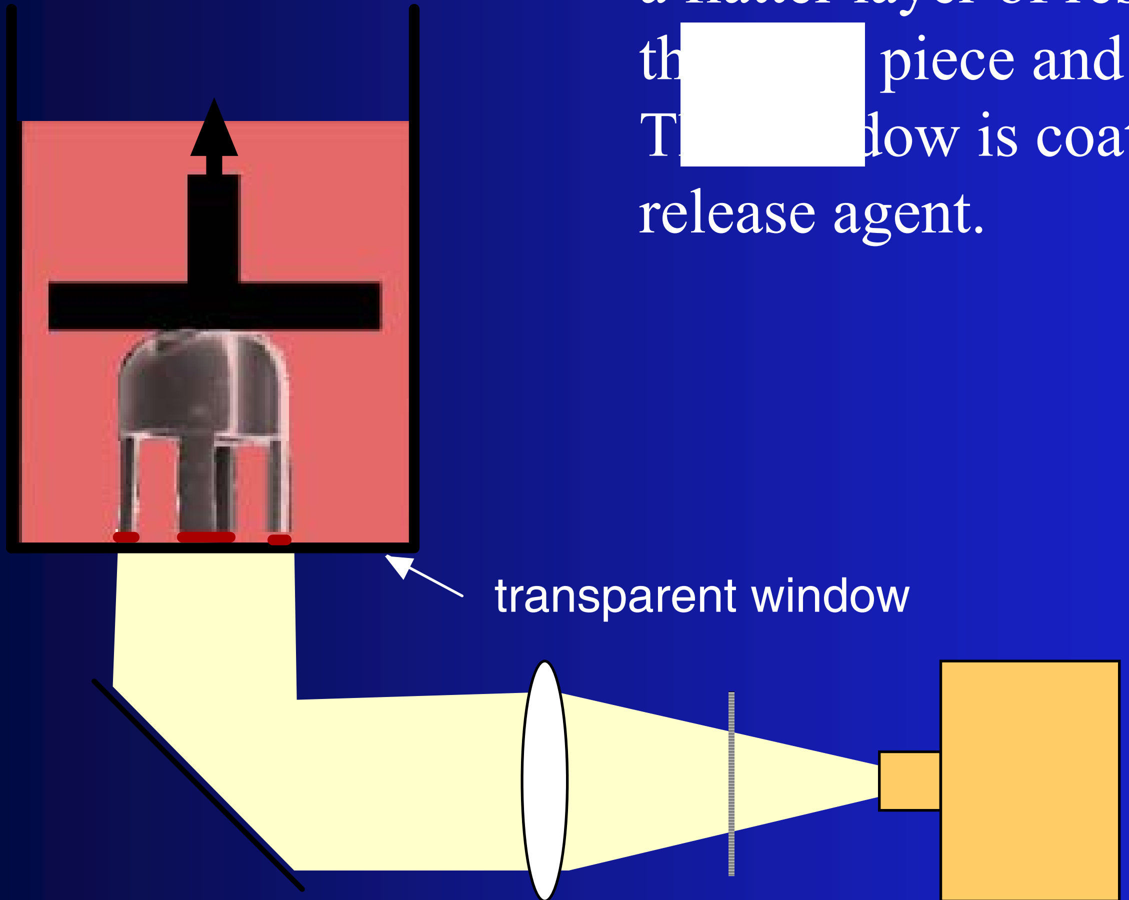
Use the pattern of each "slice" to build up consecutive layers of hardened polymer, photopolymerized from the liquid resin.



Micro stereo lithography

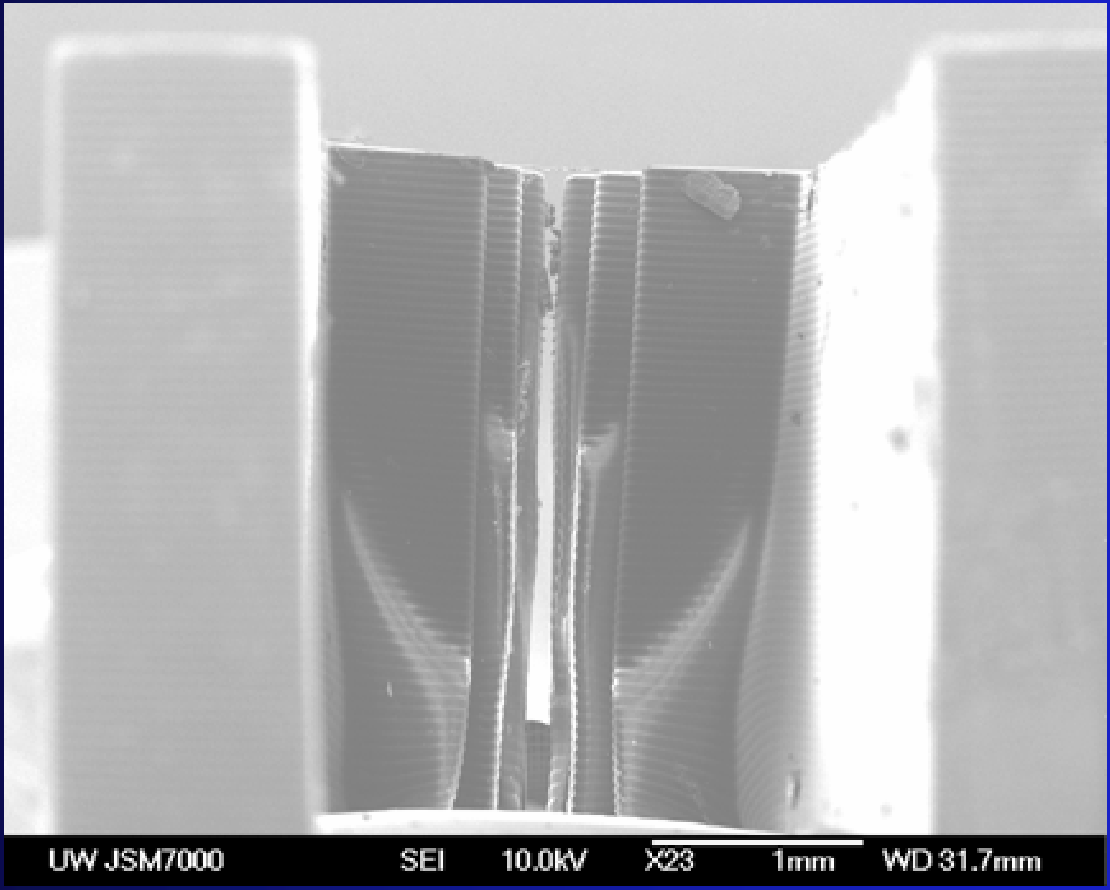
Alternate geometry

Expose from the bottom, giving a flatter layer of resin between th[illegible] piece and the window. T[illegible]dow is coated with a release agent.



Micro stereo lithography

This 3 mm tall structure was made with 53 µm layers, and the layer striations and distorted walls can be easily seen.



Micro stereo lithography

New directions

Directly create ceramic structures by loading resin with ceramic particles, and firing structure to vaporize the polymer and fuse the ceramic. With proper loading and firing, little volume change occurs.

Directly create metallic structures by loading resin with metal particles, etc.

Two-photon lithography

- Overview
- Details
- Potential new directions

Absorption of light

- Normal optical absorption

$$dI/dx = -\alpha I \longrightarrow I(x) = I_o e^{-\alpha x}$$

α has units of cm^{-1}

Absorption of light

- Normal optical absorption

$$dI/dx = -\alpha I \longrightarrow I(x) = I_o e^{-\alpha x}$$

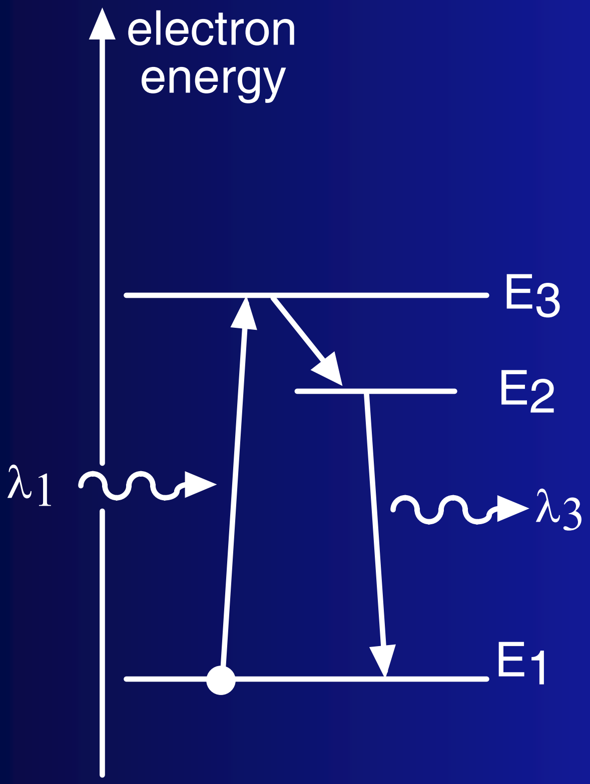
α has units of cm^{-1}

- Two-photon (non-linear) absorption

$$dI/dx = -\beta I^2 \longrightarrow I(x) = I_o/(1+I_o\beta x)$$

β has units of cm/Watt

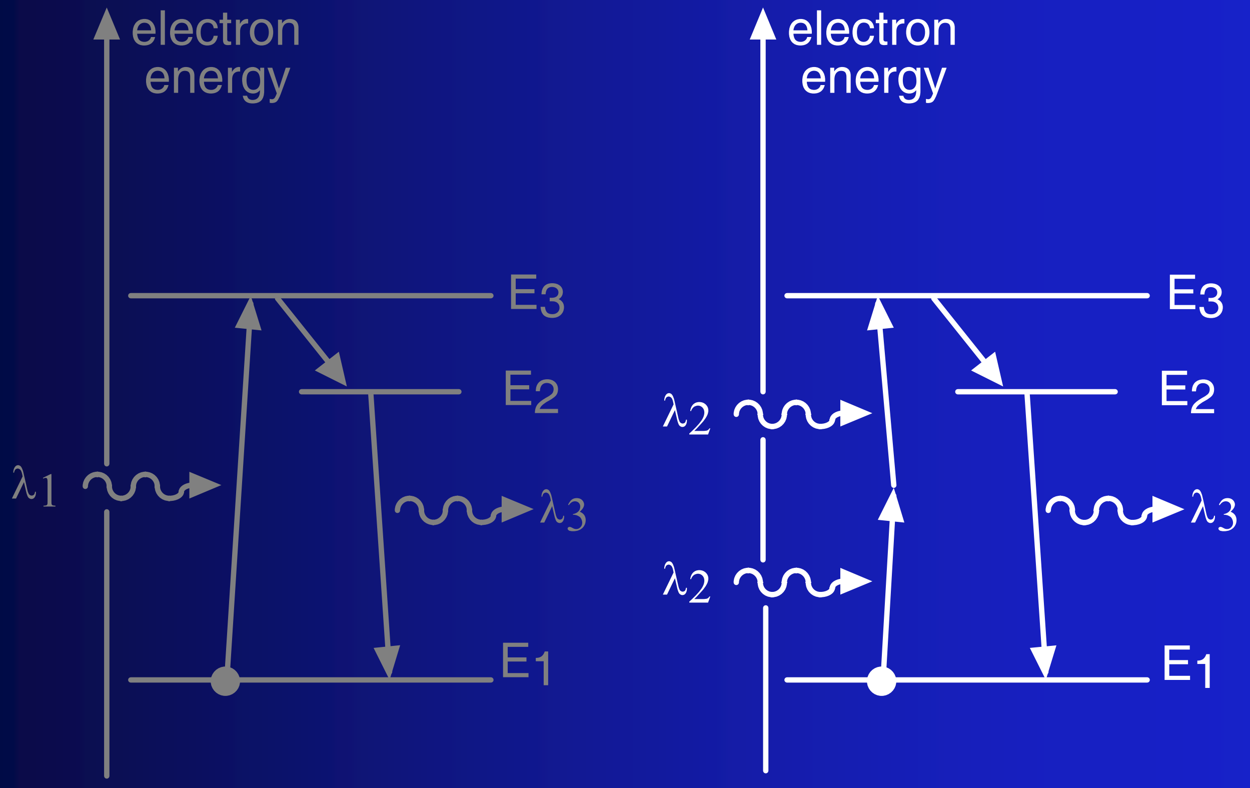
Equivalence of one- and two-photon absorption



one-photon absorption and luminescence

$\lambda_1 < \lambda_3$

Equivalence of one- and two-photon absorption



one-photon absorption and luminescence

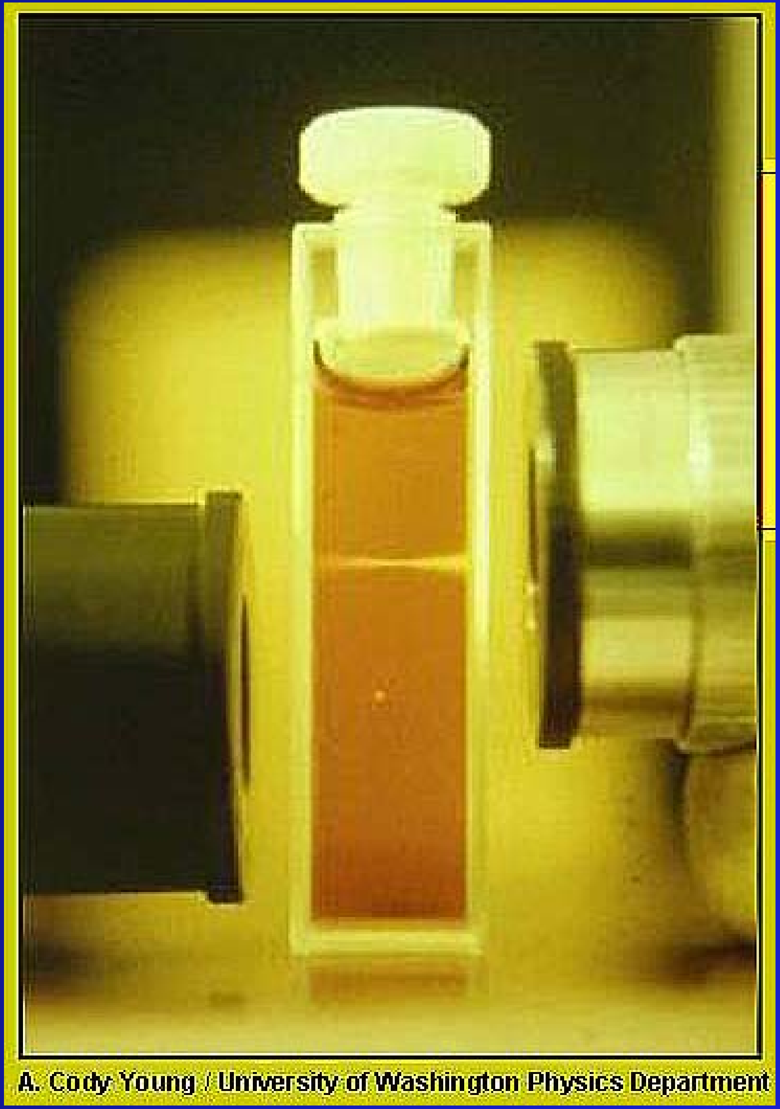
$\lambda_1 < \lambda_3$

two-photon absorption and luminescence

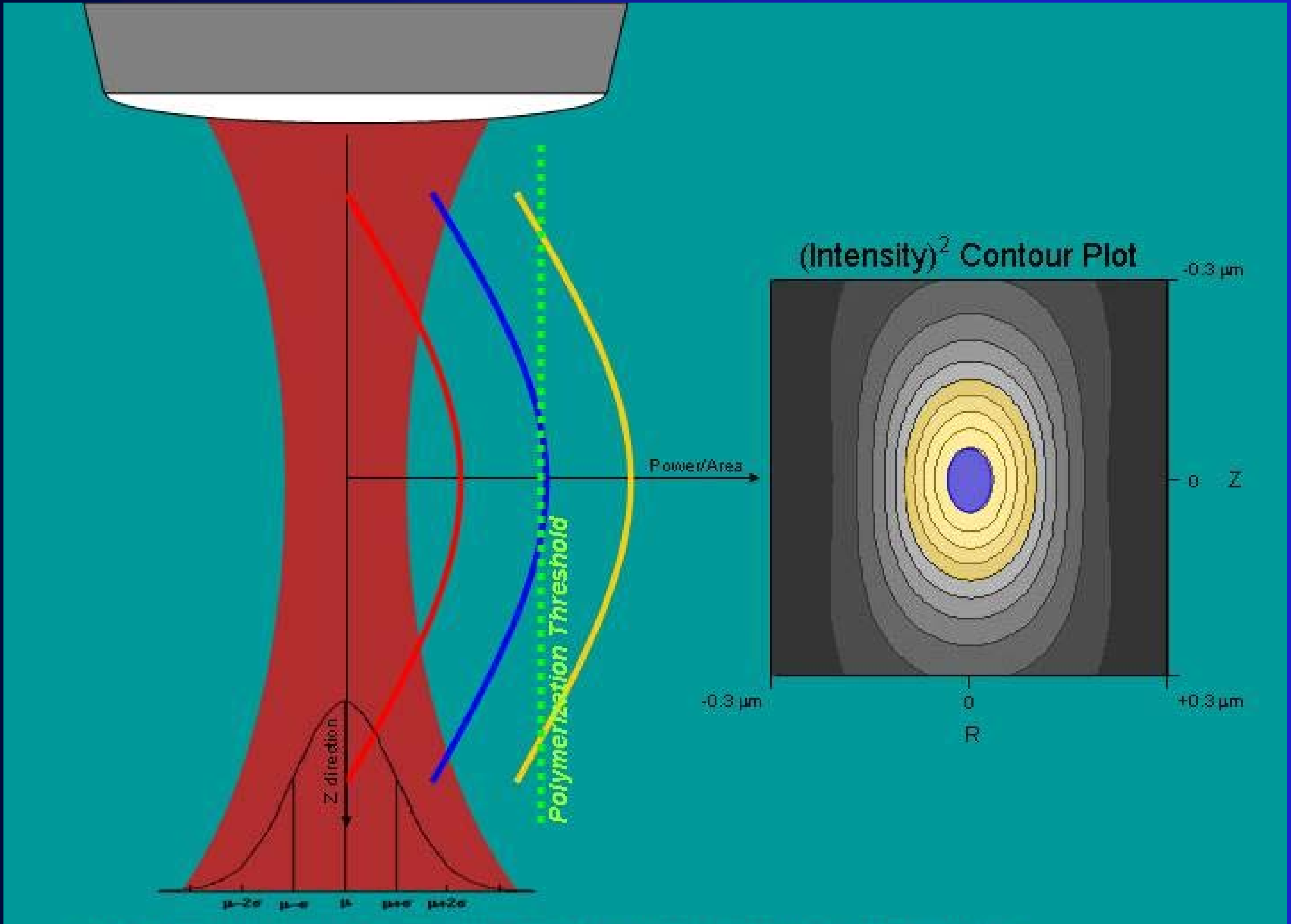
$\lambda_2 = 2\,\lambda_1$

Two-photon luminescence

- Upper beam from right: luminescence from one-photon absorption at λ = 400 nm
- Lower beam from left: luminescence from two-photon absorption at λ = 800 nm

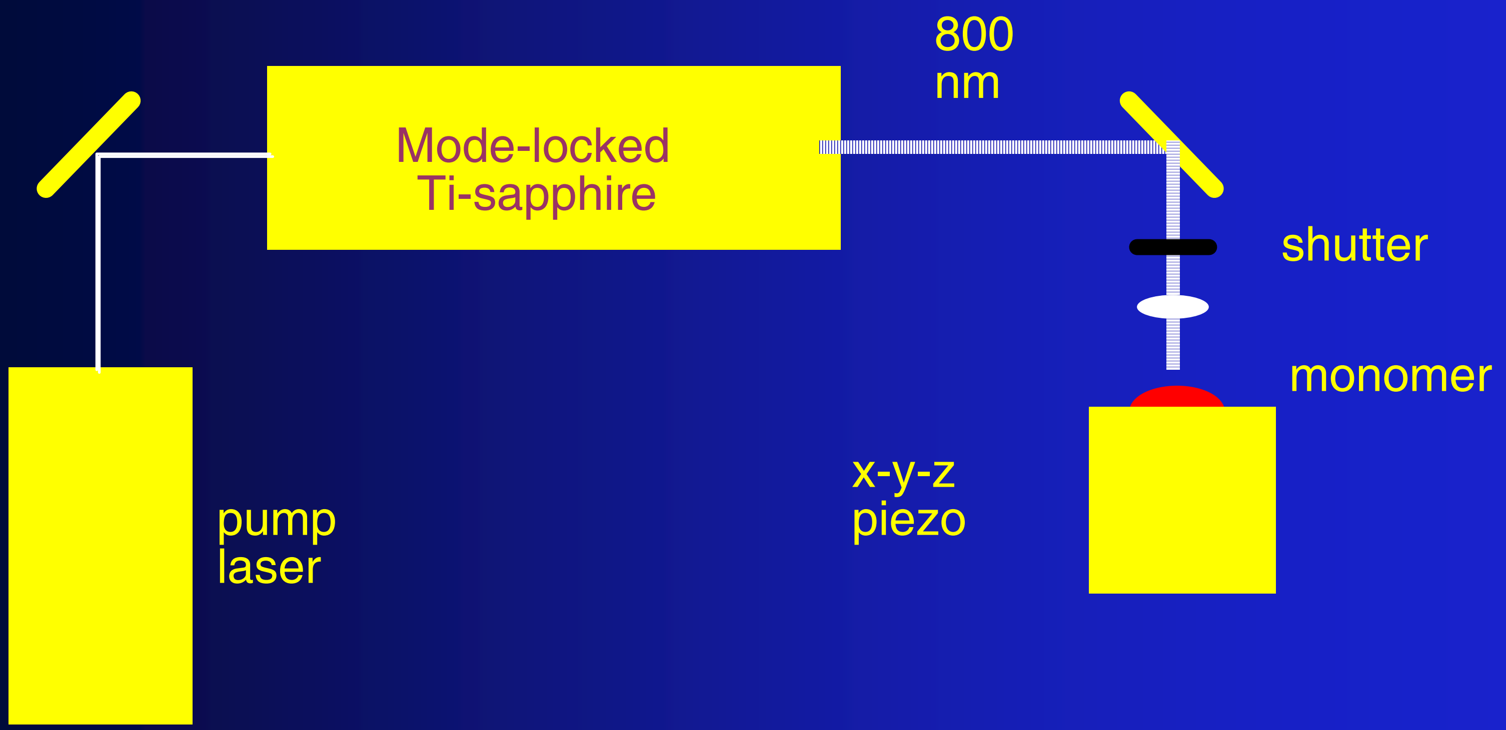

A. Cody Young / University of Washington Physics Department

Focus of a Gaussian beam

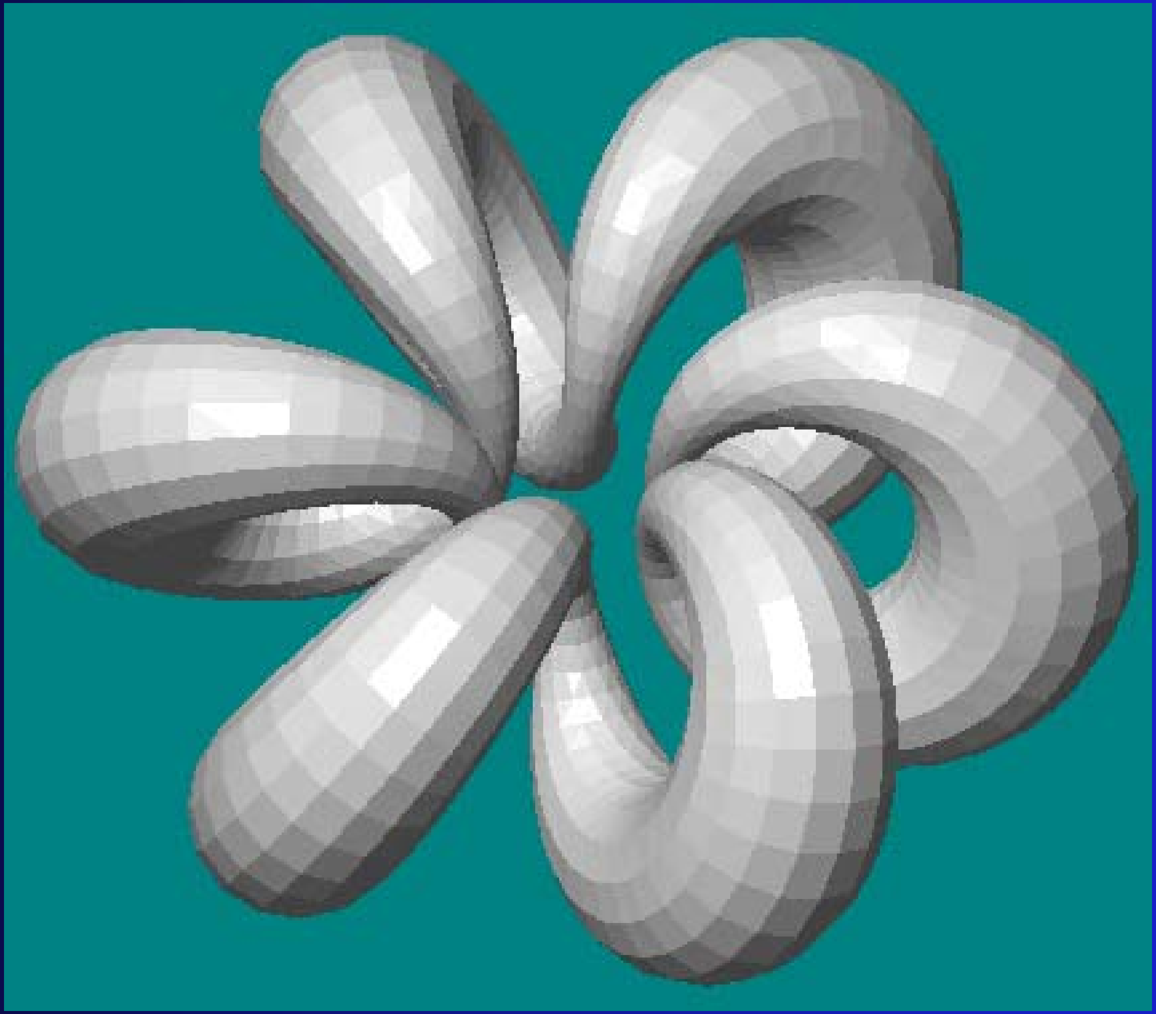


A. Cody Young / University of Washington Physics Department / acyoung@u.washington.edu

Two-photon lithography set-up

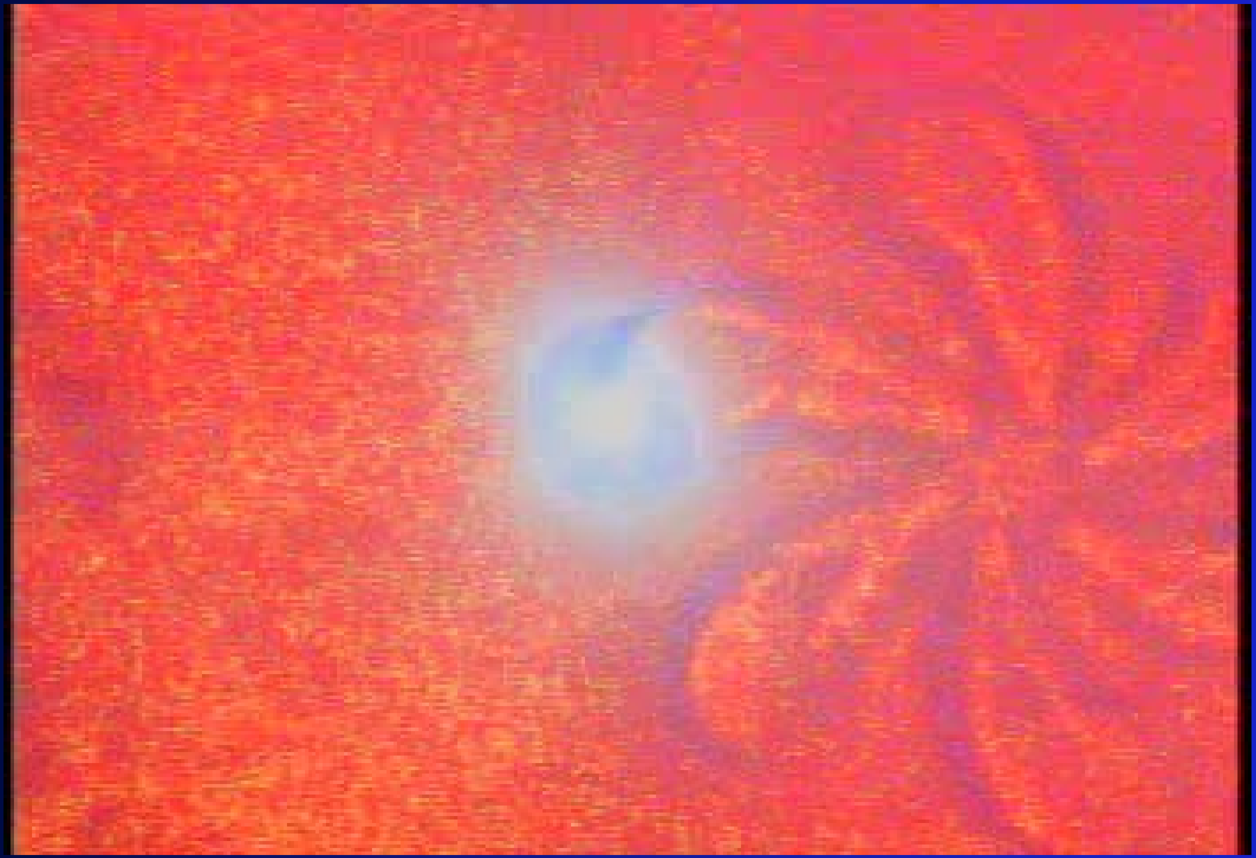


Model of “the twist”



Two-photon lithography

Process



Fabricated twist

The challenge of two-photon lithography

- Is there a compelling application?
- Can devices by made cost-effectively?
- Will other techniques catch up?

Current and future research on two-photon lithography

- Polymerize conducting materials

Current and future research on two-photon lithography

- Polymerize conducting materials
- Polymerize semiconducting materials

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- Polymerize conducting materials
- Polymerize semiconducting materials
- Construct contiguous regions of conductors, semiconductors and insulators (with 50 nm features)!

Current and future research on two-photon lithography

- Polymerize conducting materials
- Polymerize semiconducting materials
- Construct contiguous regions of conductors, semiconductors and insulators (with 50 nm features)!
- Integrate organic light emitters and other photonic devices in 3-D photonic circuits

Different materials may be polymerizable simultaneously using different wavelengths, by attaching the different monomers to chromophores with different absorption bands.

Challenges for the future of two-photon lithography

- The technique is inherently a unit by unit fabrication method.

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- The technique is inherently a unit by unit fabrication method.
- Silicon processing (a mass-production technique) is intent on reaching the 40 nm feature size within 10 years.
- Never underestimate the inventiveness of silicon processing engineers!