Lecture 6

Photoresist

Simple exposure system

Last lecture

formation of an areal image

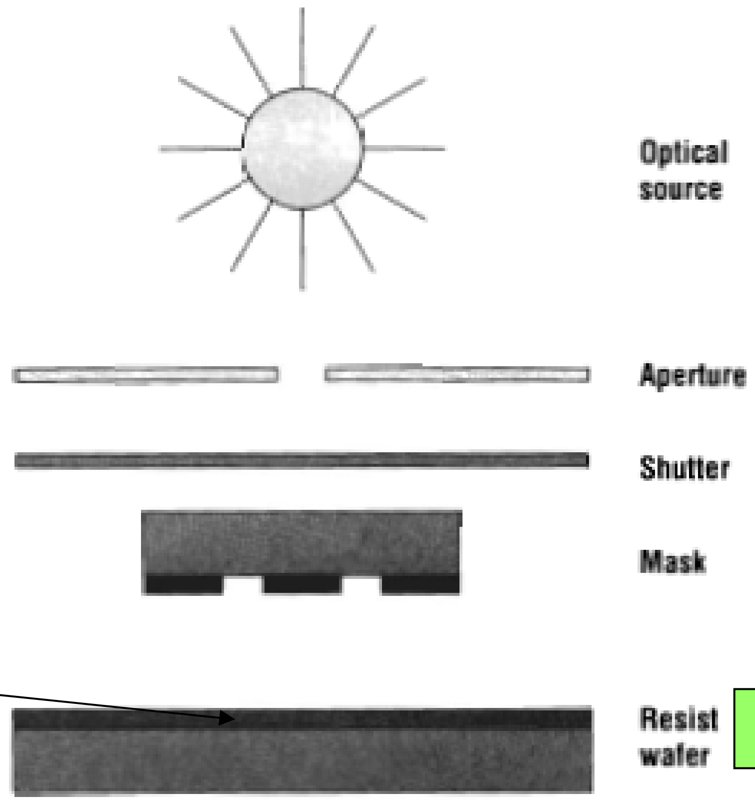


Figure 7.4 Schematic of a simple lithographic exposure system.

Today's lecture

registration of an areal image in a photosensitive layer

Lecture content

- Resist chemistry
- Resist resolution and line profile
- Resist technology
- Advanced resists

Resolution of the aerial image

Contact/proximity

$$W_{min} \approx k \frac{\lambda}{NA}$$

~1 – 0.3

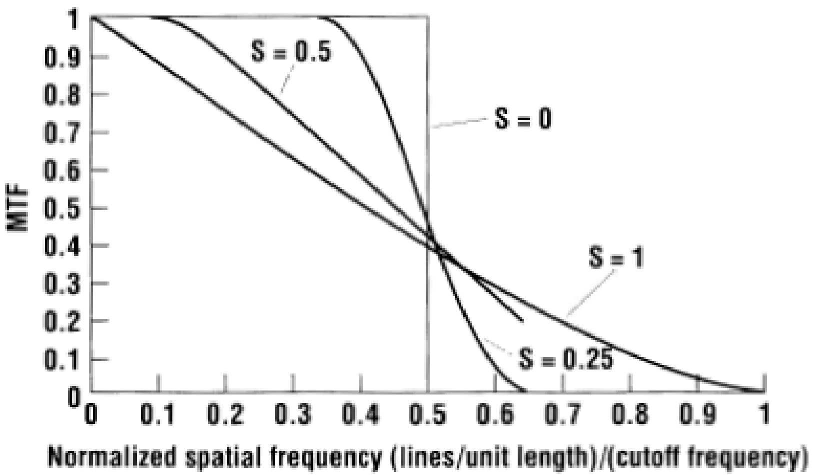
$$W \approx \sqrt{k\lambda(z+g)}$$

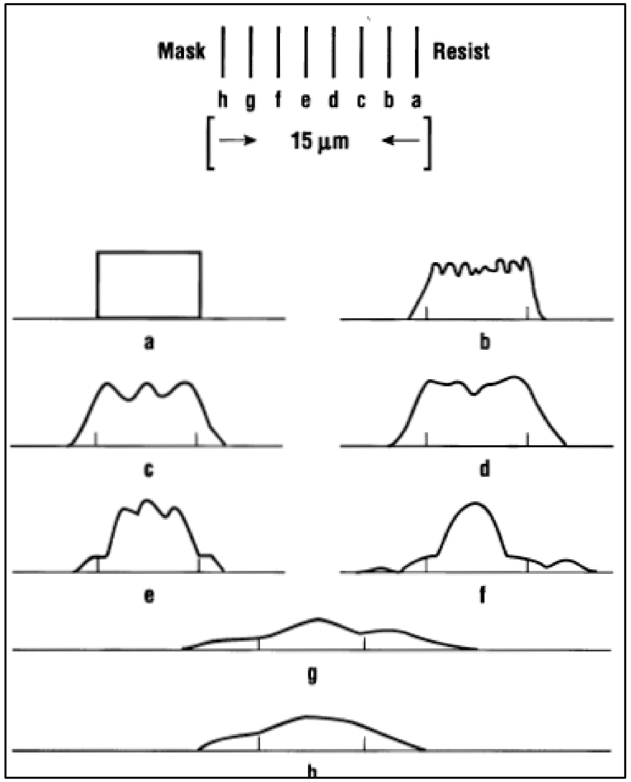
~1

wavelength

distance

• **k** depends on many factors incl. illumination system, mask etc.





Photoresists

- **Resist polarity**
  - **positive resists**: exposed regions dissolve in the developer
  - **negative resist:** unexposed regions dissolve

better resolution, commonly used

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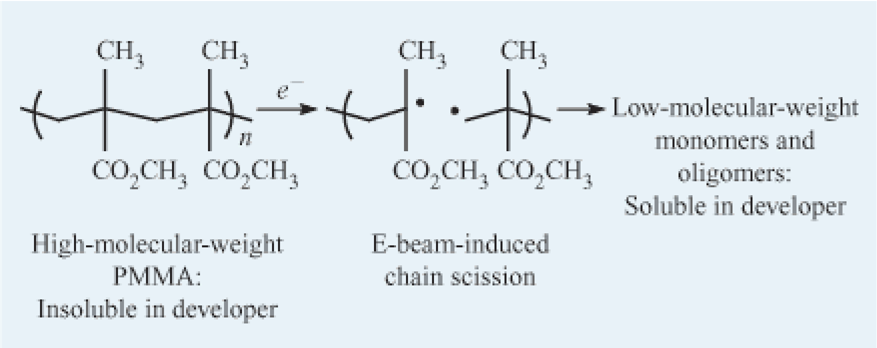
photoresist = resin (base material) + photoactive component (PAC) + solvent

desired qualities:

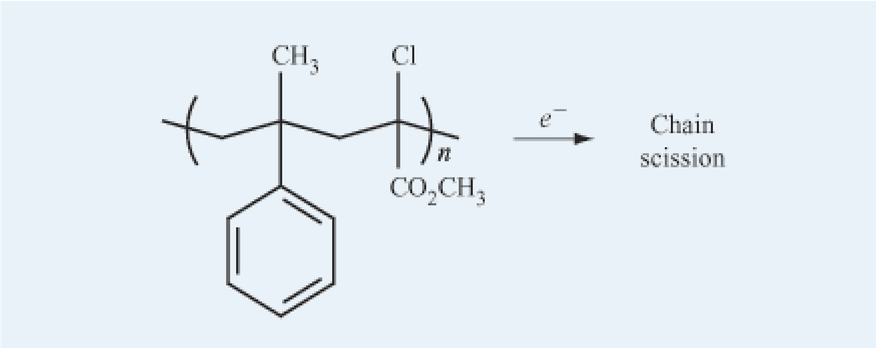
sensitivity (mJ/cm^2)
resolution

Mechanism of a simple photoresist

- Solubility of a polymer ~ MW^{-2}.
  - so, scission of a polymer during exposure leads to better solubility: positive resist, e.g. PMMA, ZEP



Poly(methylmethacrylate) - PMMA resist

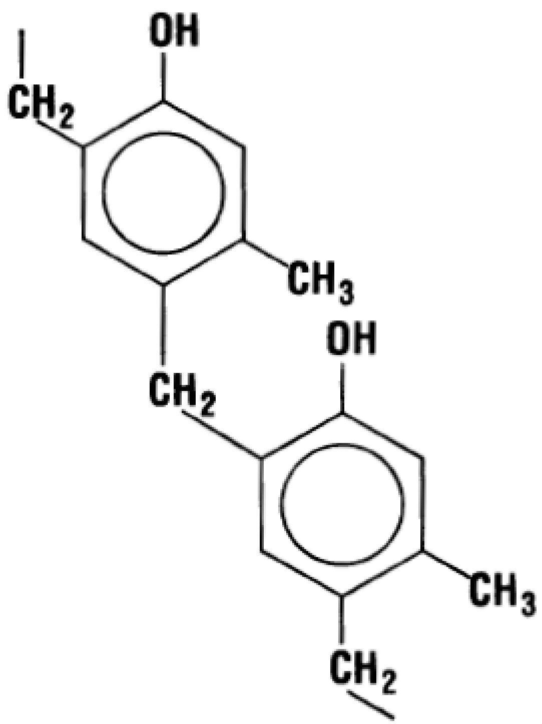


poly(methyl-α-chloroacrylate-co- α-methylstyrene)

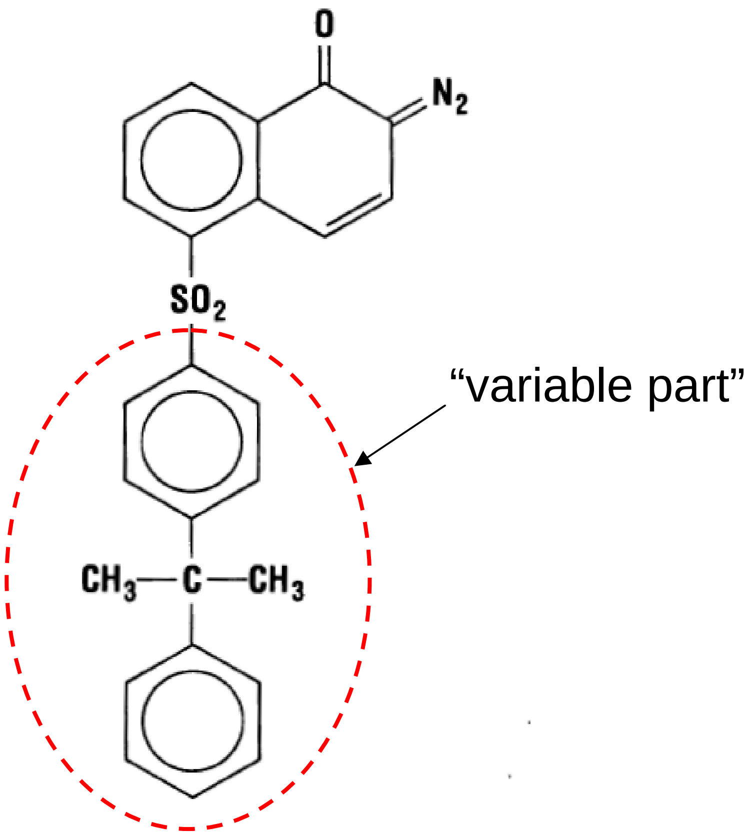
  - cross-linking of a polymer during exposure leads to reduced solubility: negative photoresist, e.g. Polystyrene

DQN Positive Photoresists

- Most current positive resists are based on **DQN** combination



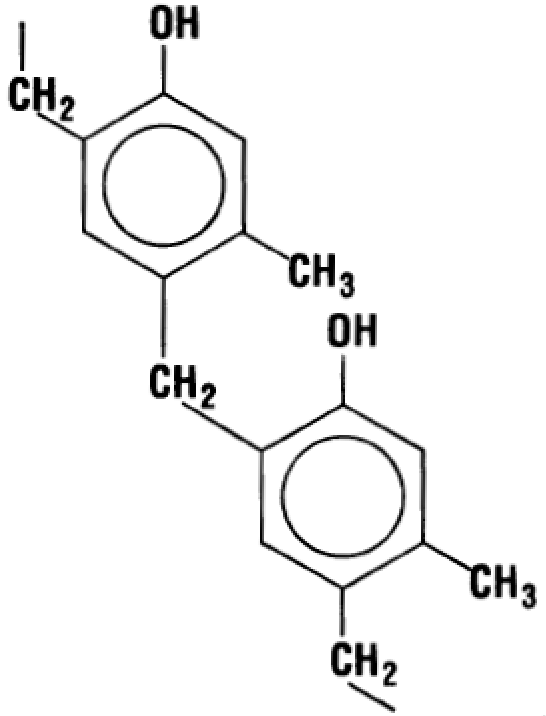
Meta-cresol novolac



Diazoquinon

DQN Positive Photoresists

- Novolac:
  - viscous liquid, viscosity can be adjusted with organic solvents;
  - dissolves easily in aqueous solutions

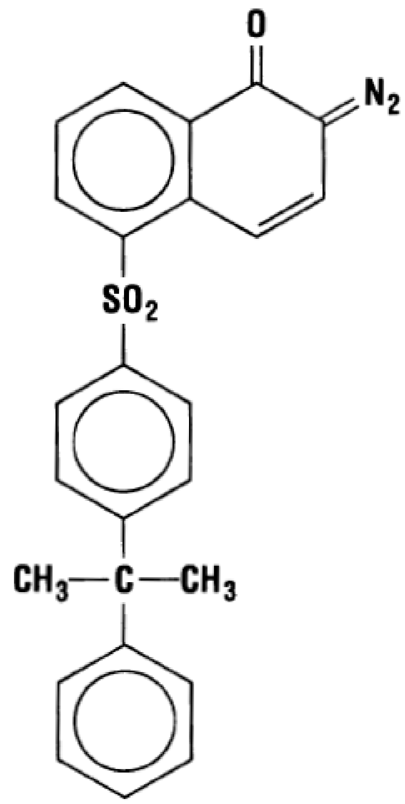


Meta-cresol novolac

DQN Positive Photoresists

Diazoquinon

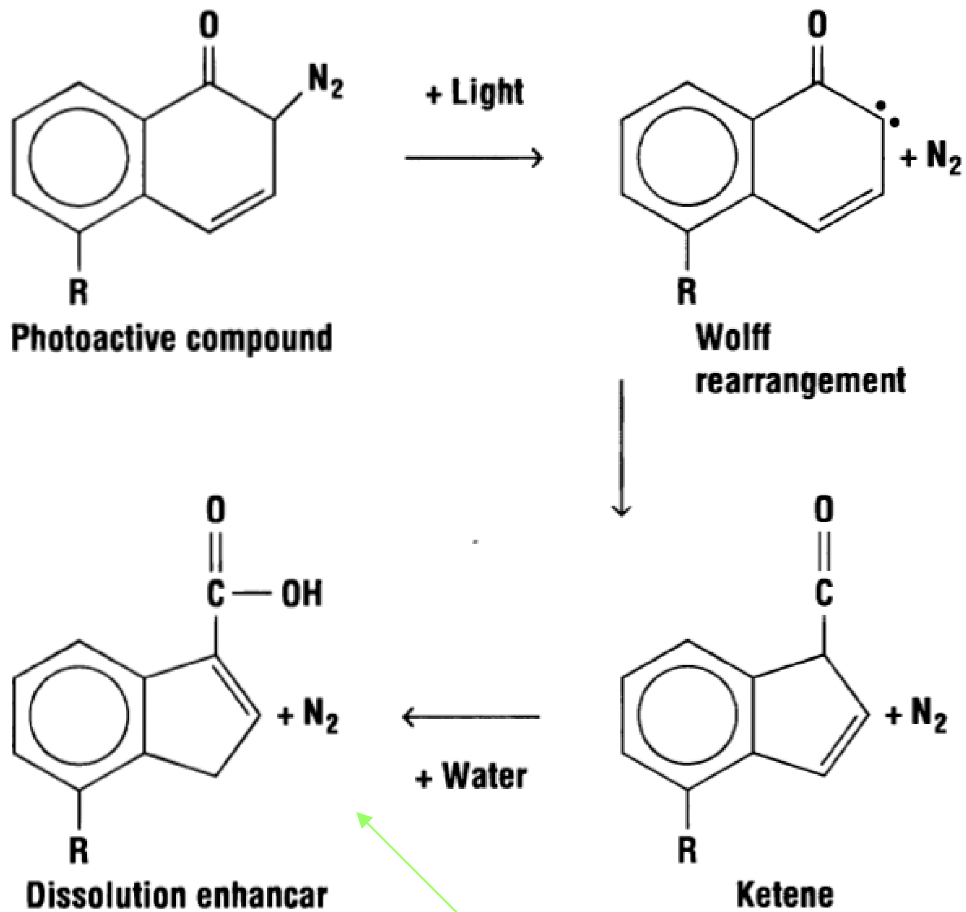
- in unexposed state acts as inhibitor, reduces dissolution rate in developer by factor >10 (softbake crucial!)
- in exposed state helps dissolution in developer



Diazoquinon

DQN Positive Photoresists

- Photolysis of DQ



carboxylic acid, dissolves in base solution

foams resist, assist dissolution

DQN Positive Photoresists

- Advantages:
  - unexposed areas are not attacked by the developer: possible to create narrow lines on a blank field
  - fairly resistant to chemical attack (incl. plasma etching)

- Example: Shipley S1800 family of resists

Negative resists

- usually employ crosslinking: larger molecules are less soluble
- high photo speed
- main disadvantage: swelling during development in organic solvents
- generally not used for features smaller than 2um

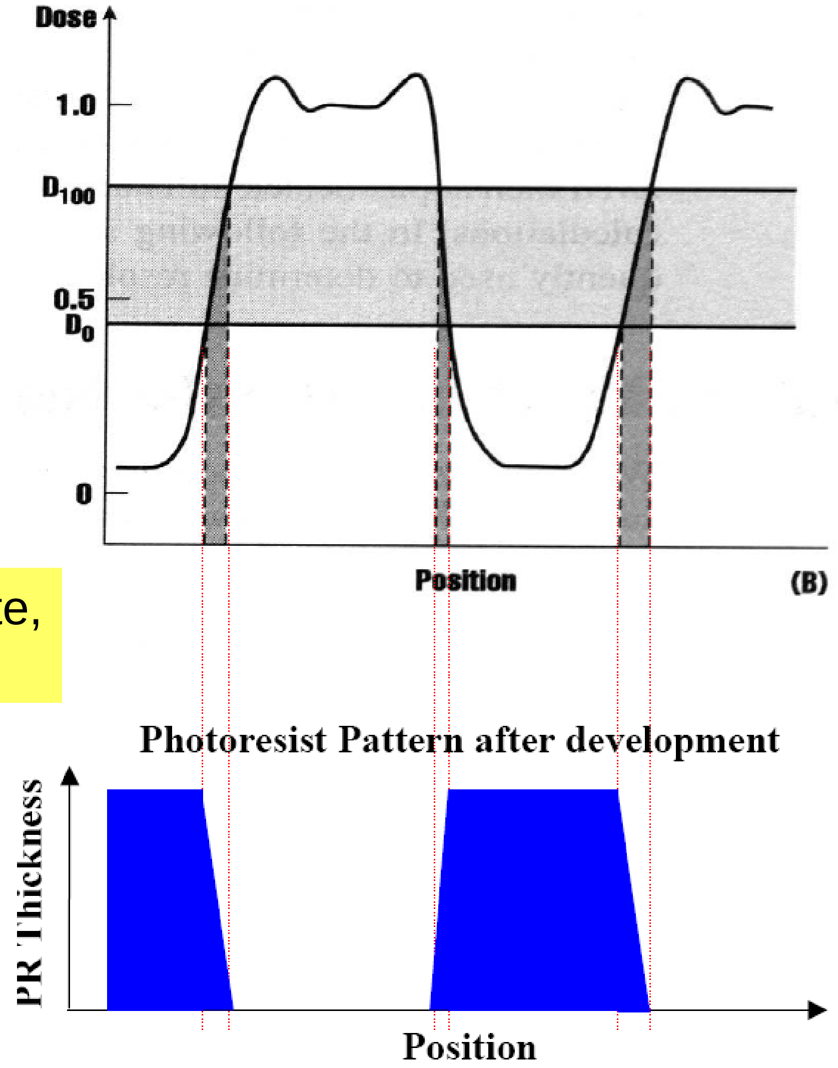
Contrast curves and Resolution

- Slope of photoresist lines:

$$\frac{dZ}{dX} = \left(\frac{dZ}{dD}\right)\left(\frac{dD}{dX}\right)$$

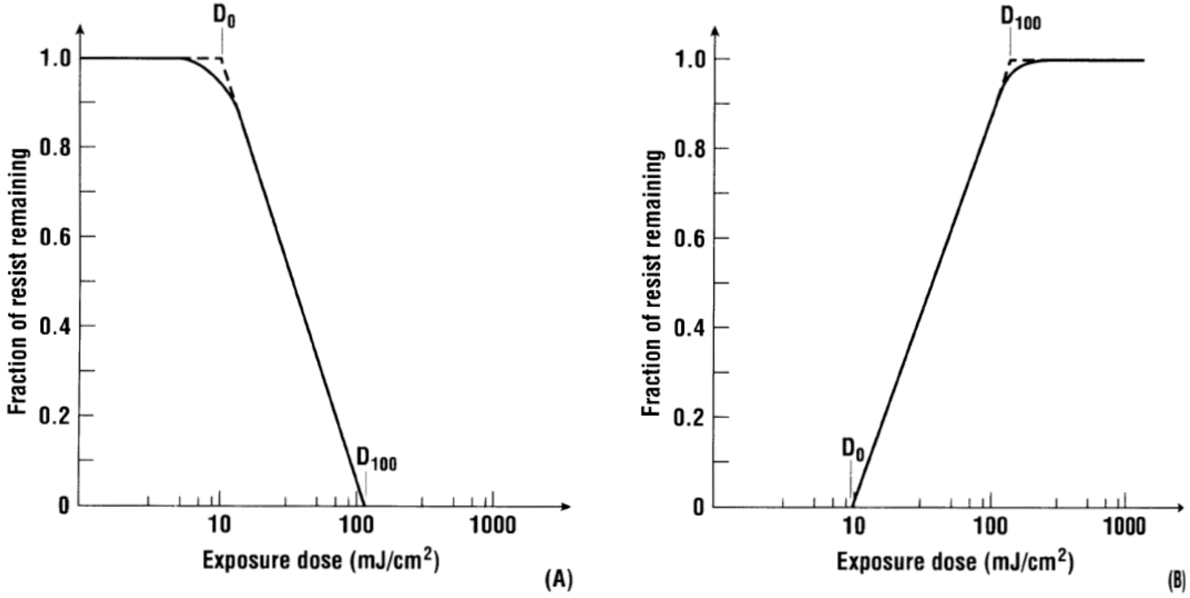
profile vs. dose, i.e. contrast

dose vs. coordinate, i.e. aerial image



Contrast curves and Resolution

- contrast curves for idealized positive and negative tone resists



The measure of the ability of a resist to distinguish between black and white areas of the mask :

the contrast

$$\gamma = \frac{1}{\log(D_{100} / D_0)}$$

energy dose
for 100% removal

energy dose
for to start ph/chem

Contrast curves and Resolution

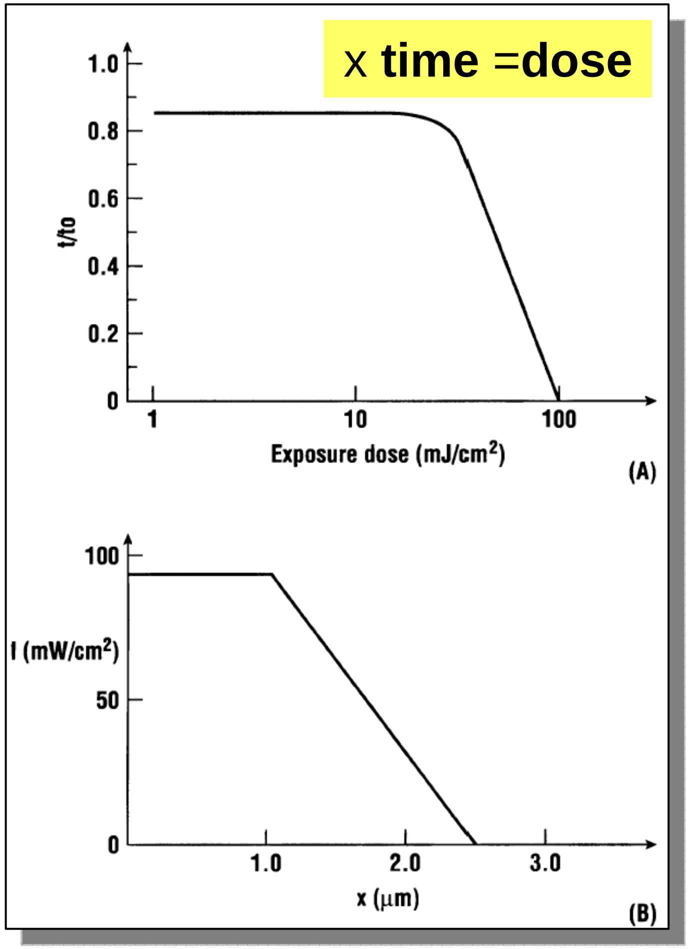
- contrast values for common resists

λ (nm)	AZ-1350	AZ-1450	Hunt 204
248	0.7	0.7	0.85
313	3.4	3.4	1.9
365	3.6	3.6	2
436	3.6	3.6	2.1

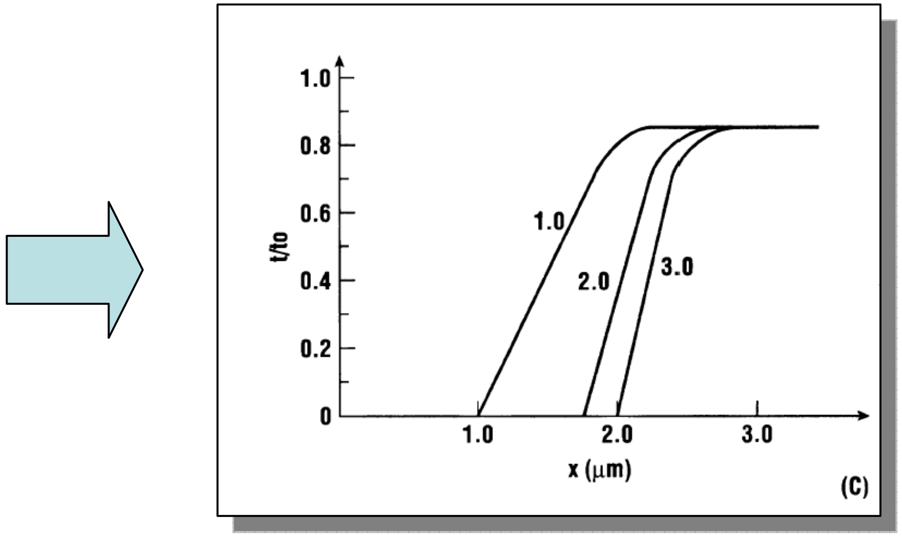
- typical contrast 2-5, i.e. $D_{100} / D_0 = 10^{\frac{1}{2}} - 10^{\frac{1}{5}}$
- contrast depends on the processing e.g. softbake, postbake, wavelength, development etc.

Contrast curves and Resolution

- calculating the resist profile $$\frac{dZ}{dX} = \left(\frac{dZ}{dD}\right)\left(\frac{dD}{dX}\right)$$



resist profile at several exposure times



- **lower exposures (< 50mJ/cm²):** shallow angle resist profile
- **high exposure (>150mJ/cm²):** sharp profile determined by the quality of aerial image and scattering

- typically exposure is in moderate or high exposure regimes

Contrast curves and Resolution

- light absorption in the resist

$$I = I_0 e^{-\alpha z}$$

- D_0 – independent on the resist thickness (T_R)
- D_{100} – inversely proportional to adsorbance A:

$$A = \frac{\int_0^{T_R} (I - I(z))dz}{I_0 I_R} = 1 - \frac{1 - e^{-\alpha T_R}}{\alpha T_R}$$

- the contrast is

$$\gamma = \frac{1}{\beta + \alpha T_R}$$

contrast drops with the resist thickness!

! thinner resist has higher contrast though less stable against etch and might limit the thickness of lift-off layer.

Contrast curves and Resolution

- The Critical Modulation Transfer Function (CMTF)

$$CMTF_{resist} = \frac{D_{100} - D_0}{D_{100} + D_0}$$

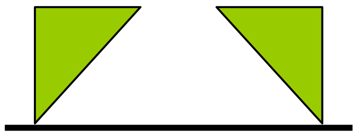
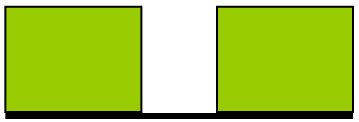
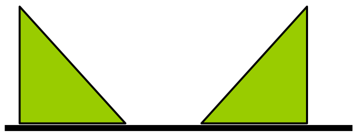
$$\gamma = \left(\log(D_{100} / D_0)\right)^{-1} \Rightarrow CMTF_{resist} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1}$$

- The resolution criterion:
  For successfully resolved image the MTF should be larger than CMTF

Radiation and Resist profiles

- scattering at the resist interface and adsorption affect the resist profile

develop rate for exposed/unexposed resist

Profile	Dose	Developer influence	R/R_0	Uses
	high	low	>10	lift-off, ion implant
	moderate	moderate	5-10	dry etch, lift-off, wet etch
	low	dominant	<5	wet etch

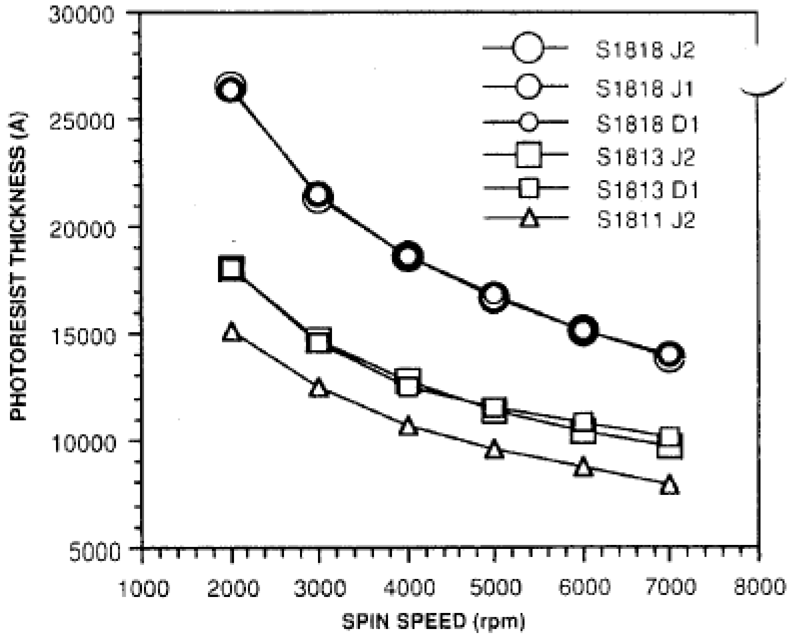
Resist technology

- **Dehydrate bake** — 150 – 200 ^{o}C in vacuum or dry nitrogen
- **Adhesion promoter application** — usually, HMDS (hexamethyldisilazane) via spin coating or vapour deposition
- **Resist application** — spin coating with static or dynamic dispense $T_R \propto 1/\sqrt{\omega}$
- **Softbake** — to remove solvent and establish exposure characteristics, typ. 90-100 ^{o}C
- **Exposure**
- **Post exposure bake** — required for some (negative) resists
- **Develop cycle** — alkaline develop for DQN (or alkaline-free based on TMAH (tetramethyl ammonium hydroxide)
- **Hardbake** — to increase resist stability for etching
- **Resist stabilization**

Resist technology

- **spin coating** – critical process!
  depends on:
  - deposition technique (static, dynamic, prespin)
  - acceleration (important for uniformity)
  - spin rate (2000 – 6000 rpm)
  - resist viscosity

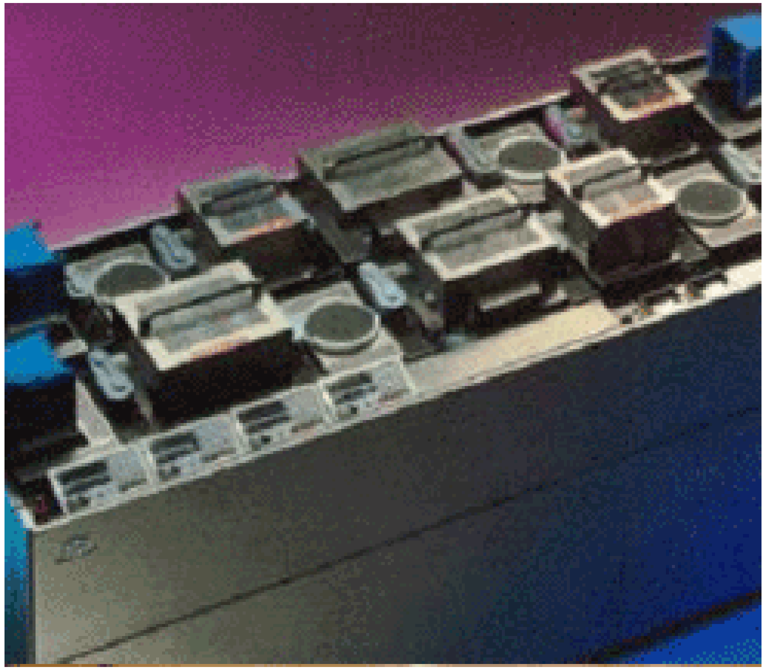
Spin curves for Shipley S1800



$$T_R \propto \frac{1}{\sqrt{\omega}}$$

Resist technology

- **spin coating** – equipment:
  - – automated track systems: high reproducibility, high costs
  - – manual spin coater + hot plate/oven



Resist technology

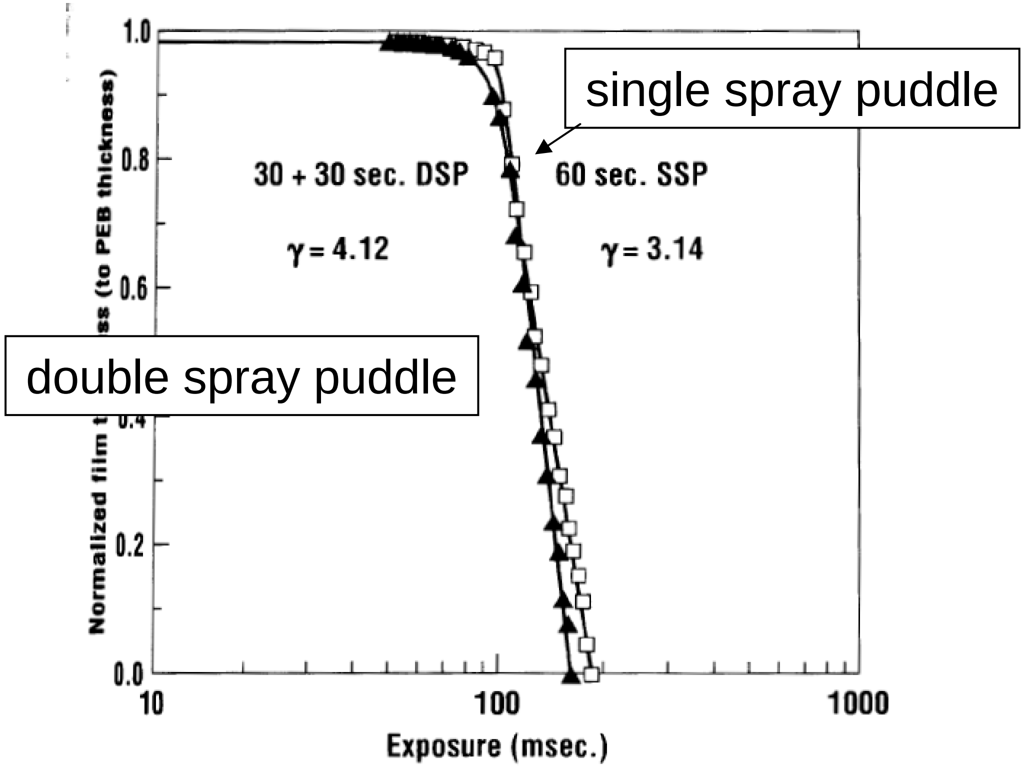
- Develop – can change the image contrast

<u>techniques</u>

- tank
- puddle
- spray etc.

<u>Developer</u>

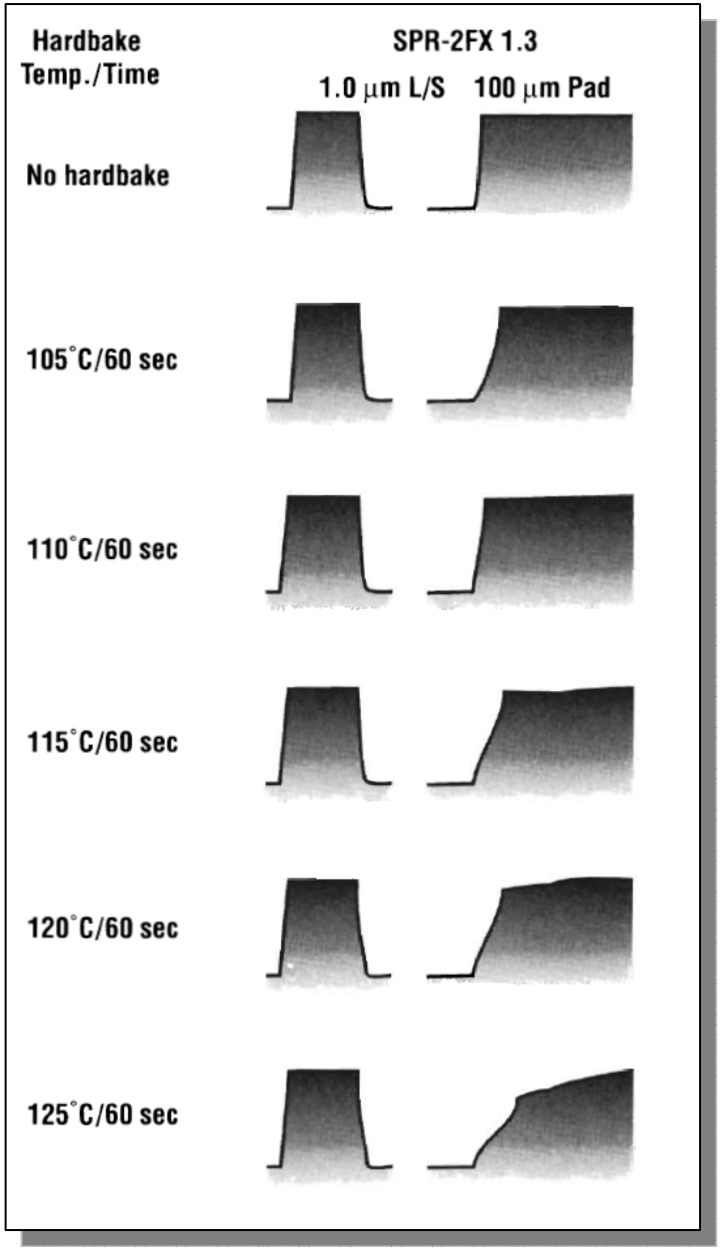
- metal bearing
- metal free



Resist technology

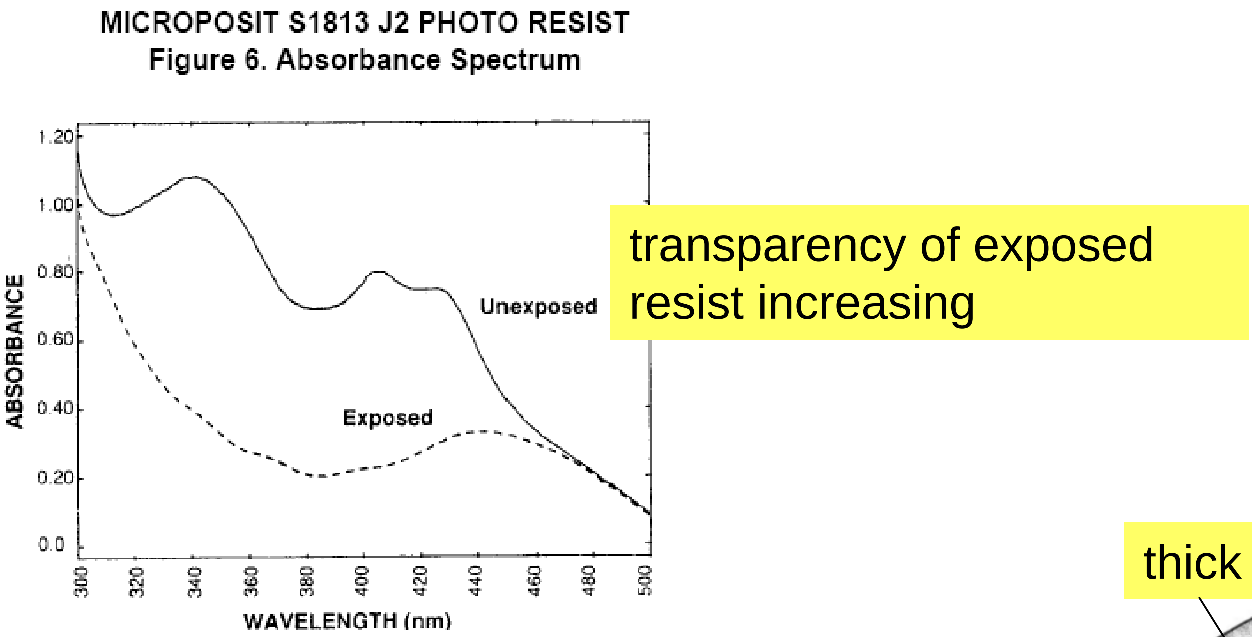
- **hardbake** – changes chemical/physical properties, affects the pattern

  - resist profiles of 1 μm line vs. hardbake T

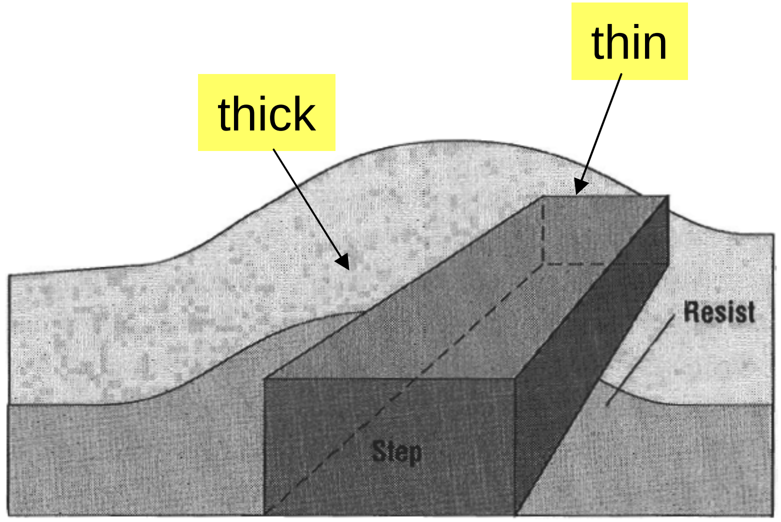


Second-order exposure effects

- absorption in the resist and absorption spectrum
- actinic effect (bleaching)



- effect of the underlying topography:
  thickness variation will cause line width variation.

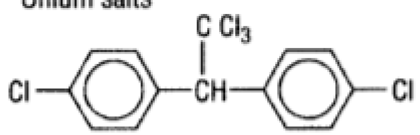


Advanced Photoresists

- Resist for 193 nm and 157 nm lines
  - Novolac strongly adsorbs below 248 nm and DQ doesn’t bleach significantly
  - Possibilities:
    - Chemically amplified resist (CAR) system based on DQN. Typically: Photoacid generator (PAG)
    - PMMA or other polymers that undergo chain scission or crosslinking. (high contrast, but low sensitivity ~200 mJ/cm^2, against 5-10 mJ/cm^2 required, very low etch resistance).
    - acrylic-based resins with PAG and a protection agent

Photoacid generators

Onium salts



DDT

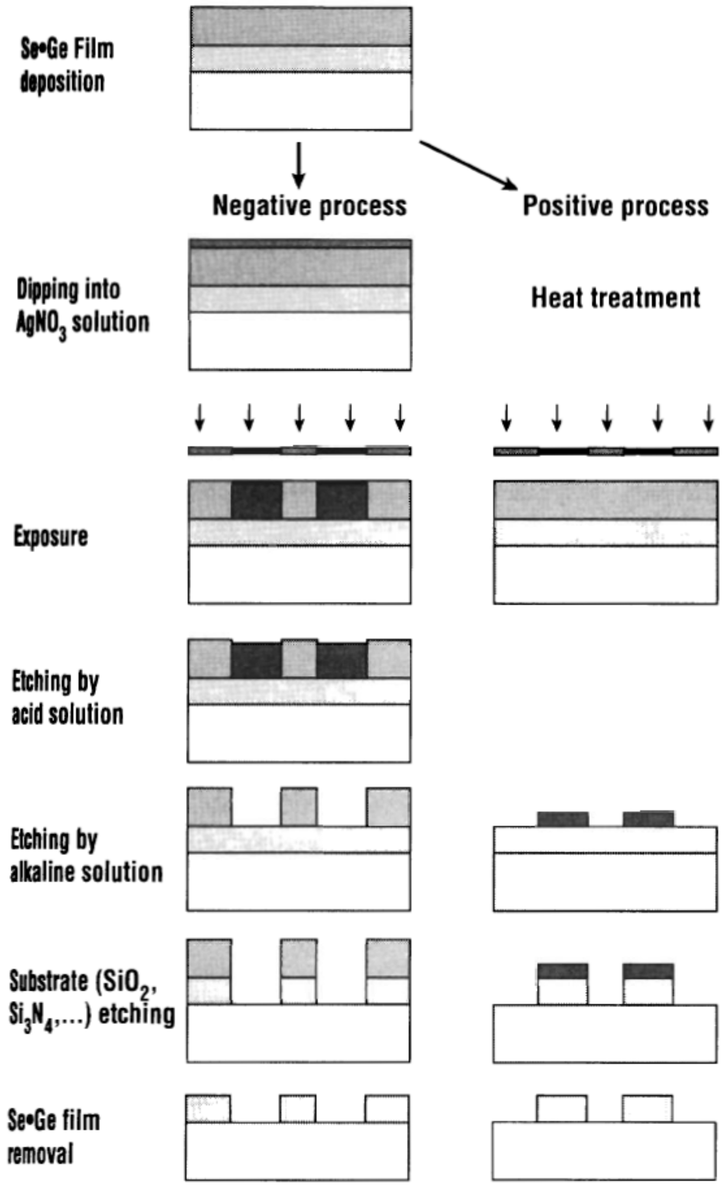
Advanced Photoresists

- CAR related effects:
  - diffusion of PAG from exposed to unexposed regions
  - deterioration of the surface of the resist upon exposure to air

Advanced Photoresists

- **Inorganic resists**

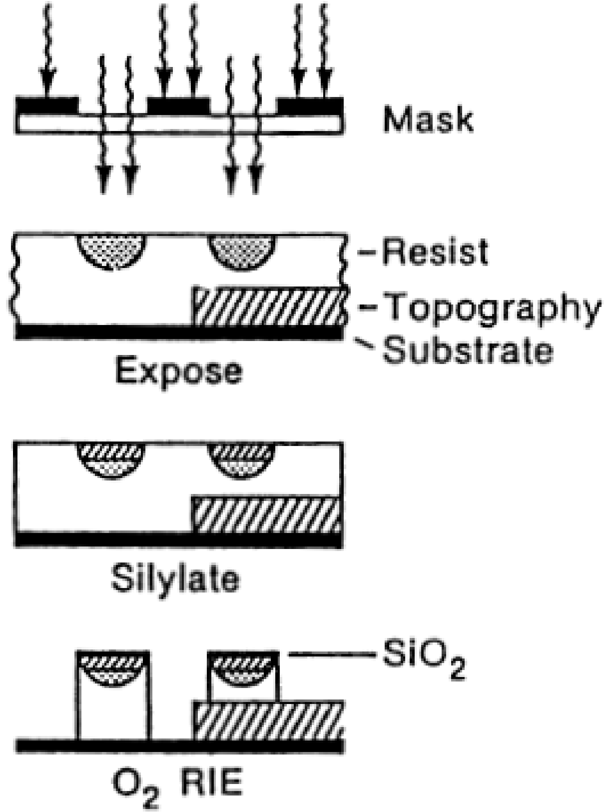
- Ag/Se-Ge:
  - very high contrast γ~7
  - requires planarization
  - tends to have pinholes
  - defects added during plating



Advanced Photoresists

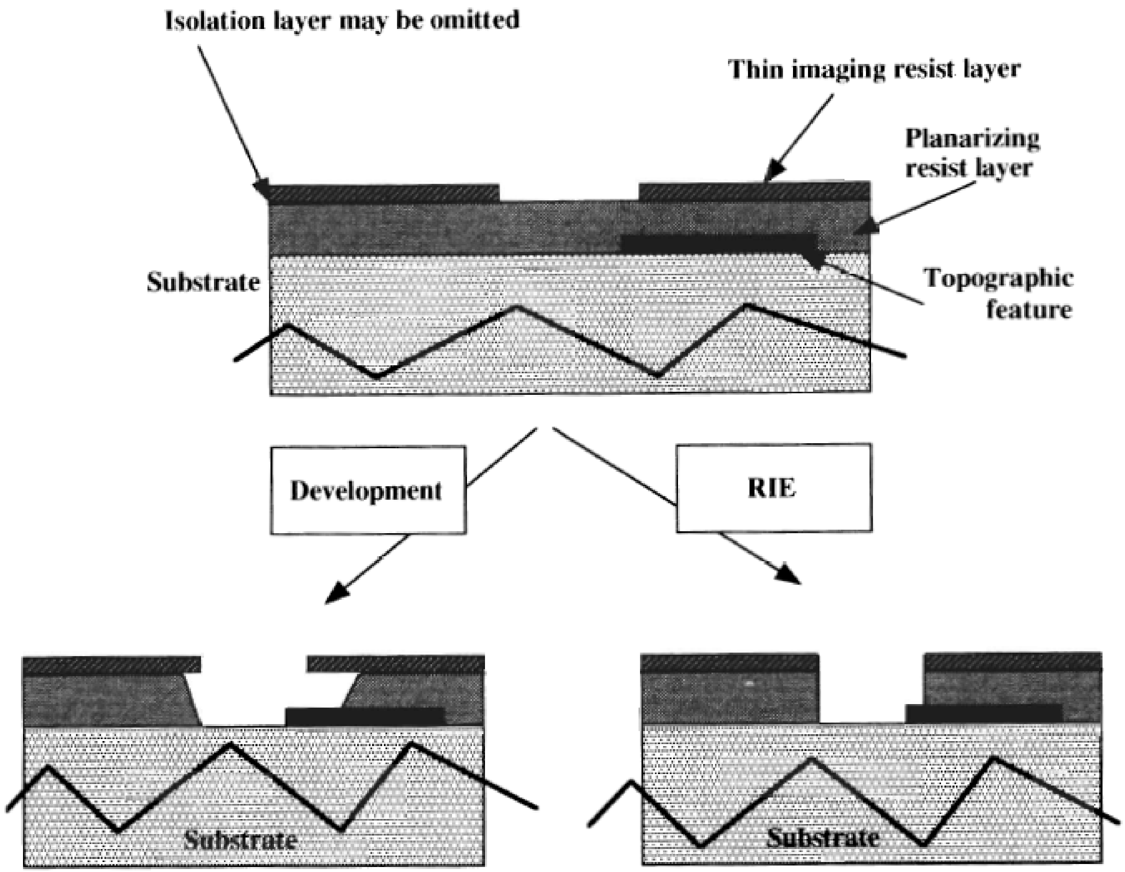
- dry developable resists

<u>Example:</u> Si-containing resists (polysilynes-based)



Multilayer resist

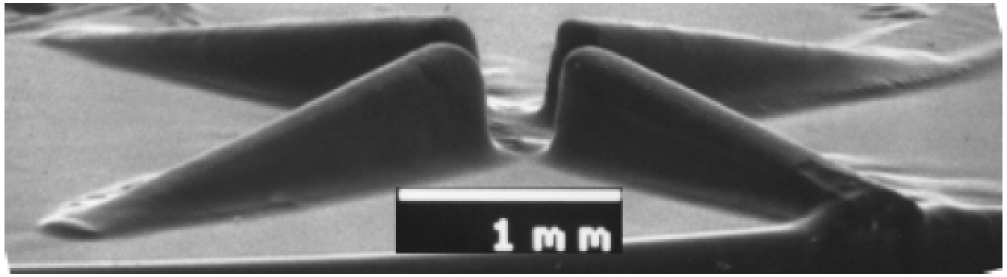
- multilayer resist may be required for
  - resolution improvement
  - topography planarization
  - lift-off improvement
  - etching improvement etc.



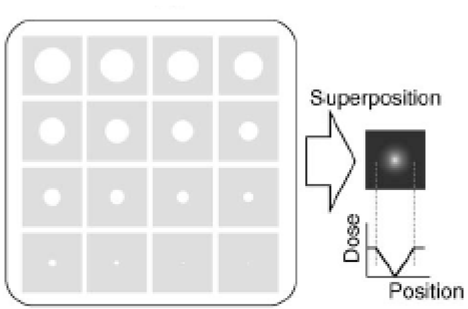
Gray-scale lithography

- regime where resist profile strongly depends on exposure (low doses) can be used to create 3D structures

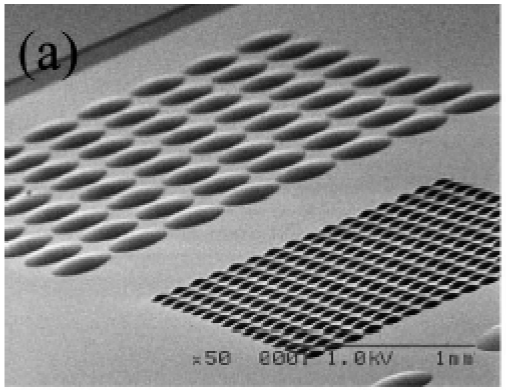
SU8 gray scale lithography



fabrication of aspherical lens array by gray scale lithography

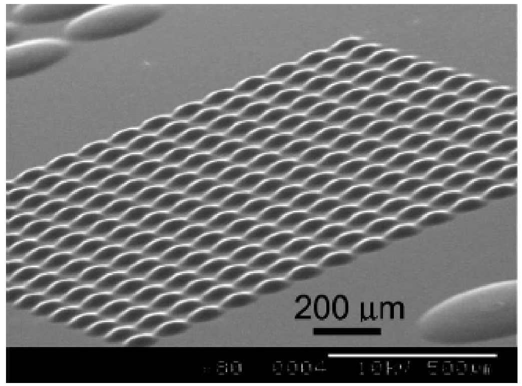


DMD superposition of an image stack



photoresist pattern

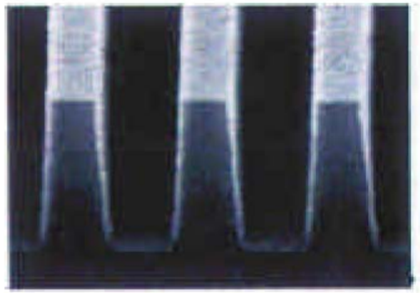
dry etch



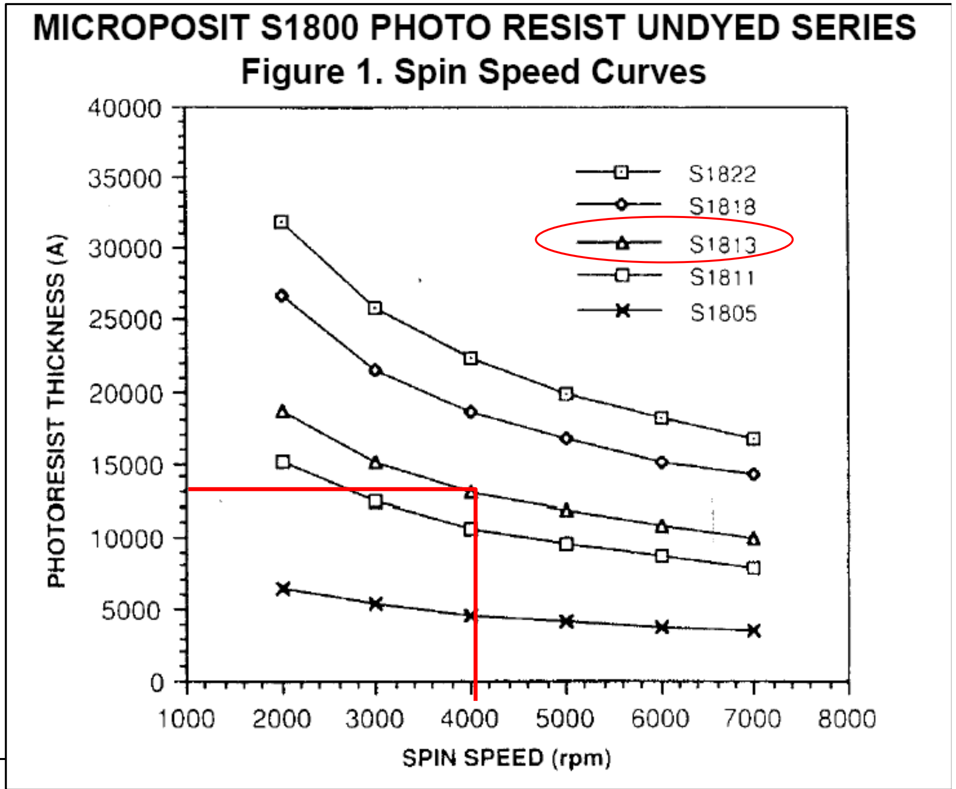
pattern in silicon

Shipley S1800 resist

- positive resist
- exist in a number of different viscosity formulation, we use S1813



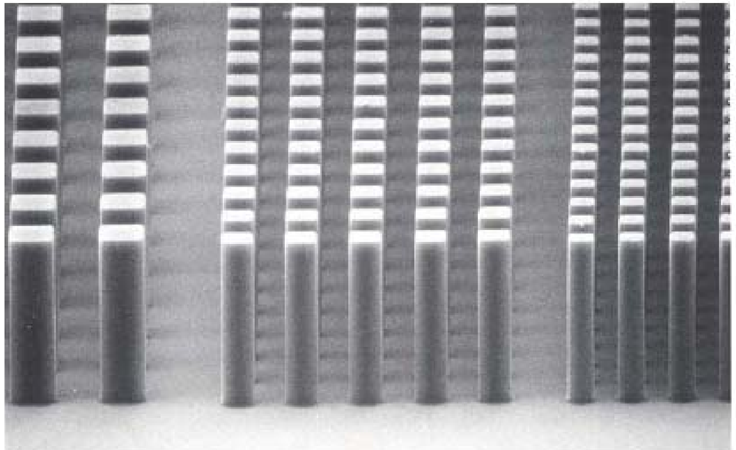
0.48 µm Lines/Spaces



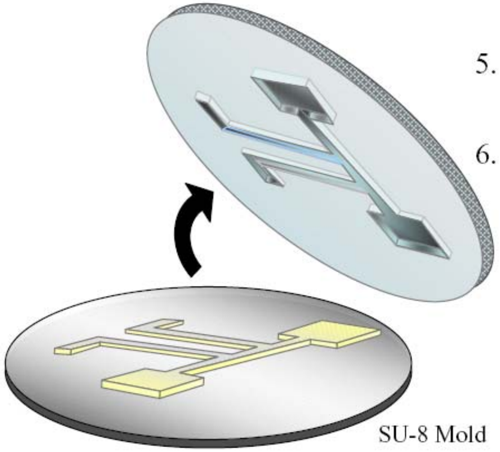
High Resolution Process Parameters (Refer to Figure 1)	
Substrate:	Polysilicon
Photoresist:	MICROPOSIT® S1813® PHOTO RESIST
Coat:	12,300Å
Softbake:	115°C/60 sec. Hotplate
Exposure:	Nikon 1505 G6E, G-Line (0.54 NA), 150 mJ/cm^2
Develop:	MICROPOSIT® MF®-321 DEVELOPER 15 + 50 sec. Double Spray Puddle (DSP) @ 21°C

SU8-2000

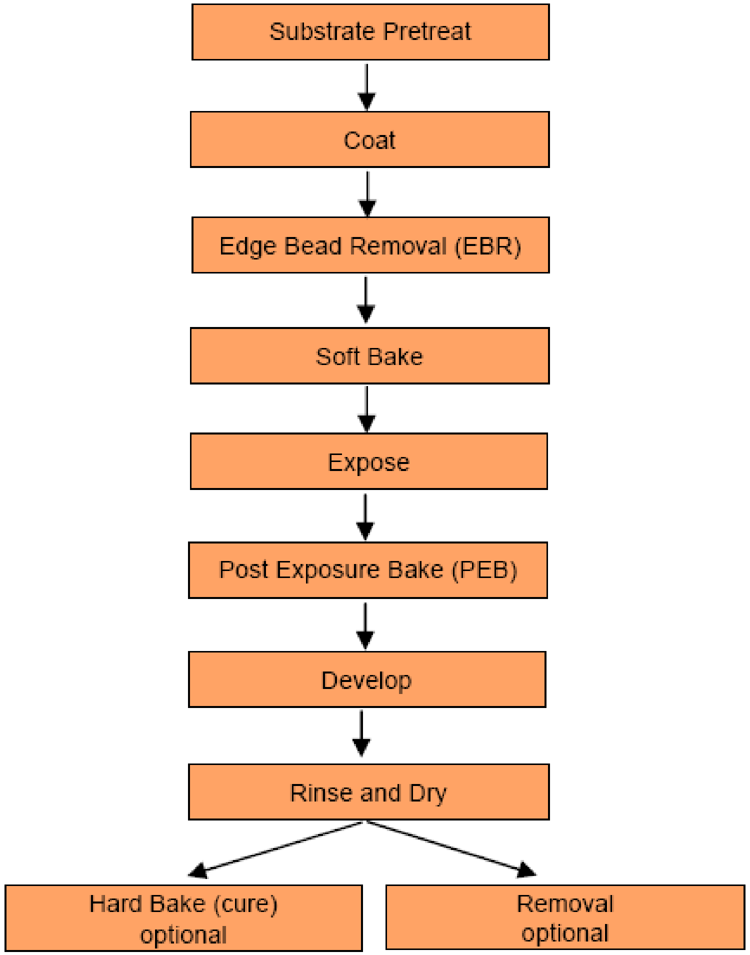
- negative resist,
- thick layers <200mm in a single coat
- high aspect ratios, up to 1:10
- vertical sidewalls



10 um features, 50 um SU-8 2000 coating



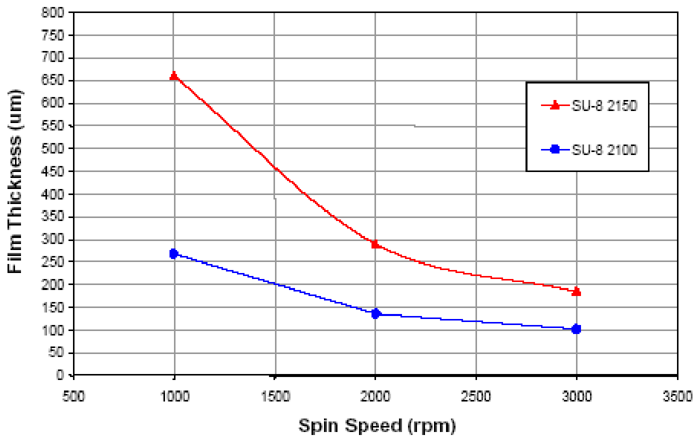
Process Flow



SU-8 2000 (cont)

- spin coat

Figure 1. SU-8 2000 Spin Speed versus Thickness



- postbake

THICKNESS microns	PEB TIME (65°C)* minutes	PEB TIME (95°C) minutes
100 - 150	5	10 - 12
160 - 225	5	12 - 15
230 - 270	5	15 - 20
280 - 550	5	20 - 30

* Optional step for stress reduction

- soft bake

THICKNESS microns	SOFT BAKE TIMES (65°C)* minutes	(95°C) minutes
100 - 150	5	20 - 30
160 - 225	5 - 7	30 - 45
230 - 270	7	45 - 60
280 - 550	7 - 10	60 - 120

- exposure

THICKNESS microns	EXPOSURE ENERGY mJ/cm^2
100 - 150	240 - 260
160 - 225	260 - 350
230 - 270	350 - 370
280 - 550	370 - 600

Problems

λ (nm)	Contrast AZ-1450
248	0.7
313	3.4
365	3.6
436	3.6

- **8.1:** Calculate CMTF for AZ-1450 at the wavelengths listed in the table. Assuming NA=0.4 use figure 7.22 to determine the minimum feature for an aligner with S=0.5.

- **8.15:** Assume that a wafer is being exposed with a proximity printer. In the far field limit in one dimension intensity depends as:

$$I(x) = I(0)\left[\frac{2W}{\lambda g}\right]^2 I_x^{\,2}; I_x = \sin\left[\frac{2\pi xW}{\lambda g}\right] \Big/ \frac{2\pi xW}{\lambda g}$$

- Assume that you are using 1 µm thick positive tone resist with D0=30mJ/cm2 and D100=100mJ/cm2. For l=436nm, g=10µm, and I(0)=100mW.µm2/cm2 calculate resist profiles for W=1µm and exposure times 1, 2, 4, and 7 sec.

Problems

Problem 8.1