Micro Electro Mechanical Systems
for mechanical engineering applications

Lecture 5:
MEMS fabrication II: surface micromachining (2)
Photolithography

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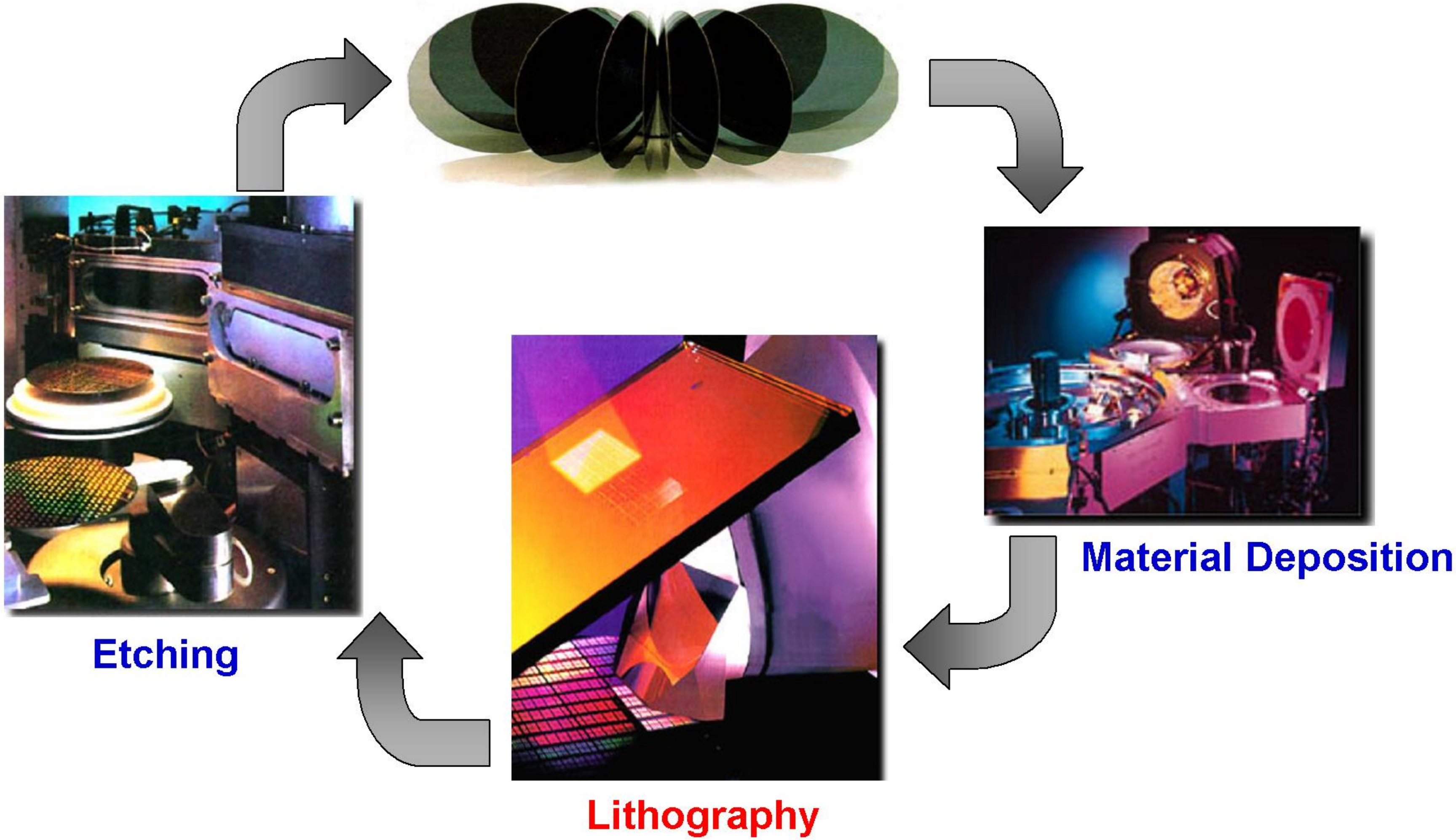
Surface Micromachining

Conventional Silicon Technology



Contents

- What is photolithography?

- Photoresists (PR)
- Lithography process
- Photomask
- Mask to wafer alignment
- Exposure techniques and system
- Problems of photolithography process
- Resolution enhancement techniques

- Lift off process

- Next generation lithography methods

What is photolithography?

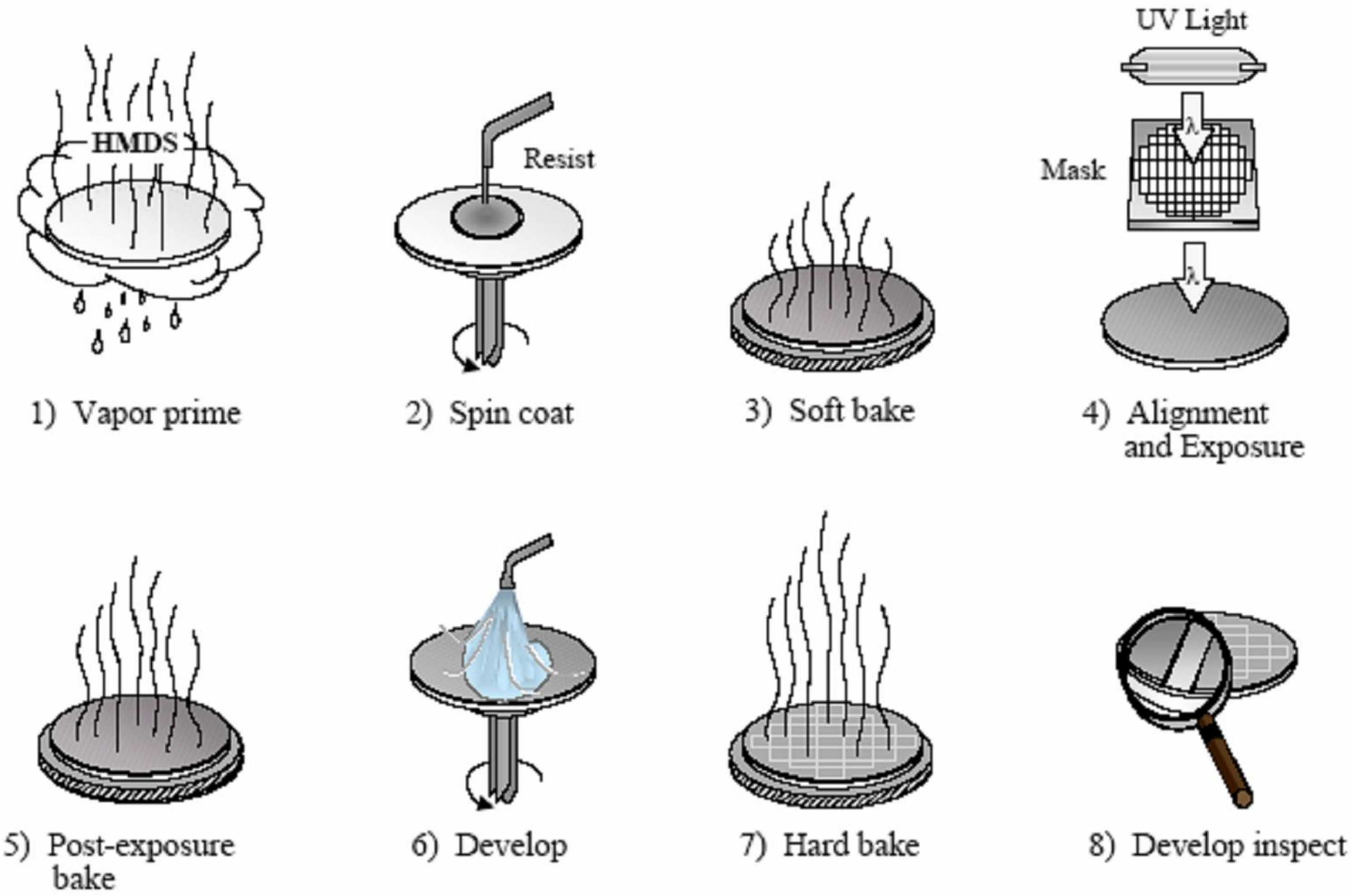
- Photolithography: the process of transferring geometric shapes on a mask to the surface of a silicon wafer

Photoresist spin coating

Bake in the oven

Mask to wafer alignment

Overview

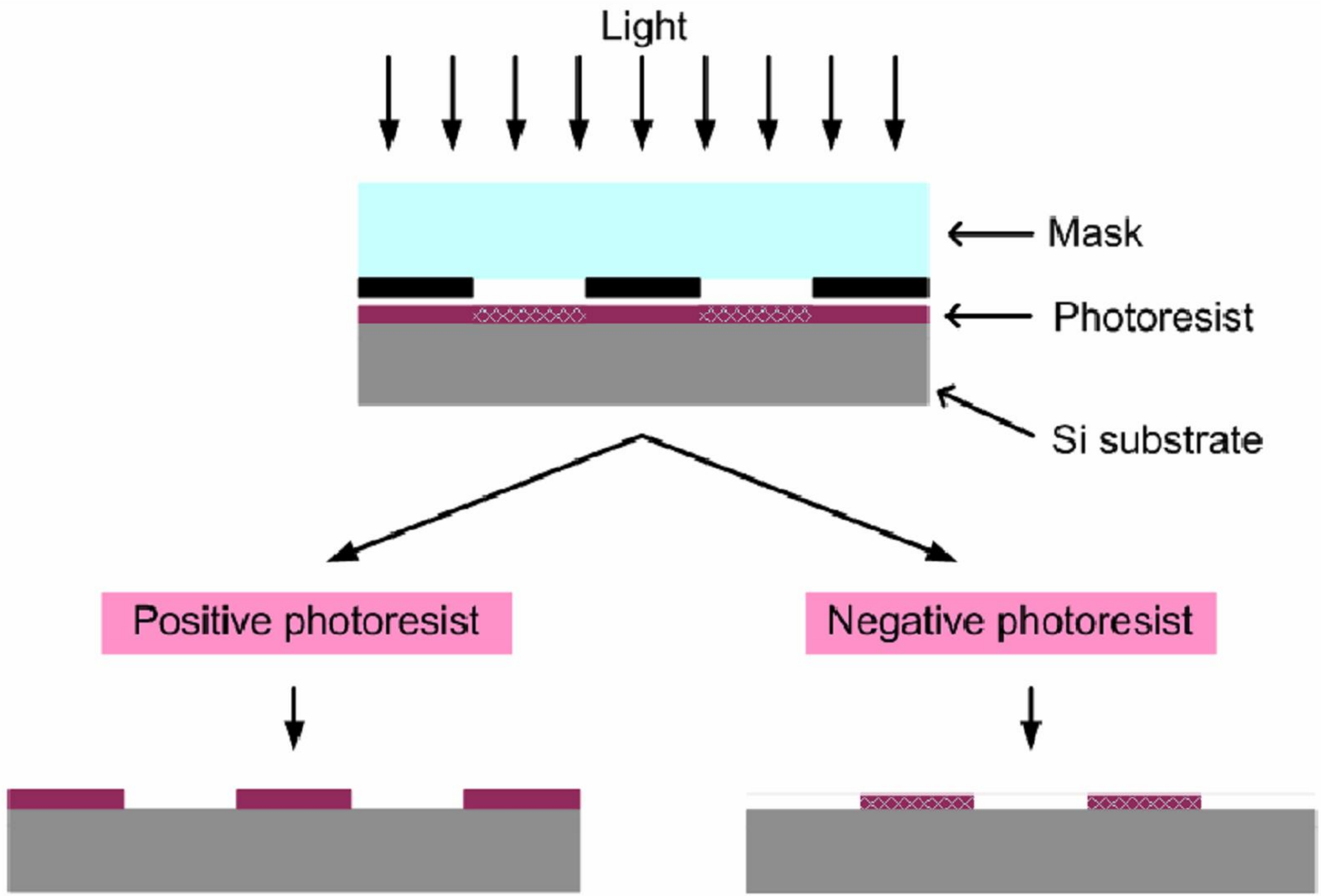

HMDS
Resist
UV Light
Mask
λ
λ
1) Vapor prime
2) Spin coat
3) Soft bake
4) Alignment and Exposure
5) Post-exposure bake
6) Develop
7) Hard bake
8) Develop inspect

General photoresist

- Components of photoresists
  - Polymer (base resin): changes structure when exposed to radiation
  - Sensitizer: control the photochemical reaction in the polymeric phase
  - Casting solvent: allow spin application and formation of thin layer on the wafer

- Type of photoresists
  - Positive
  - Negative

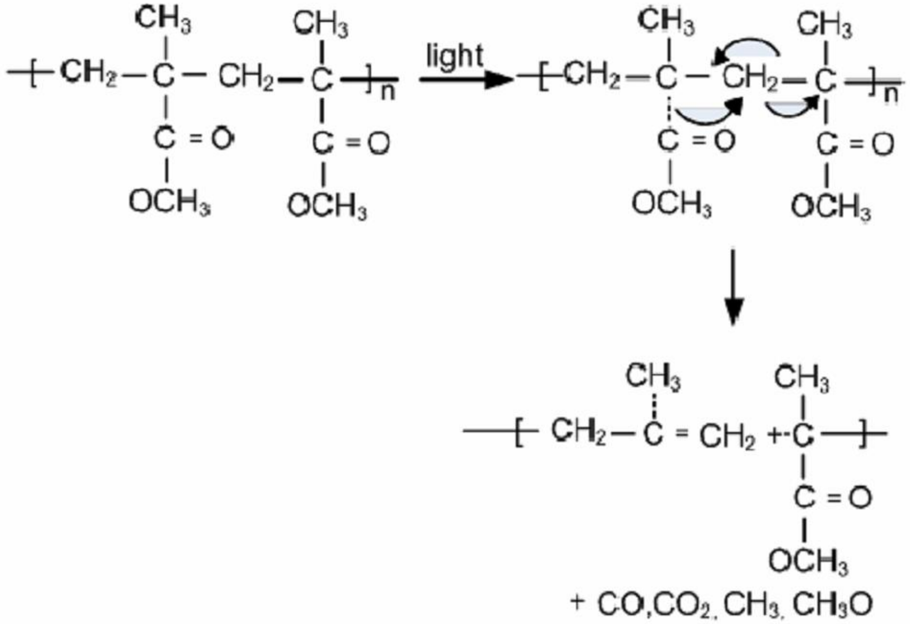
Procedure



Light
Mask
Photoresist
Si substrate
Positive photoresist
Negative photoresist

Positive PR (1)

- **Poly(methylmethacrylate) or PMMA**
  - Single component
  - Photo induces chain scission of PMMA resist
  - Short-wavelength lithography: deep UV, electron beam, X-ray, ion-beam lithography
  - High resolution



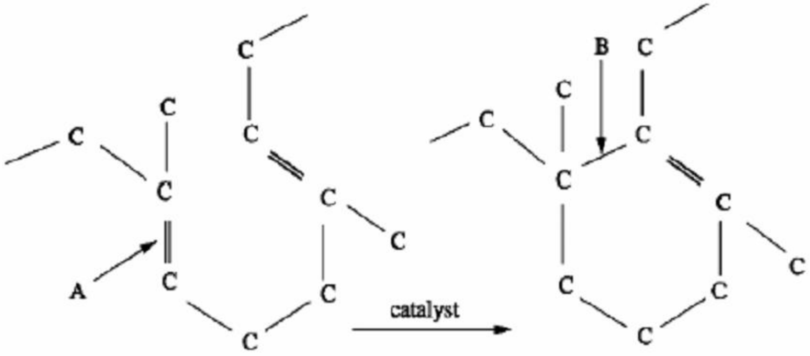
Positive PR (2)

- DQN resist
  - Most popular positive resist
  - Exposure source: 365, 400 nm mercury line

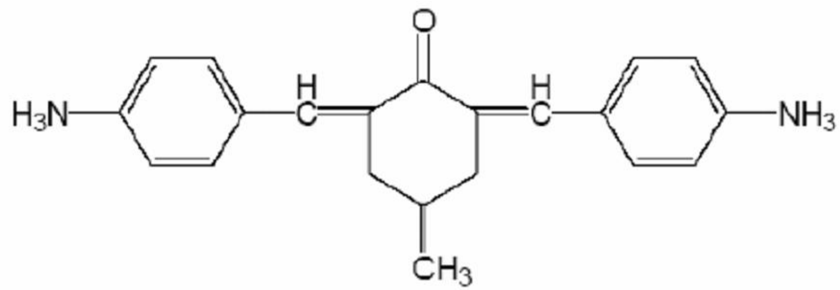
  - Two component
    - N (Novolak matrix resin)
      - Solvent added to adjust viscosity
      - Hydrophilic, itself alkali soluble
    - DQ (diazoquinone)
      - insoluble in base solution
      - photo-active compound

Negative PR (1)

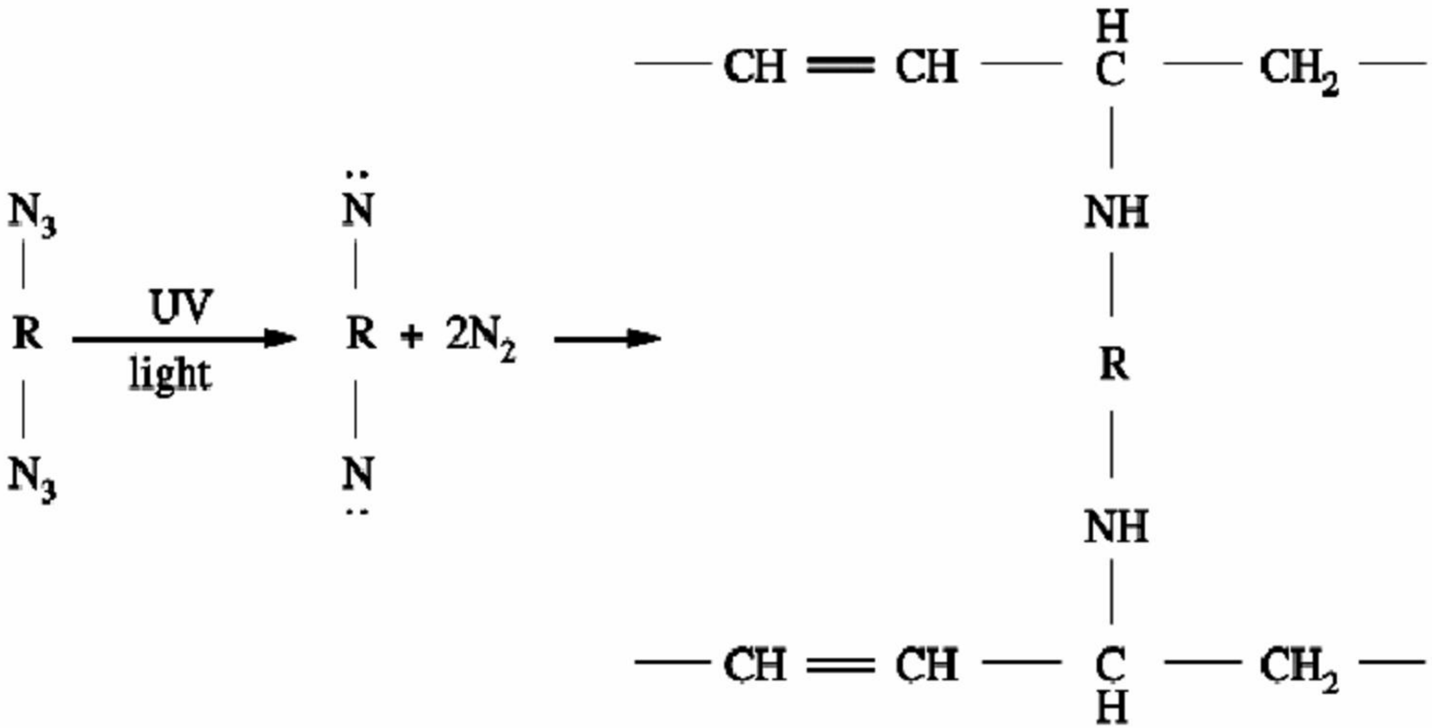
- Bis(aryl)azide rubber resist
  - Cyclized polyisoprene
    - Non-photosensitive substrate material
    - Synthetic rubber
  - Bis(aryl)azide ABC compound
    - Photosensitive cross-linking agent



Catalyst of polyisoprene



Agent (Azide) for polyisoprene cross-linking



Cross-linking of polyisoprene

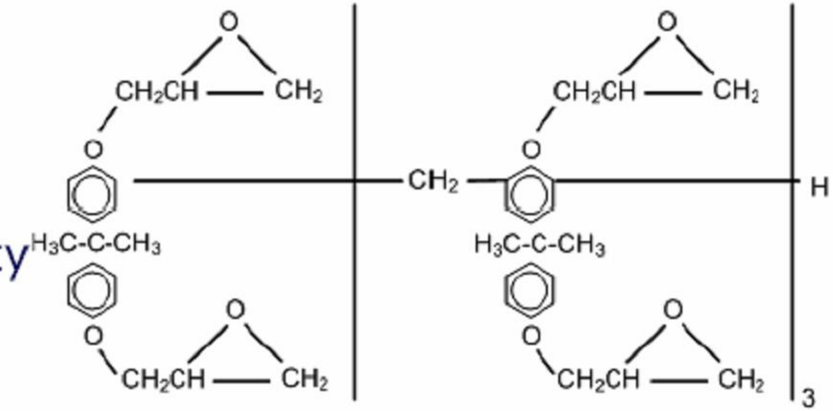
Comparison of PRs

- Comparison of positive and negative photoresists

Characteristic	Resist type	
	Positive	Negative
Adhesion to Si	Fair	Excellent
Step coverage	better	lower
Exposure time	Slower (10-15 sec)	Faster (2-3 sec)
Developer	Aqueous based	Organic solvent
Influence of oxygen	No	Yes
Minimum feature	0.5 μm and below	±2 μm
Wet chemical resistance	Good	Fair
Plasma etch resistance	Very good	Not very good
Pinhole count	Higher	Lower
material cost	More expensive	Less expensive

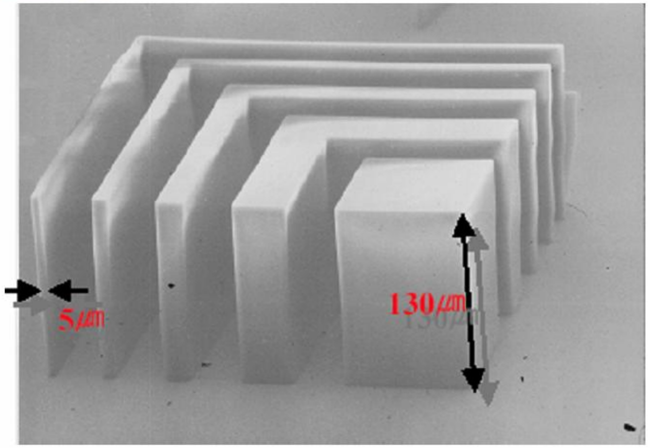
Special photoresist

- Thick PR: structures often require thick PR layer that are capable of high resolution and high aspect ratio.
- SU-8
  - Can be spin-coated as very thick films (to 500 μm in a single coat)
  - Excellent sensitivity
  - High resolution
  - Low optical absorption
  - High aspect ratio
  - Good thermal, chemical stability
  - Exposure source
    - 365, 436 nm UV light
    - e-beam
    - x-ray



SU-8

- SU-8 process
  - Dehydrate bake
  - Coating
  - Relax
  - Soft bake: remove solvent
  - Exposure: photogenerated acid
  - Hard bake: cross-links the resist
  - Develop



High aspect ratio structure using SU-8 resist

Lithography process (1)

- Basic step of photolithography

Clean wafers

(Solvent removal, hydrous oxide removal, removal of residual organic, ionic contamination..)

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Deposit barrier layer

(SiO_2, Si_3N_4, metal..)

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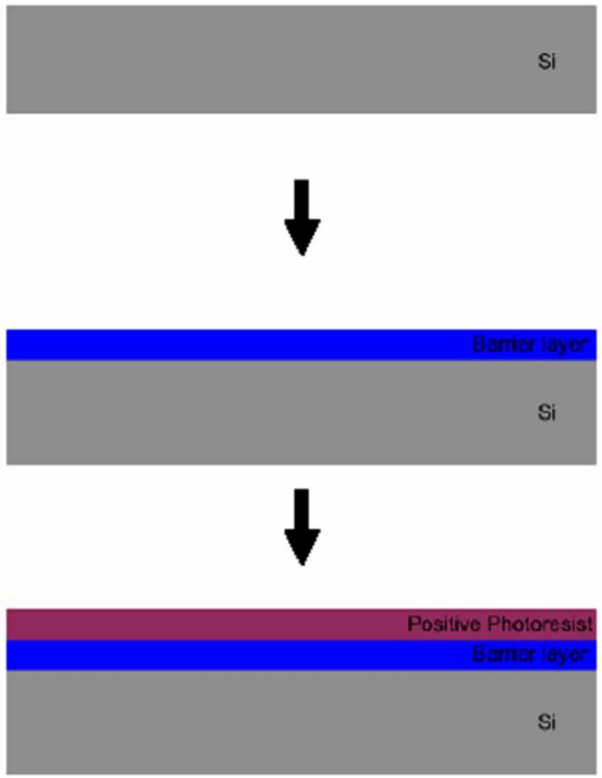
Coat with photoresist

- HMDS (enhance adhesion to Si) coating
- Photoresist coating



Lithography process (2)

Soft bake

- Improve adhesion
- Remove solvent from PR
- 5-30 min in the oven at 60-100 ℃

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Align masks

- Each mask must be aligned to the previous pattern on the wafer

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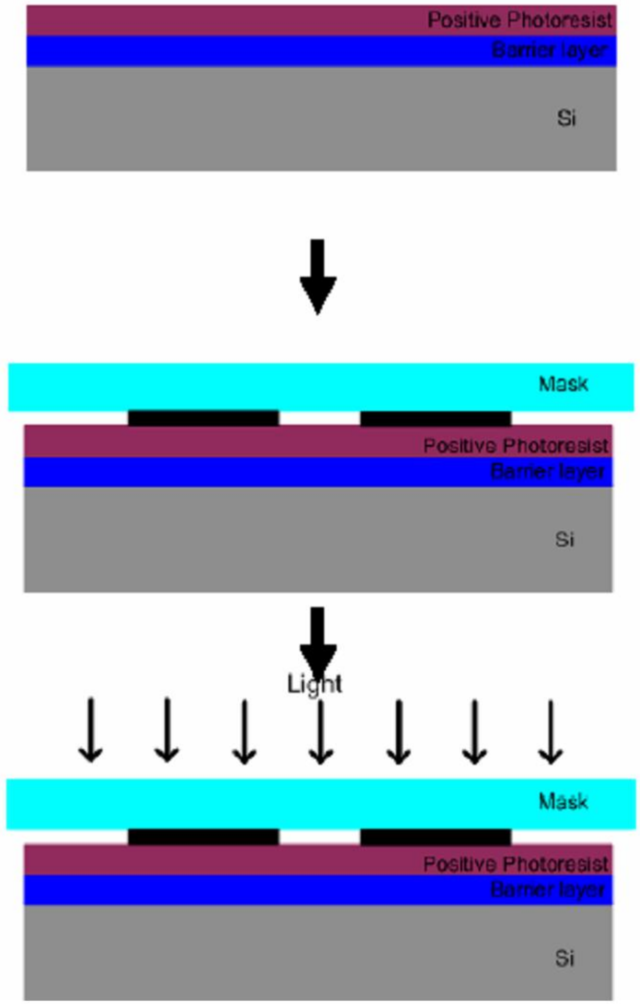
Expose pattern

- Expose through mask with high-intensity UV light



Lithography process (3)

Develop photoresist

- develop the PR pattern on substrate

↓

Hard bake

- harden the PR
- improve adhesion to substrate
- 20-30 min in the oven at 120-180 ℃

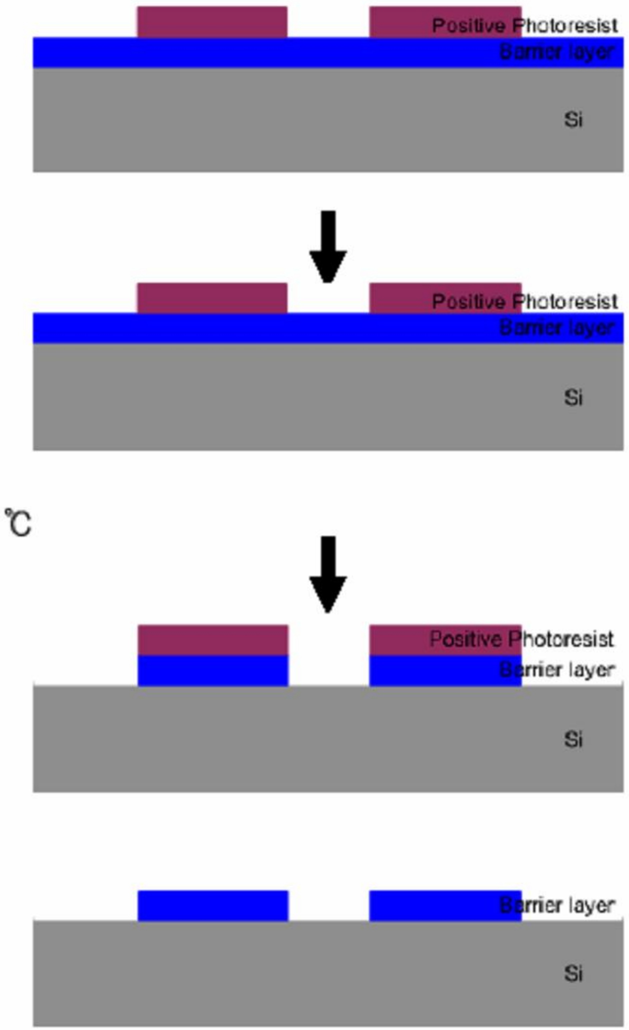
↓

Etch windows in barrier layer

- wet / dry etch

↓

Remove photoresist



Resolution

$$Resolution(R) = K_1 \frac{\lambda}{NA}$$

$$DOF = K_2 \frac{\lambda}{NA^2}$$

To get higher Resolution (small R)

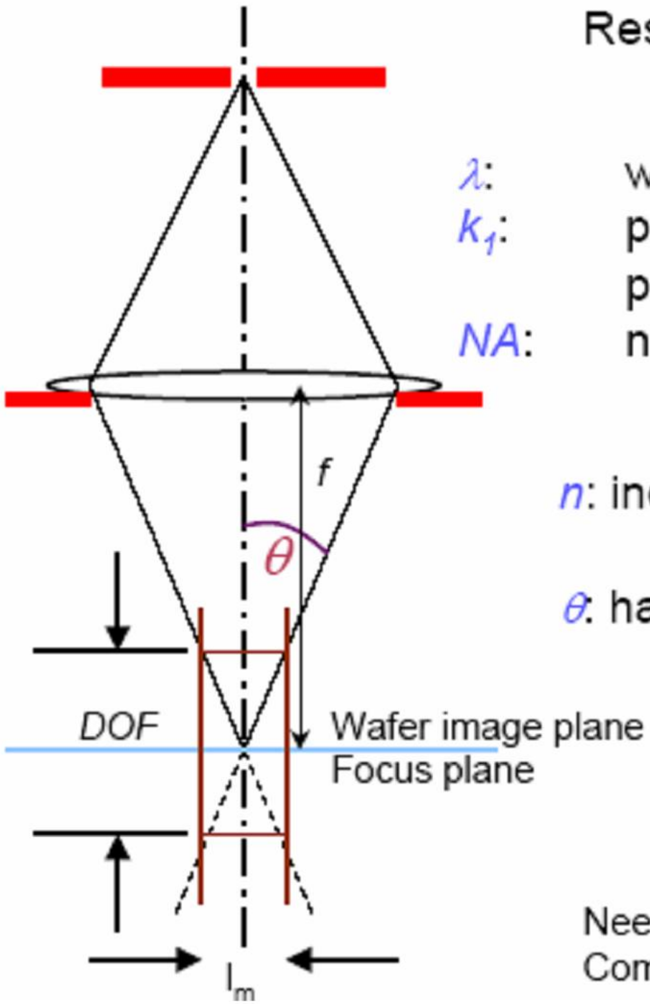
1. increase *NA*
2. shorten wavelength λ
3. decrease K_1

To get higher Depth of Focus

1. decrease *NA*
2. lengthen λ
3. increase K_2

Here, λ is wavelangeth of light, *NA is* numerical aperture of lens,
K_1 and K_2 are proportional constant of resist process
$NA = D/2f$ (*D*: diameter of the lens, *f*: focal length)

Projection: Key Parameters



Resolution: $l_m = k_1 \frac{\lambda}{NA}$

λ: wavelength of exposure
k_1: parameter characterizing system and process dependence (typically between 0.25 and 1)
NA: numerical aperture

$$NA = n \sin\theta$$

n: index of refraction (light transmission med., 1 for air)

$$NA \approx \sin\theta$$

θ: half-angle of cone of light

$$DOF = \frac{\pm l_m/2}{\tan\theta} \approx \frac{\pm l_m/2}{\sin\theta} = k_2 \frac{\lambda}{NA^2}$$

DOF: Depth of field

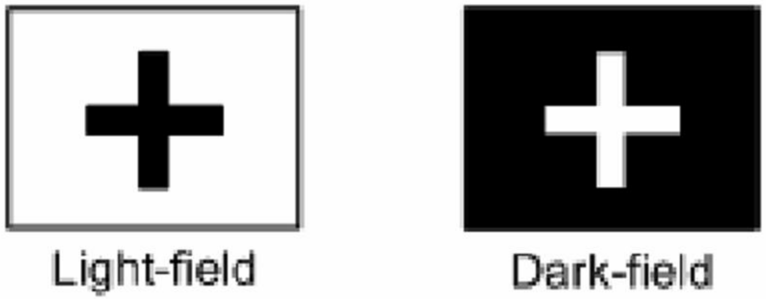
Need smaller l_m and higher DOF
Compromises of the optical design

Photomask

- Mask: the stencil used to repeatedly generate a desired pattern on resist-coated wafers

- Substrates of photomask: usually use optically flat glass or quartz

- Type of photo mask (mask polarity)
  - Light field: mostly clear, drawn feature=opaque
  - Dark field: mostly dark, drawn feature=clear

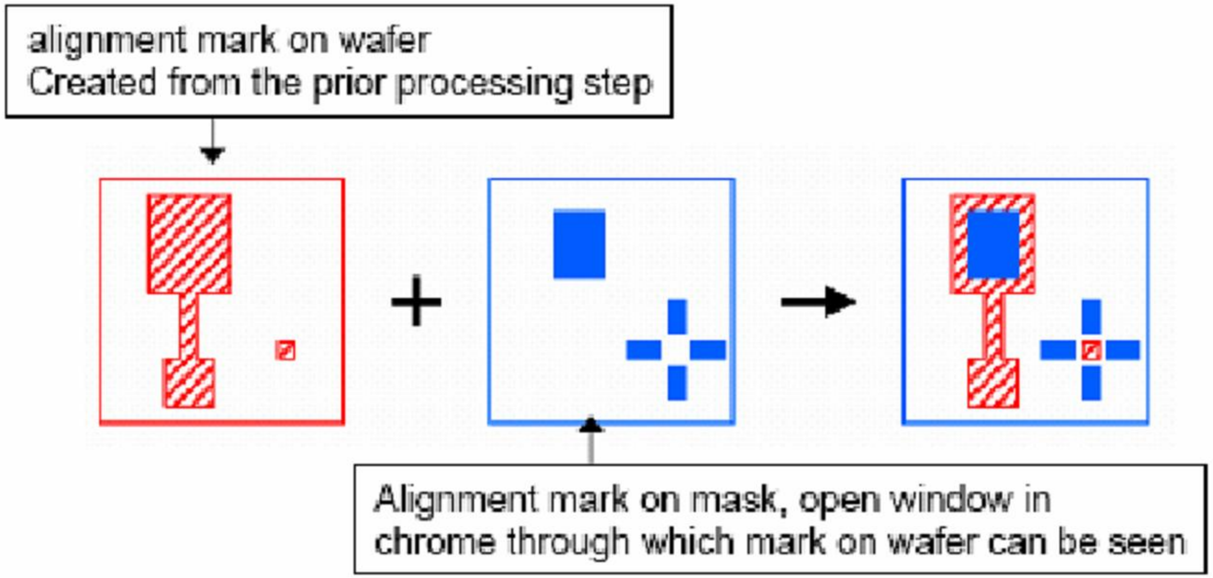


Photomask

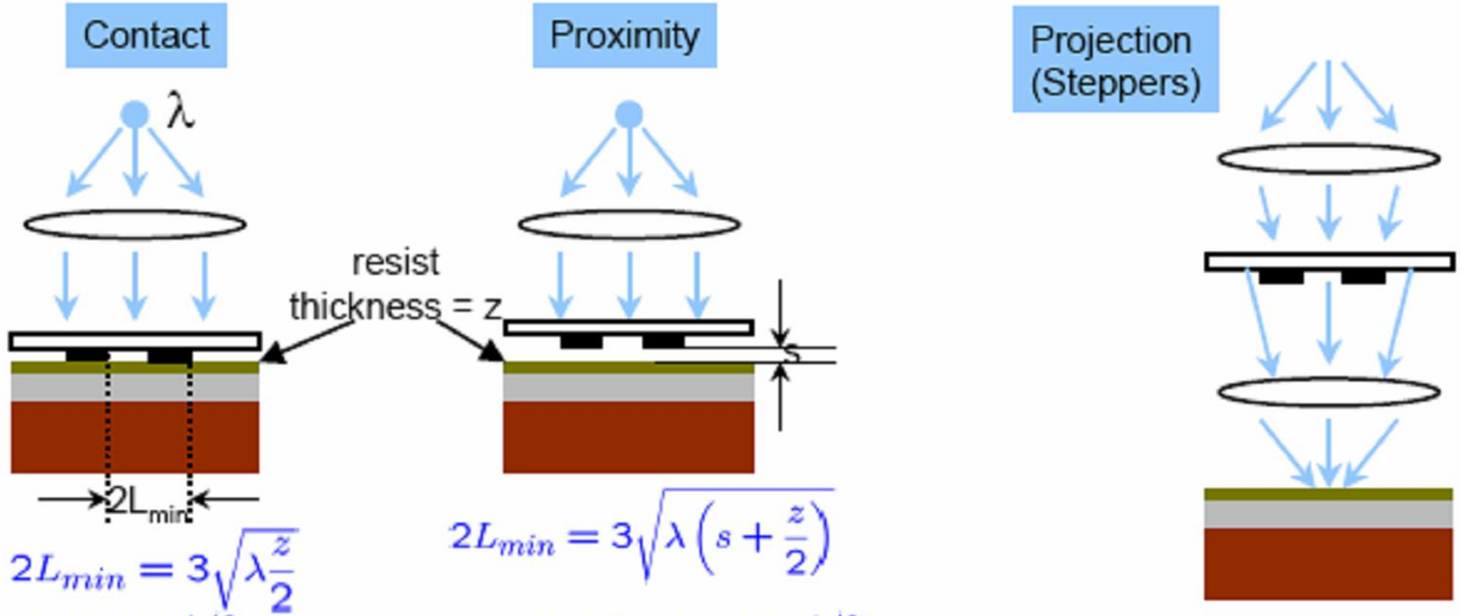
- Degradation of photomask
  - Repeat alignment
  - Particle between mask and wafer
  - Exposure mode: contact due to high nitrogen pressure
  - Mask life: proportional to the number of exposure time
  - Automated alignment system: improvement of process speed, precision and mask degradation

Mask to wafer alignment

- Alignment: Each mask following the first must be carefully aligned to the previous pattern on the wafer
- 3 degrees of freedom between mask and wafer: (x,y,q)
- Use alignment marks on mask to register patterns prior to expose



Exposure technique



$$2L_{min} = 3\sqrt{\lambda\frac{z}{2}}$$

$$R = k(\lambda z/2)^{1/2}$$

$$2L_{min} = 3\sqrt{\lambda\left(s+\frac{z}{2}\right)}$$

$$R = k\{\lambda(s+z/2)\}^{1/2}$$

R: resolution, *k* a constant that is a function of the design/set-up parameters

Contact

Diffraction minimized by small (~0) mask-resist gap

Fast, simple & inexpensive

But, mask-wear, defect generation & wafer-sized mask and light scattering in resist limits resolution

Proximity

Less mask wear/contamination
Fast, simple & inexpensive

But, Greater diffraction & less resolution
Wafer sized mask

Projection (Steppers)

No mask contact/contamination
Mask demagnified
4x and 5x usually
Mask pattern at chip size with wafer stepped for exposure

Expensive instrumentation

Harvard_Fabrication_ES174Si4.ppt – 2006 6

Exposure source

- Mercury lamp
  - Common method
  - Usually use 365-nm(i-line) and 436-nm(g-line) spectral component
- Electron-beam
  - Can be focused to spots of the 100 nm
  - Can be used to directly write patterns in electron-sensitive resists
  - Usually use to make photomasks
- X-ray
  - Finest feature size
  - Mask material: heavy metal (ex: gold)

Problems of photolithography (1)

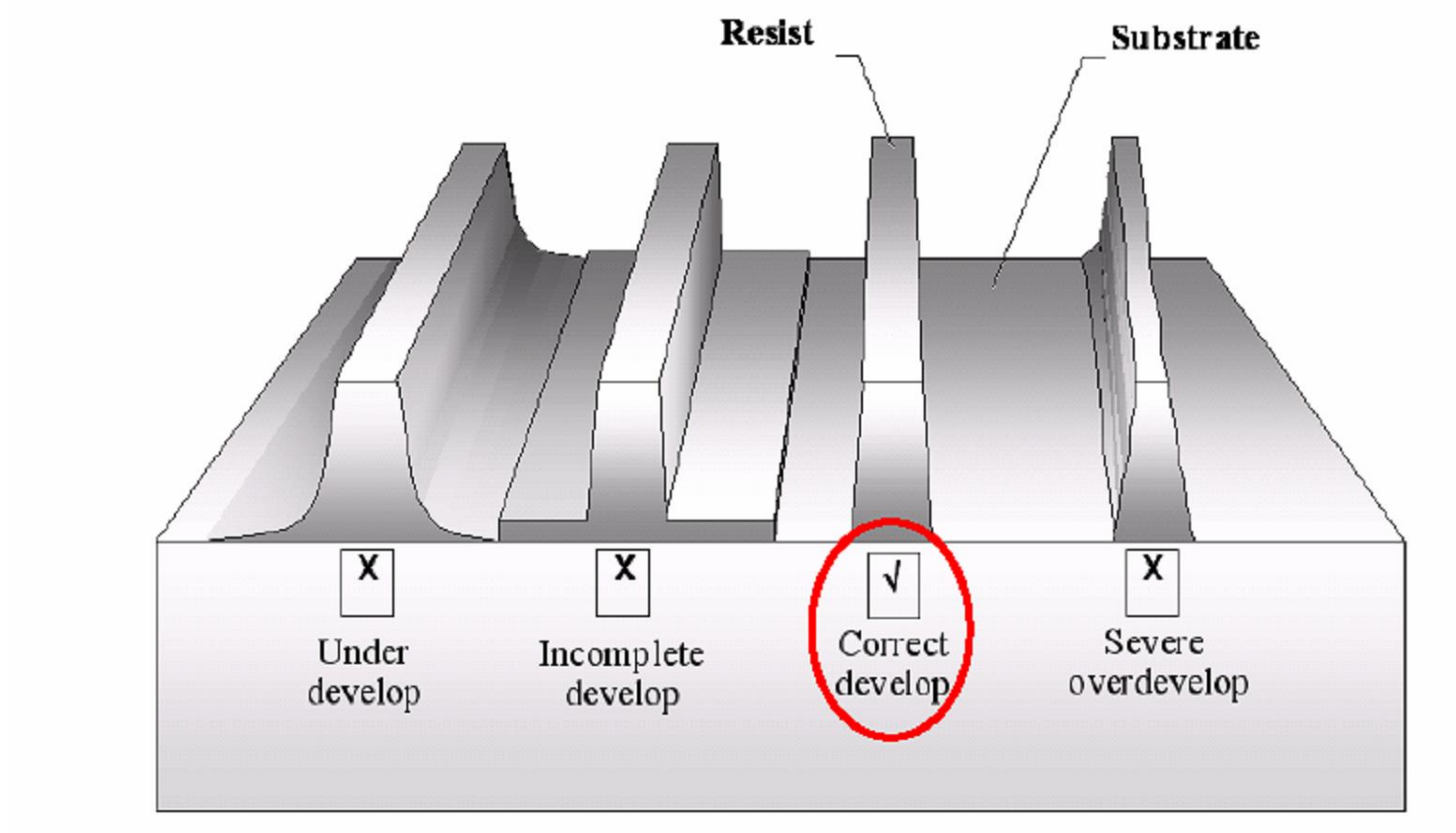
- Nonuniform spin coating
  - Phenomena: irregular coating, green color ring
  - Cause
    - Lack of photoresist
    - Wafer flexion due to vacuum
    - Bubble in the photoresist
  - Effect
    - Change the pattern size if the nonuniformity of thickness of photoresist film excess 10%
- Speed boat
  - Phenomena: boat wake originated from certain point
  - Cause: impurities, Si chip, epi spike etc.
  - Effect: rework

Problems of photolithography (2)

- Orange peel
  - Phenomena: spot such as orange peel
  - Cause: lack of exposure time, thick PR film, lack of soft bake time, standing wave
  - Effect: Thin PR film, appear pin hole, difficult to align
- Scum
  - Phenomena: residue of PR where must be removed
  - Cause: response of oxygen, excessive soft bake time
  - Effect: obstruct etching
- Development badness
  - Phenomena: the edge of pattern
    - Clear field mask: blue halo
    - Dark field mask: residue of PR
  - Cause: bad developer, lack of cleaning time
  - Effect: obstruct etching

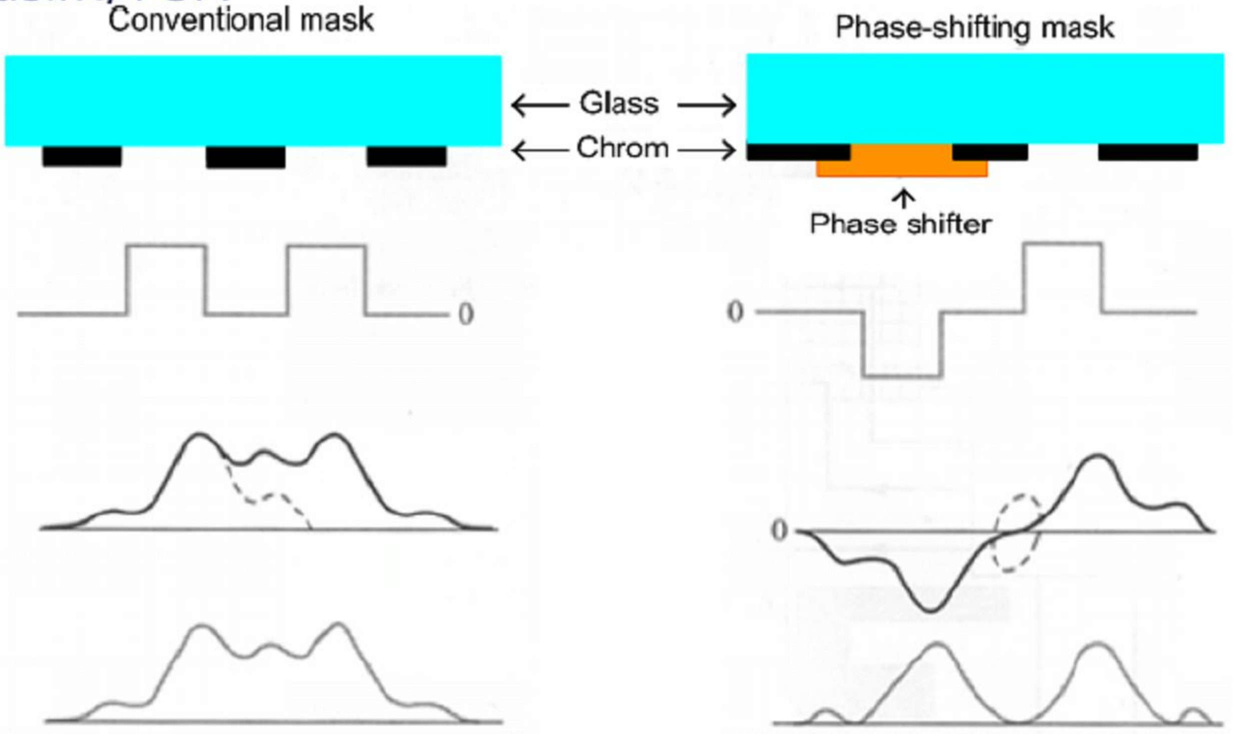
Problems of photolithography (3)

- Various photoresist profiles after develop



Resolution enhancement technique (1)

- Phase shifting mask (PSM)
  - Minimum feature size approaching one-half of the wavelength of the illumination source can be achieved using PSM

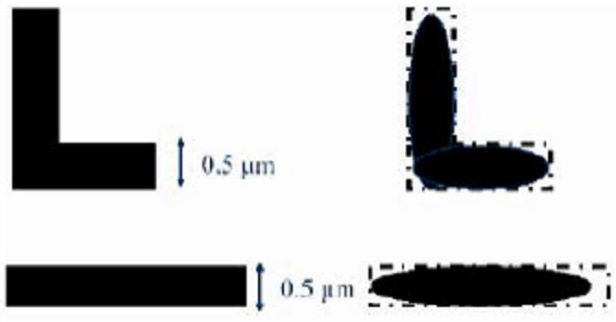


Principle of phase-shifting technology

Resolution enhancement technique (2)

- Optical proximity correction (OPC)
  - Use modified shapes of adjacent subresolution geometry to improve imaging capability

Figure on the mask   Pattern on the wafer



- When the feature size is smaller than the resolution, the pattern will be distorted in several ways.

•Line width variation

•Corner rounding

•Line shortening

- Modify the mask based on rules or model

Lift-off process

- Lift off process
  - the substrate is first covered with photoresist layer patterned with openings where the final material is to appear