Lecture 9:

Photolithography

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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

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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

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Photoresist

Light

Mask

Photoresist

Si substrate

Positive photoresist

Negative photoresist

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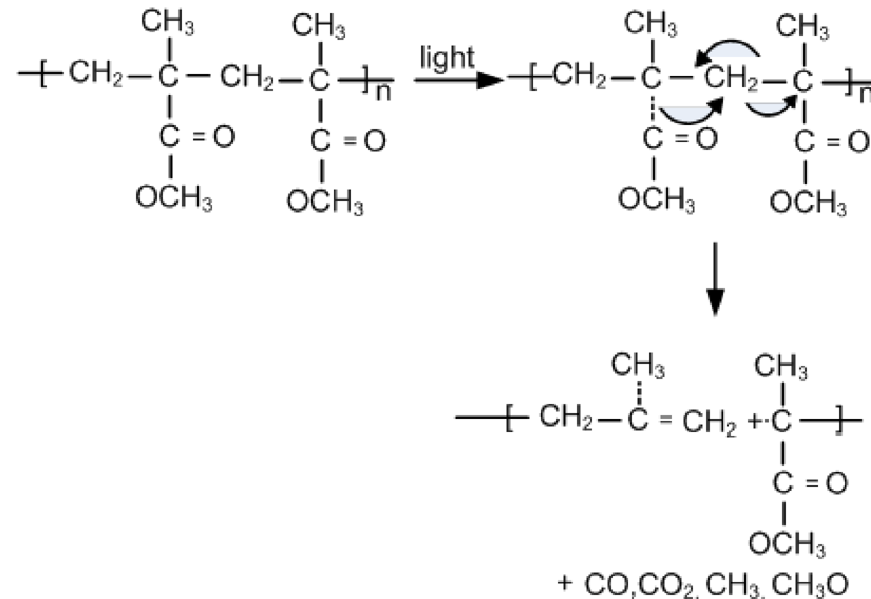
Positive photoresist (I)

- Poly(methylmethancrylate) 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



Poly(methylmethancrylate) PMMA

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Positive photoresist (II)

- 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

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Positive photoresist (II)

base insoluble sensitizer

$h\nu$ → $+ N_2$

rearrangement

ketene(carboxylic acid) dissolution enhancer

H_2O

base insoluble photoproduct

$+ H_2C = O \xrightarrow{H^+}$

N (Novolak resin)

DQ (diazoquinone)

Optical change of quinonediazide resist

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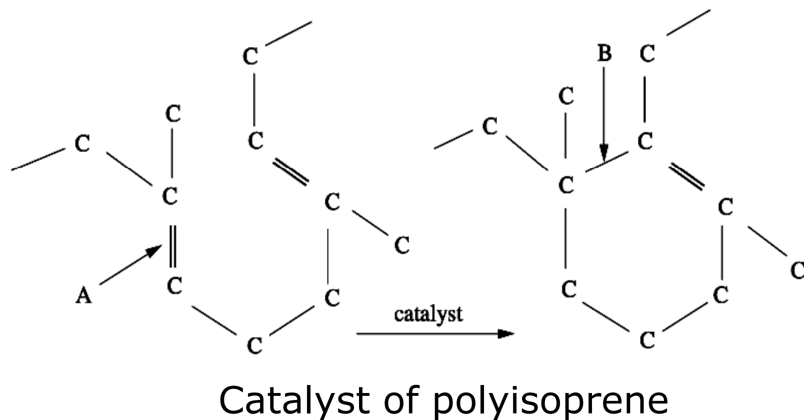
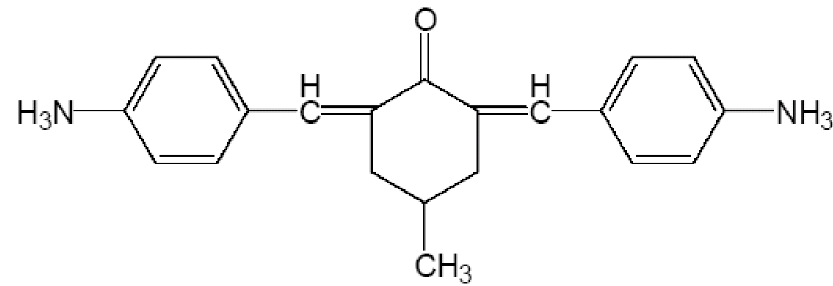
Negative photoresist

- 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

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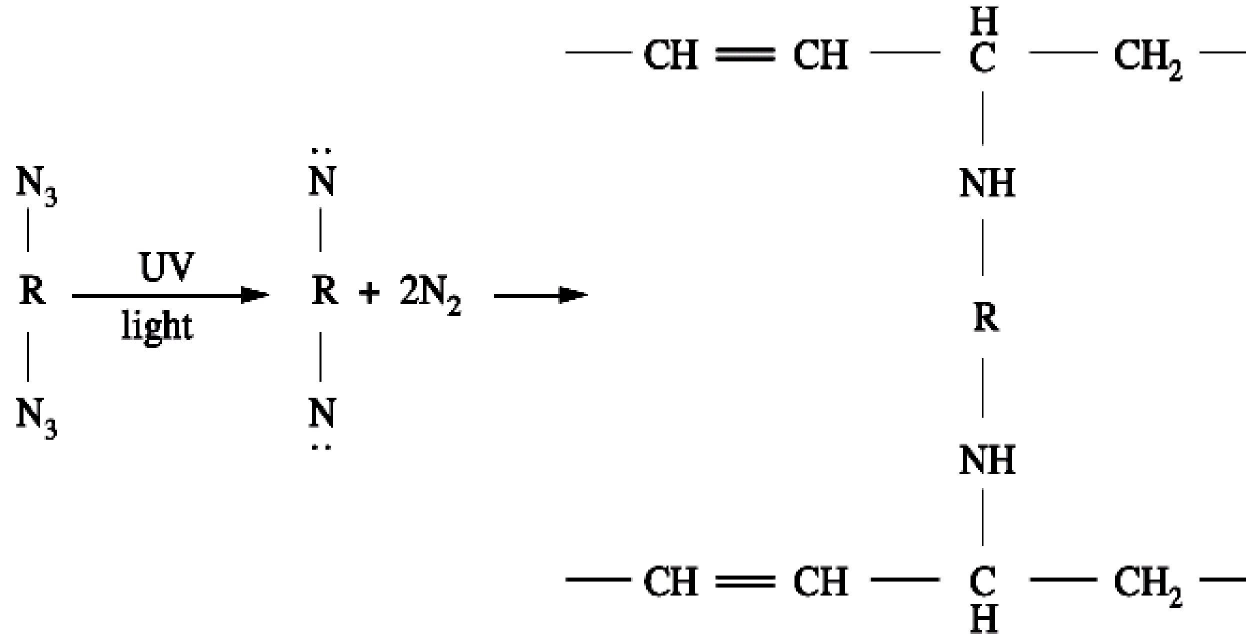
Negative photoresist



Cross-linking of polyisoprene

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Comparison of photoresists

- 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

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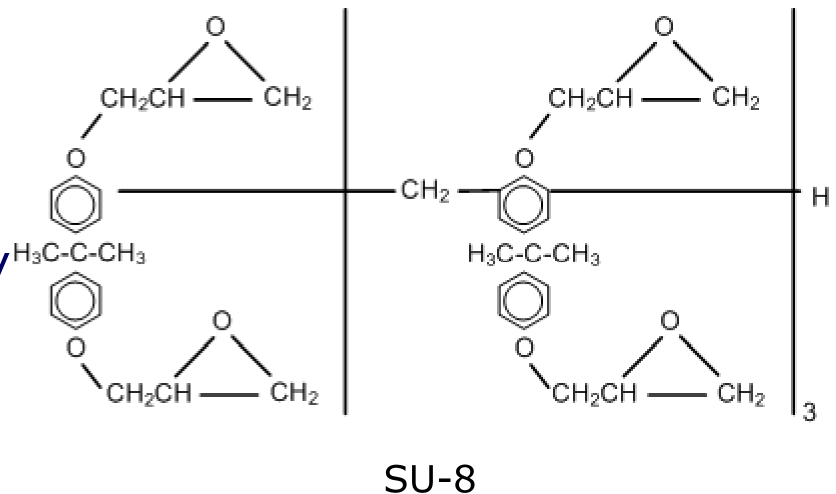
Photoresist

- 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

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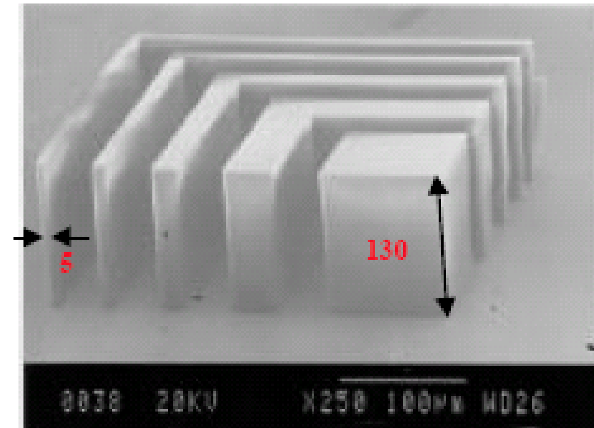
Photoresist

- 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

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Lithography process (I)

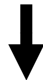
- Basic step of photolithography

Clean wafers

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

Deposit barrier layer

(SiO_2, Si_3N_4, metal..)



Coat with photoresist

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

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Lithography process (II)

Soft bake

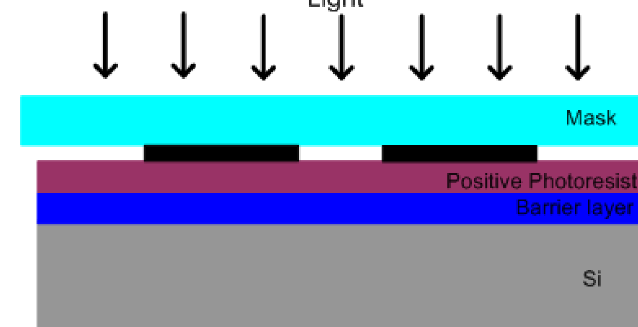
- Improve adhesion
- Remove solvent from PR
- 5-30 min in the oven at 60-100 ℃

Align masks

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

Expose pattern

- Expose through mask with high-intensity UV light



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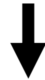
Lithography process (III)

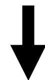
Develop photoresist

- develop the PR pattern on substrate



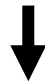
Hard bake

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

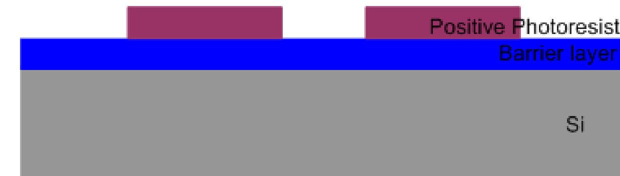


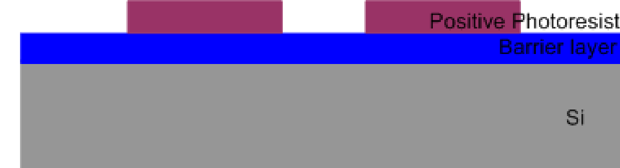
Etch windows in barrier layer

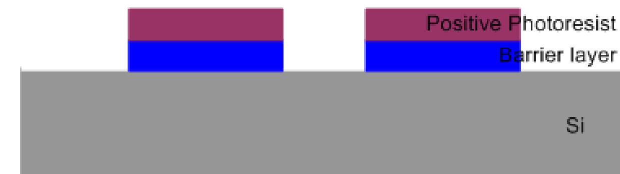
- wet / dry etch

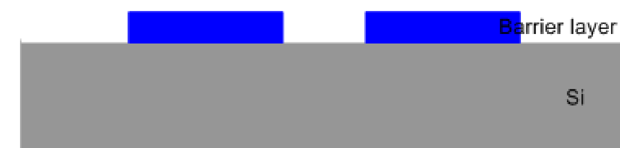


Remove photoresist









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Recipes of various photoresists

	AZ1512	AZ7220	AZ4620	AZ5214
PR type	positive	positive	positive	negative
Thickness	1.2 μm	2.0 μm	7 μm	1.6 μm
Pre bake	-	-	30 min at 130 ℃ in oven	30 min at 95 ℃ in oven
spin coating	35 sec at 4000 rpm	35 sec at 4000 rpm	35 sec at 4000 rpm	35 sec at 4000 rpm
Soft bake	30 min at 95 ℃ in oven	30 min at 95 ℃ in oven	2 min at 105 ℃ on hotplate	5 min at 90 ℃ on hotplate
Exposure	8.5 sec at 12 mW	6 sec at 16 mW	50-60 sec at 14 mW	8.5 sec at 12 mW
Post-exposure bake	-	-	-	2.5 min at 95℃ on hotplate
Whole surface exposure	-	-	-	10.5 sec at 12 mW
Development (AZ300 MIF)	70 sec (6:1 developer)	50 sec (100 % developer)	2-3 min (100 % developer)	75 sec (6:1 developer)
Hard bake	30 min at 110 ℃ in oven	30 min at 110 ℃ in oven	2 min at 120 ℃ on hotplate	-

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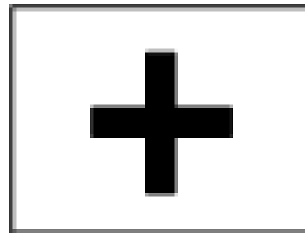
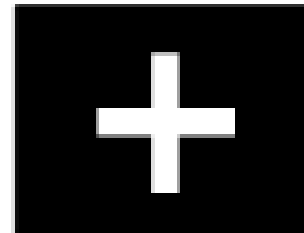
Photomask

- 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


Light-field


Dark-field

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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

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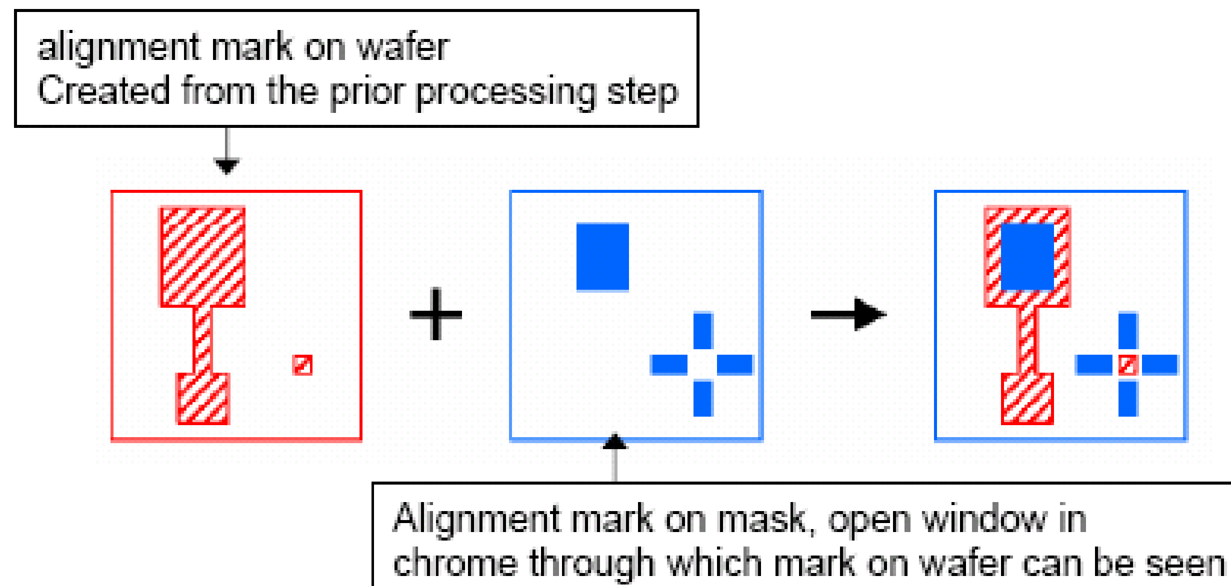
Mask to wafer alignment

- 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



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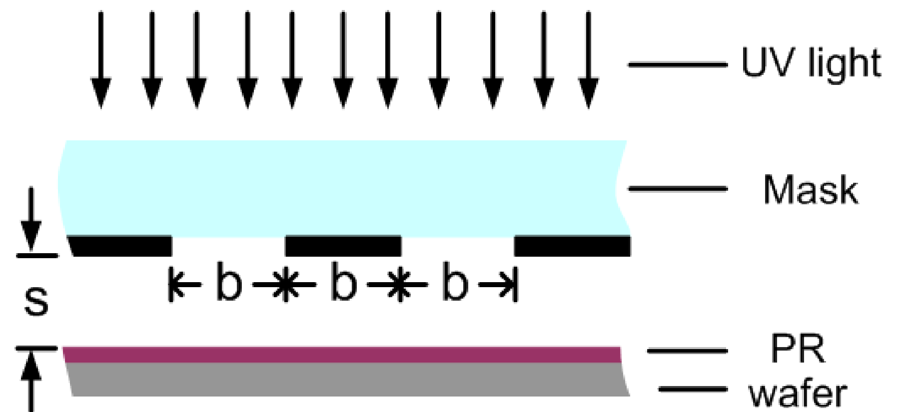
Exposure technique

- Exposure: Following alignment, the photoresist is exposed through the mask with high-intensity UV light.

- Critical dimension: specific minimal feature size and is a measure of the resolution of lithographic process
- Resolution in photolithgraphy

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



$b_{\min}$:half the grating period and the minimum feature size transferable
s:gap between the mask and the photo resist surface
λ:wavelength of the exposing radiation
z:photoresist thickness

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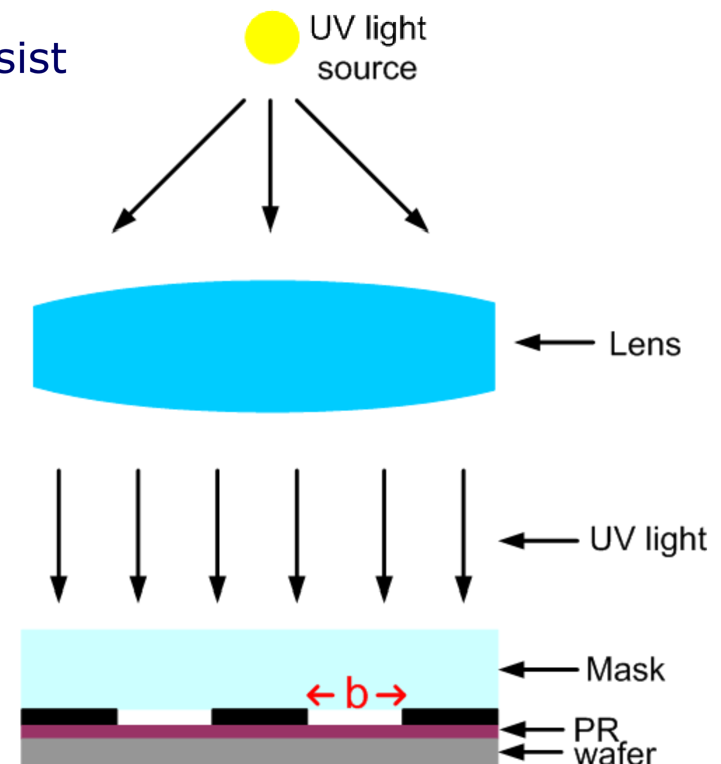
Exposure system (I)

- Contact printing (aligner)
  - Photomask is pressed against the resist covered wafer with pressure in the range of 0.05 to 0.3 atm and s is zero
  - Resolution
    - Limited by light scattering in the resist

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

  - Advantages
    - Not complex
    - Inexpensive
    - Fast
    - Diffraction effect is minimized
  - Disadvantages
    - Mask wear
    - Contamination
    - Mask the same size as the wafer (large and expensive)



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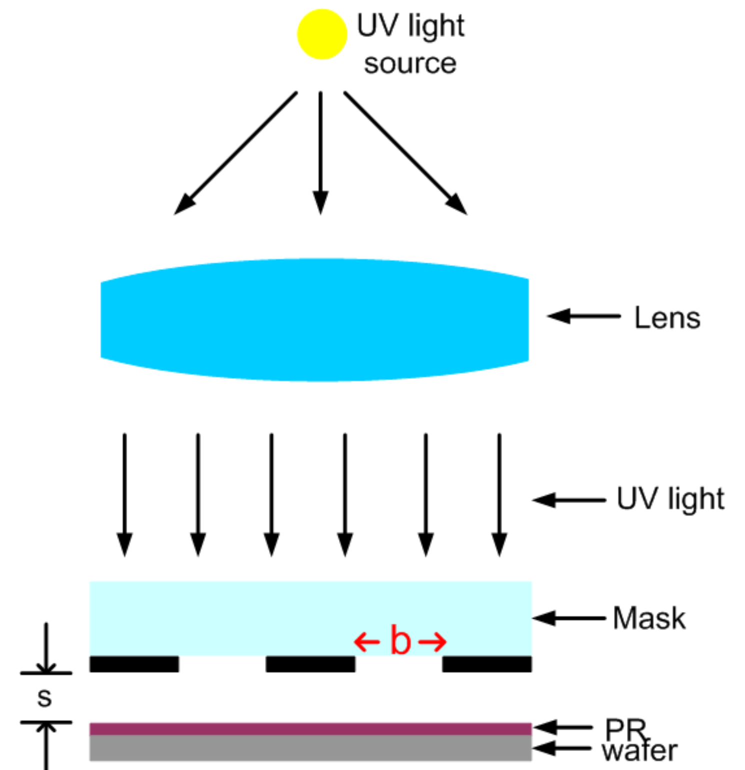
Exposure system (II)

- Proximity printing (aligner)
  - Spacing of the mask away (at least 10 μm) from the substrate minimizes defect the result form contact.
  - Resolution
    - S >> z

$$R = b_{\min} = \frac{3}{2}\sqrt{\lambda s}$$

  - Advantages
    - No mask wear and contamination
    - fast
  - Disadvantages
    - Greater diffraction leads to less resolution
    - Mask the same size as the wafer, large and expensive



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Exposure system (III)

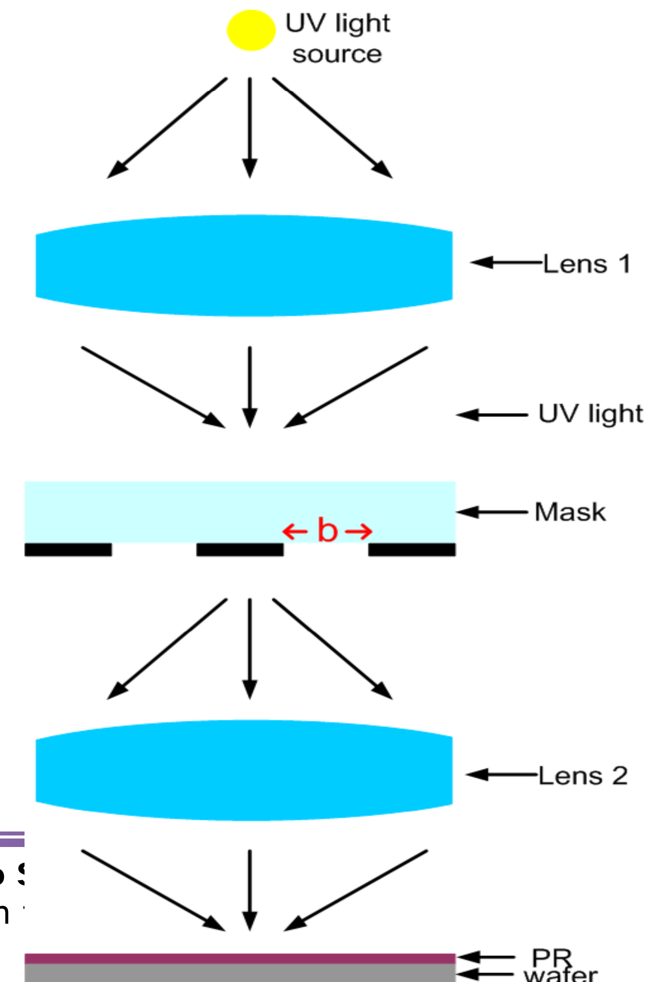
- Projection printing (stepper)
  - Wafer contact is completely avoided, a high resolution lens projects an image of the photomask onto the photoresist-covered wafer
  - Resolution
    - Limited by lens features

$$R = \frac{K\lambda}{NA}$$

k: depend on resister parameter and aligner optics

NA: numerical aperture of lens

  - Advantages
    - No mask wear contamination
    - De-magnification (1 X to 10 X)
  - Disadvantages
    - Expensive equipment
    - Longer exposure time
    - Very complex



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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)

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Alignment & Exposure system

- MA-6 aligner at ISRC
  - Manufacturer: Karl-suss
  - Can use double side alignment
  - Can align the fragment of wafer and 4" wafer
  - Can align the wafer of nonstandard thickness
  - Various contact program: vacuum, low vacuum, hard, soft and proximity contact

MA-6 aligner

- Light source : Mercury lamp 350W
- Alignment accuracy :Top side: 0.5 μm
  Bottom side: 1 μm
- Microscope objectives : 5X, 10X, 20X
- Resolution: Vacuum contact : 1 μm
  Soft contact : 2-3 μm
  Proximity : 3-5 μm

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Alignment & Exposure system

- EV-620 aligner at ISRC
  - Manufacturer: EVG
  - Can use double side alignment
  - Can align 4" wafer and 5" wafer
  - Various contact program: vacuum, low vacuum, hard, soft and proximity contact
  - Bottom side align is more accurate than MA-6 aligner (using cross-hair method)

EV-620 aligner

- Light source : Mercury lamp 500 W
- Alignment accuracy :Top side: 0.5 μm
  Bottom side: 1 μm
- Microscope objectives : 5X, 10X, 20X
- Resolution: Vacuum contact : 1 μm
  Soft contact : 2-3 μm
  Proximity : 3-5 μm

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Alignment & Exposure system

- UT1100 stepper at ISRC
  - Manufacturer: ULTRATECH
  - Use reticle that have single image
  - Step-by-step method (align + expose → repeat)
  - Can align 4" Si wafer
  - Automated alignment ability

UT1100 stepper

- Light source : Hg arc lamp 500 W
- Auto alignment accuracy :0.15 μm
- Projection ratio: 1:1
- Numerical aperture: 0.34
- Reticle size: 3" X 5" X 0.09"
- Resolution: AZ1512 positive PR: 1.5 μm

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Problems of photolithography process

- 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

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Problems of photolithography process

- 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

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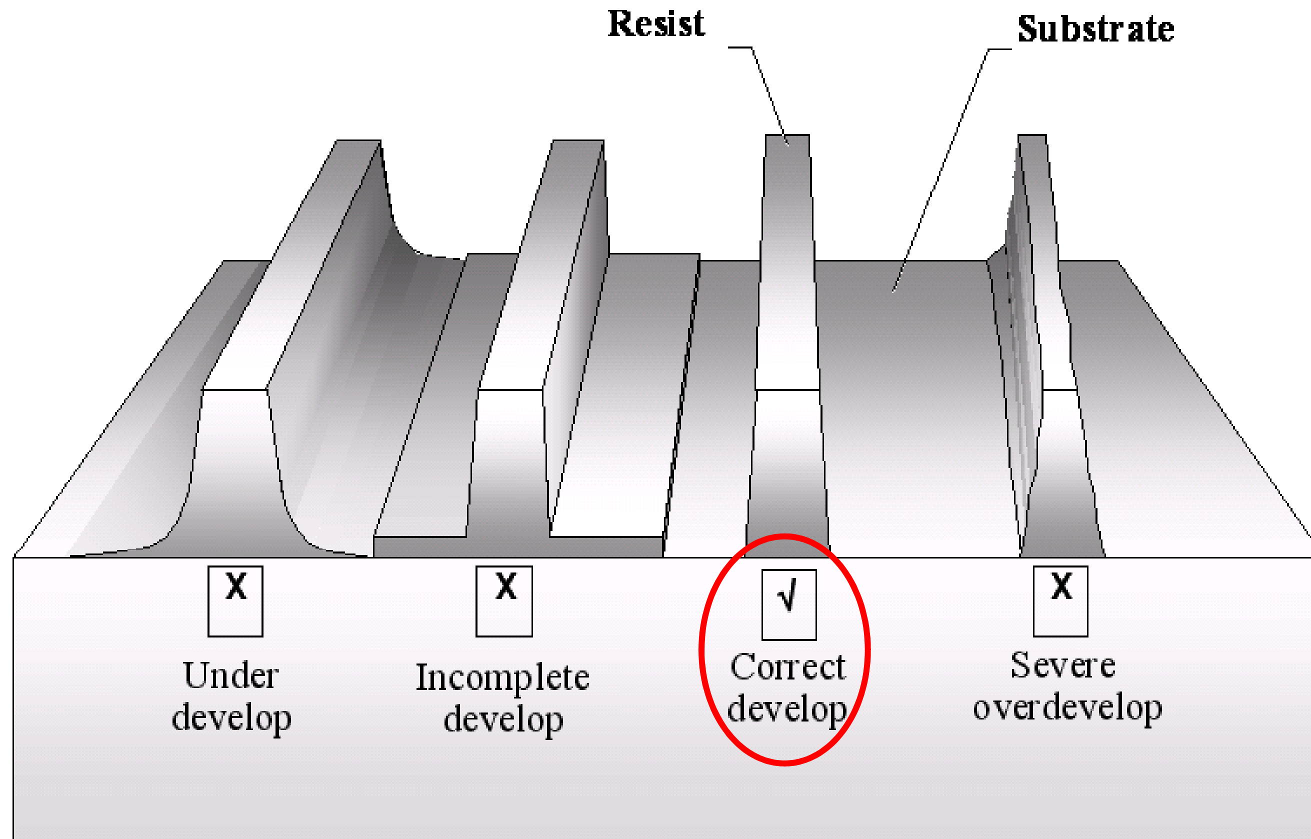
Problems of photolithography process

- Various photoresist profiles after develop



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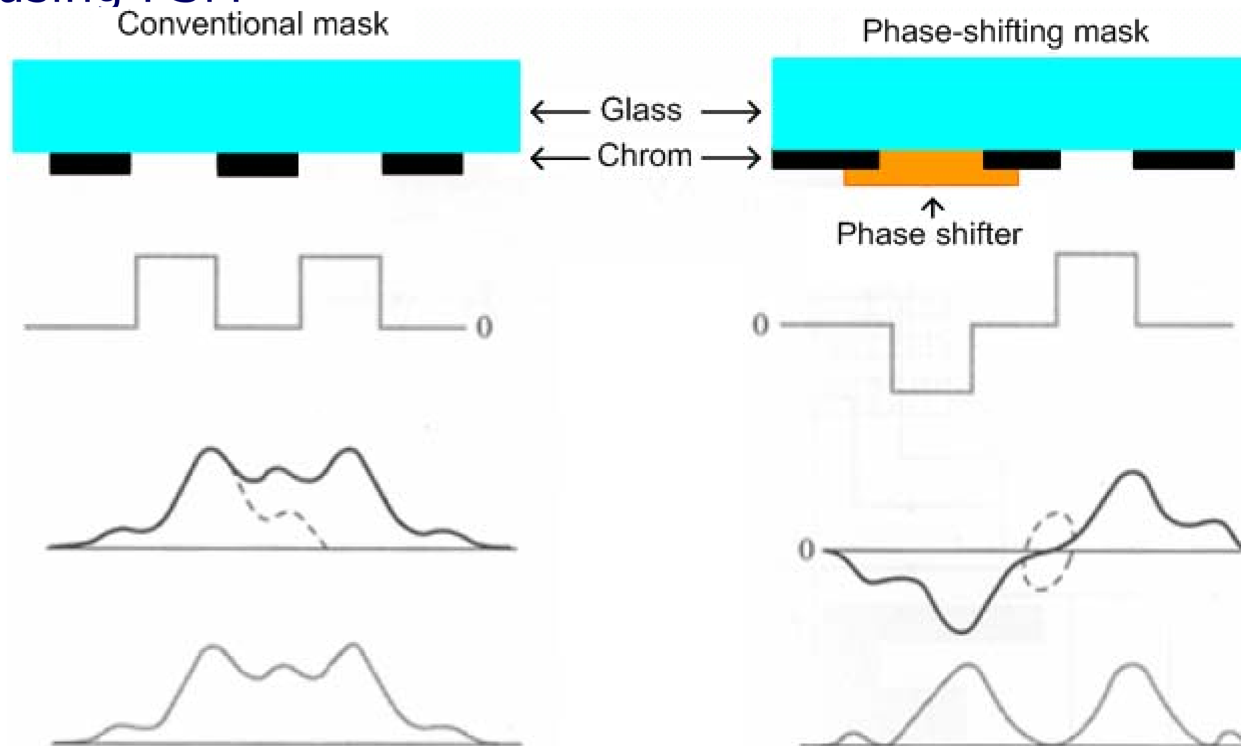
Resolution enhancement technique

- 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

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Resolution enhancement technique

- 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

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Soft lithography

- Soft lithography: New tool in the nanofabrication arsenal
- Comparison of photolithography and soft lithography

Photolithography	Soft lithography
-rigid photomask	-elastic stamp or mold
-high cost	-non-photolithography
-optical diffraction	-low cost, easy to use
-not apply for nonplanar surface	-30 nm ~ 500 μm
-2-D structure	-2-D, 3-D structure
-limited by photosensitive material	-use variety of material
	-surface chemistry

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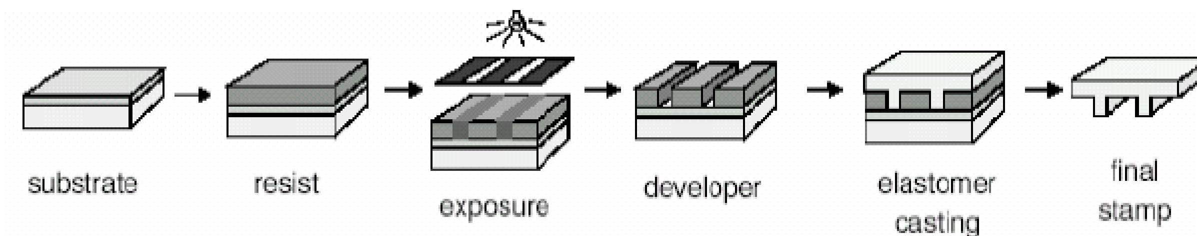
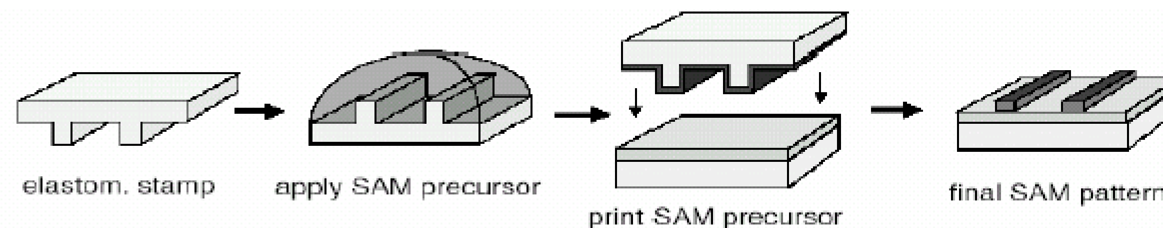
Soft lithography (I)

- Micro-contact printing
  - PDMS rubber stamp is coated with an ink of the molecules that want to print in selected patterns on solid substrate
  - Stamp is obtained by casting of elastomer (ex:PDMS) over master



  - pattern generation by stamping of SAM precursor onto substrate



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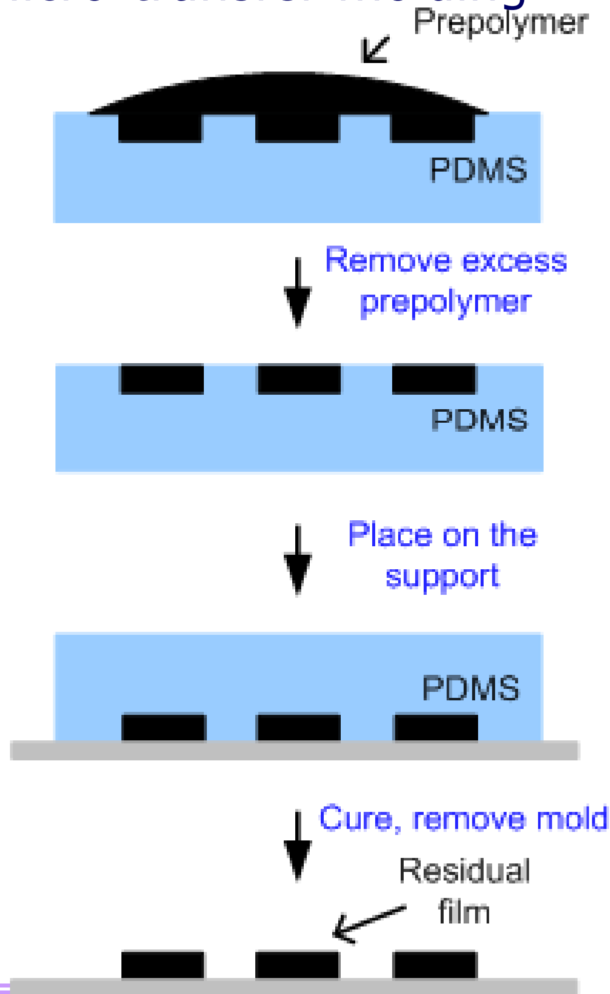
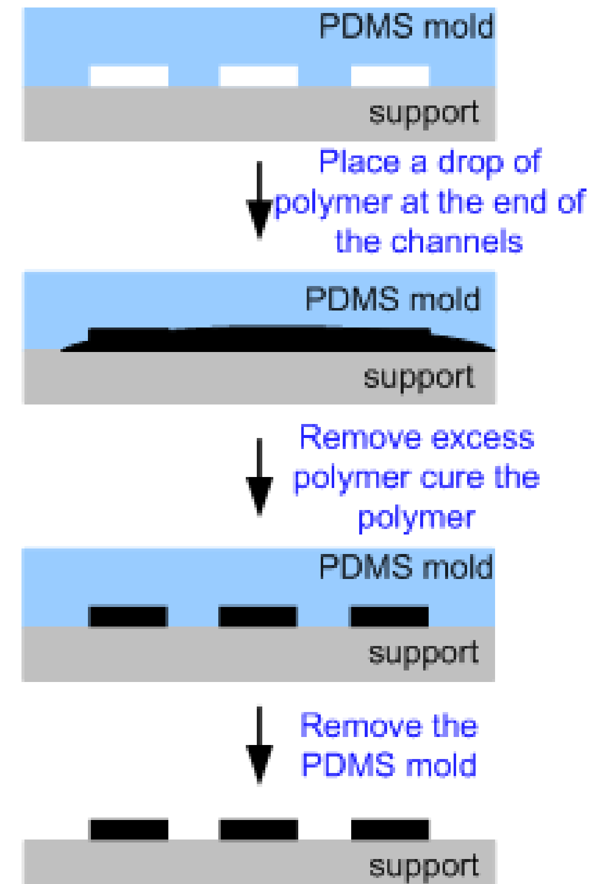
Soft lithography (II)

- Micro-transfer molding



- Micromolding in capillaries



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Soft lithography (III)

- Micro-replica molding
  - The master mold is replicated in PDMS casting and curing the PDMS pre-polymer
  - Elasticity and low surface energy of stamp make release of mold easy
  - Allows duplication of three-dimensional topologies in a single step
  - Faithful duplication of complex structure in the master

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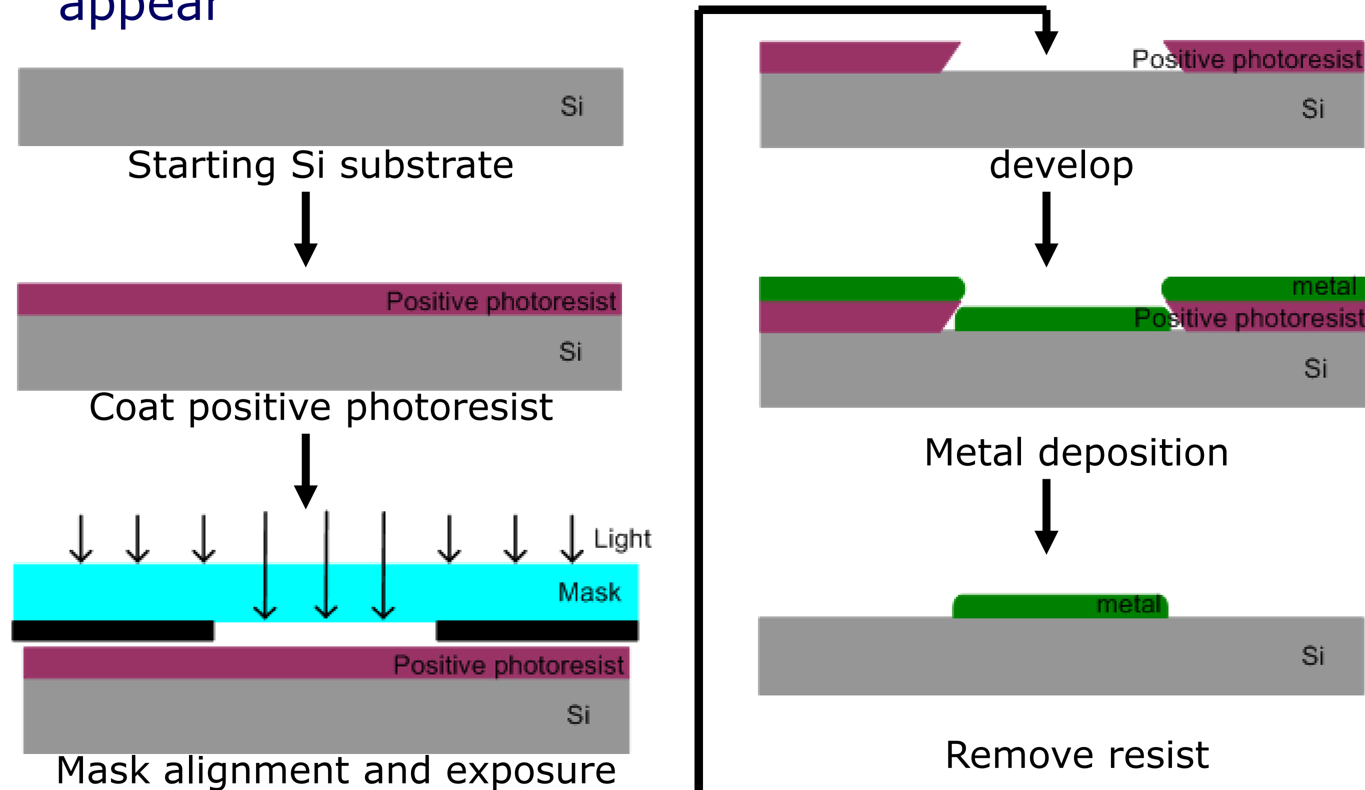
Lift off process

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



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Next generation lithography methods

- Electron Beam (E-Beam) Lithography
  - E-beam is used for direct writing
  - E-beam lithography is primarily used to produce photomasks
  - Electron resist: PMMA

  - Advantages
    - Sub-micron resolution (less than 20 nm)
    - Direct patterning without mask
    - Greater depth of focus
    - Highly automated and precise control
  - Disadvantages
    - Proximity effect due to electron scattering
    - Very low throughput
    - Very expensive

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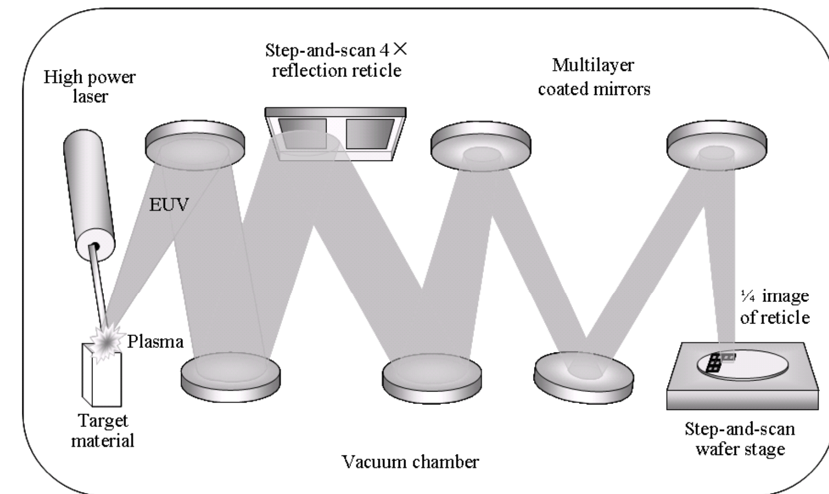
Next generation lithography methods

- Extreme Ultraviolet Lithography
  - A laser-produced plasma or synchrotron radiation serves as the source of EVU
  - A mask is produced by patterning an absorber materials deposited on a multilayer coated silicon or glass mask blank
  - Photoresist: PMMA
  - Advantages
    - Extending minimum line width without throughput loss
  - Disadvantages
    - must be performed in vacuum
    - Mask blank fabrication difficulty



Conceptual schematic of EVU lithography system

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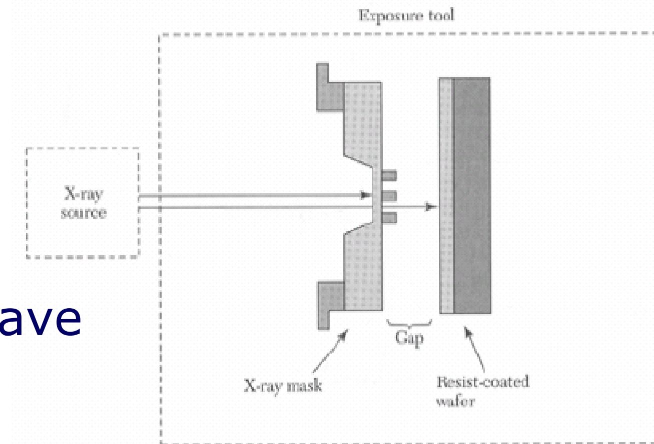
Next generation lithography methods

- X-ray Lithography (XLR)
  - X-ray(1nm) generated by a synchrotron storage ring is used as the energy source
  - As most materials have low transparency at λ~1nm, the mask substrate must be thin membrane, and pattern is defined high-atomic-number materials (W and Au…)

  - Advantages
    - High resolution and high depth of focus
    - No reflection from the substrate to create standing wave
  - Disadvantages
    - Complex and expensive system
    - Complex mask fabrication



Schematic of proximity x-ray lithography system

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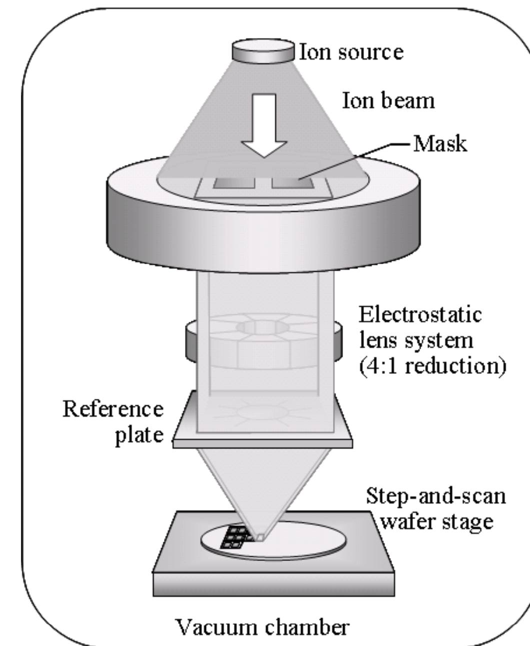
Next generation lithography methods

- Ion Beam Lithography
  - High energy ion beam is used for writing
  - Photoresist: PMMA
  - Advantages
    - Higher resolution than optical, x-ray, e-beam lithography
  - Disadvantages
    - Ion beam lithography may suffer form random space-charge effects



Schematic of ion beam lithography system

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