Lecture 9:

Photolithography

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Contents

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

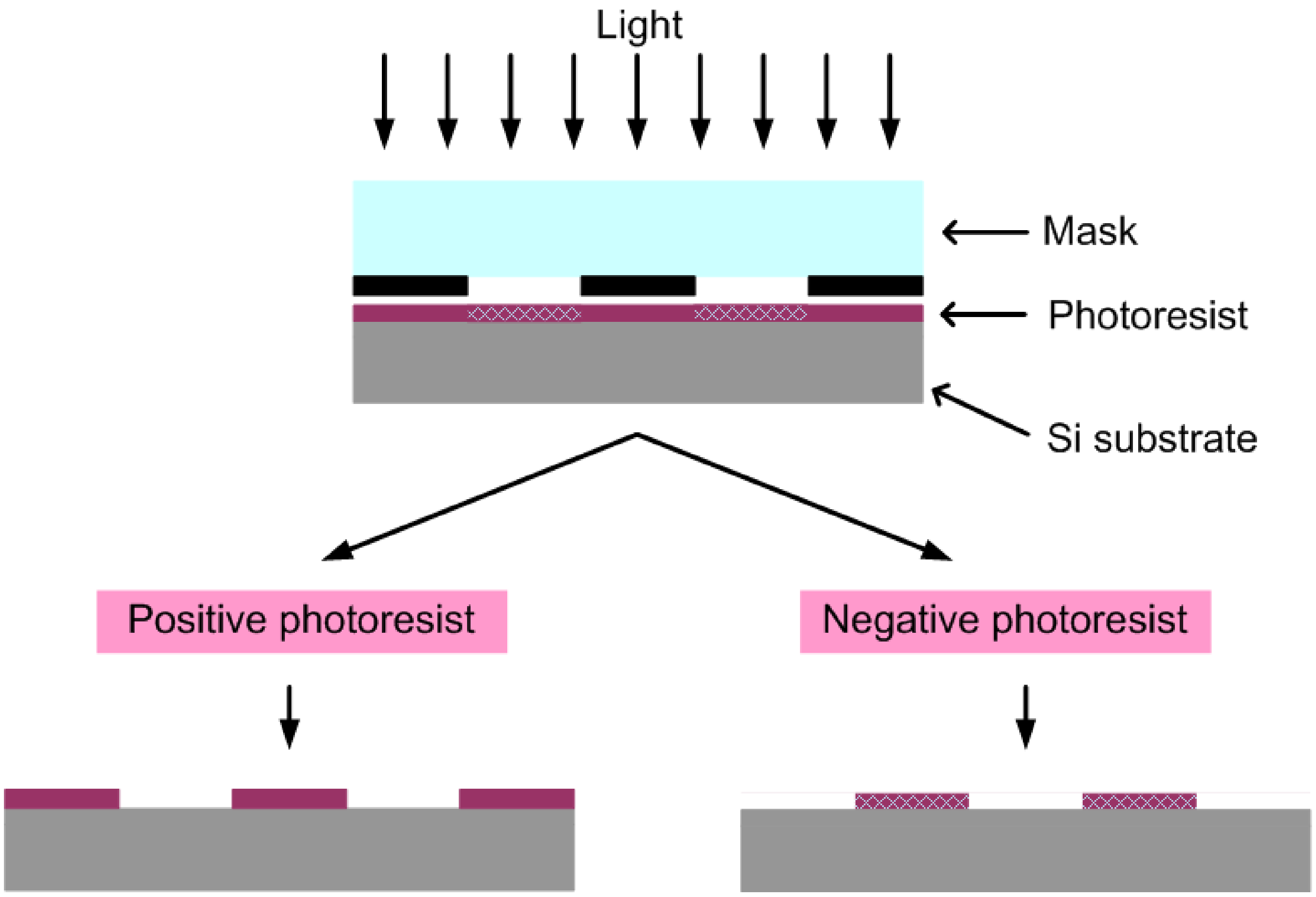
Mask to wafer alignment

Photoresist (I)

- 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

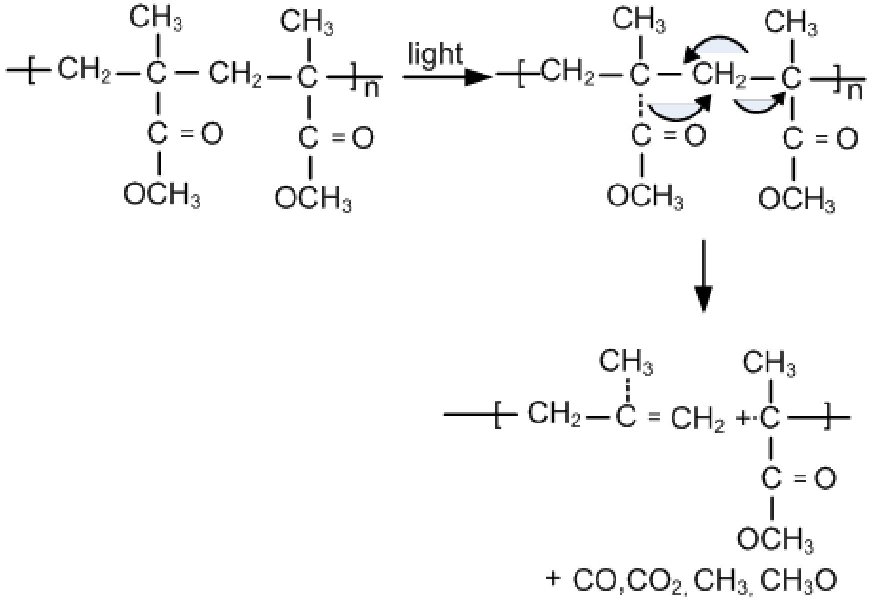
- Type of photoresists
  - Positive
  - Negative

Photoresist (II)



Positive Photoresist (I)

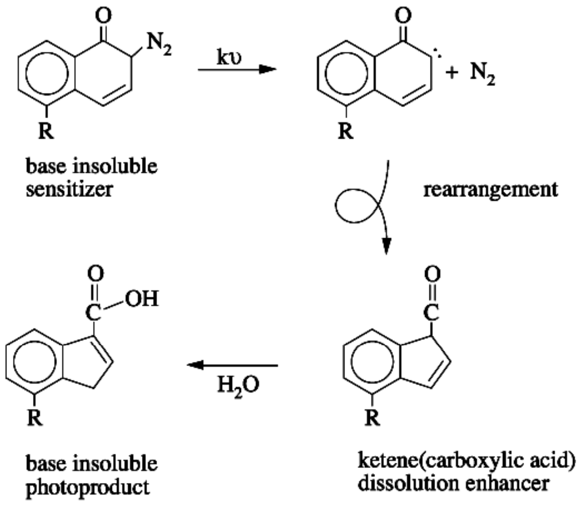
- Poly(methylmethancrylate) or PMMA
  - Single component
  - Photo induces chain scission of PMMA resist
  - Short-wavelength lithography: deep UV, electron beam, X-ray, ion-beam lithography
  - High resolution



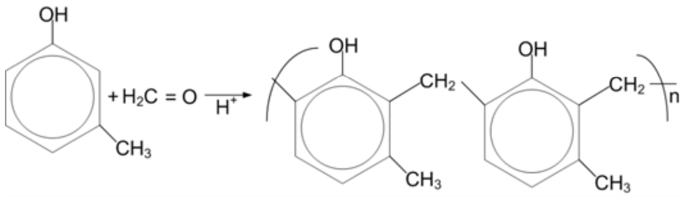
Poly(methylmethancrylate) PMMA

Positive Photoresist (II)

- DQN resist
  - Most popular positive resist
  - Exposure source: 365, 400 nm mercury line
  - Two component
    - DQ (diazoquinone)
      - insoluble in base solution
      - photo-active compound
    - N (Novolak matrix resin)
      - Solvent added to adjust viscosity
      - Hydrophilic, itself alkali soluble



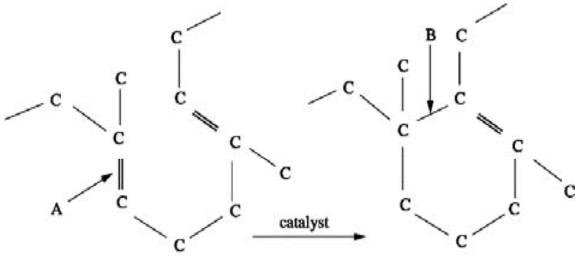
Optical change of quinonediazide resist



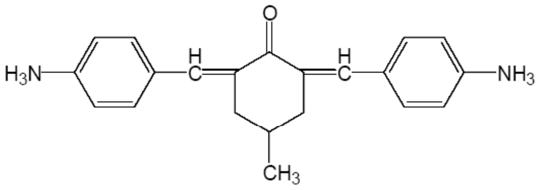
N (Novolak resin)

Negative Photoresist

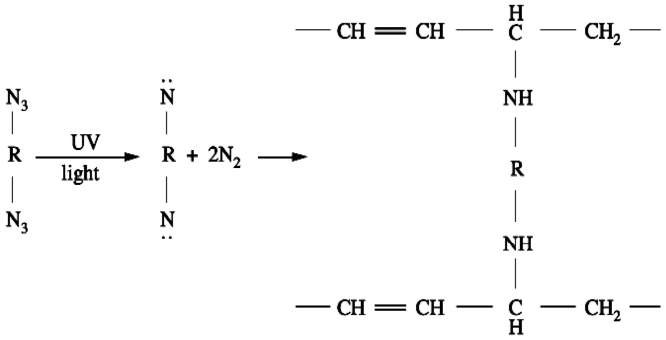
- Bis(aryl)azide rubber resist
  - Cyclized polyisoprene
    - Non-photosensitive substrate material
    - Synthetic rubber
  - Bis(aryl)azide ABC compound
    - Photosensitive cross-linking agent



Catalyst of polyisoprene



Agent (Azide) for polyisoprene cross-linking



Cross-linking of polyisoprene

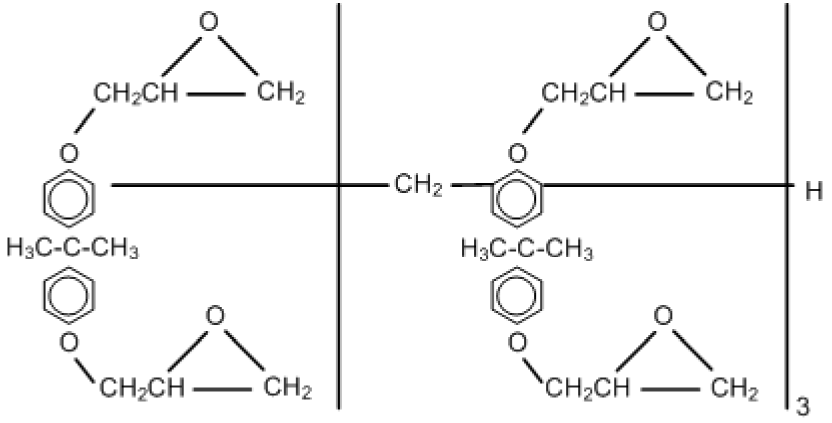
Comparison of Photoresists

- 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

Thick Photoresist

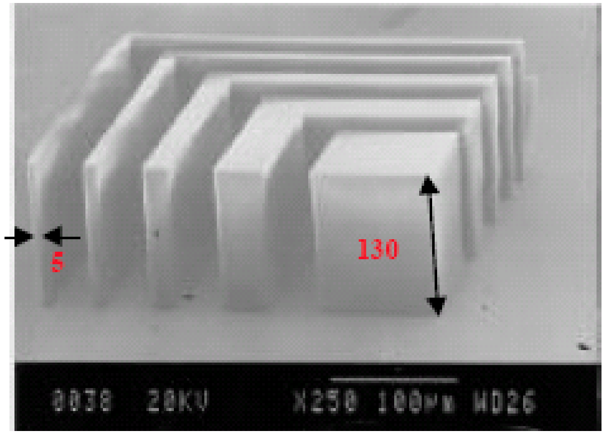
- Thick PR: structures often require thick PR layer that are capable of high resolution and high aspect ratio.
- SU-8
  - Can be spin-coated as very thick films (to 500 μm in a single coat)
  - Negative PR
  - Excellent sensitivity
  - High resolution
  - Low optical absorption
  - High aspect ratio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



SU-8

SU-8 Photoresist

- SU-8 process
  - Dehydrate bake
  - Coating
  - Relax
  - Soft bake: remove solvent
  - Exposure: photogenerated acid
  - PEB (Post Exposure Bake): cross-links the resist
  - Develop



High aspect ratio structure using SU-8 resist

Lithography Process (I)

- 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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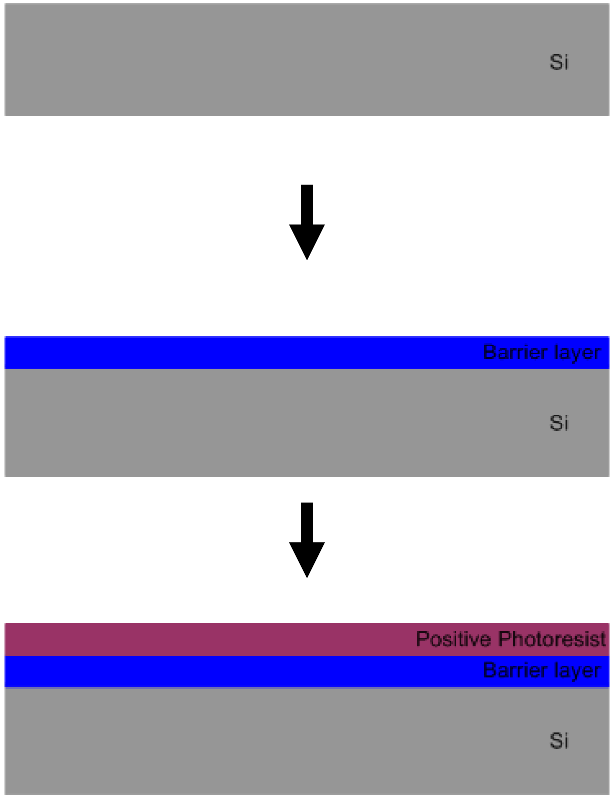
Coat with photoresist

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



Lithography Process (II)

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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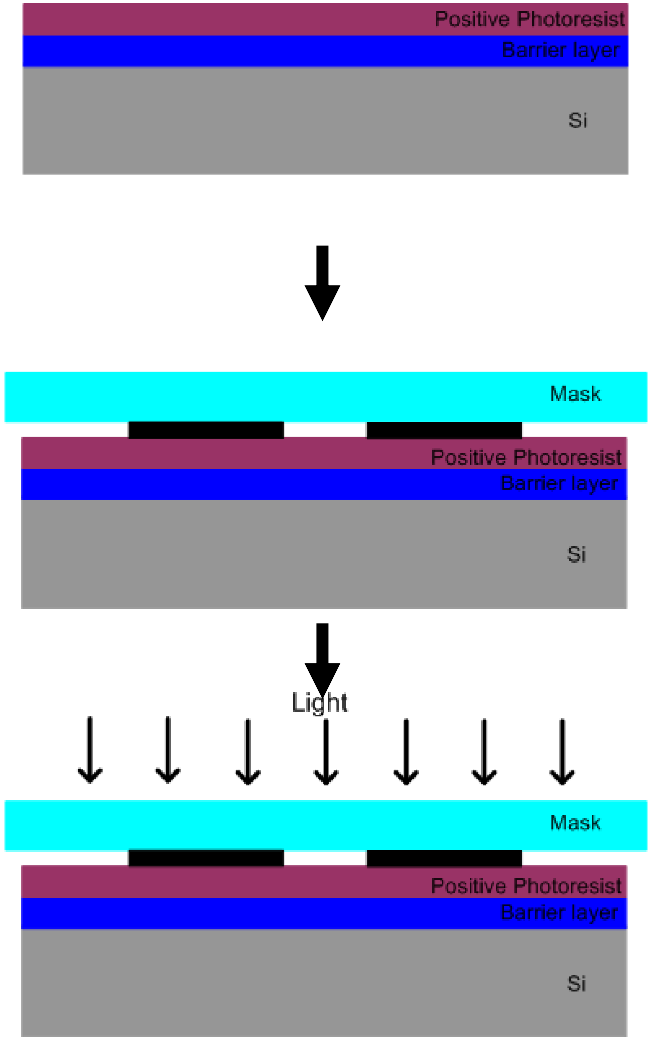
Expose pattern

- Expose through mask with high-intensity UV light



Lithography Process (III)

Develop photoresist

- develop the PR pattern on substrate

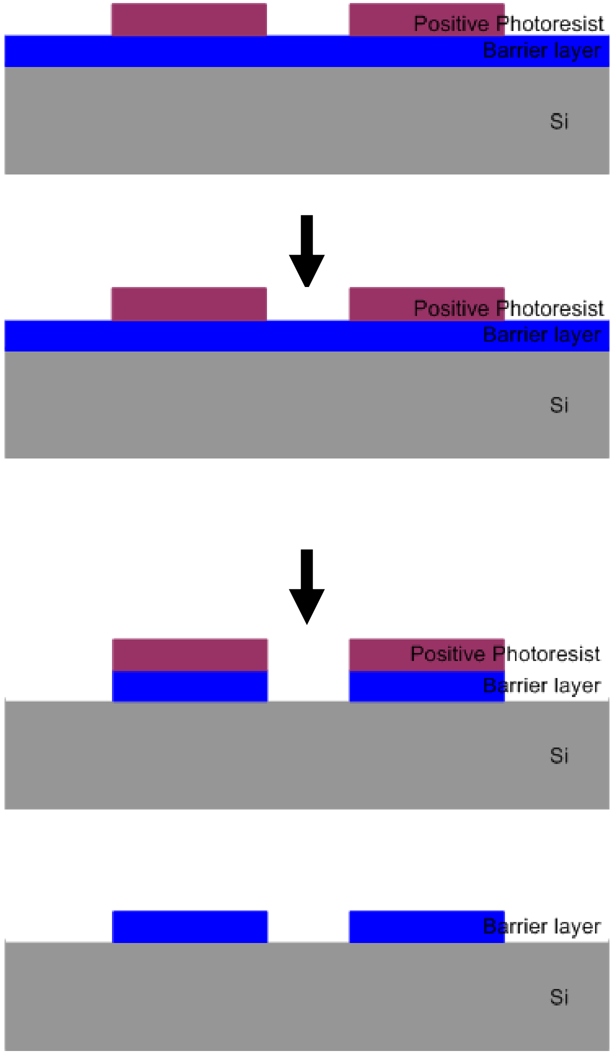
Hard bake

- 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



Recipes of Various Photoresists

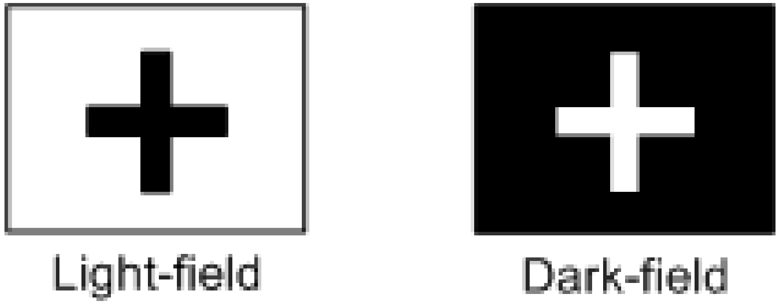
	AZ1512	AZ7220	AZ4620	AZ5214
PR type	positive	positive	positive	negative
Thickness	1.2 µm	2.0 µm	7 µm	1.6 µm
Pre bake	-	-	30 min at 130 ℃ in oven	30 min at 95 ℃ in oven
spin coating	35 sec at 4000 rpm	35 sec at 4000 rpm	35 sec at 4000 rpm	35 sec at 4000 rpm
Soft bake	30 min at 95 ℃ in oven	30 min at 95 ℃ 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	-

Photomask (I)

- 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

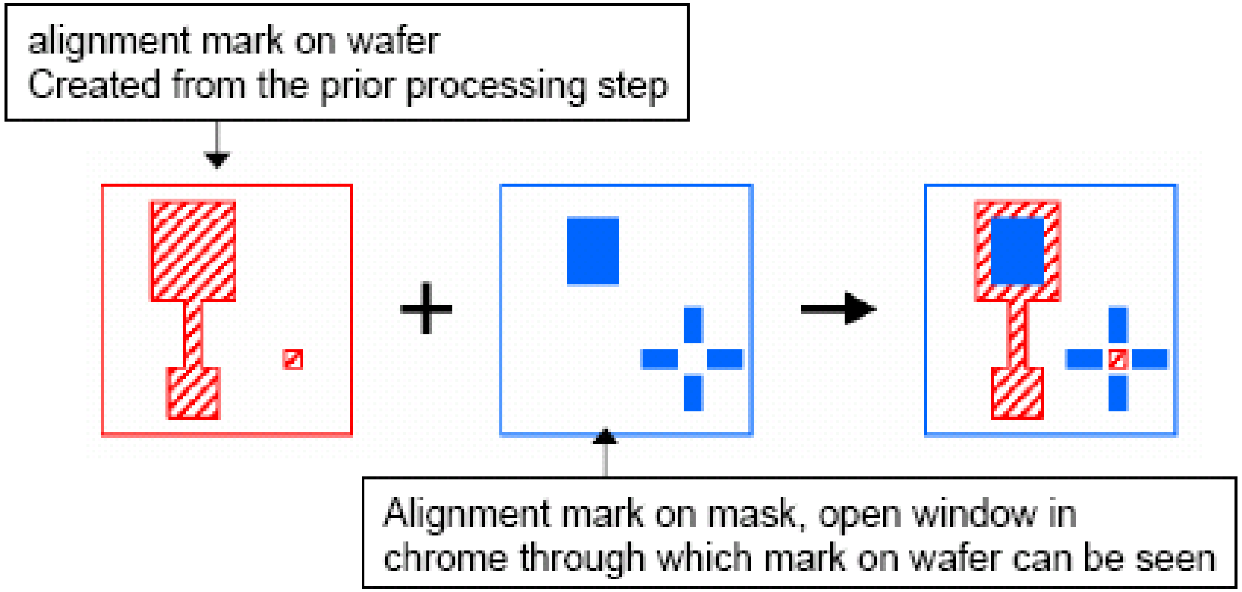


Photomask (II)

- 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



alignment mark on wafer
Created from the prior processing step

Alignment mark on mask, open window in chrome through which mark on wafer can be seen

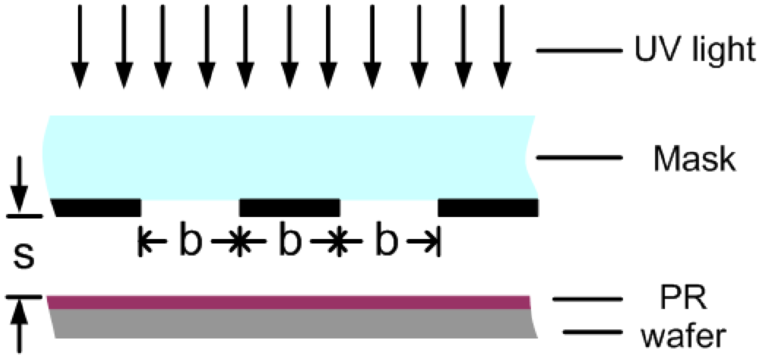
Exposure Technique

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

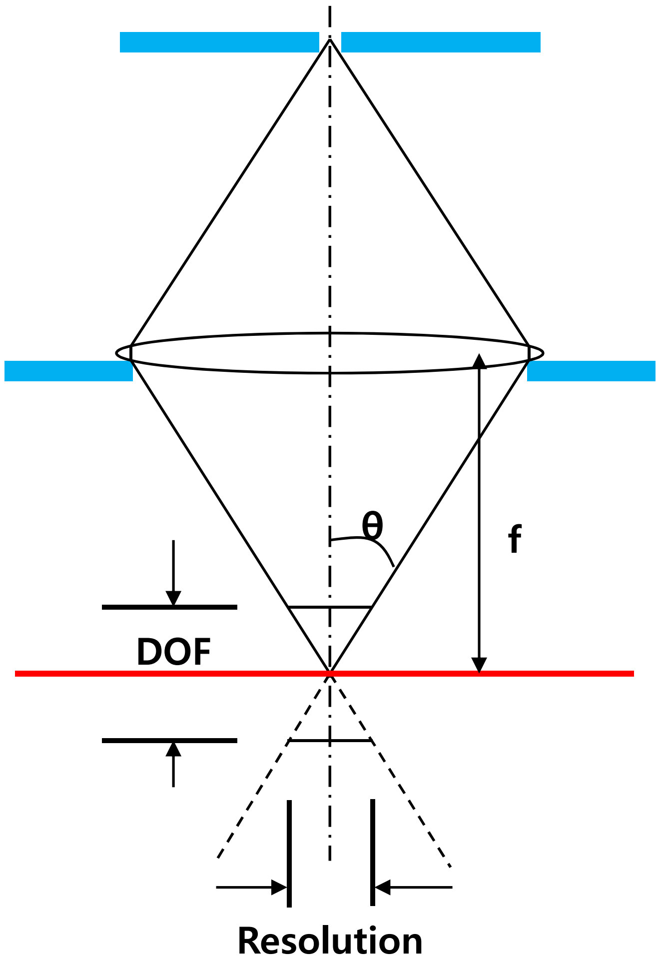
- Critical dimension: specific minimal feature size and is a measure of the resolution of lithographic process
- Resolution in photolithgraphy

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

$b_{\min}$: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



Resolution and Depth of Focus



$$\boxed{\text{Resolution} = K_1 \frac{\lambda}{NA}}$$

λ = Wavelength of illuminating light

K1= Process constant

NA= Numerical aperture (nsinΘ)

n : Refractive index of the media

Θ: half-angle of cone of light

Smaller λ ➡ Light source & Optics

Lower K1 ➡ Process/resist/optical schemes improvements

Higher NA ➡ Lens design improvements

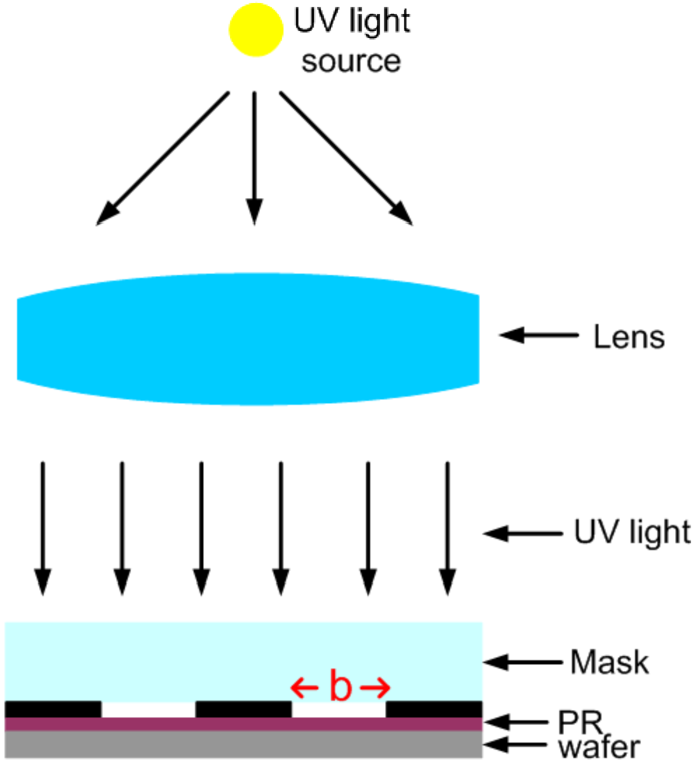
$$\boxed{DOF = \frac{\pm R/2}{\tan\theta} \approx \frac{\pm R/2}{\sin\theta} = k_2 \frac{\lambda}{NA^2}}$$

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)

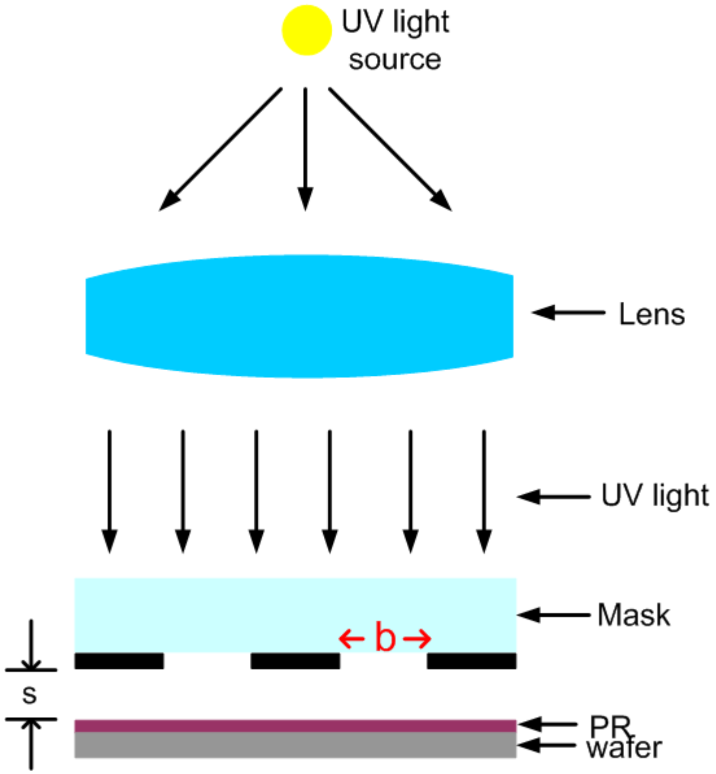


Exposure System (II)

- 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



Exposure System (III)

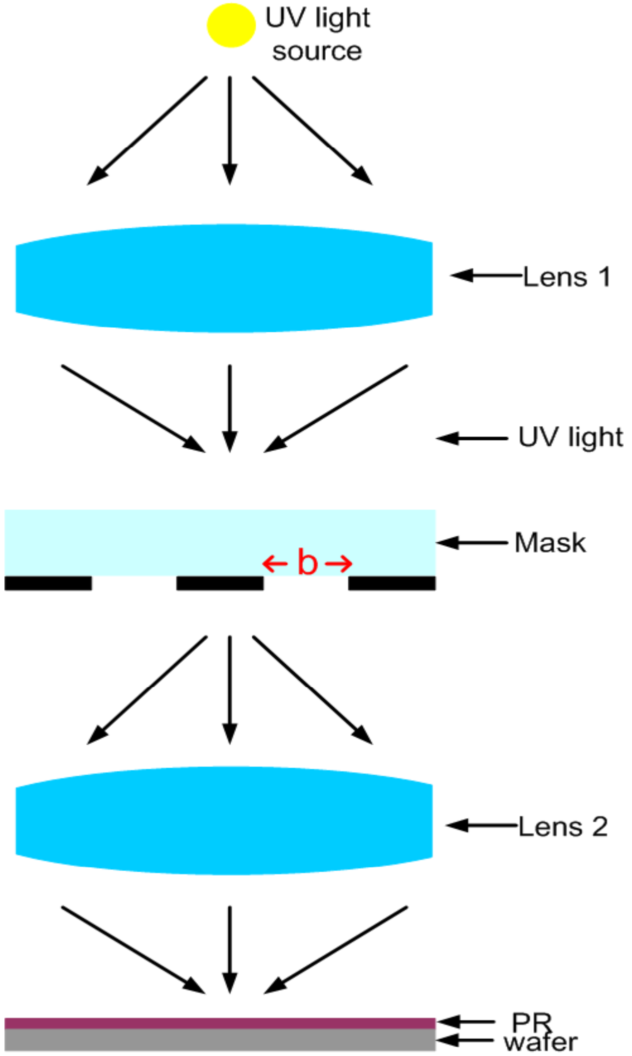
- Projection printing (stepper)
  - Wafer contact is completely avoided, a high resolution lens projects an image of the photomask onto the photoresist-covered wafer
  - Resolution
    - Limited by lens features

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

k: depend on resister parameter and aligner optics

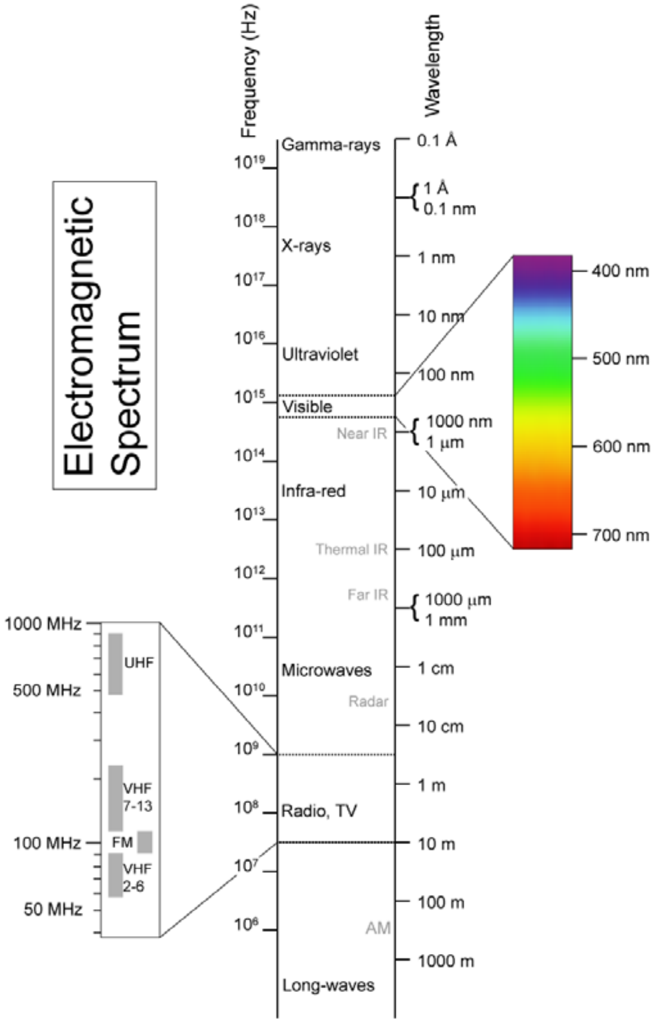
NA: numerical aperture of lens

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



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)



Louis E. Keiner - Coastal Carolina University

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

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

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**

Problems of Photolithography Process

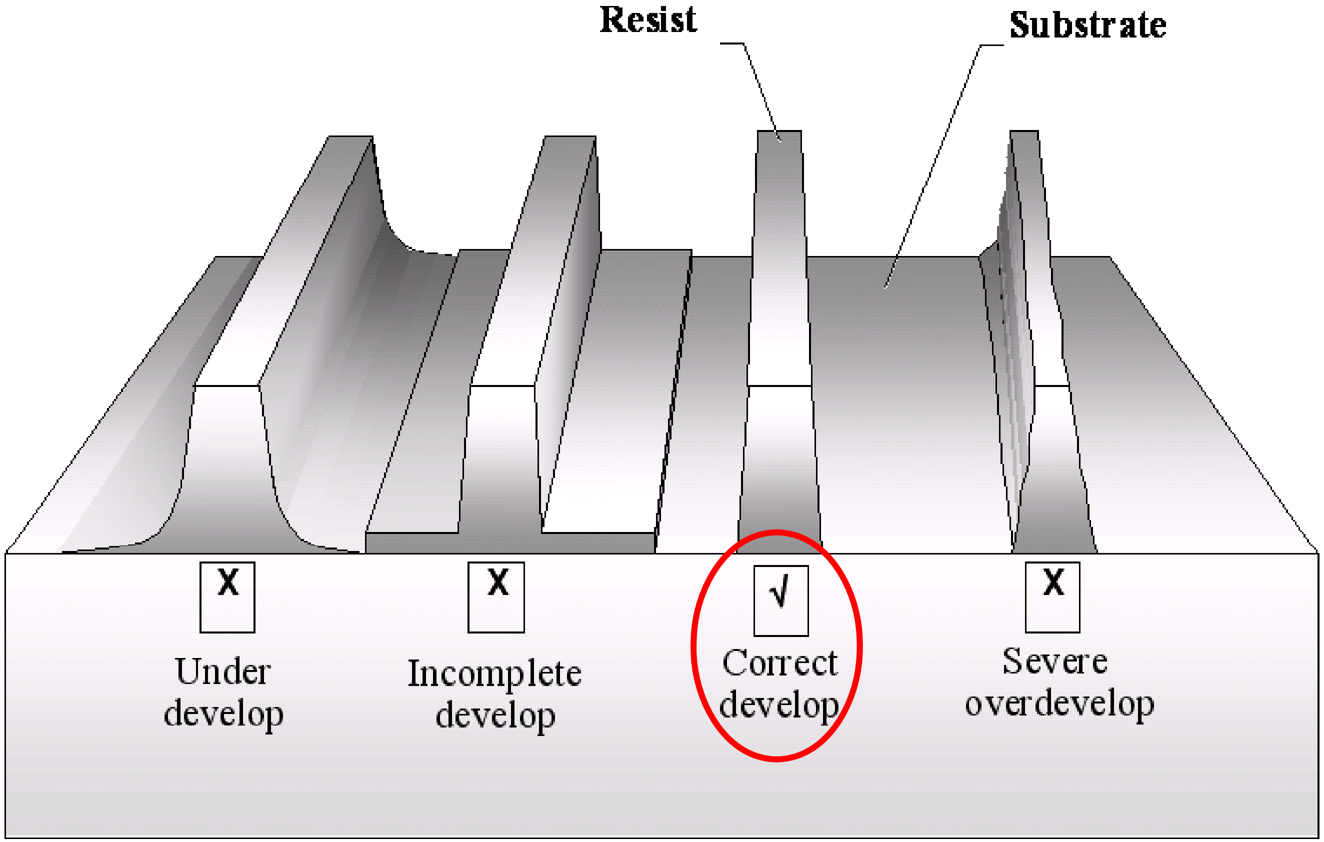
- Nonuniform spin coating
  - Phenomena: irregular coating, green color ring
  - Cause
    - Lack of photoresist
    - Wafer flexion due to vacuum
    - Bubble in the photoresist
  - Effect
    - Change the pattern size if the nonuniformity of thickness of photoresist film excess 10%
- Speed boat
  -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

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

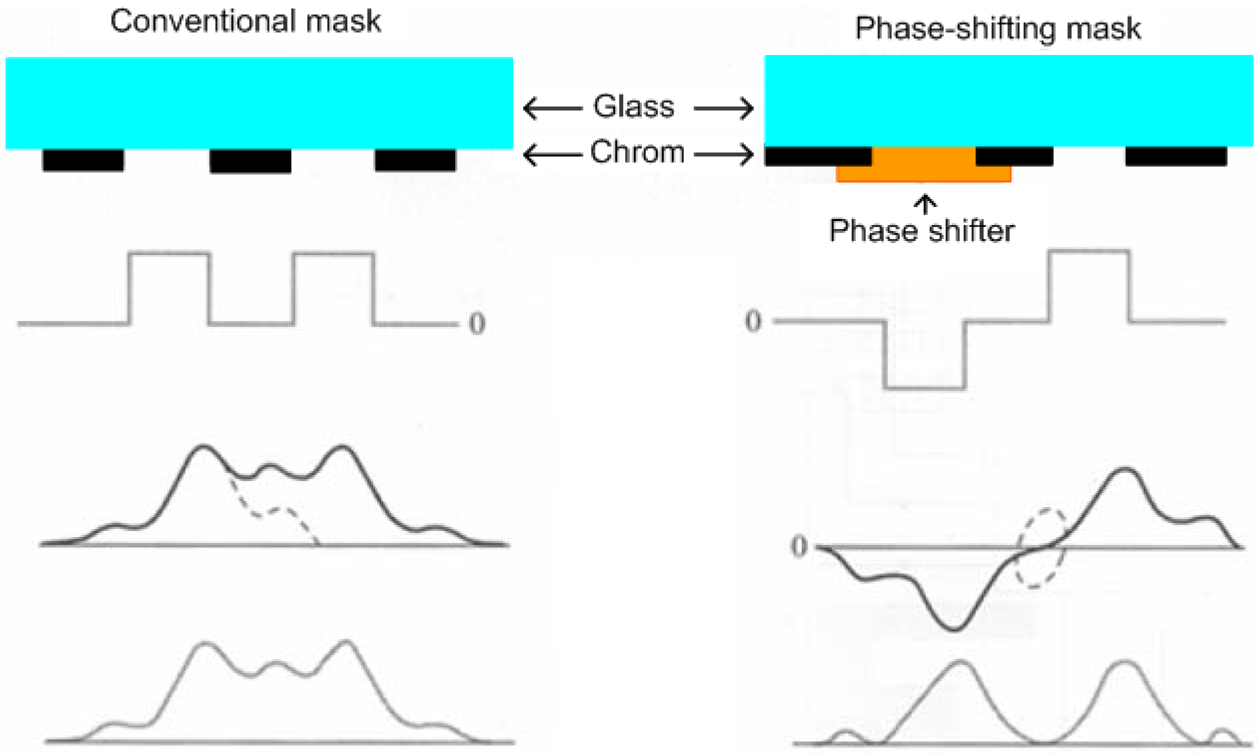
Problems of Photolithography Process

- Various photoresist profiles after develop



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

Resolution Enhancement Technique

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

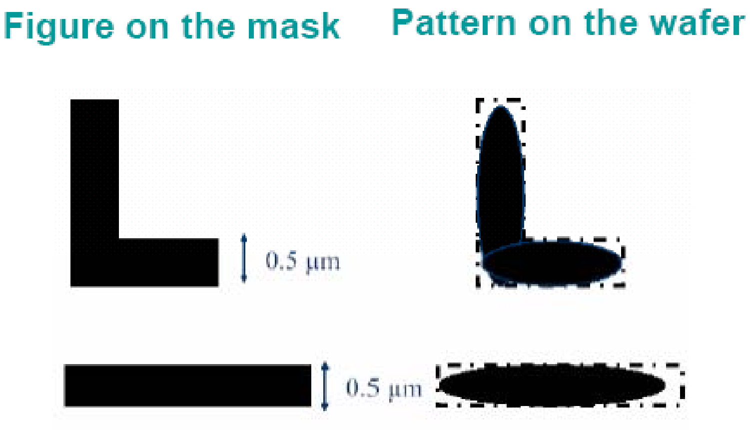


Figure on the mask
Pattern on the wafer

- 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

Soft Lithography

- Soft lithography: New tool in the nanofabrication arsenal
  - A class of techniques involving a soft elastomeric mold such as poly(dimethylsiloxane)
- Comparison of photolithography and soft lithography

Photolithography

-rigid photomask

-high cost

-optical diffraction

-not apply for nonplanar surface

-2-D structure

-limited by photosensitive material

Soft lithography

-elastic stamp or mold

-non-photolithography

-low cost, easy to use

-30 nm ~ 500 μm

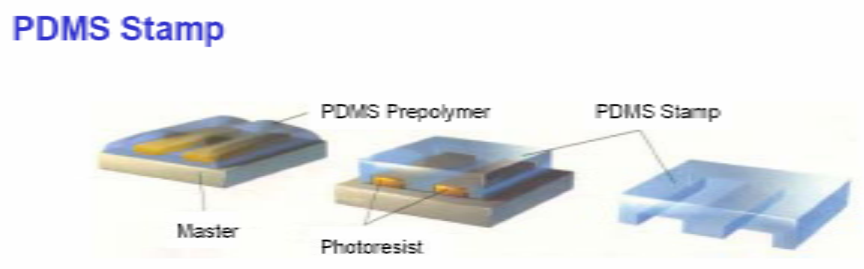
-2-D, 3-D structure

-use variety of material

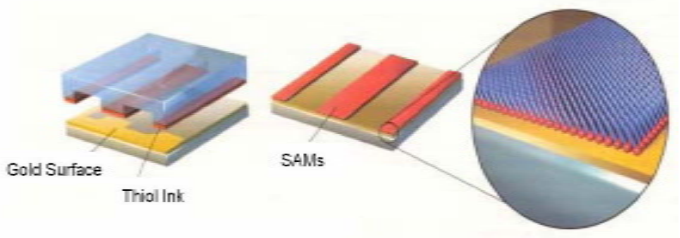
-surface chemistry

Soft Lithography (I)

- Micro-contact printing (μCP)
  - 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

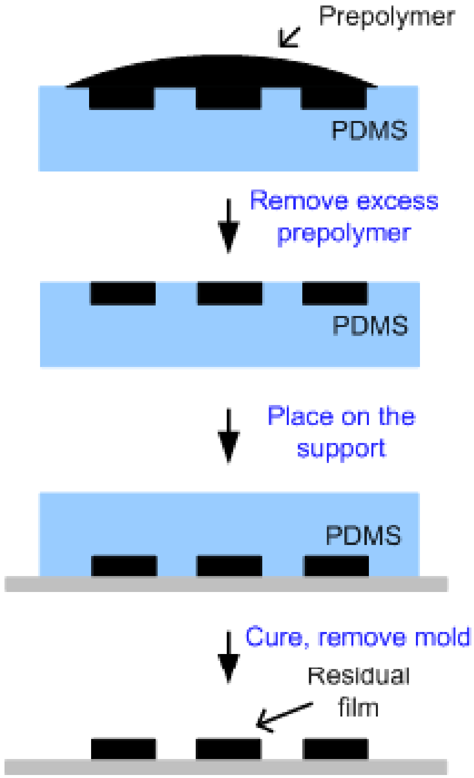


  - pattern generation by stamping of SAM precursor onto substrate



Soft Lithography (II)

- Micro-transfer molding (μTM)



Prepolymer

PDMS

Remove excess prepolymer

PDMS

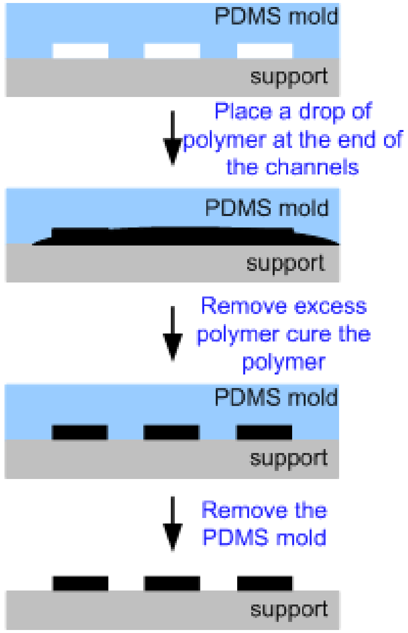
Place on the support

PDMS

Cure, remove mold

Residual film

- Micromolding in capillaries (MIMIC)



PDMS mold

support

Place a drop of polymer at the end of the channels

PDMS mold

support

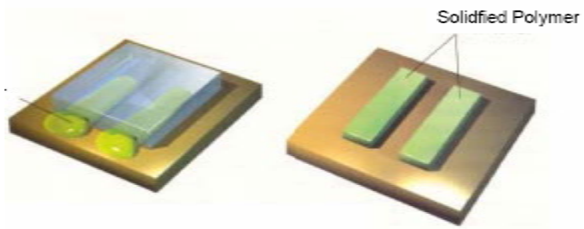
Remove excess polymer cure the polymer

PDMS mold

support

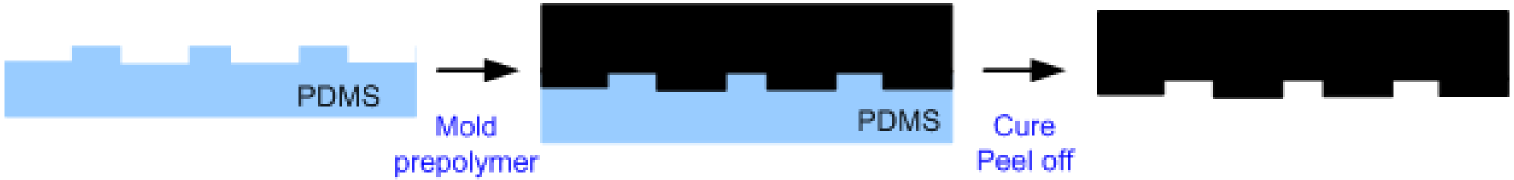
Remove the PDMS mold

support



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

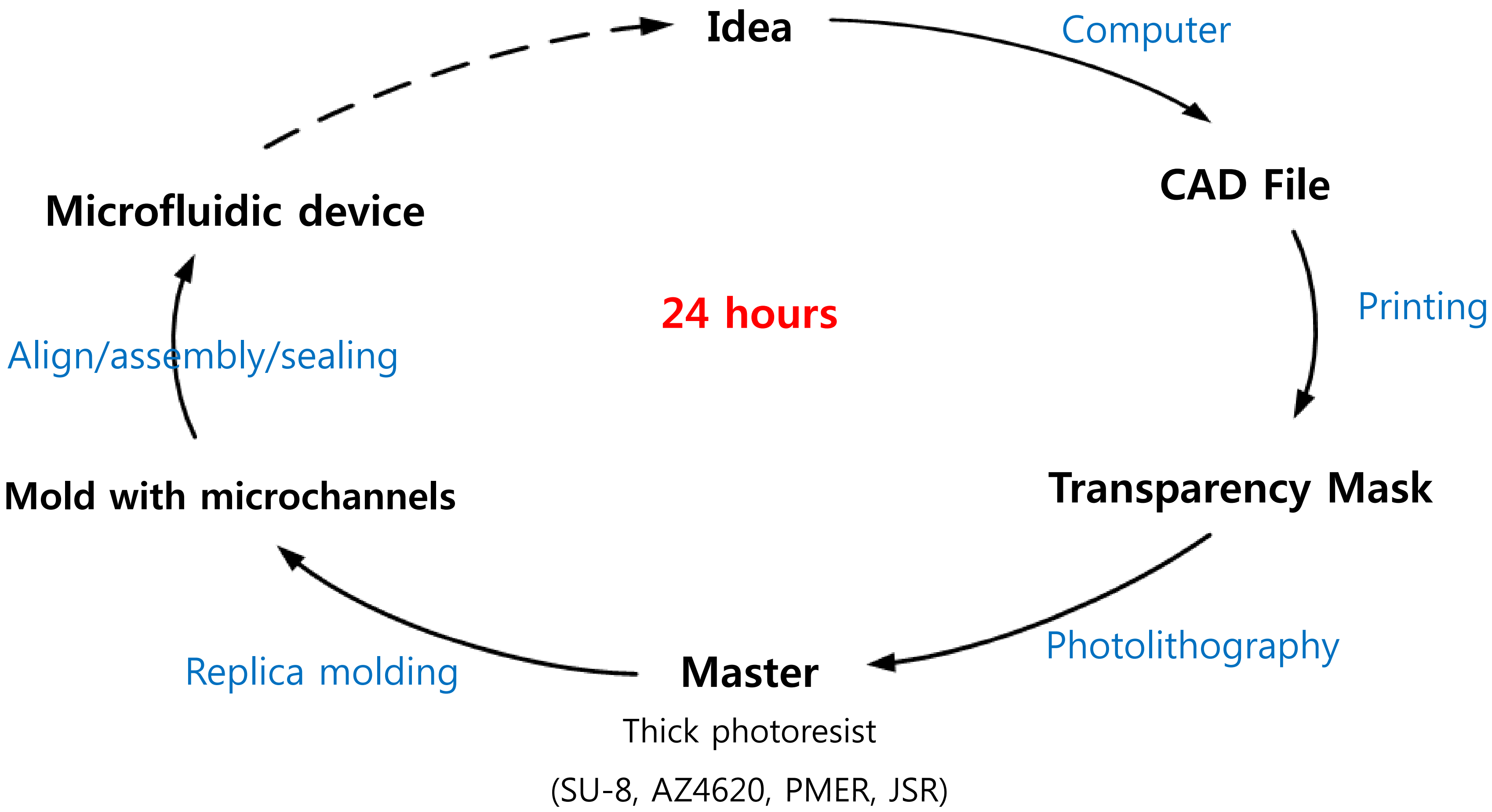


PDMS

- Elastomer, which means “deformable”
  - Conforms to the surface of the substrate over a relatively large area
  - Conformal contact achievable on nonplanar surfaces
  - Be released easily, even from complex and fragile structures
- Low in interfacial free energy and chemically inert
- Homogeneous, isotropic, and optically transparent
- Durable

Rapid Prototyping

- Rapid prototyping of microfluidic systems in PDMS



Idea

Computer

CAD File

Printing

Transparency Mask

Photolithography

Master

Thick photoresist

(SU-8, AZ4620, PMER, JSR)

Replica molding

Mold with microchannels

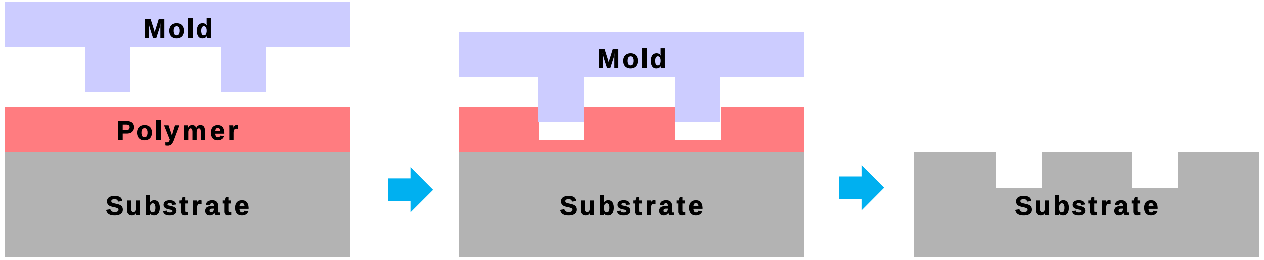
Align/assembly/sealing

Microfluidic device

24 hours

Nanoimprinting Lithography (NIL) (I)

- Nanoimprinting lithography
  - NIL is a technique of imprinting nanostructures on a substrate (polymer) using a master mold (silicon tool)



Mold preparation

Polymer coating

Pressing

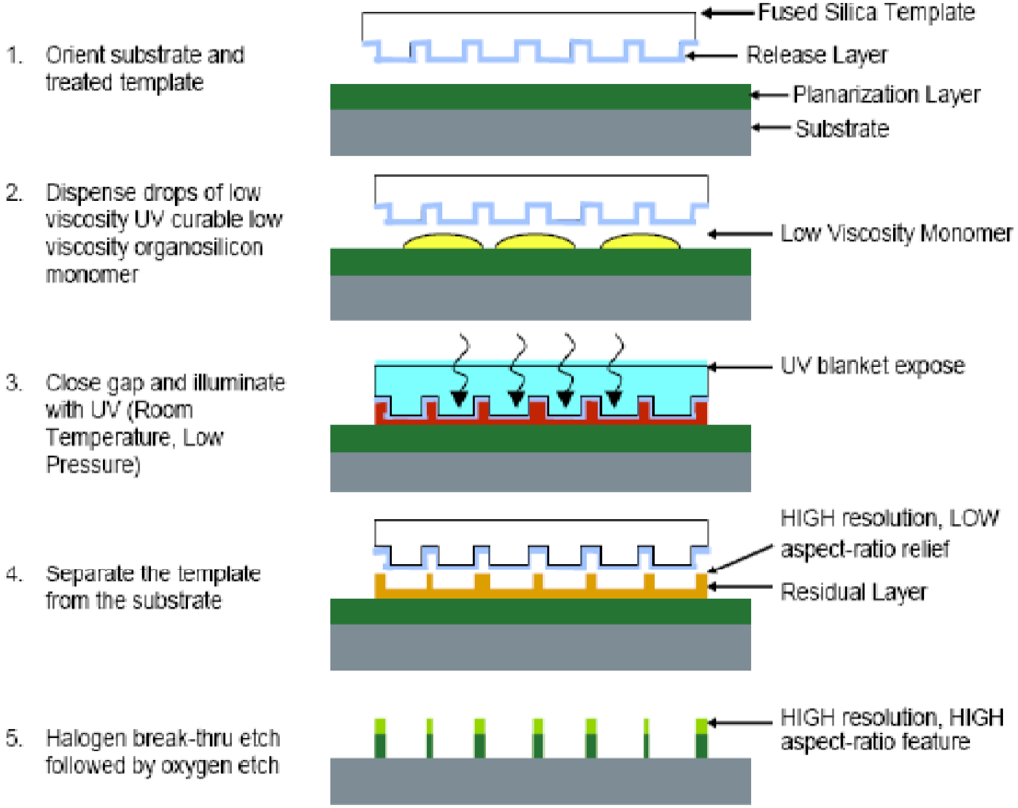
Pattern transfer

(Reactive ion etching)

Master/mold from photolithography → Heat the substrate and mold to just above T_g of the substrate → Apply embossing force on the substrate via the mold under vacuum → Cool the substrate and mold to just below Tg → De-embossing of the mold and substrate

Nanoimprinting Lithography (NIL) (II)

- UV nanoimprint lithography



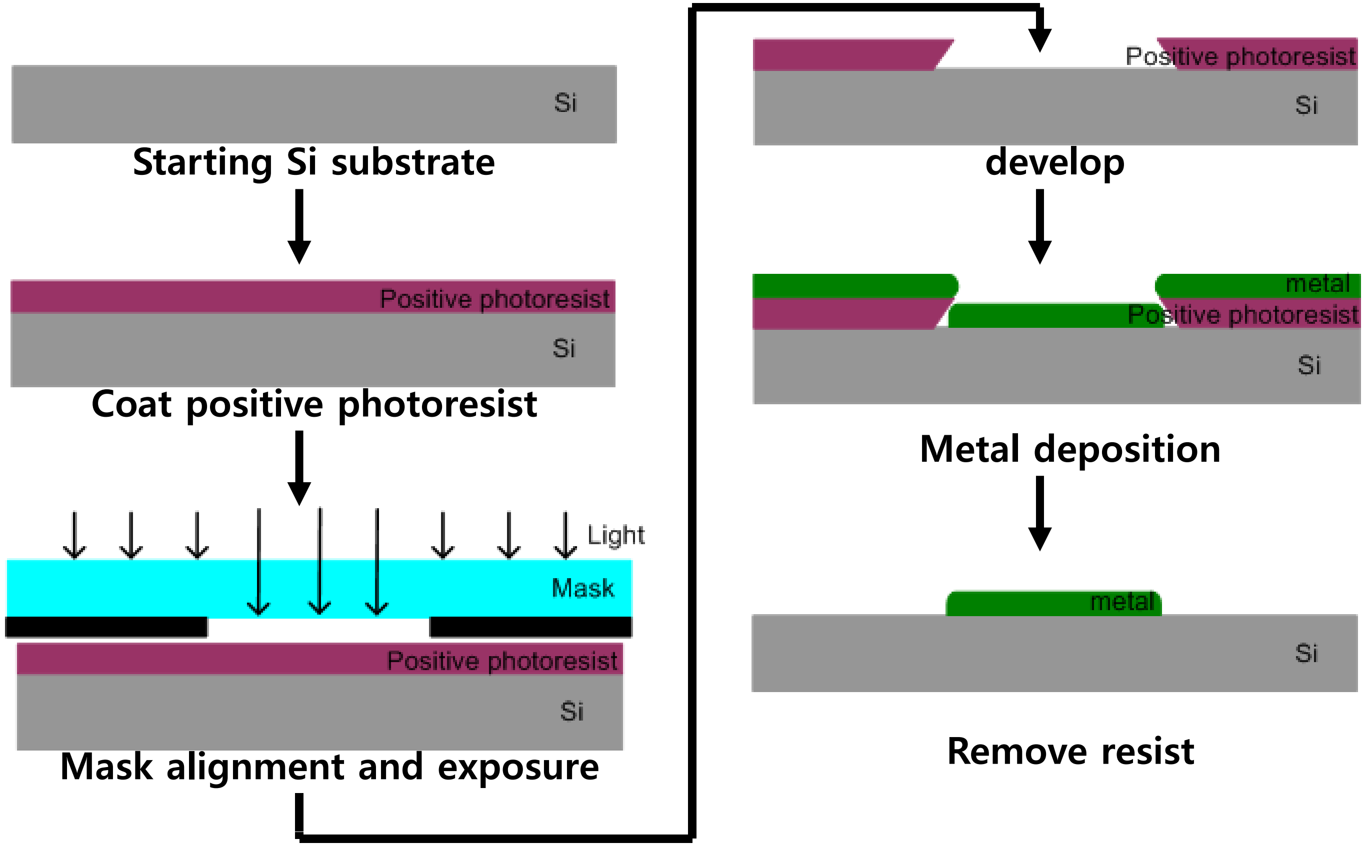
1. Orient substrate and treated template
2. Dispense drops of low viscosity UV curable low viscosity organosilicon monomer
3. Close gap and illuminate with UV (Room Temperature, Low Pressure)
4. Separate the template from the substrate
5. Halogen break-thru etch followed by oxygen etch

Step and Flash imprinting lithography (S-FIL^{TM})

UT Austin

Lift Off Process

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



Starting Si substrate

Coat positive photoresist

Mask alignment and exposure

develop

Metal deposition

Remove resist

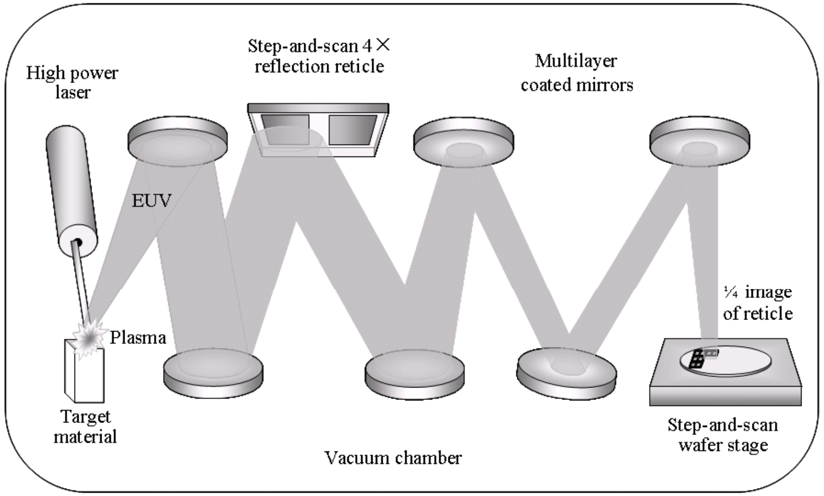
Next Generation Lithography Methods

- 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

Next Generation Lithography Methods

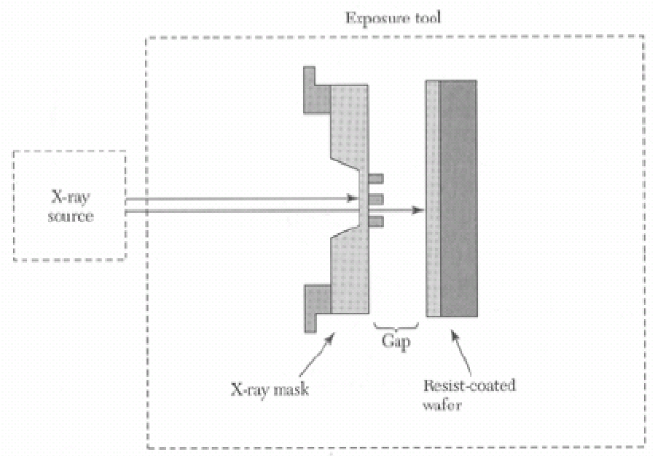
- Extreme Ultraviolet Lithography
  - A laser-produced plasma or synchrotron radiation serves as the source of EVU
  - A mask is produced by patterning an absorber materials deposited on a multilayer coated silicon or glass mask blank
  - Photoresist: PMMA
  - Advantages
    - Extending minimum line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



Conceptual schematic of EVU lithography system

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

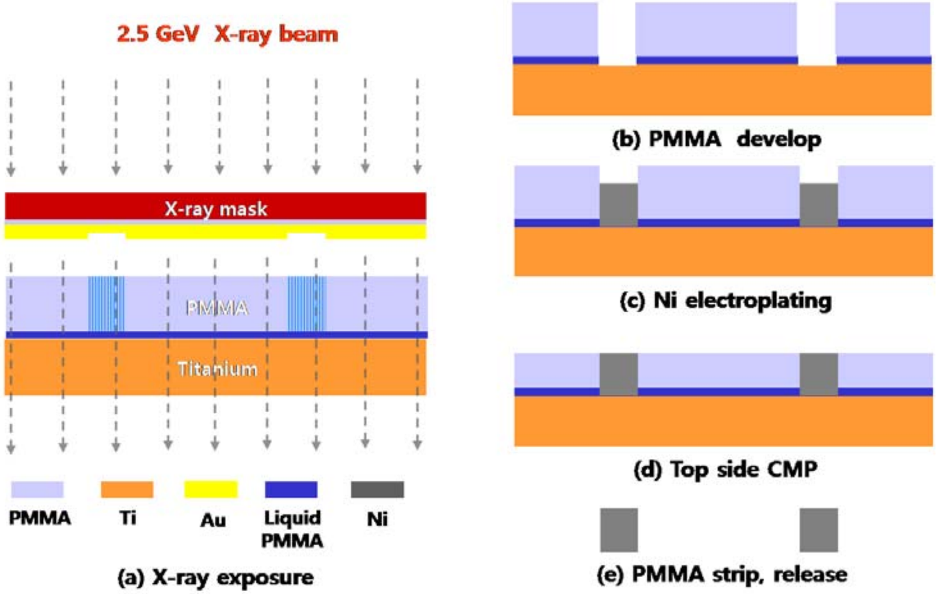


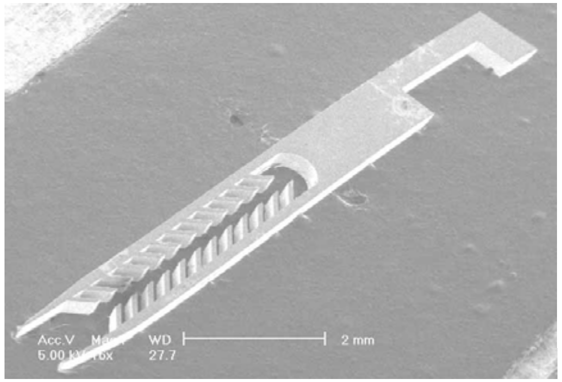
Schematic of proximity x-ray lithography system

X-ray Lithography

- LiGA
  - **Li**thographie (lithography)
  - **G**alvanoformung (development)
  - **A**bformung (electroplating)
  - X-ray exposure on PMMA at PAL
  - Ni electroplating

9C1 X-ray Nano/Micromachining beamline

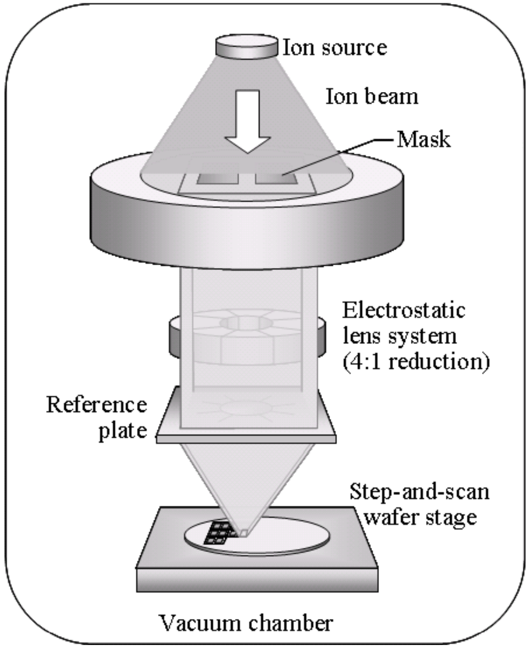




SEM picture of fabricated Ni micro-spike

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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