



Introduction to Photolithography

Concept, Processes, Tricks, and Beyond

Jiangdong (JD) Deng, Ph.D
Center for Nanoscale Systems
Harvard University



Outline (1)

Photolithography (Talk 1) - *Fundamentals, Process Skills*

- **Overview of Photolithography**
 - *The trend of Nanofabrication*
 - *Micro/Nano fabrication processes*
 - *Basic steps of photolithography*
- **Fundamentals of photolithography**
 - *Photoresist and related processes*
 - *UV exposure (light source, exposure optics, equipment)*
- **Process issues and advanced skills**
 - *Resolution limits and profile control*
- **Summary and References**
- **Q/A**



Outline (2)

Photolithography (Talk 2, Date –TBD, Nov.) - *Advanced Process and Application Notes*

- PhotoMask Design
- Lift-off Resist and Process
- Image Reverse Resist Process and Application
- Advanced lithography for Nanofabrication
 - *Nanoimprinting Lithography*
 - *E-beam lithography*
 - *SPM lithography*
 - *X-ray Lithography*
- Q/A



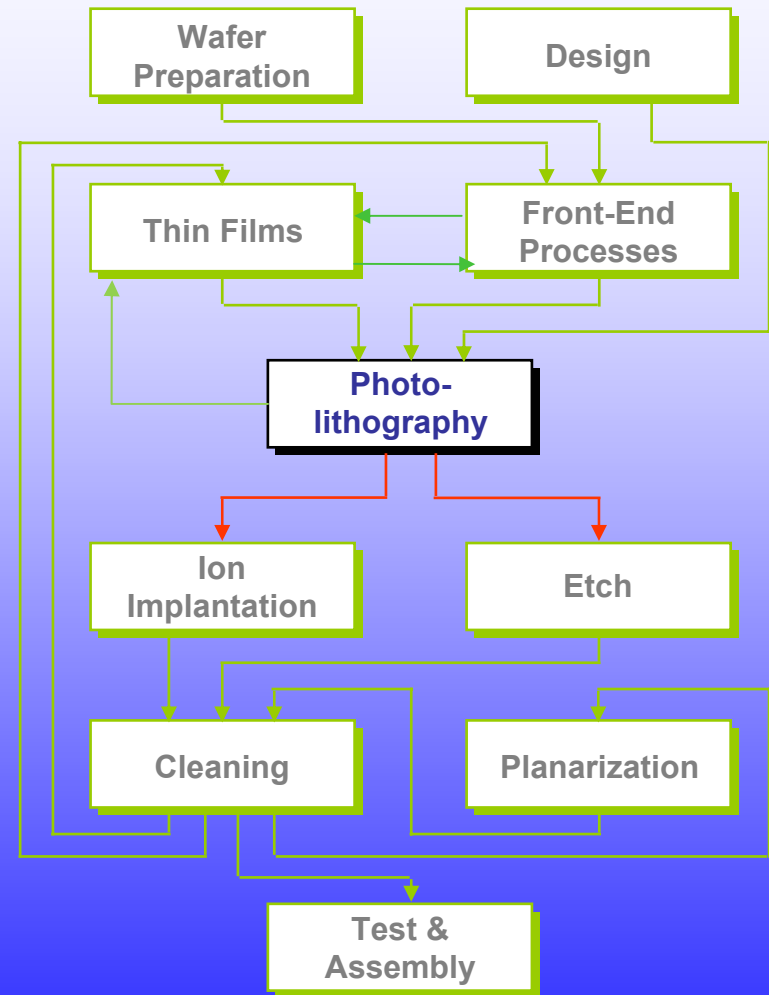
Trend of Nanofabrication

Year of 1st DRAM Shipment	1997	1999	2003	2006	2009	2012
DRAM Bits/Chip	256M	1G	4G	16G	64G	256G
Minimum Feature Size nm						
Isolated Lines (MPU)	200	140	100	70	50	35
Dense Lines (DRAM)	250	180	130	100	70	50
Contacts	280	200	140	110	80	60
Gate CD Control 3σ (nm)	20	14	10	7	5	4
Alignment (mean + 3σ) (nm)	85	65	45	35	25	20
Depth of Focus (μm)	0.8	0.7	0.6	0.5	0.5	0.5
Defect Density (per layer/ m^2)	100	80	60	50	40	30
@ Defect Size (nm)	@ 80	@ 60	@ 40	@ 30	@ 20	@ 15
DRAM Chip Size (mm^2)	280	400	560	790	1120	1580
MPU Chip Size (mm^2)	300	360	430	520	620	750
Field Size (mm)	22x22	25x32	25x36	25x40	25x44	25x52
Exposure Technology	248nm DUV	248nm DUV	248nm or 193nm DUV	193nm DUV or ???	193nm DUV or ???	???
Minimum Mask Count	22	22/24	24	24/26	26/28	28



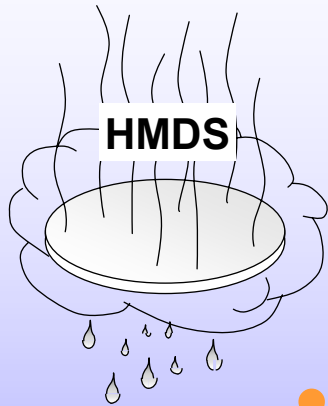
Photolithography

- **Photo-litho-graphy: *light-stone-writing***
- Purpose: Transfer same circuit patterns onto a large number of wafers.
- Key role in Nanofabrication
 - ***Critical dimension generations***
- Major Concerns in Photolithography
 - ***Resolution***
 - ***Overlay accuracy***
 - ***Process latitude***

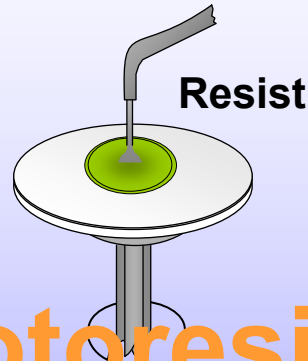




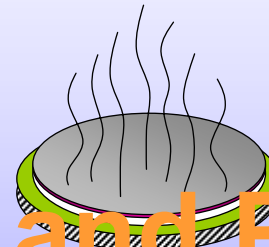
8 Steps in Photolithography



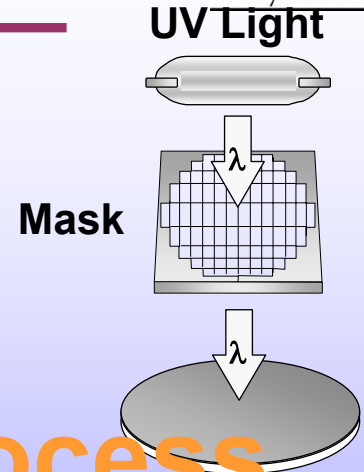
1) Surface preparation



2) Spin coat



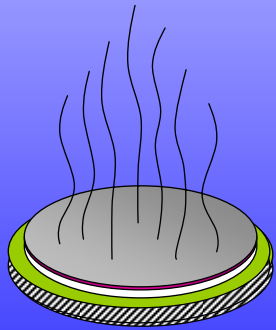
3) Soft bake



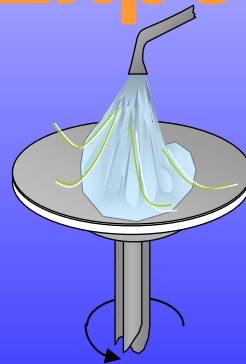
4) Alignment and Exposure

•Photoresist and Process

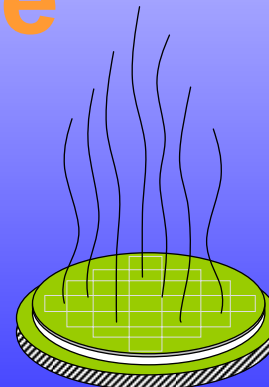
•UV Exposure



5) Post-exposure bake (option)



6) Develop



7) Hard bake (option)

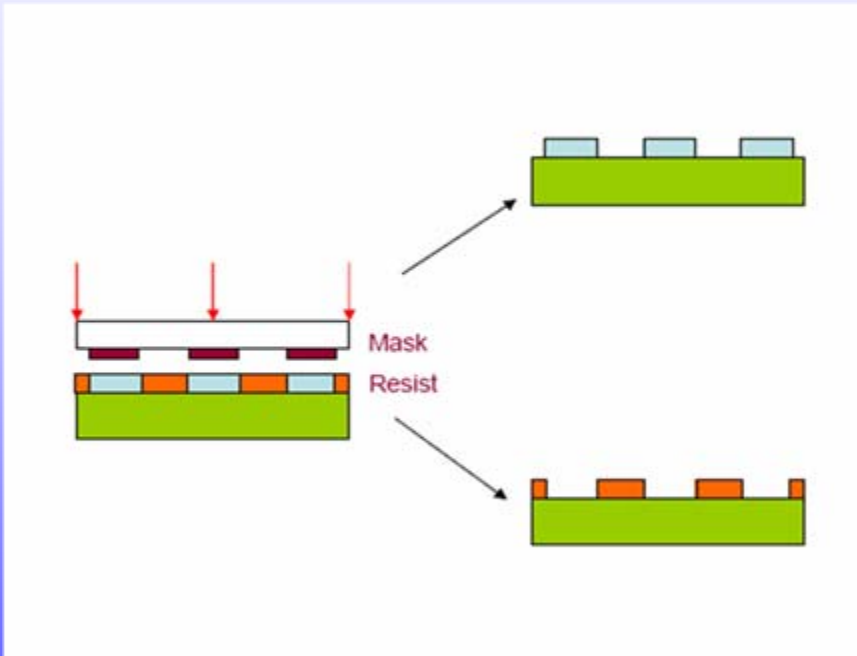


8) Develop inspect



Photolithography Physical Characteristics

- Resolution
 - Contrast (profile control)
 - Sensitivity
 - Viscosity
 - Adhesion
 - Etch resistance
 - Surface tension
 - Surface roughness
 - Storage and handling
 - Contaminants and particles
- Photoresist and Process
- UV Exposure



- Positive tone:

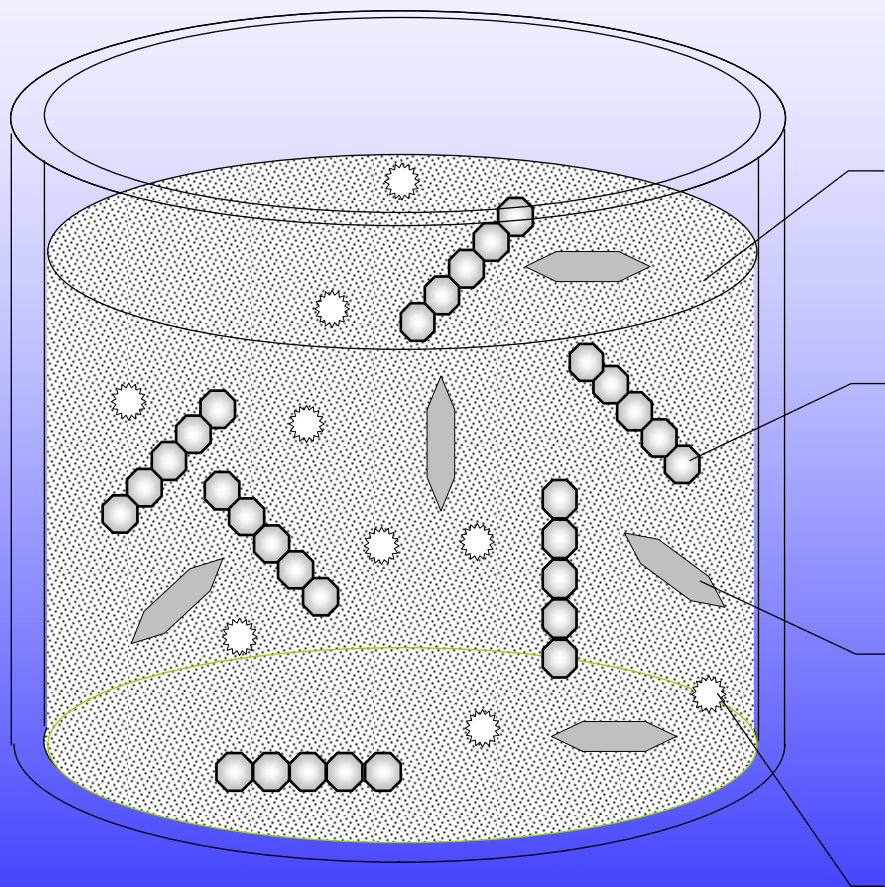
- **exposure increases solubility**
- Low molecular-weight (<10,000) polymer
- Pre-cross linked before exposure. exposure weakens polymer by rupture or scission of polymer chains
- Mask image is same as wafer image
- **CNS supply**, Shipley 1800 (1805, 1813, 1818, 1822)

- Negative tone

- **exposure decreases solubility**
- High molecular-weight (~65,000) polymer
- Exposure causes cross-linking of polymer chains
- Wafer image is opposite of mask image
- **CNS supply**, SU-8 (2002, 2005, 2010, 2025, 2050, 2100)



Components of Conventional Photoresist



Solvent:

- gives resist its flow characteristics
- PGMEA

Resin:

- mix of polymers used as binder;
- gives resist mechanical and chemical properties

Sensitizers: (inhibitor, PAC)

- photosensitive component of the resist material

Additives:

- chemicals that control specific aspects of resist material



Positive Photoresist -(DNQ-novolak resist)

Resin in photoresist (positive)

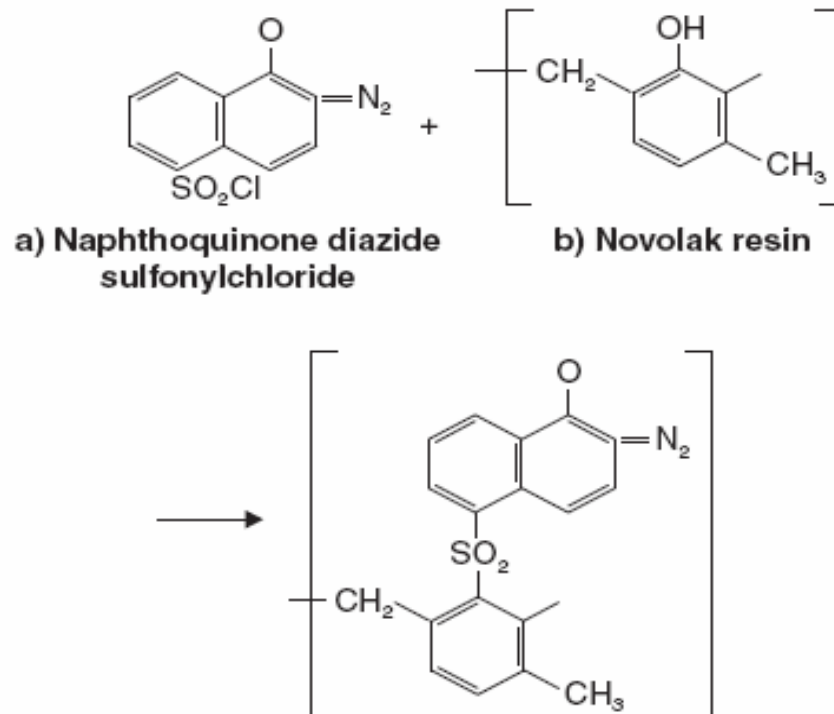


Figure 5.19: Generation of light sensitive novolak resin - DQN.

W.S. Deforest, 'Photoresist', McGraw Hill (1975)



Photo Chemical Reaction in P-PR (DNQ-novolak resist)

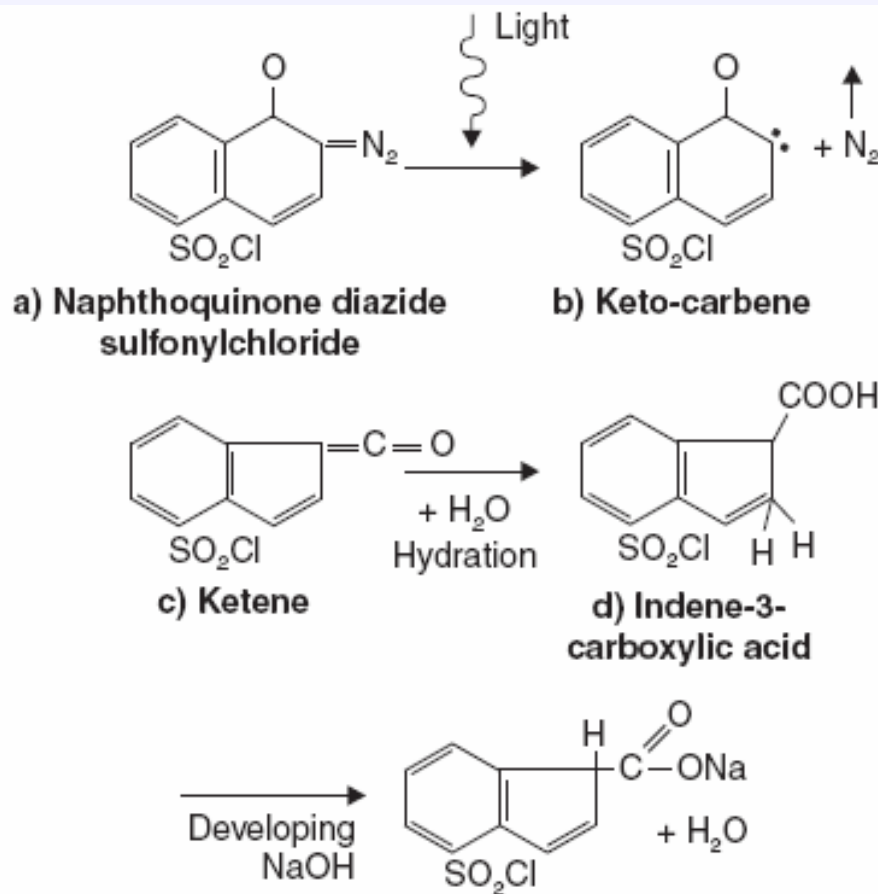


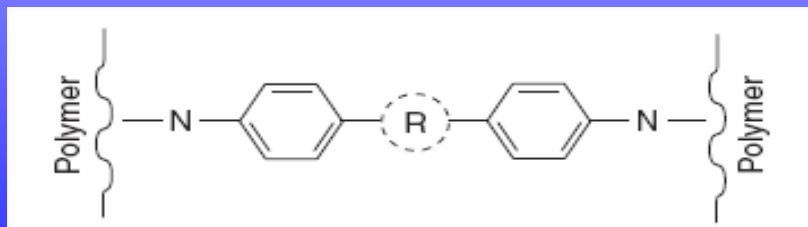
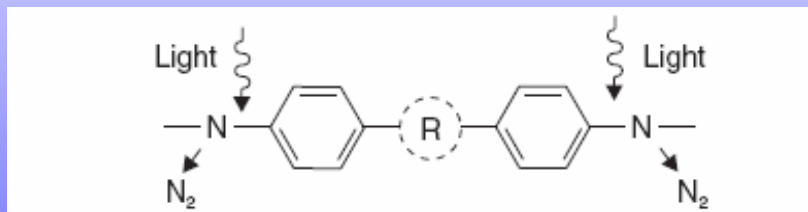
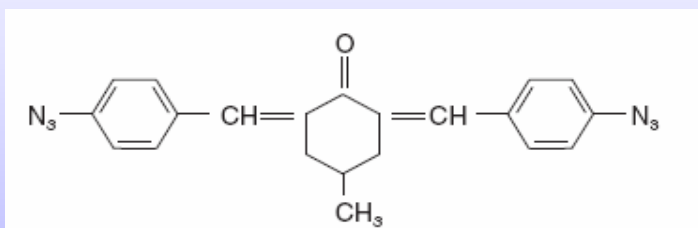
Figure 5.20: Naphthoquinone diazide sulfonylchloride photochemical reaction.



Photo Recation in Negative PR (KTFR resist)

KTFR – Kodak Thin Film Resist,

-invented in 1957, dominated in the early years of semiconductor



Sensitizer,

-bis arylazide...

Sensitizer reacts with light.

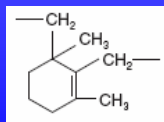
- Exposure**
- releasing N₂ and**
- very active**

Polymer(resin)-sensitizer- cross link

- Post exposure baking (PEB)**
- Higher insolubility**

Cyclized poly-isoprene

9/7/2009



Jiangdong Deng



Negative Photoresist

SU-8 Chemical Composition:

- EPON epoxy resin
- Solvent,
 - gamma-butyrolactone (GBL), or
cyclopentanone (in Su-8 2000 series)
- Photoinitiator,
 - triarylium-sulfonium salts (I-line-365nm)



Surface Preparation

- **Cleaning:**

- Remove any contaminants on the wafers prior to photoresist coating
 - Dusts/particles, oil, residue, grease, wax...
 - Cleaning approaches: solvent cleaning, TCA (1,1,1-trichloroethane), TCE (trichloroethylene), Piranha cleaning (H_2SO_4 & H_2O_2), RCA (I, II), acid-based Nanostriper, O_2 plasma...

- **Dehydration:**

- remove water prior to priming and coating
 - 200 C hotplate >5 min, or 15 min 80C oven

- **Priming:**

- form a polar (electrostatic) surface to isolate moisture adhesion on wafer surface and
- Increase the adhesion between wafers and photoresist coating layer



Surface Preparation

-Surface Priming (1)

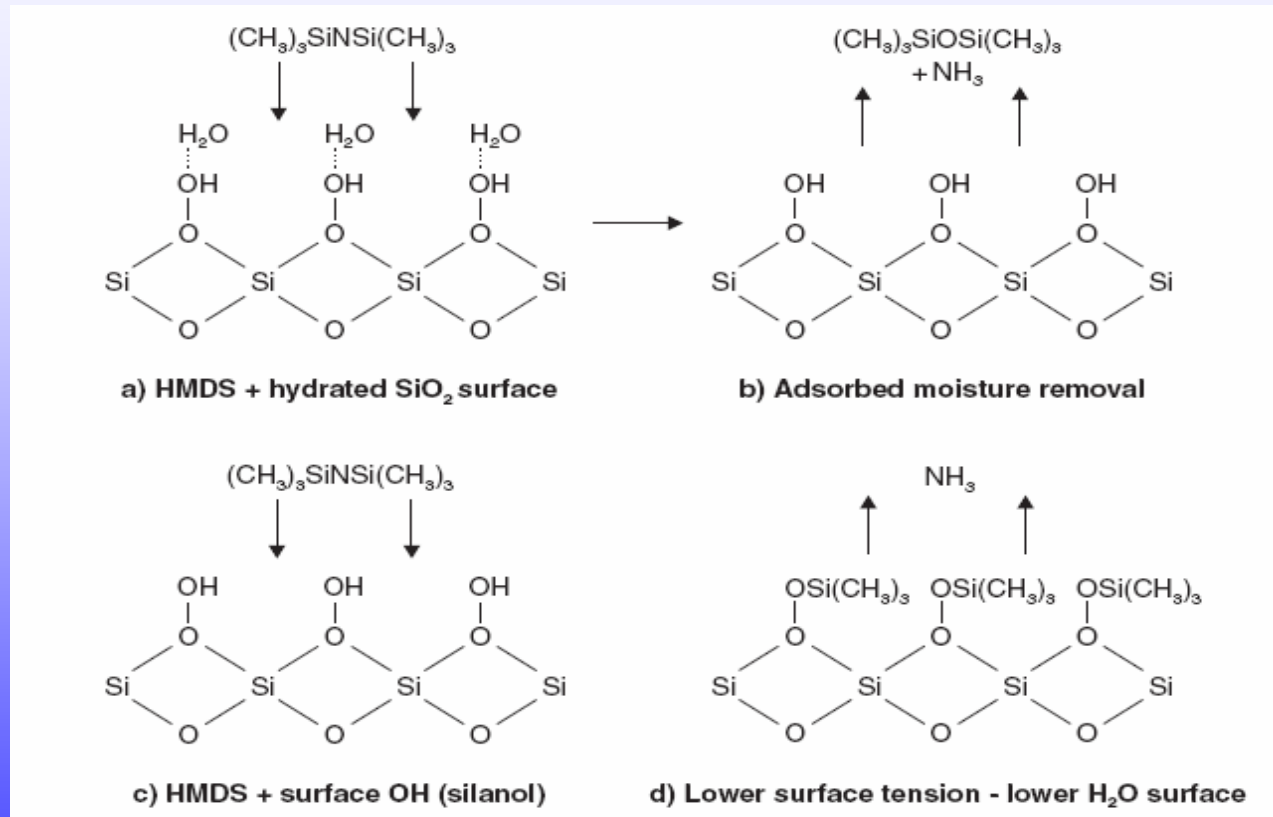
- **For Si, SiO₂, and other dielectric material:**
 - primers form bonds with surface and produce a polar (electrostatic) surface
 - most are based upon siloxane linkages (Si-O-Si)
 - 1,1,1,3,3,3-hexamethyldisilazane (HMDS), $(\text{CH}_3)_3\text{SiNHSi}(\text{CH}_3)_3$
 - trichlorophenylsilane (TCPS), $\text{C}_6\text{H}_5\text{SiCl}_3$
 - bistrimethylsilylacetamide (BSA), $(\text{CH}_3)_3\text{SiNCH}_3\text{COSi}(\text{CH}_3)_3$
- **For GaAs and other III-V materials:**
 - GaAs already has a polar surface
 - monazoline C
 - trichlorobenzene
 - xylene
- **Priming approach:**
 - 1) Vapor coating (Industry)
 - 2) Spin-coating (R&D, 2000rpm for 20s)



Surface Preparation

-Surface Priming (2)

HMDS adhesion promotion on SiO₂



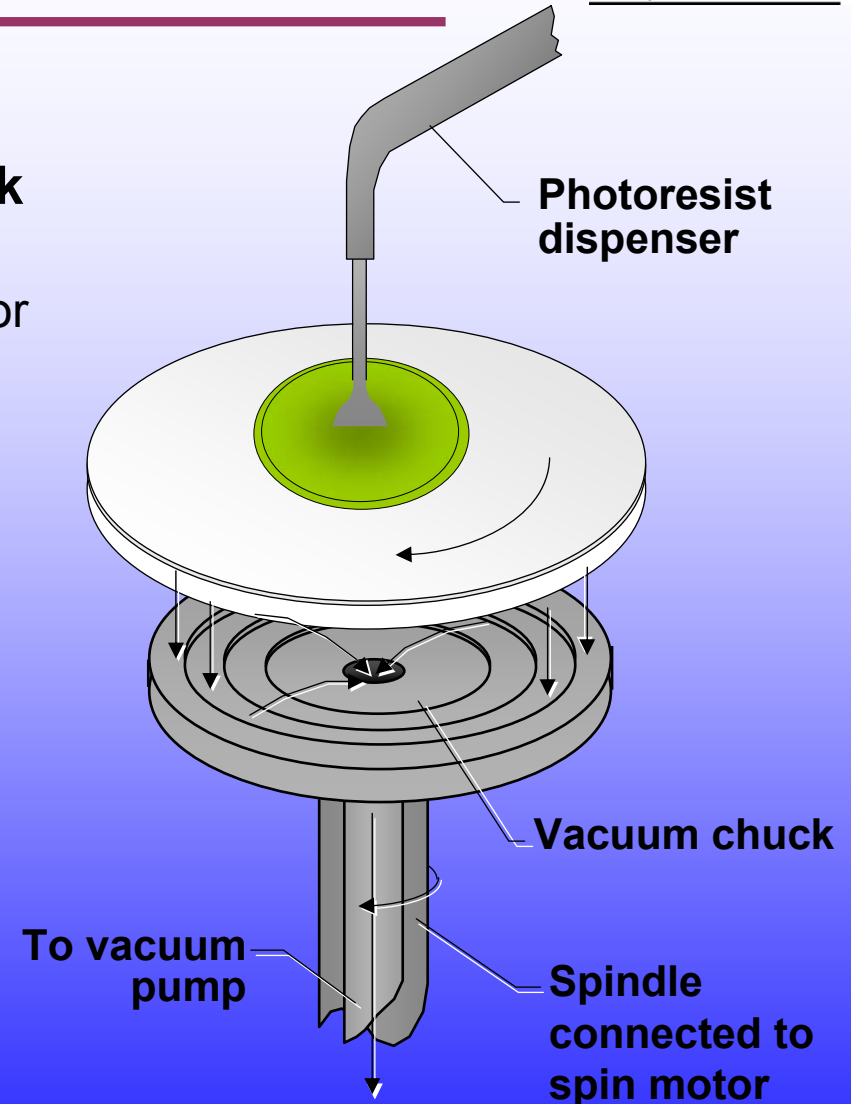
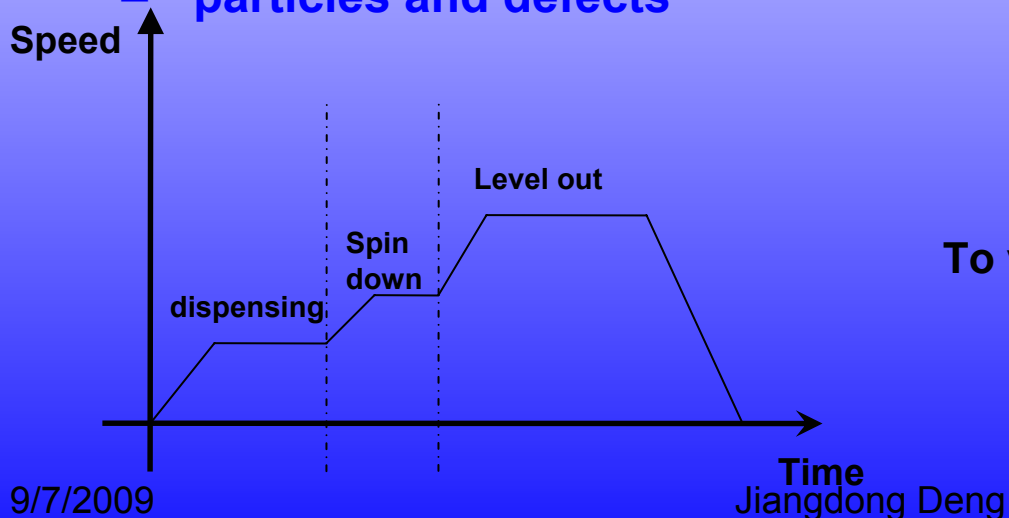
	Surface tension (dyne/cm)	H2O on surface (molecule/um ²)
Pre-HMDS	78	>35
Post-HMDS	21	<1



PR Spin Coat

Process Summary:

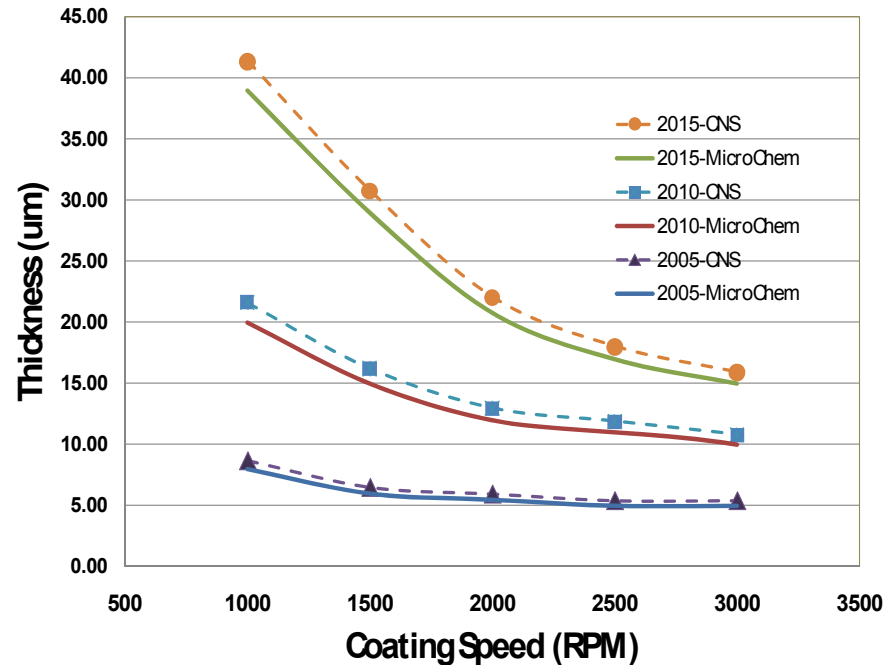
- Wafer is held onto vacuum chuck
- Typical coating steps:
 - Dispensing (low speed ~500rpm for 4-10s)
 - Level out (high speed-1000-to 5000rpm, 30-60s)
- Quality measures:
 - thickness
 - uniformity
 - particles and defects



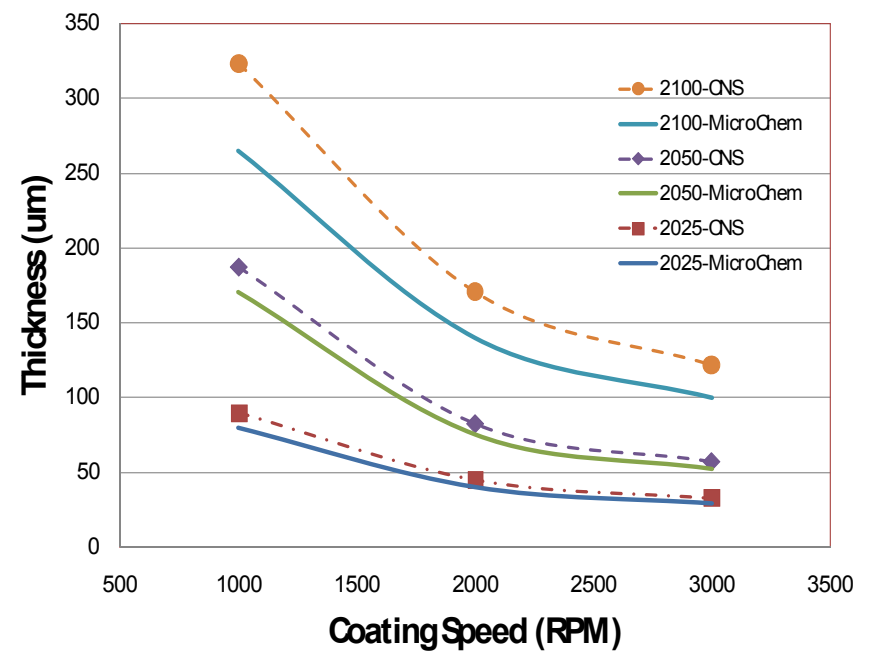


SU-8 2000 Photoresist Spin Curve

SU-8 Spin Curve (MicroChem and CNS-LISE)



Su-8 Spin Curve (MicroChem and CNS)



- Su-8 resist thickness in CNS is 10-20% thicker than the data of MicroChem
- Resist substrate: Si,
- Resist coating performance depends on:
 - a) Solvent Concentration, b) Speed control, c) Coating environment (air flow, T, Humidity), d) surface conditions (adhesion, energy...)



PR Spin-coating Process

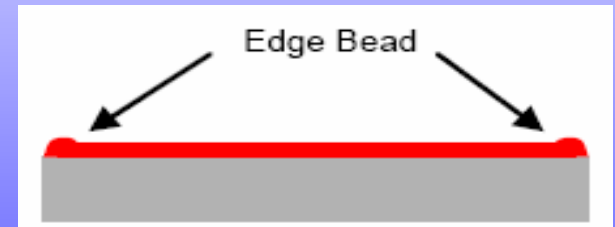
-Uniformity (artifacts)

- **Striations and streaks**

- Nonuniform drying of solvent during spin coating
- Wafer flatness and waveness ($\sim 50\text{-}100\text{ }\mu\text{m}$), radially out from center of wafer
- Radial patterns caused by hard particles or micro-air bubbles
- Vacuum chuck effect
- **Trick: filtering particle out, avoid air bubble**

- **Edge Bead**

- residual ridge in resist at edge of wafer
- non-circular wafers greatly increase the edge bead height
- **Trick: edge bead removers** (solvents, PGMEA), spun on after resist coating or soft-baking.





Soft baking

- **Drives off most of solvent in photoresist**
- **Impacts to post fabrication processes**
 - Photoresist-to-Wafer Adhesion
 - Thermal stress within PR-film
 - Resist Uniformity on Wafer
 - Etching rate and Linewidth Control During Development
- **Typical bake temperatures are 90 to 115°C**
 - Shipley 1800, 115°C; SU-8, 65/95 °C
 - Baking time (>2min) varies with the thickness
 - On a Hot Plate (better uniformity than oven baking)
 - **Tricks:**
 - a) Control heating/cooling step for thick resist
 - b) Multiple coating/baking
 - c) Reducing air exposure time after coating

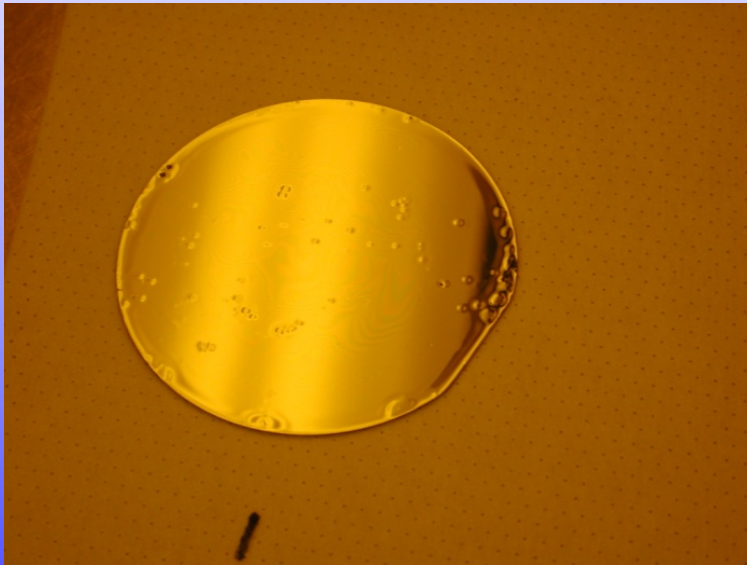


Soft-baking Example

- 'Bump'-like surface defect

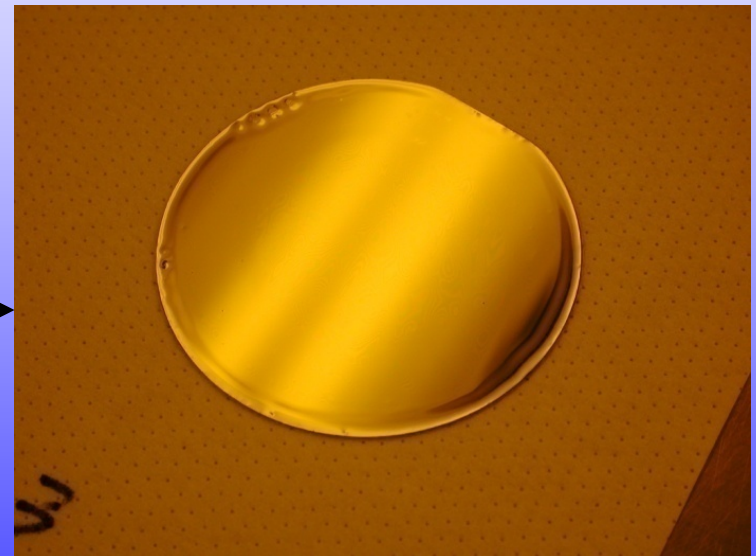
The 'bumps' are induced by the solvent trapped in the resist after softbaking, especially in the thicker SU-8 film

Solutions 1: Balance the spinning time, soft-baking process



Previous film surface (solvent
'bubble' everywhere)

(SU-8 2050, CR-1, Reynold)



Bump free film surface (good)

(SU-8 2050, CR-1, Reynold)

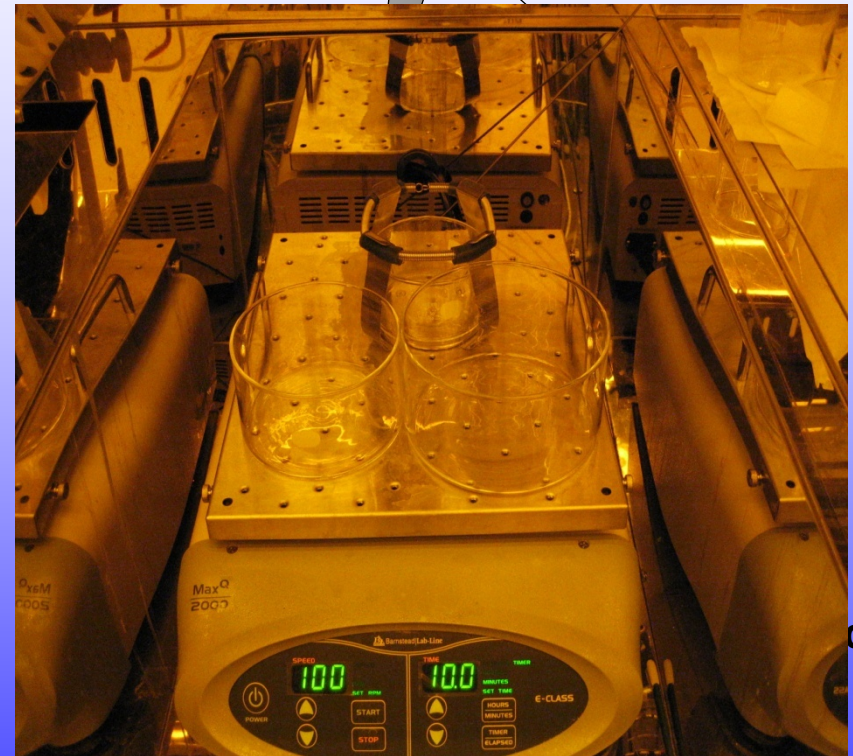


Post-Exposure Bake (PEB)

- **Required for negative PR (like SU-8), to ensure cross-link in the resist**
- **Typical Temperatures 90 to 110°C on a hot plate**
 - SU-8, 65/95 °C
 - **Tricks :**
 - Controlled cooling step is also critical for thick resist
 - Immediately after Exposure

Process Summary:

- Soluble areas of photoresist are dissolved by developer chemical
- Developer:
 - For Shipley 1800
 - KOH (CD-351),
 - NaOH (CD-30), or
 - $(\text{CH}_3)_4\text{NOH}$ (TMAH, CD-26, MF319)
 - Time: 30-90s
 - For SU-8
 - PGMEA (SU-8 developer, or BTS-220)
 - Time: 1-20min



pump

Spindle
connected to
spin motor

• Spinning option (bath option in CNS)



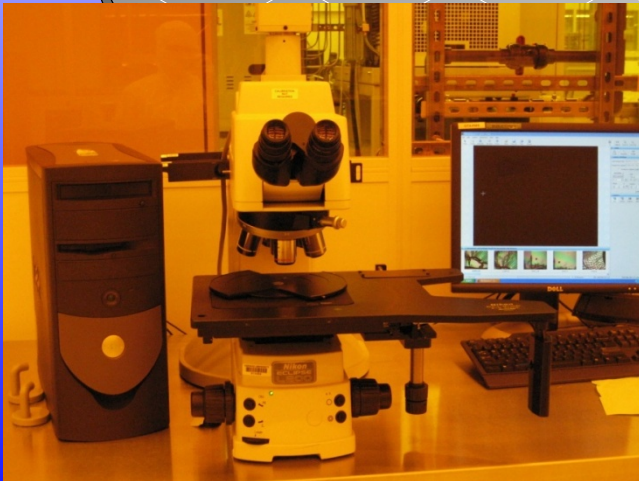
- **An Optional Post-Development Thermal Bake to**
 - Evaporate Remaining Solvent
 - Stabilize and harden the developed photoresist
- **Impacts to the post processes**
 - Improve Resist-to-Wafer Adhesion
 - Improve the resistance for dry or wet etching
 - Improve the edge roughness due to plastic flowing
 - Not easy to be removed, thus not good for lift-off process
 - May cause extra thermal stress
- **Higher Temperature than Soft Bake, for >5min**
 - Shipley 1800, 140-160°C
 - SU-8, 150°C



- **Inspect to Verify a Quality Pattern**

- Identify Quality Problems (Defects)
- Characterize the Performance of the Photolithography Process
- Prevents Passing Defects to Other Areas
 - Etch
 - Implant
- Rework Mis-processed or Defective Resist-coated Wafers

Resist liftoff





- Master patterns which are transferred to wafers
- Types:
 - Laser-plotting on plastic film (cheapest)
 - photographic emulsion on soda lime glass
 - Fe_2O_3 on soda lime glass
 - Cr on soda lime glass
 - Cr on quartz glass (most expensive, needed for deep UV litho)
- Polarity:
 - “light-field” = mostly clear, drawn feature = opaque
 - “dark-field” = mostly opaque, drawn feature = clear



Photomasks

Two Types of Photomasks in CNS

Mask	Materials	Writing Method	Smallest Feature	Pattern Quality	Price	Vendors	Others
Hard' Mask	Cr on glass plate (Soda-lime or Quartz)	Laser Writing, or E-beam Lithography (EBL)	1um (EBL can reach sub-um)	Smooth edge	expensive (\$80/hour in CNS)	CNS, Advance Reproductions ...	good for alignment
Transparent Film	Ink on plastic film	High-precision laser printer (5k - 20k dpi)	>10um	Rough edge	cheap (<\$35)	Outputcity, Advance Reproductions ...	not good for alignment



Wavelengths of Exposure Sources

UV Wavelength (nm)	Wavelength Name	UV Emission Source	Energy (eV)
436	g-line	Mercury arc lamp	2.84
405	h-line	Mercury arc lamp	3.1
365	i-line	Mercury arc lamp	3.4
248	Deep UV (DUV)	Mercury arc lamp or Krypton Fluoride (KrF) excimer laser	4.96
193	Deep UV (DUV)	Argon Fluoride (ArF) excimer laser	6.42
157	Vacuum UV (VUV)	Fluorine (F ₂) excimer laser	7.9
13.4	EUV (Extreme UV, soft-X-ray)	Plasma from Xe gas excited by high power laser	92.6
0.5	X-Ray	X-ray	2480
0.062	Electron		20 keV
0.012	Ion		100 keV

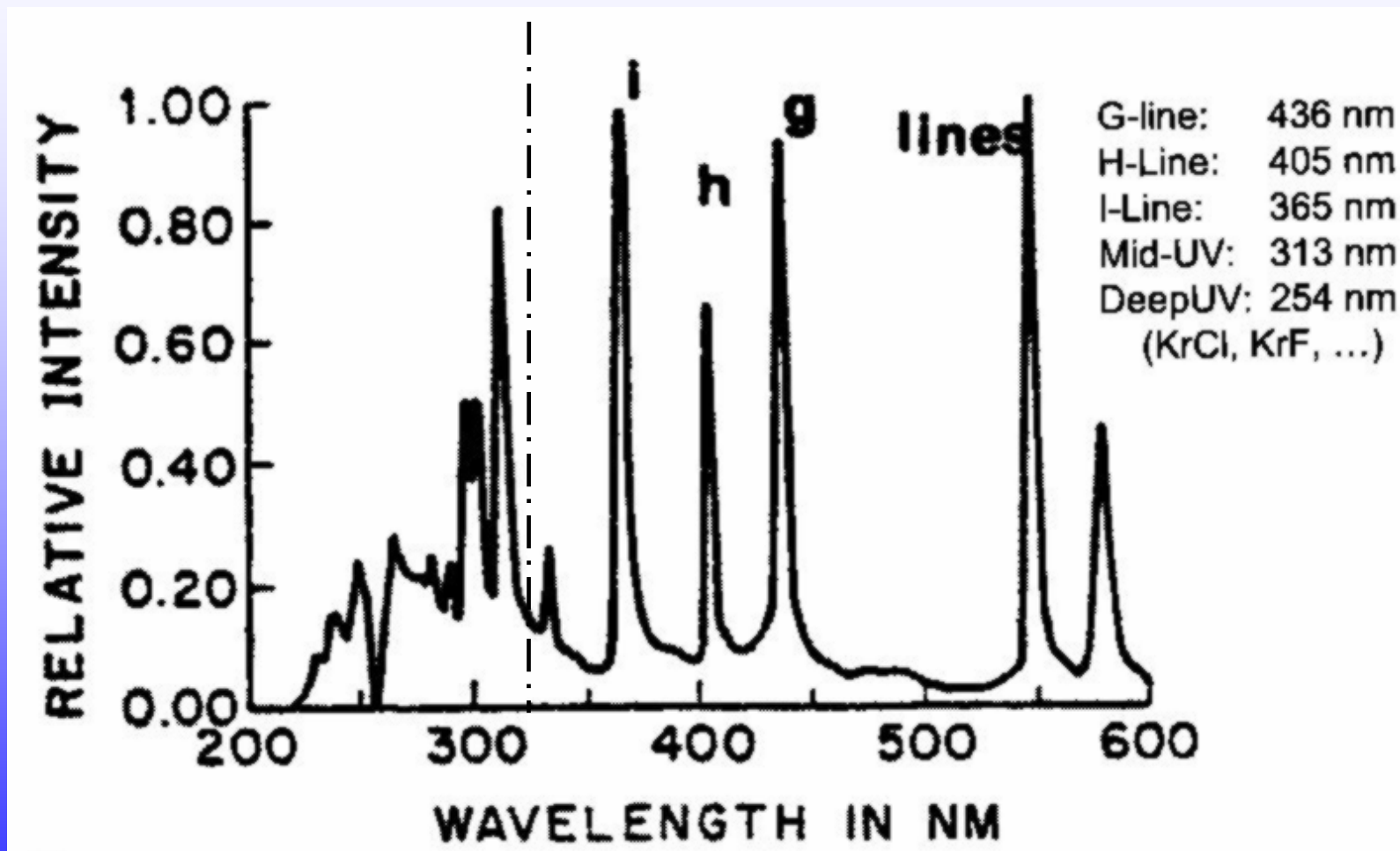
Decreasing feature sizes requires shorter λ .

Jiangdong Deng

$$E = h\nu = \frac{hc}{\lambda}$$



Light source: Mercury Arc Lamp



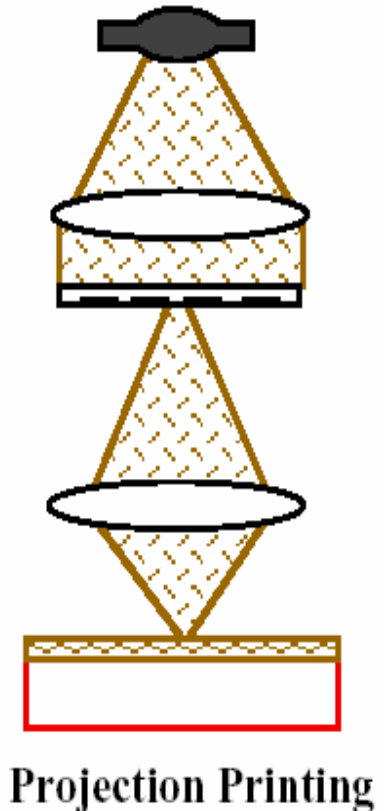
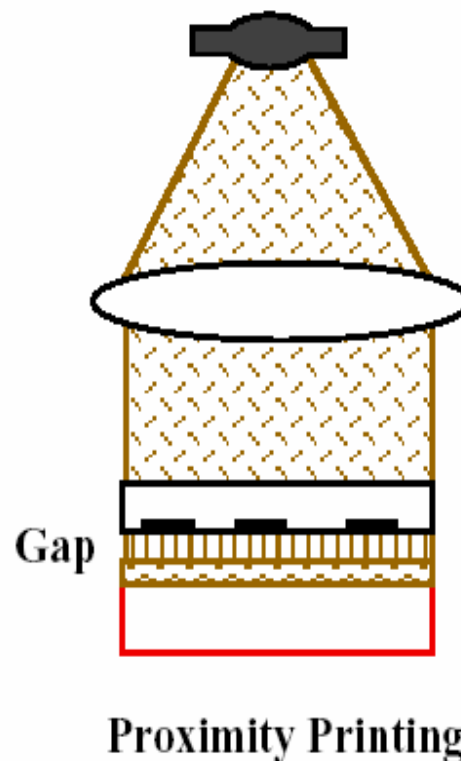
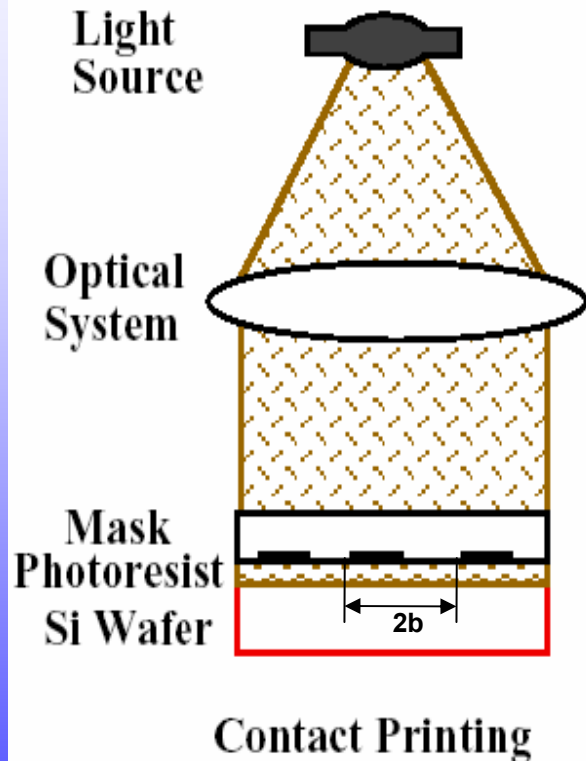


Three Basic Exposure Methods

1:1 Exposure

1:1 Exposure

~5:1 Exposure



Resolution ($2b$): $2b = k\sqrt{0.5\lambda d}$

$$2b = k\sqrt{\lambda(s + 0.5d)}$$

$$2b = K_1 \frac{\lambda}{NA}$$

$$DOF = K_2 \frac{\lambda}{NA^2} \quad K_{1,2} \sim 0.3-0.9$$

d , the thickness of photoresist, s , the gap of mask-resit, $k \sim 3$



Comparisons of three exposure modes

Exposure System	Advantage	Disadvantage	Application
Contact	High resolution (Near-field) Low cost (<200K) High throughput	Mask contamination and damage Sensitive to wafer bowing Defects impact	R&D
Proximity	Low mask/sample contamination	Poor resolution	R&D
Projection	High resolution Low mask contamination High throughput (50 wafer/h)	Expensive (>\$5M)	Dominates in production



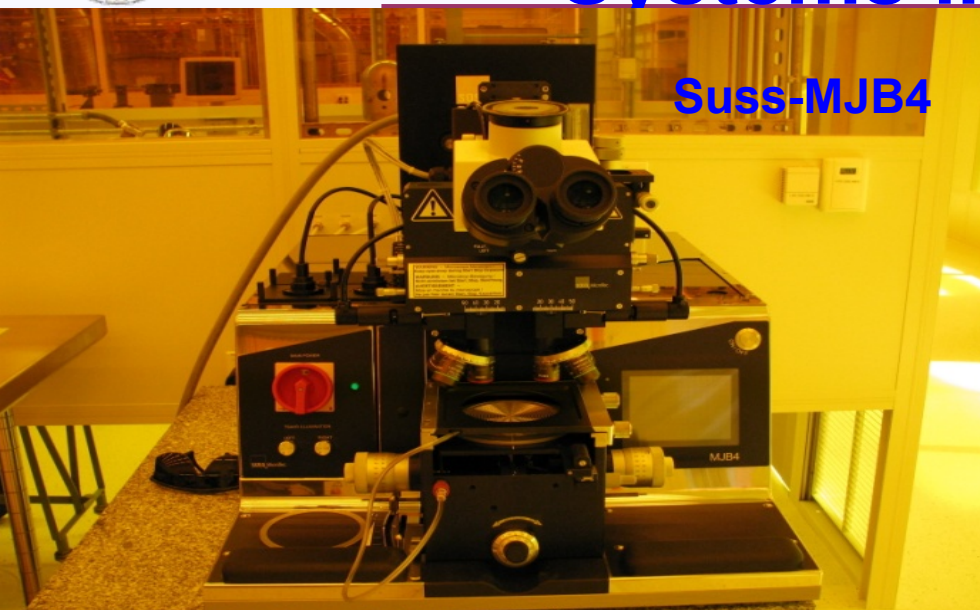
Exposure Equipment

- **Contact Aligner**
- **Proximity Aligner**
- **Scanning Projection Aligner (scanner)**
- **Step-and-Repeat Aligner (stepper)**
- **Step-and Scan System**



Contact/Proximity Aligner Systems in CNS

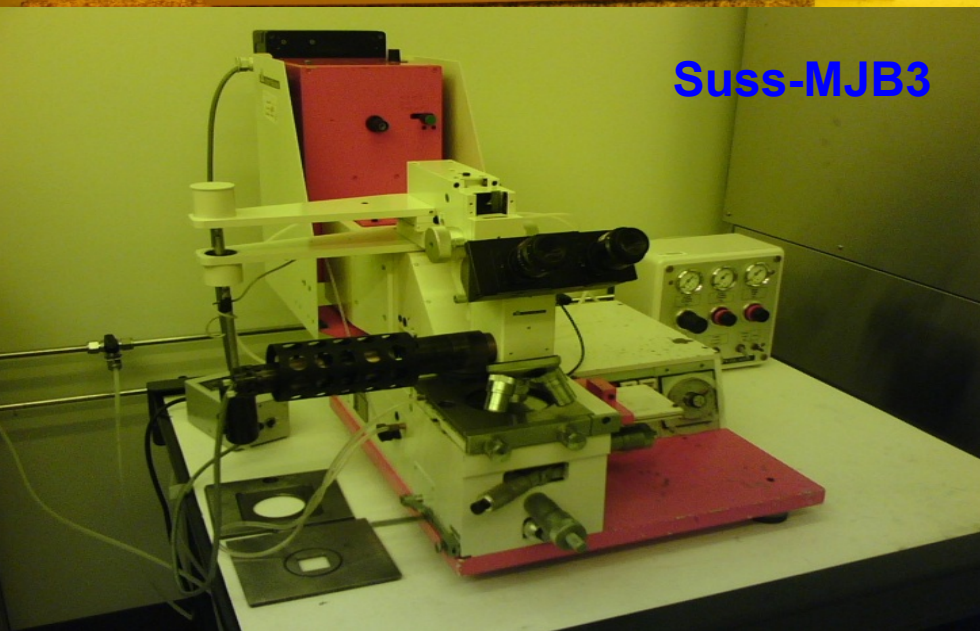
Harvard University
Center for
Nanoscale
Systems



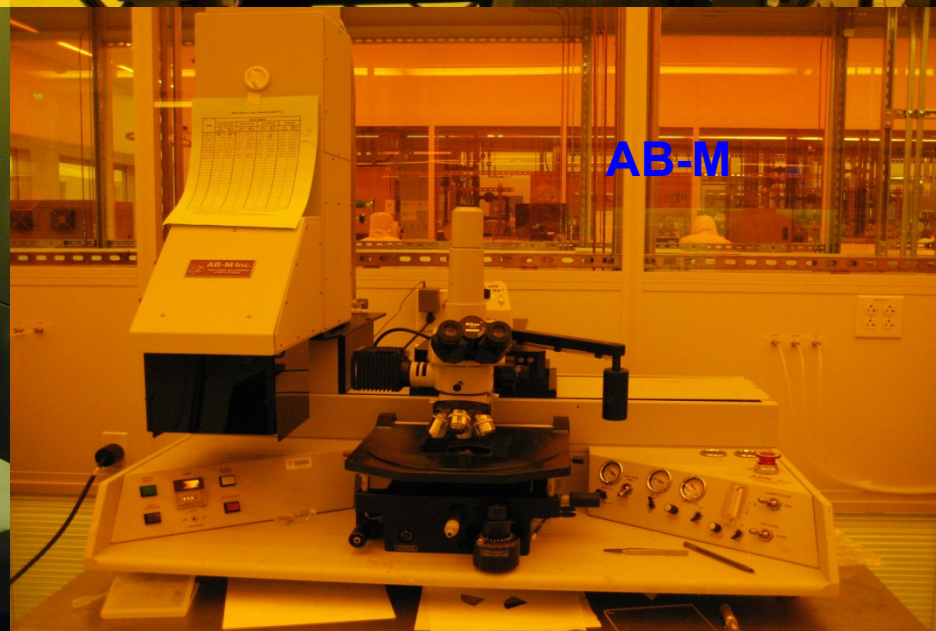
Suss-MJB4



Suss-MA6



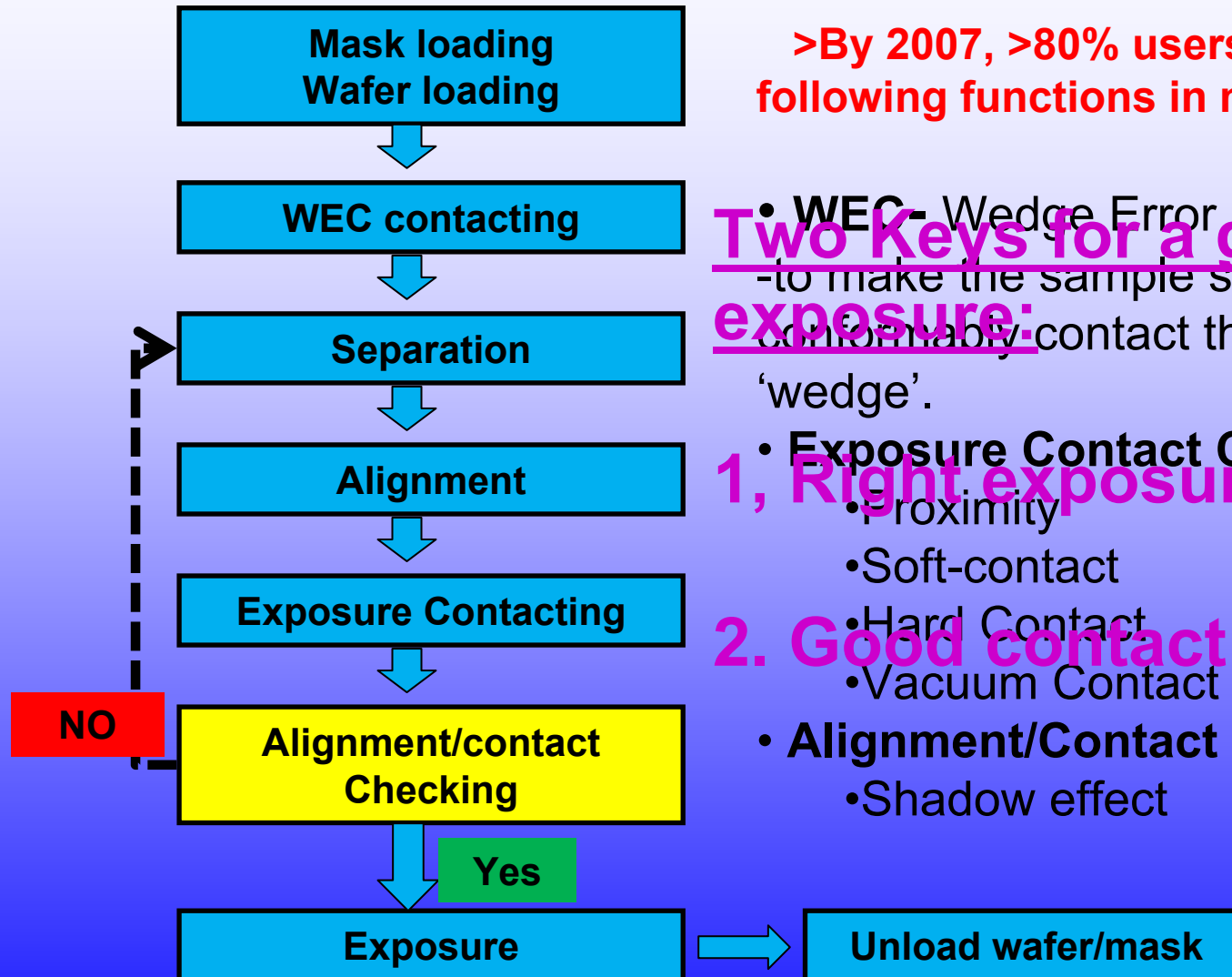
Suss-MJB3



AB-M



Exposure Procedure (Contact Mask Aligner)



>By 2007, >80% users did NOT know following functions in mask aligners

Two Keys for a good exposure:

- **WEC**- Wedge Error Compensation, -to make the sample surface conformably contact the mask without 'wedge'.

1, Right exposure dosage

- Proximity
- Soft-contact

2. Good contact!!!

- Hard Contact
- Vacuum Contact

- **Alignment/Contact Check**
 - Shadow effect



SU-8 Photolithography Process Conditions

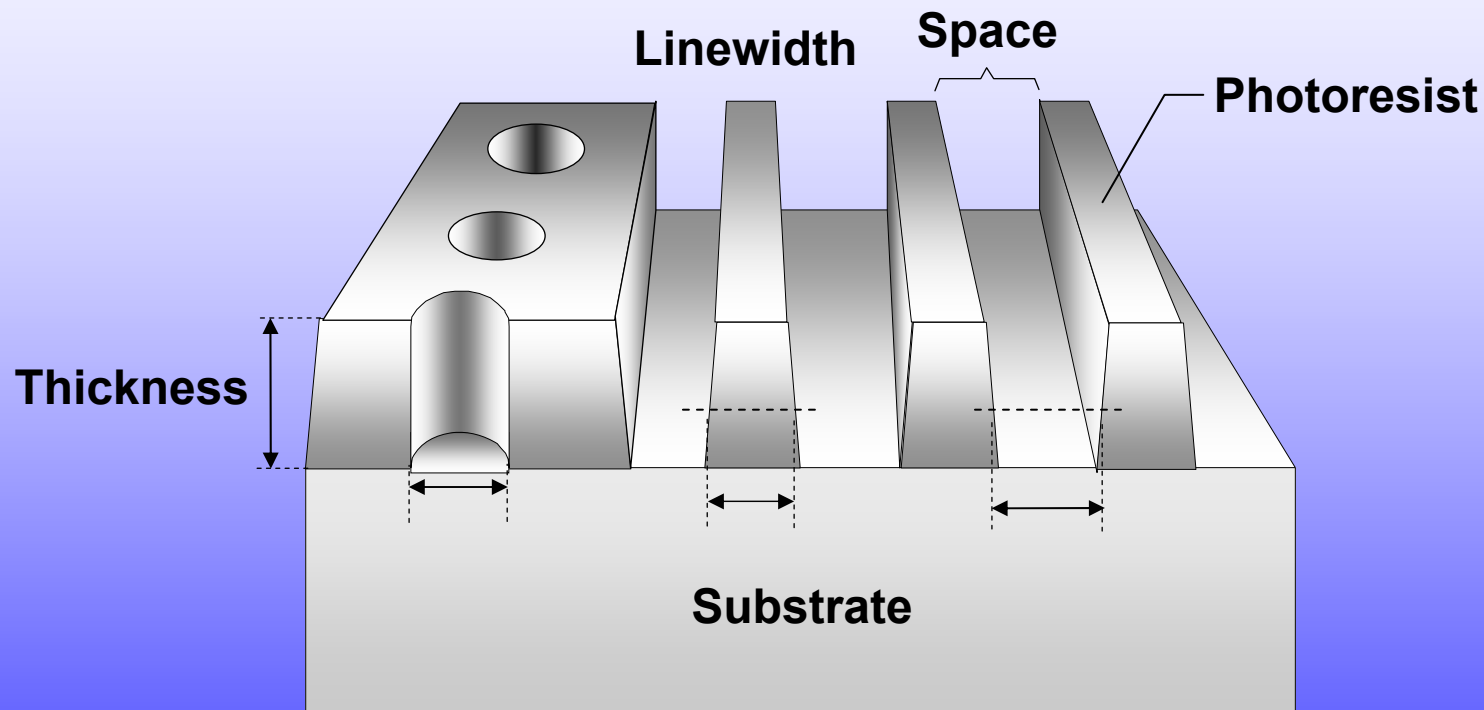
	Required SU8 Thickness (um)	SU-8 type	(*1) Spin speed (rpm)/ramp-time/hold-time	Pre-baking time (65C, min)	Soft-baking time (95C, min)	Exposure Energy (mJ/cm^2)	(*2) Suggest Exposure Energy (mJ/cm^2) (+/-10%)	(*3) Suggest Exposure time (AB-M) (sec)	Post-Exp Baking 1 PEB1 (65C,min)	Post-Exp Baking 2 PEB2 (95C,min)	PGMEA Develop time (min)	Comment (*4)	Verified Thickness (um) -CNS (*5)
	1.5	2	3000/ 8s /60s	1	1	70-100	85	3.5	1	1	1		
	2	2002	3000/ 8s /60s	1	2	70-100	85	3.5	1	1	1	CNS	
	5	2005	3000/ 8s /60s	1	2	80-120	100	4.2	1	1	1		5.4
	5	5	3000/ 8s /60s	1	3	80-110	100	4.2	1	1	1		
	7	2007	3000/ 8s /60s	1	2	90-140	115	4.5	1	1.5	1		
	10	2010	3000/ 8s /60s	1	2	110-170	140	5.5	1	2.5	2	CNS	10.8
	10	10	3000/ 8s /60s	2	5	100-170	140	5.5	1	2.5	2		
	15	2015	3000 / 8s /60s	1	2	120-190	160	6.5	1	2+1	3	CNS	15.8
	20	2015	2000 / 5s /60s	1	3	140-230	190	7.4	1	2+1	3	CNS	
	25	2025	3000 / 8s /60s	1	3	150-250	200	8	1	3+1	4	CNS	32.3
	35	2035	3000 / 8s /60s	2	5	180-300	240	9.5	1	3+1	5		
	40	50	3000 / 8s /60s	5	15	250-300	280	11	1	4+1	6	CNS	
	50	2050	3000 / 8s /45s	3	6	230-380	310	12	1	7+1	6	CNS	57.2
	75	2075	3000 / 8s /45s	3	9	280-470	380	15	1	7+1	7		
	100	2100	3000 / 8s /45s	5	20	320-540	430	17.5	1	10+1	10	CNS	124

Note:

- 3000 rpm of spin speed is recommended for better repeatability of film thickness
- Suggest exposure energy is given under following conditions: Plastic film pattern mask, a 360nm LP filter to hold the mask and Si substrate
- Suggest exposure time is based on the intensity of AB-M at 365nm ~25mW/cm^2
- Some of SU8 are provided by CNS, as marked in the Comment column,
- 6 types of SU-8 (2005, 2010, 2015, 2025, 2050, 2100) have been verified in LISE clean-room of CNS (SU-8 banch, rightside spinner, which are highlighted



Three Dimensional Pattern in Photoresist

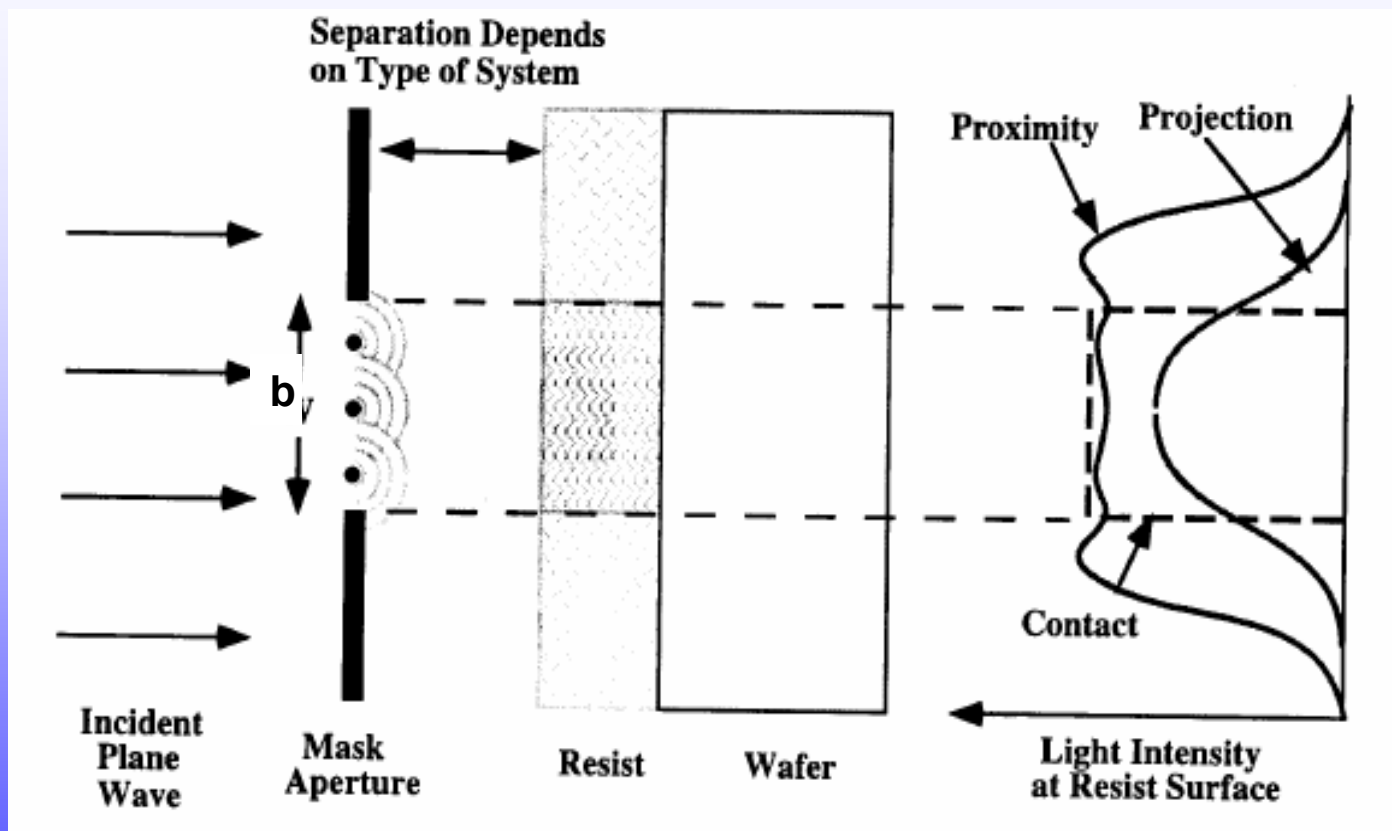


Criteria for 'good photolithography'

- Line/space size
- Adhesion
- Uniformity
- Profile control
- Sidewall roughness
- Defects
- Etching resistance
- Surface tension



Light Profile Comparisons of three exposure modes



Contact/Proximity exposure: Fresnel diffraction (near-field)

Projection exposure: Frounhofer diffraction (far-filed)



Resolution Limit and Profile Control

– Light intensity profile

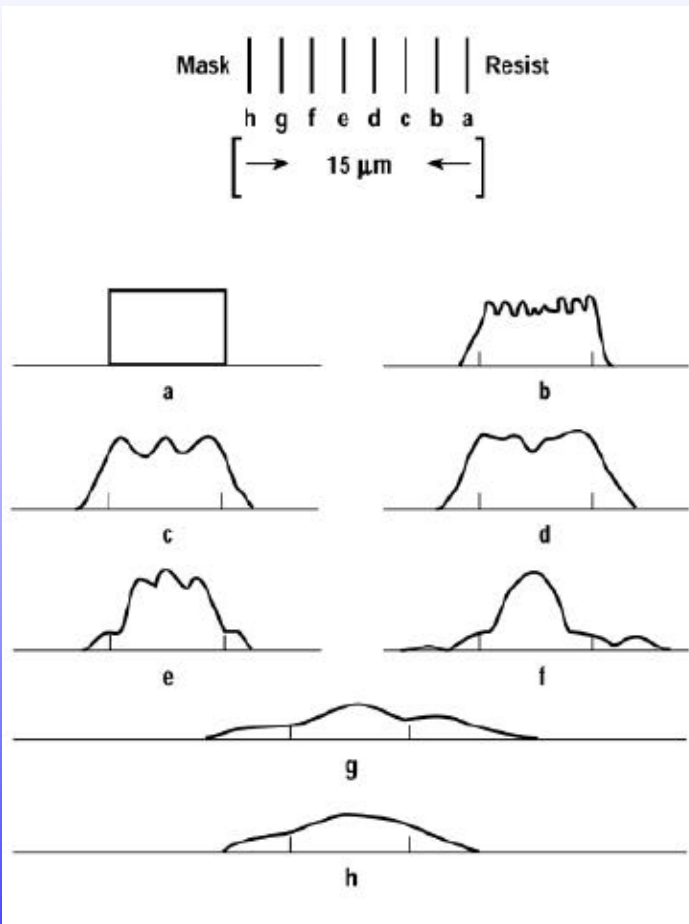
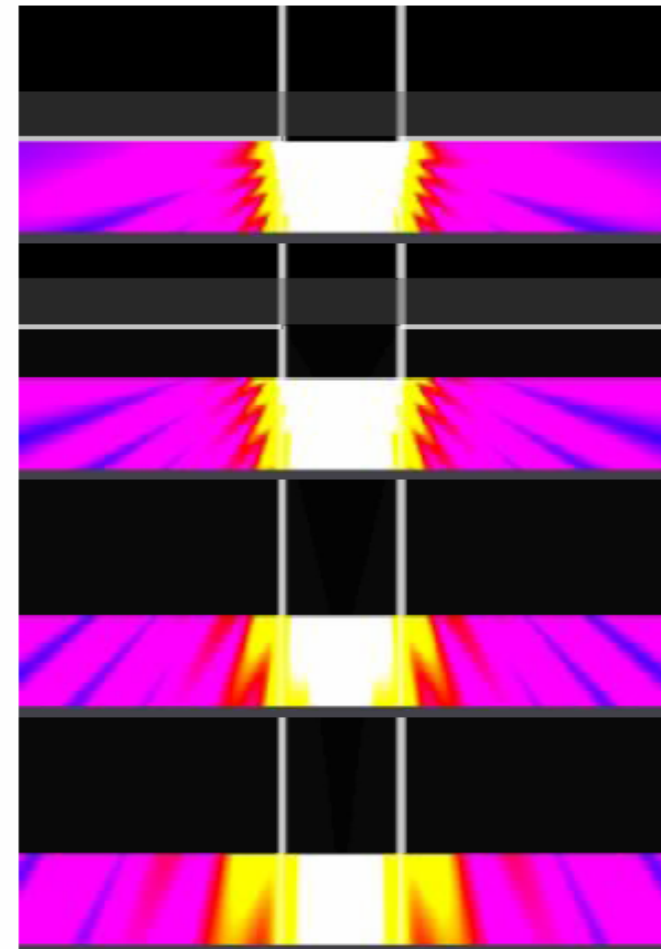


Figure 7.16 Intensity as a function of position on the wafer for a proximity printing system where the gap increases linearly from $g = 0$ to $g = 15$ mm (after Geikas and Ables).



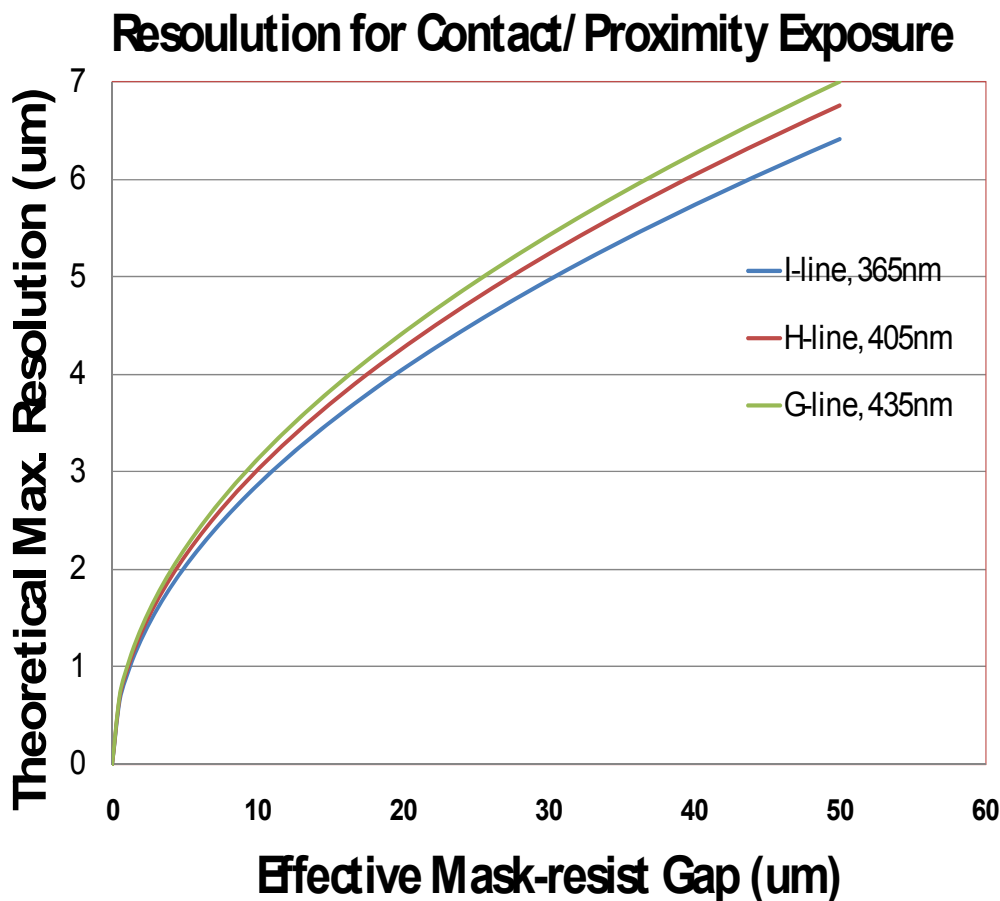
Light intensity distribution in a photo resist film (cross section) with a - from top to bottom - increasing gap between mask and resist film.



Resolution Limit and Profile Control

– Mask-resist Gap

Gap between mask and resist



Resolution for
Contact/proximity
exposure:

$$b = 1.5\sqrt{\lambda(s + 0.5d)} = 1.5\sqrt{\lambda g}$$

Effective mask-resist gap:

$$g = s + 0.5d$$

Example

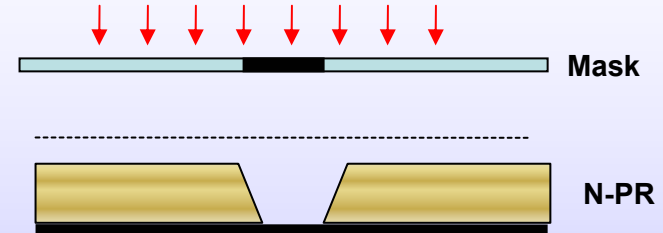
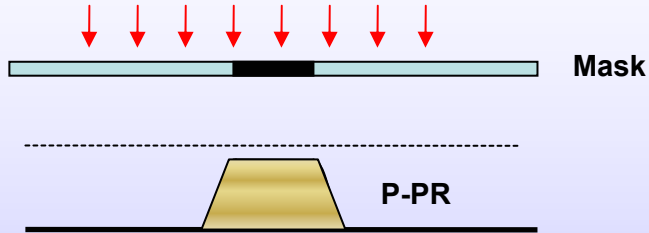
$$\begin{aligned}\lambda &= 435 \text{ nm (g-line)} \\ d &= 0.5 \text{ } \mu\text{m} \\ s &= 10 \text{ } \mu\text{m}\end{aligned}$$

b (contact)	~ 0.5 μm
b (Proximity)	~ 2.6 μm

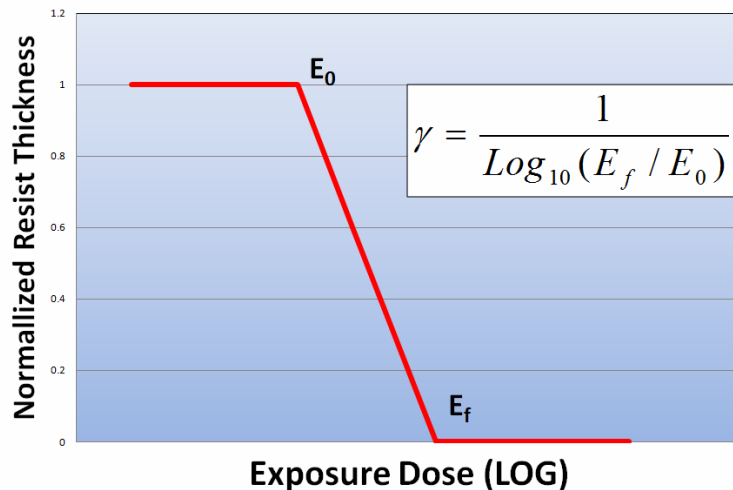


Resolution Limit and Profile Control

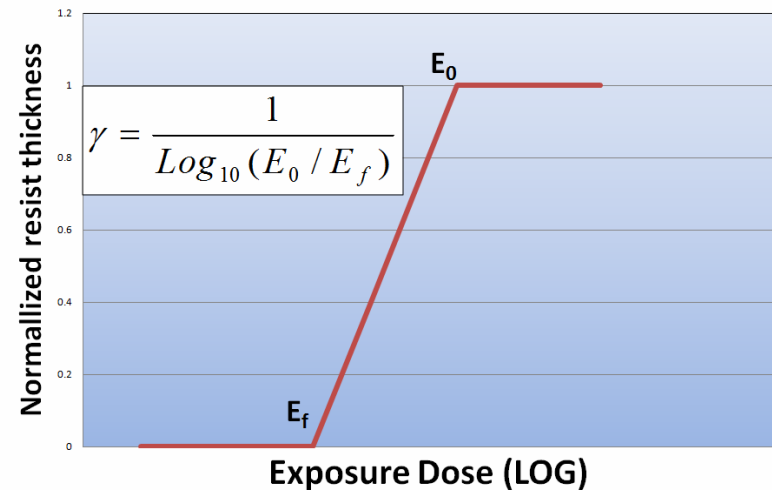
- PR Contract (1)



Positive PR



Negative PR



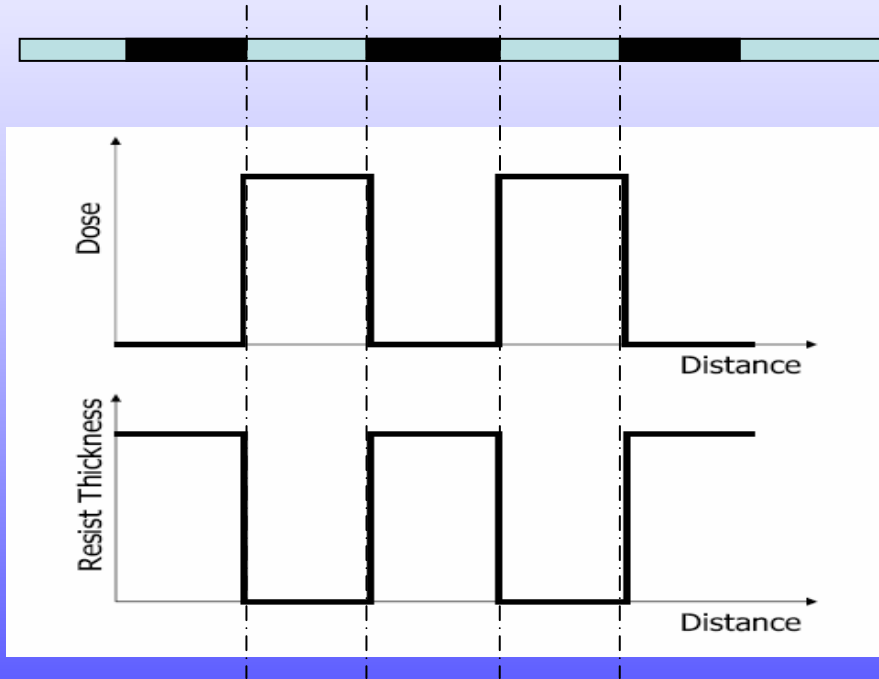
- γ , Photoresist Contrast.
- E_0 - disolution dose, E_f - Resist sensitivity, 100% solution dose
- Ideal: a) $E_0 \sim E_f$ step function, $\gamma \sim \infty$, b) E_f small
- Reality, $\gamma \sim 5-8$



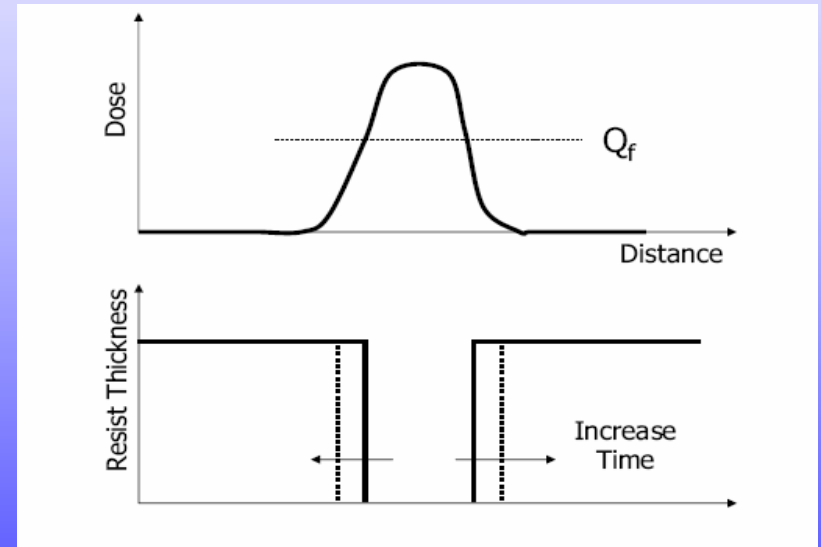
Resolution Limit and Profile Control

- PR Contract (2)

Ideal Exposure - Ideal Resist



Real Exposure - Ideal Resist



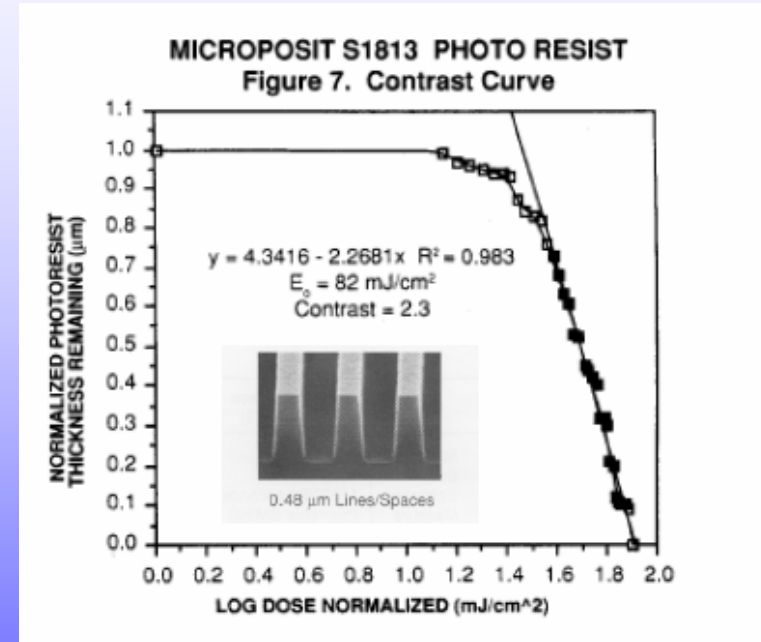
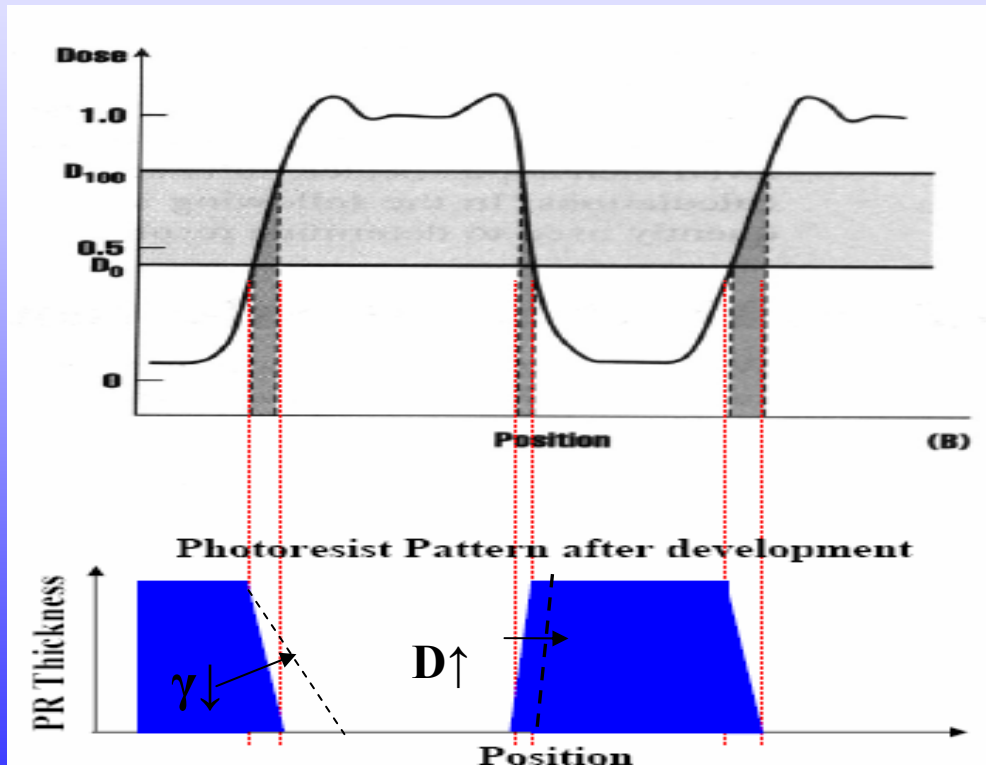


Resolution Limit and Profile Control

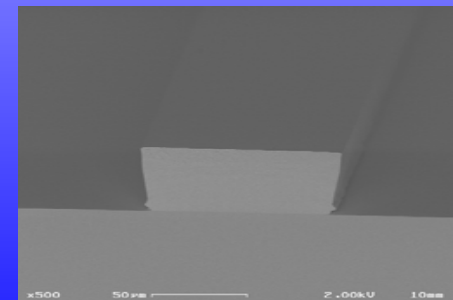
- PR Contract (3)

Real Exposure - Real Resist (positive)

mask



N-PR
→
Su-8-2025





Resolution Limit and Profile Control

- PR Contract (3)

mask



Resolution and Profile Control

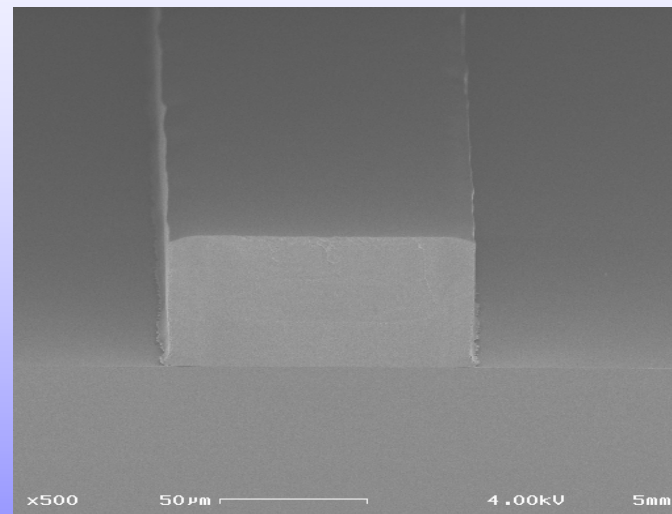
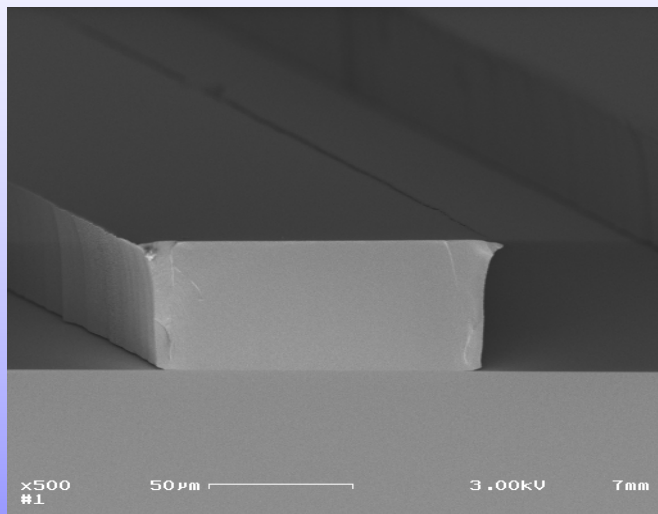
Conditions	Resolution	Profile (Slope)	Adhesion
Exposure Contact Gap ↑	↓	↓	↓
Exposure Dosage ↑	↓	N	Depends on the feature density, PR type, thickness
PR contrast ↑	↑	↑	N
Softbaking temperatue/time ↑	↑	↑	↑
Development ↑	↑	↑	↓



Resolution Limit and Profile Control

- PR Absorption (1)

- Trick: Short wavelength effect (add 360 LP filter)



Conditions

- SU-8, 2050, ~47µm
- Dosage ~310 mJ/cm²
- 6 min develop

Conditions

- SU-8, 2050, ~45µm
- **add 360nm LP filter**
- Dosage ~330 mJ/cm²
- 6 min develop

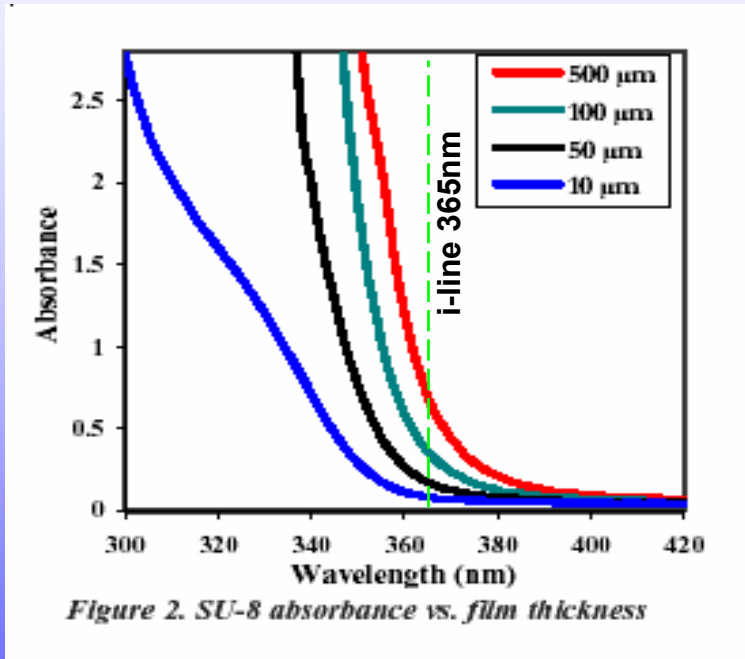
Jiangdong Deng, "Soft-Lithography-summary-2-1-06-user-meeting-02", SLF at Harvard CNS



Resolution Limit and Profile Control

- PR Absorption (2)

- Short wavelength effect

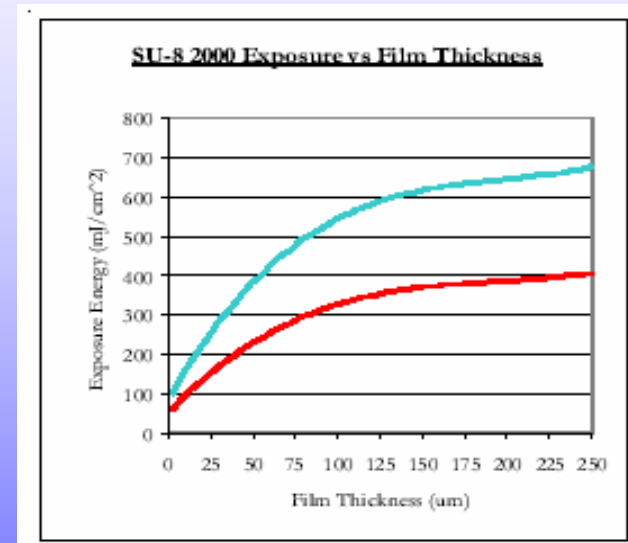


SU-8 Strong absorption in N-UV region:

- 1) Reduce the light penetrating depth
- 2) Cure the surface faster

→ T-shape profile

- Exposure dosage curve



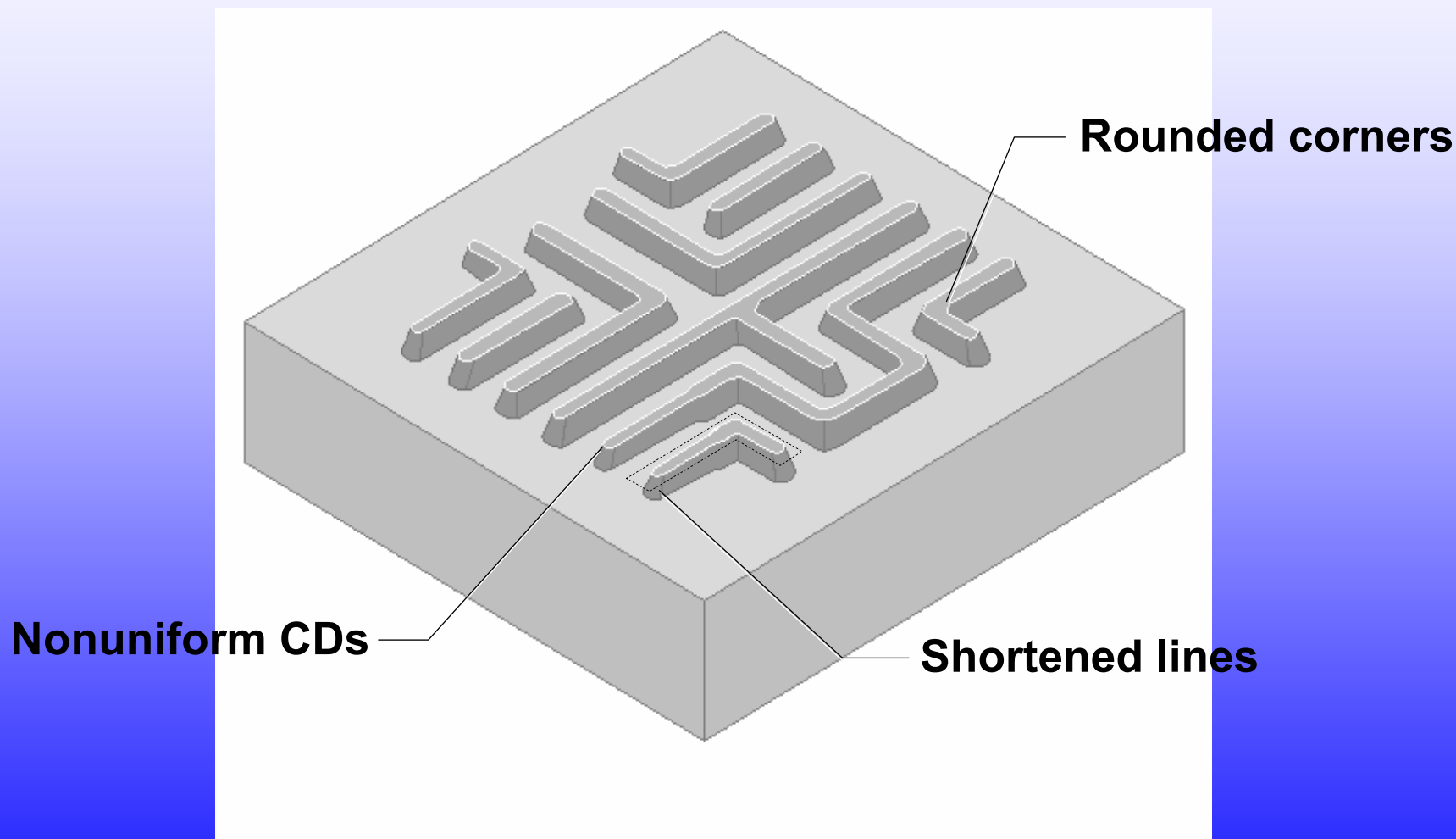
- 1) The H-end curve for non-reflective substrate;
- 2) The L-end curve for reflective substrate
- 3) Over exposure will cause a hard skin formation at the SU-8 surface

→ T-shape profile



Resolution Limit and Profile Control

- Optical Proximity Effect (1)

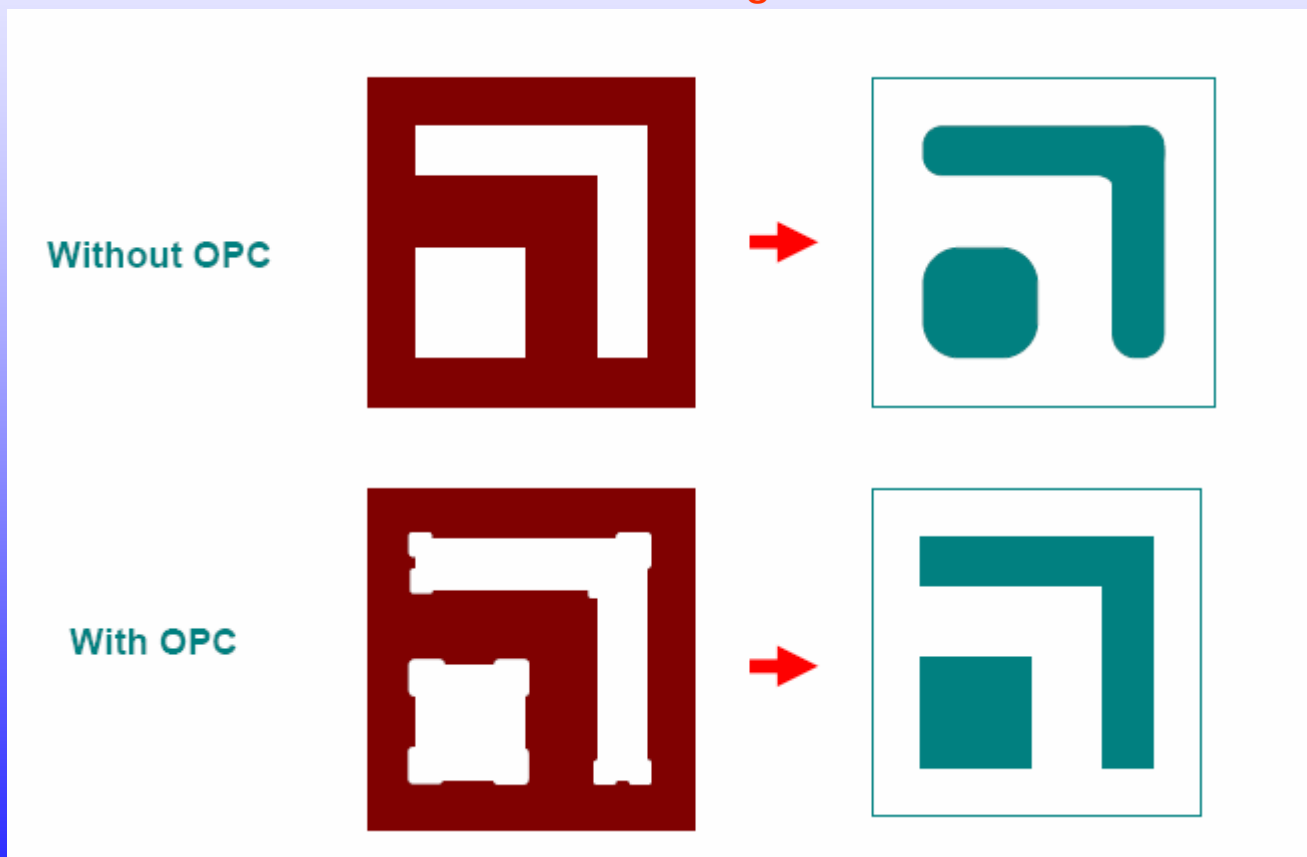




Resolution Limit and Profile Control

- Optical Proximity Effect (2)

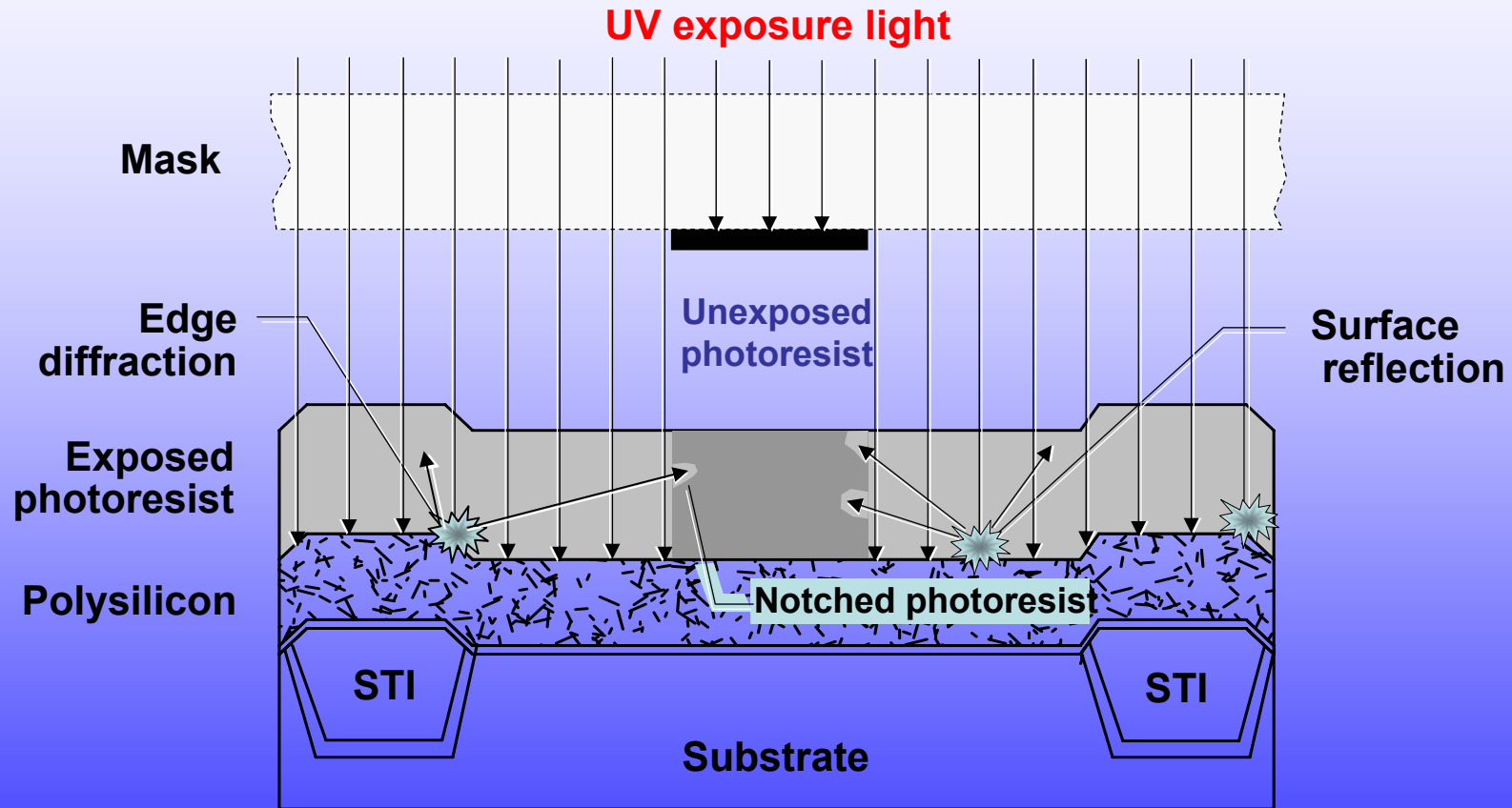
Trick: Optical Proximity Correction (OPC) in Photomask design





Resolution Limit and Profile Control

- Light Reflections Effects (1)

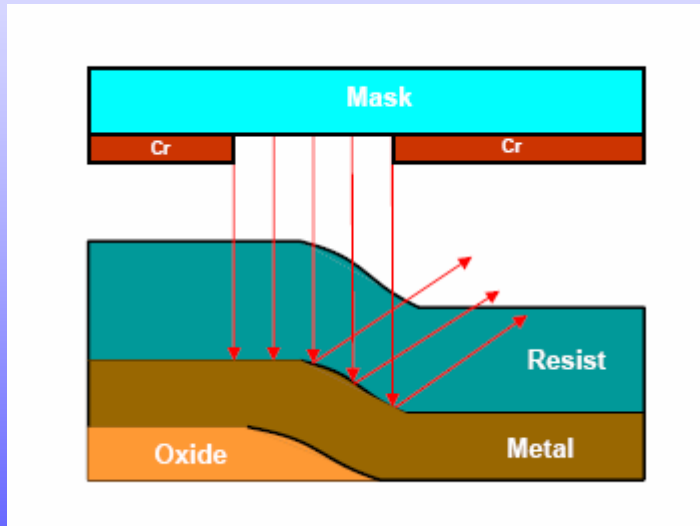




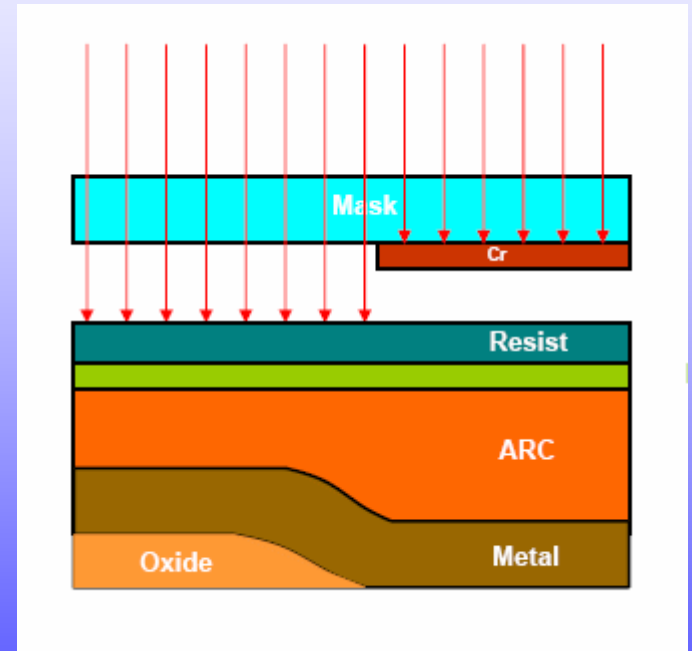
Resolution Limit and Profile Control

- Light Reflections Effects (2)

Trick: Planarization



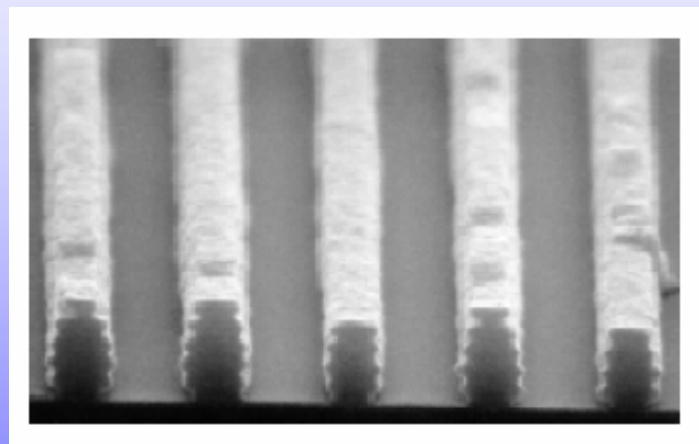
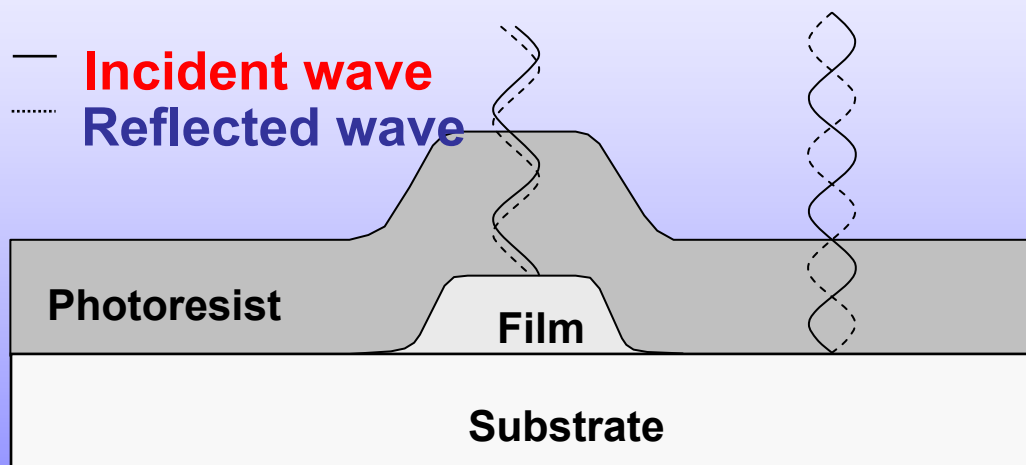
→
Planarization





Resolution Limit and Profile Control

- Standwave Effects



Standing waves cause non-uniform exposure along the thickness of the photoresist film.

Solution Trick: B-ARC (Bottom Anti-Reflection Coating)
polymer type, dielectric multilayer...



Summary

- **Challenge Photolitho process:**

- High resolution ($<1\mu\text{m}$), with
- High aspect ratio ($>5:1$), and
- Dense patterns

- **Keys to 'good exposure'**

- 1) Right photoresist

- 2) **Right Dosage**

- Thickness, substrate, feature size and density

- 3) **Good contact!!!**

- Uniform PR film, particle/defect control, pre-patterns, right exposure contact control...



References

- ‘Microlithography- Science and Technology’, Jams Sheats and Bruce Smith, Marcel-Dekker, 1998
- ‘Silicon Processing for the VLSI Era, V1, process technology’, Stanley Wolf, Lattice Press., 1987
- ‘Silicon VLSI Technology- Fundamentals, Practice and Modeling’, James Plummer, M Deal, P. Griffin, Prentice Hall press, 2000
- ‘Photoressit’, W.S. Deforest, ‘McGraw Hill (1975)
- Jiangdong Deng, “Soft-Lithography-summary-2-1-06-user-meeting-02”, SLF at Harvard CNS (2005)