ELECTRONICKS
Design Division

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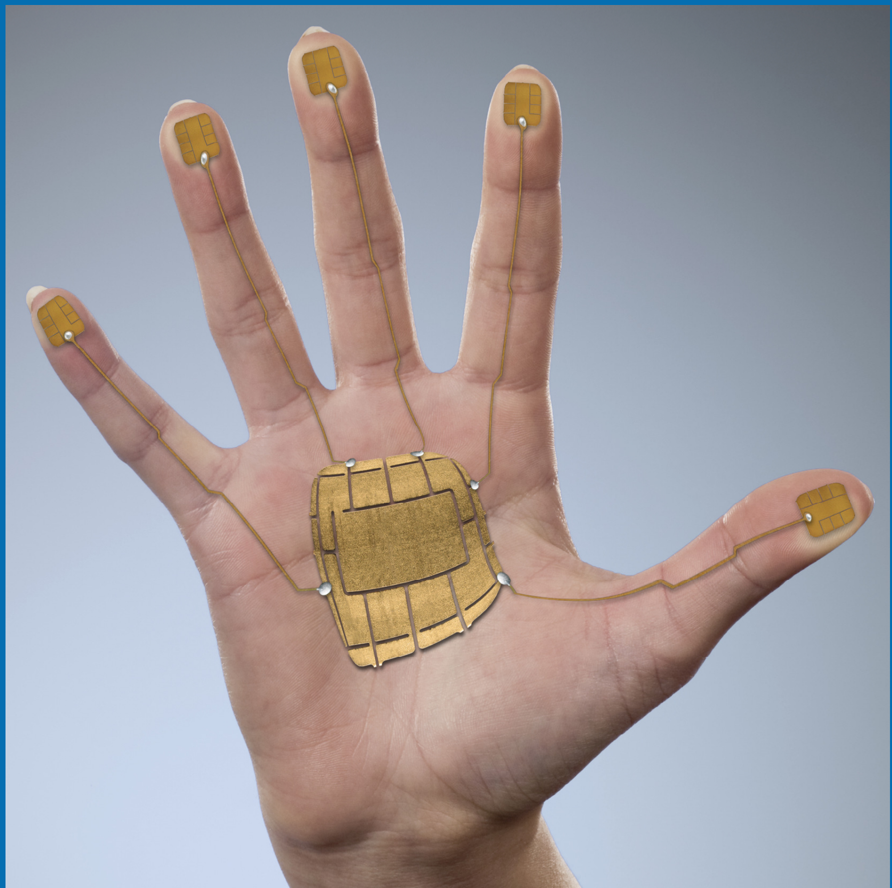
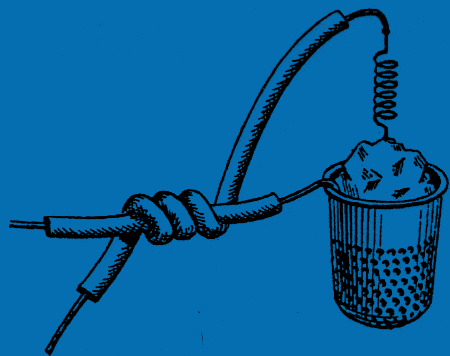
SENSOR DEVICES





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OUTLINE

- Planning
- Lecture 1
    - 1 Classification and terminology of sensors
    - 2 Semiconductor Sensor Technologies
- Lecture 2
    - 2 Semiconductor Sensor Technologies (cont.)

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COURSE ACTIVITIES

- 10 LECTURES
- LABORATORY WORK, WRITTEN REPORTS
  - Attend scheduled class!
  - Trondheim students have local laboratory work, HIST is responsible
- WRITTEN EXAM IN JANUARY
- ISBN 0-471-54609-7 “Semiconductor sensors” S.M.Sze
- http://apachepersonal.miun.se/~bornor/sensor/

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LECTURE PLAN

- L1 CLASSIFICATION AND TERMINOLOGY OF SENSORS
- L2 SEMICONDUCTOR SENSOR TECHNOLOGIES
- L3 ACOUSTIC SENSORS
- L4 MECHANICAL SENSORS
- L5 MAGNETIC SENSORS
- L6 RADIATION SENSORS
- L7 THERMAL SENSORS
- L8 CHEMICAL SENSORS
- L9 BIOSENSORS AND INTEGRATED SENSORS

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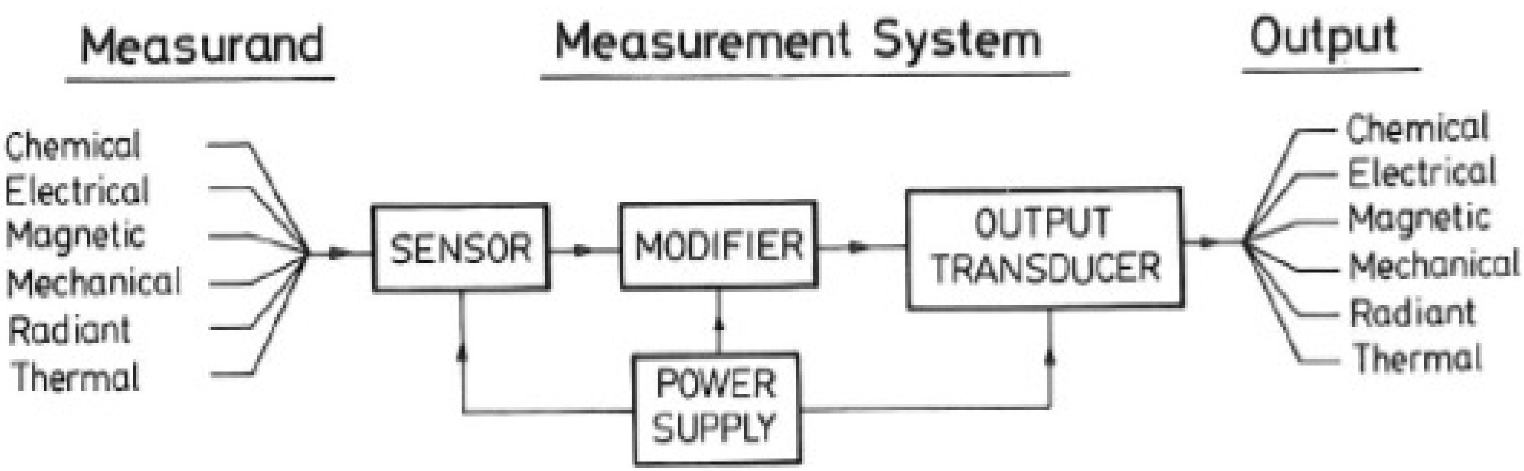
CLASSIFICATION AND TERMINOLOGY OF SENSORS



THE SENSOR PRODUCE IN MOST CASE AN ELECTRICAL SIGNAL

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TABLE 1 Measurands[5]

1. **Acoustic**
   - 1.1 Wave amplitude, phase, polarization, spectrum
   - 1.2 Wave velocity
   - 1.3 Other (specify)
2. **Biological**
   - 2.1 Biomass (identities, concentrations, states)
   - 2.2 Other (specify)
3. **Chemical**
   - 3.1 Components (identities, concentrations, states)
   - 3.2 Other (specify)
4. **Electric**
   - 4.1 Charge, current
   - 4.2 Potential, potential difference
   - 4.3 Electric field (amplitude, phase, polarization, spectrum)
   - 4.4 Conductivity
   - 4.5 Permittivity
   - 4.6 Other (specify)
5. **Magnetic**
   - 5.1 Magnetic field (amplitude, phase, polarization, spectrum)
   - 5.2 Magnetic flux
   - 5.3 Permeability
   - 5.4 Other (specify)

6. Mechanical
- 6.1 Position (linear, angular)
- 6.2 Velocity
- 6.3 Acceleration
- 6.4 Force
- 6.5 Stress, pressure
- 6.6 Strain
- 6.7 Mass, density
- 6.8 Moment, torque
- 6.9 Speed of flow, rate of mass transport
- 6.10 Shape, roughness, orientation
- 6.11 Stiffness, compliance
- 6.12 Viscosity
- 6.13 Crystallinity, structural integrity
- 6.14 Other (specify)

7. Optical
- 7.1 Wave amplitude, phase, polarization, spectrum
- 7.2 Wave velocity
- 7.3 Other (specify)

8. Radiation
- 8.1 Type
- 8.2 Energy
- 8.3 Intensity
- 8.4 Other (specify)

9. Thermal
- 9.1 Temperature
- 9.2 Flux
- 9.3 Specific heat
- 9.4 Thermal conductivity
- 9.5 Other (specify)

10. Other (specify)

TABLE 2 Technological Aspects, Detection Means and Conversion Phenomena of Sensors[5]

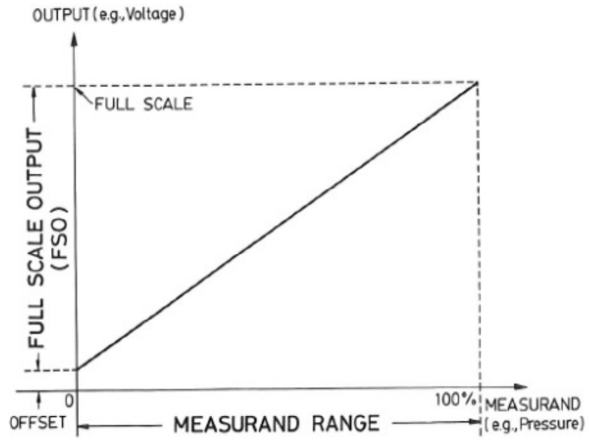
Technological Aspects	Detection Means	Conversion Phenomena
1. Ambient conditions allowed	1. Biological	1. Biological
2. Full-scale output	2. Chemical	1.1 Biochemical transformation
3. Hysteresis	3. Electric, magnetic, or electromagnetic wave	1.2 Physical transformation
4. Linearity	4. Heat, temperature	1.3 Effects on test organism
5. Measured range	5. Mechanical displacement or wave	1.4 Spectroscopy
6. Offset	6. Radioactivity, radiation	1.5 Others (specify)
7. Operating life	7. Others (specify)	2. Chemical
8. Output format		2.1 Chemical transformation
9. Overload characteristics		2.2 Physical transformation
10. Repeatability		2.3 Electrochemical process
11. Resolution		2.4 Spectroscopy
12. Selectivity		2.5 Others (specify)
13. Sensitivity		3. Physical
14. Speed of response		3.1 Thermoelectric
15. Stability		3.2 Photoelectric
16. Others (specify)		3.3 Photomagnetic
		3.4 Magnetoelectric
		3.5 Elastomagnetic
		3.6 Thermoelastic
		3.7 Elastoelectric
		3.8 Thermomagnetic
		3.9 Thermo-optic
		3.10 Photoelastic
		3.11 Others (specify)

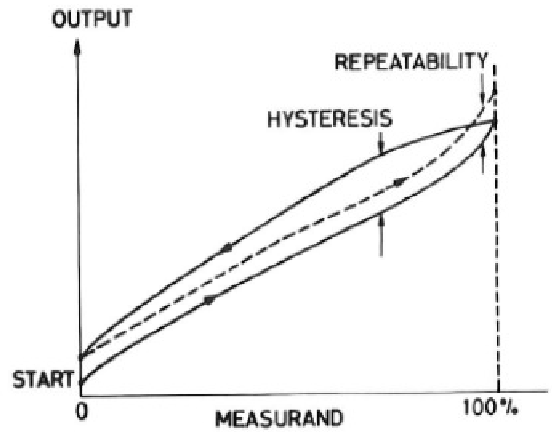
SENSOR CHARACTERIZATION

- Hysteresis
- Linearity
- Measurand Range
- Offset
- Operating Life
- Output Format
- Overload Characteristics
- Repeatability
- Resolution
- Selectivity
- Sensitivity
- Speed of Response
- Stability

Ambient Conditions Allowd

Full Scale Output (FSO)





SENSOR
EVOLUTION EXAMPLE

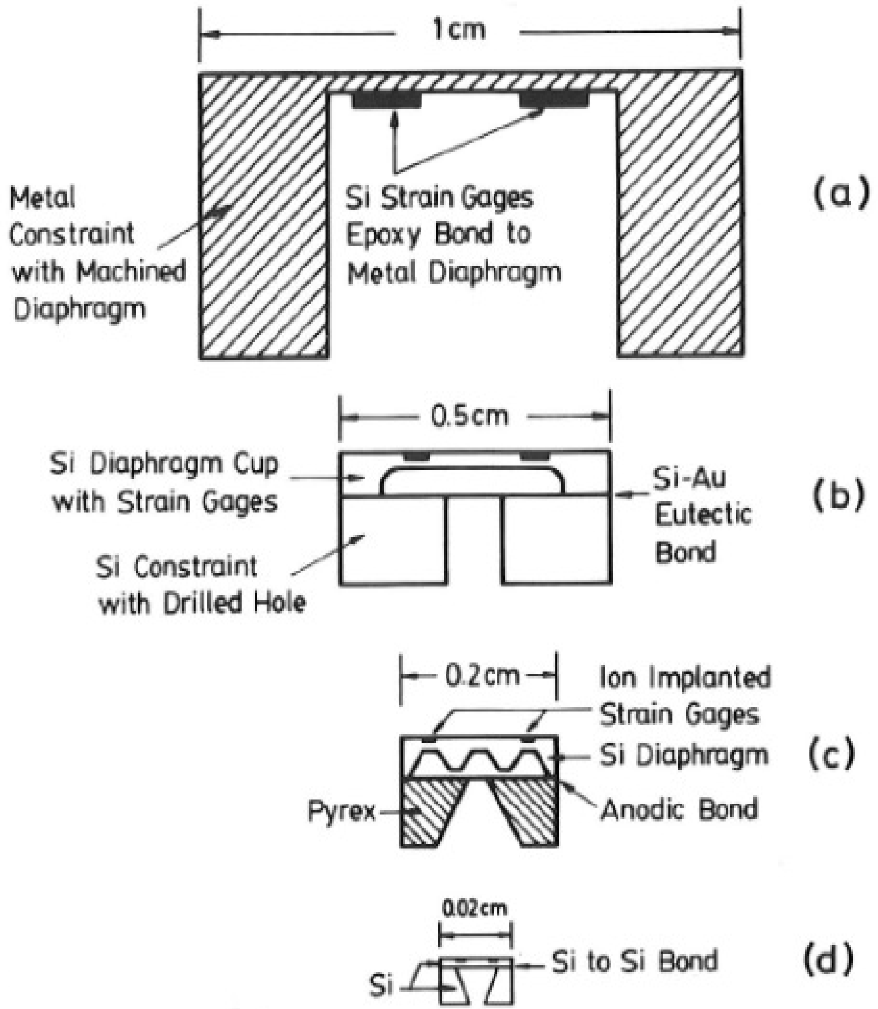


Fig. 5 Evolution of diaphragm pressure sensors. (After Ref. 11)

1958 Discovery phase

1965 Basic Technology Development phase

1975 Batch process phase

1985 Micromachining phase

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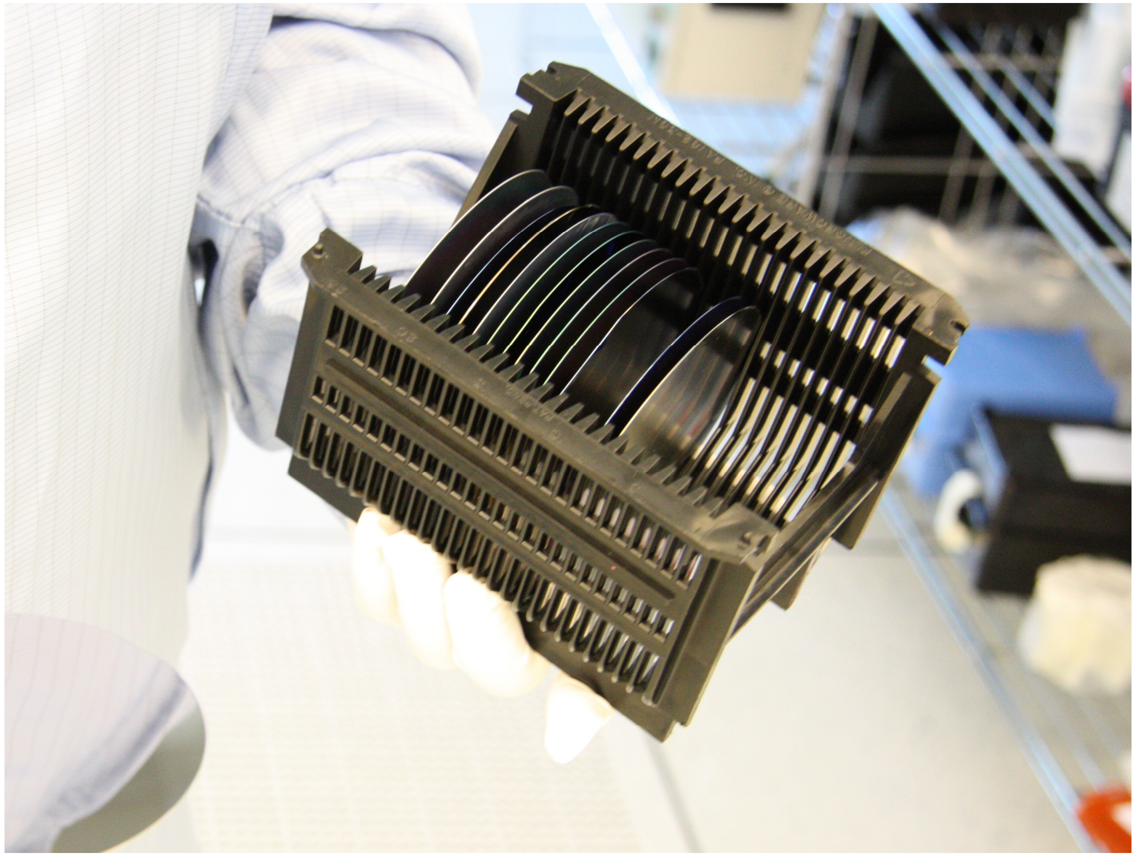
- The scope of the course is to give an introduction of sensors in semiconductor and sensors on semiconductor.
- The most important and best developed processing is by using silicon technology.
- Important is also to understand the most basic conversion techniques and how the sensors are processed/ manufactured.
- Moreover, which type of sensor should be used in a particular situation is of importance

SEMICONDUCTOR SENSOR TECHNOLOGIES

CHAPTER 2



SEMICONDUCTOR SENSOR TECHNOLOGIES

Advantage with silicon processing

- Well developed processing technology, where the microprocessor and memory manufactures have pushed the technology to a sub µm scale.
- Batch processing result in a large numbe of sensors fabricated simultaneously at a low cost.

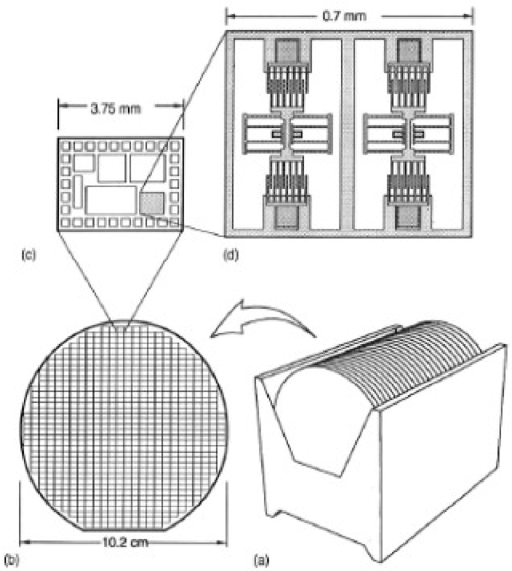


Fig. 2 Batch-fabrication process of microelectronic circuits.

SEMICONDUCTOR SENSOR TECHNOLOGIES

- Modern Semiconductor technology are based on planar techniques, i.e. 3 dimensional devices are built using stacked layer with different 2 dimensional pattern.
- Surface –micro machined sensor are based on planar techniques
- However, Bulk- micro machined sensor are primarily constructed made by accurate machining of relative thick substrates

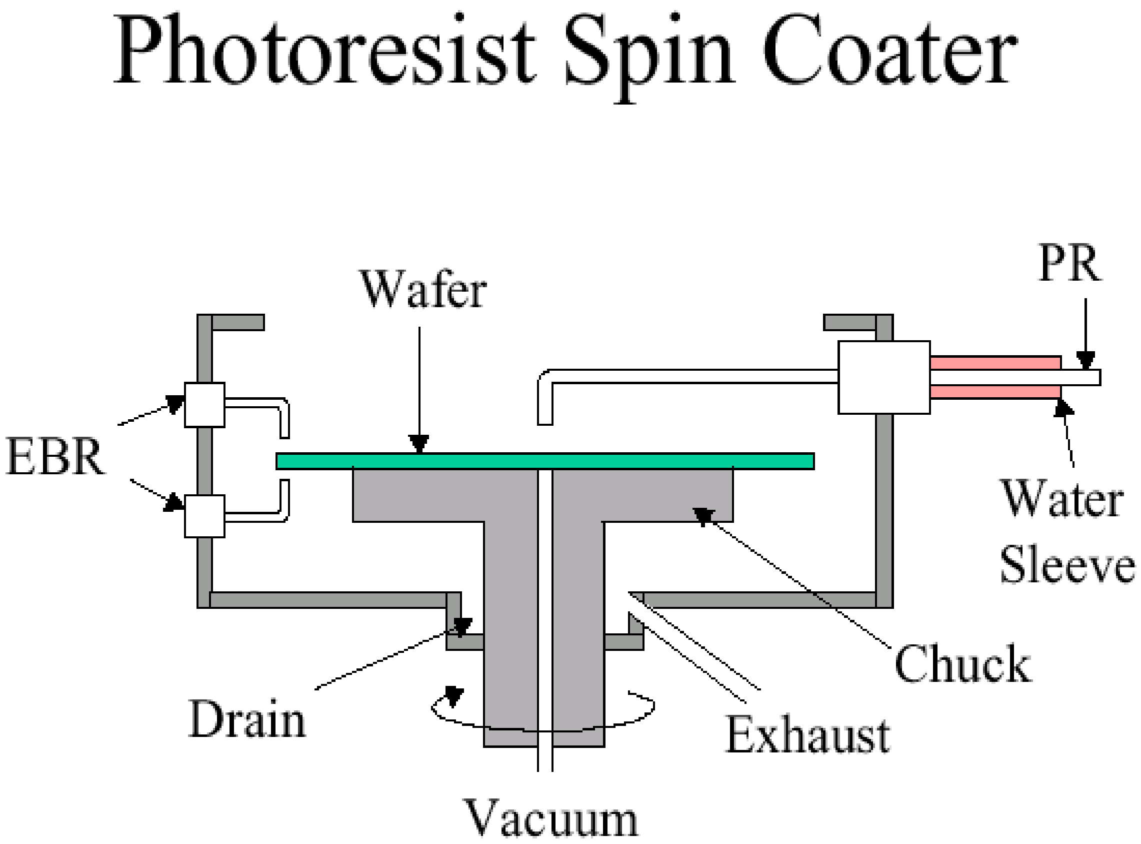
SEMICONDUCTOR SENSOR TECHNOLOGIES

- IMPORTANT PROCESSING STEPS TO FABRICATE A SENSOR ARE
  - Deposition
  - Lithography
  - Etching

SEMICONDUCTOR SENSOR TECHNOLOGIES

- BASIC FABRICATION STEPS
  - Deposition
    - Spin Casting
    - Evaporation
    - Sputtering
    - Reactive growth
    - Chemical Vapour deposition
    - Plasma deposition

SPIN CASTING



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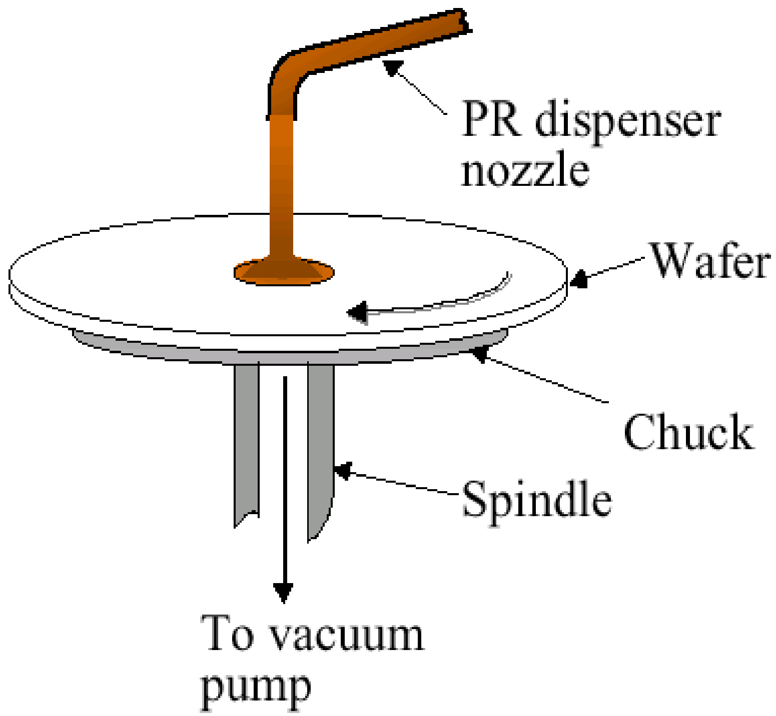
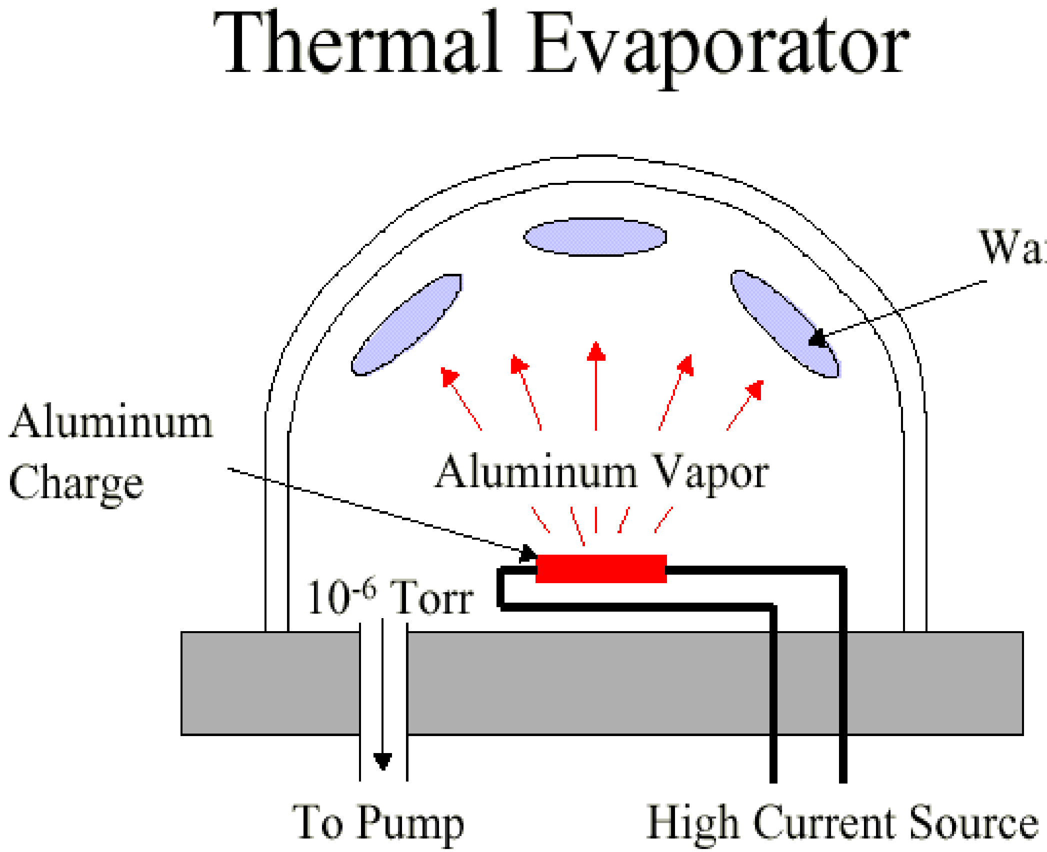
SPIN CASTING

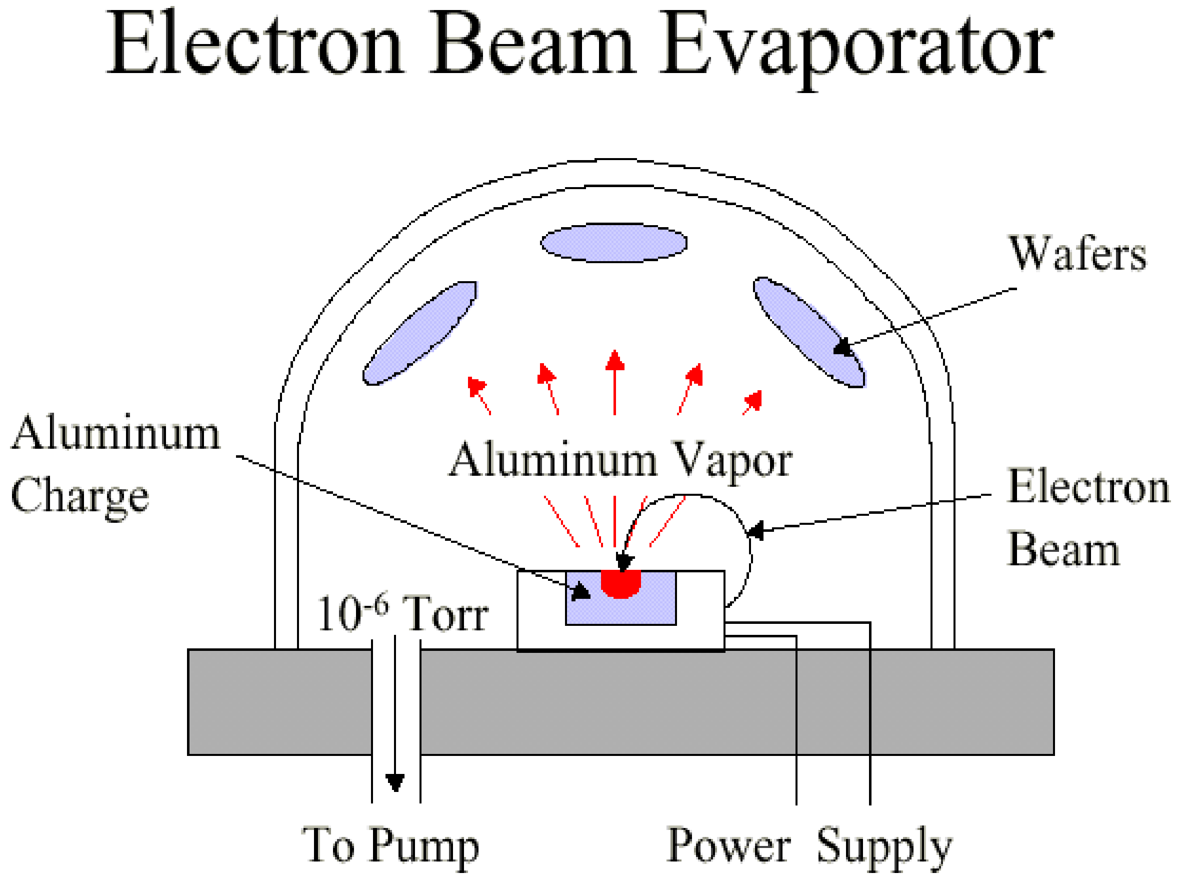
Photoresist Applying



EVAPORATION

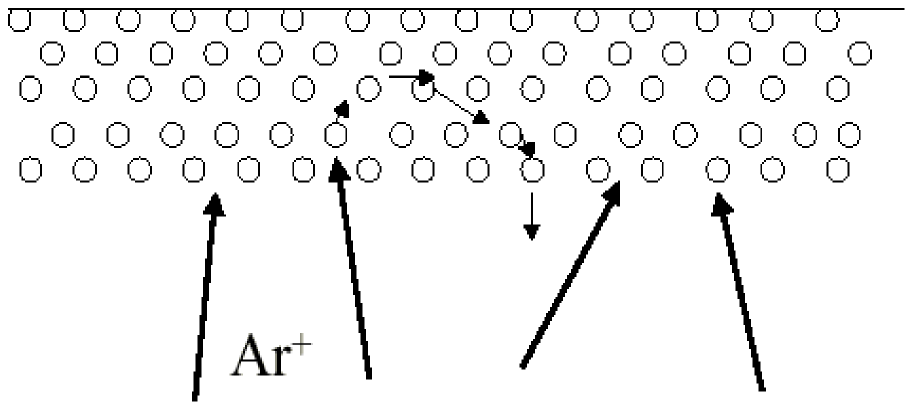


EVAPORATION



SPUTTERING

Sputtering



Momentum transfer will dislodge surface atoms off

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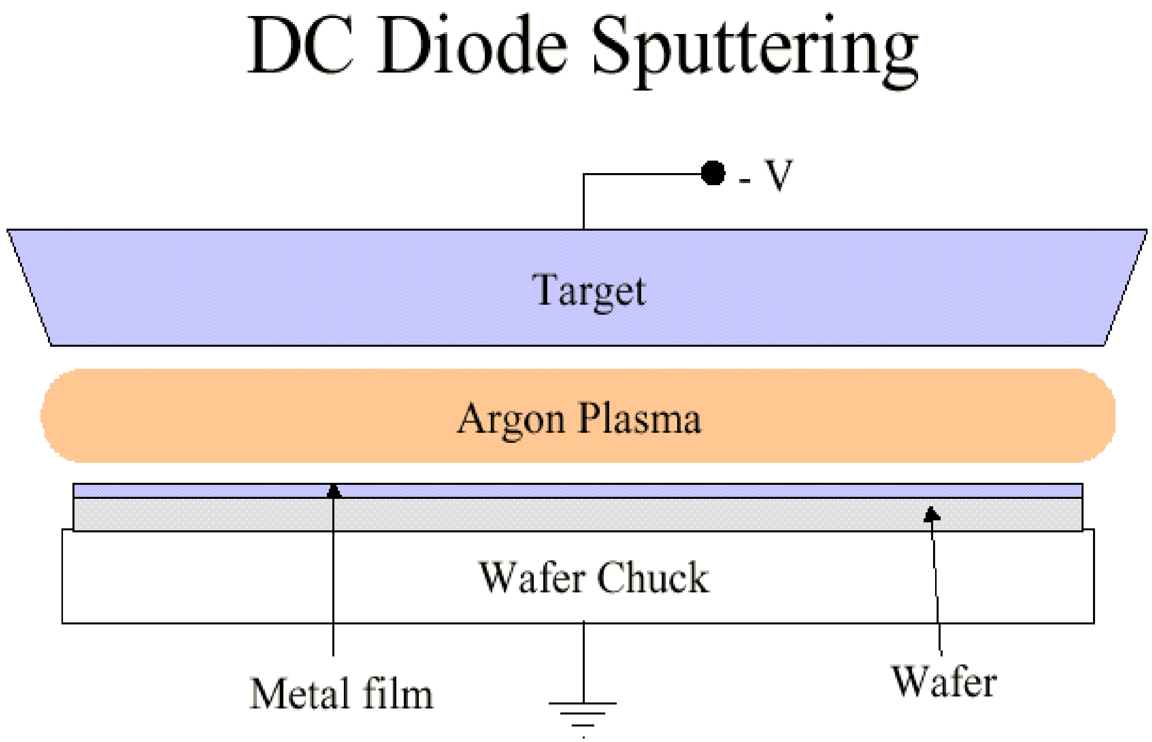

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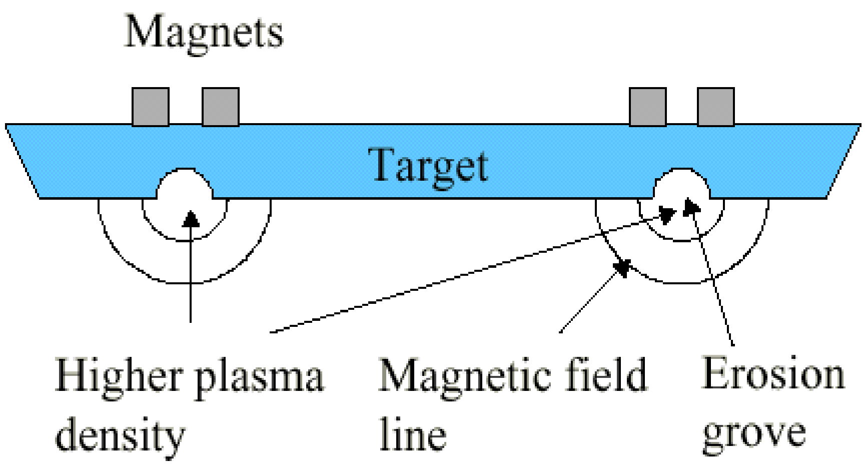
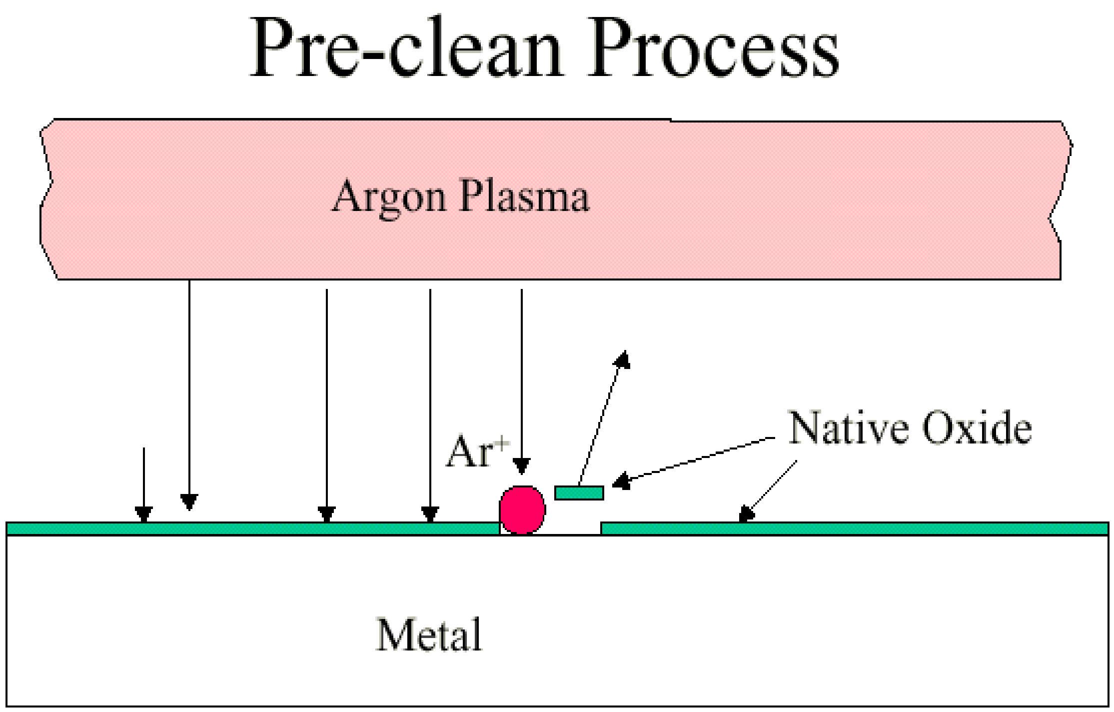
SPUTTERING

Schematic of Magnetron Sputtering



SPUTTERING



REACTIVE GROWTH

MATERIAL: SILICON

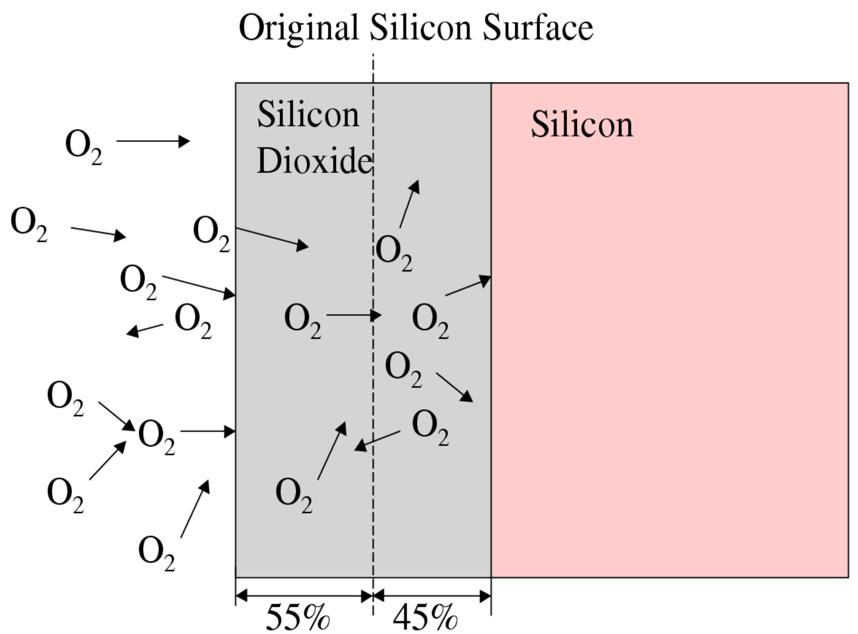
Growth of silicon dioxide, SiO_2

Introduction

- Silicon reacts with oxygen
- Stable oxide compound
- Widely used in IC manufacturing

$$Si + O_2 \rightarrow SiO_2$$

Oxidation



ong Xiao, Ph. D. 41

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REACTIVE GROWTH

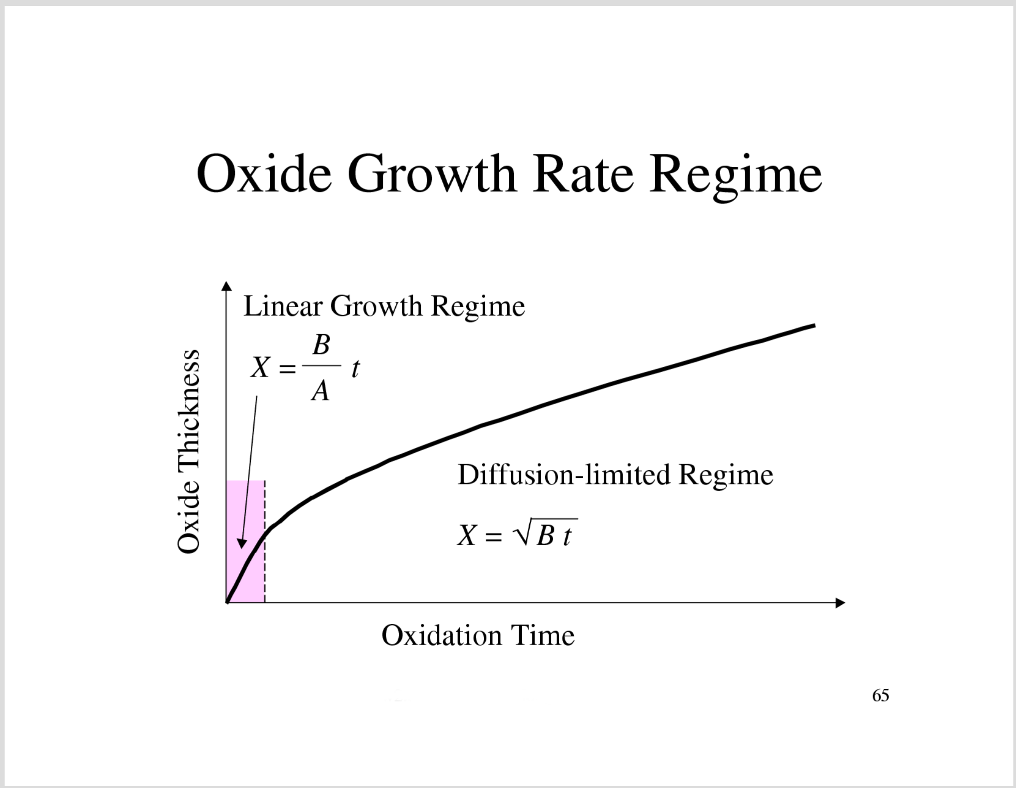
Application of Oxidation

- Diffusion Masking Layer
- Surface Passivation
  - Screen oxide, pad oxide, barrier oxide
- Isolation
  - Field oxide and LOCOS
- Gate oxide
- Etching mask

Oxidation Mechanism

- $Si + O_2 \longrightarrow SiO_2$
- Oxygen comes from gas
- Silicon comes from substrate
- Oxygen diffuse cross existing silicon dioxide layer and react with silicon
- The thicker of the film, the lower of the growth rate

REACTIVE GROWTH



- OXIDATION
  - Dry oxidation "pure O_2"
  - Wet oxidation
    - "Water steam" pyrolysis of H_2 in a O_2-ambient

REACTIVE GROWTH

Result of the Deal-Grove model for growth of silicon dioxide

$$\tau = \frac{x_i^2 + Ax_i}{B} \qquad x_i \approx 0.02\mu m \, (200\text{Å})$$

$$X_0 = \frac{A}{2}\left[\sqrt{1 + \frac{t+\tau}{A^2/4B}} - 1\right]$$

$$B = C_1 e^{-E_1/kT} \quad \textit{parabolic growth}$$

$$\frac{B}{A} = C_2 e^{-E_2/kT} \quad \textit{linear growth}$$

REACTIVE GROWTH

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Table 6–2 Rate constants describing (111) silicon oxidation kinetics at 1 Atm total pressure. For the corresponding values for (100) silicon, all C_2 values should be divided by 1.68.

Ambient	B	B/A
Dry O_2	$C_1 = 7.72 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 6.23 \times 10^6\ \mu m\ hr^{-1}$
	$E_1 = 1.23$ eV	$E_2 = 2.0$ eV
Wet O_2	$C_1 = 2.14 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 8.95 \times 10^7\ \mu m\ hr^{-1}$
	$E_1 = 0.71$ eV	$E_2 = 2.05$ eV
H_2O	$C_1 = 3.86 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 1.63 \times 10^8\ \mu m\ hr^{-1}$
	$E_1 = 0.78$ eV	$E_2 = 2.05$ eV

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REACTIVE GROWTH

Oxidation Rate

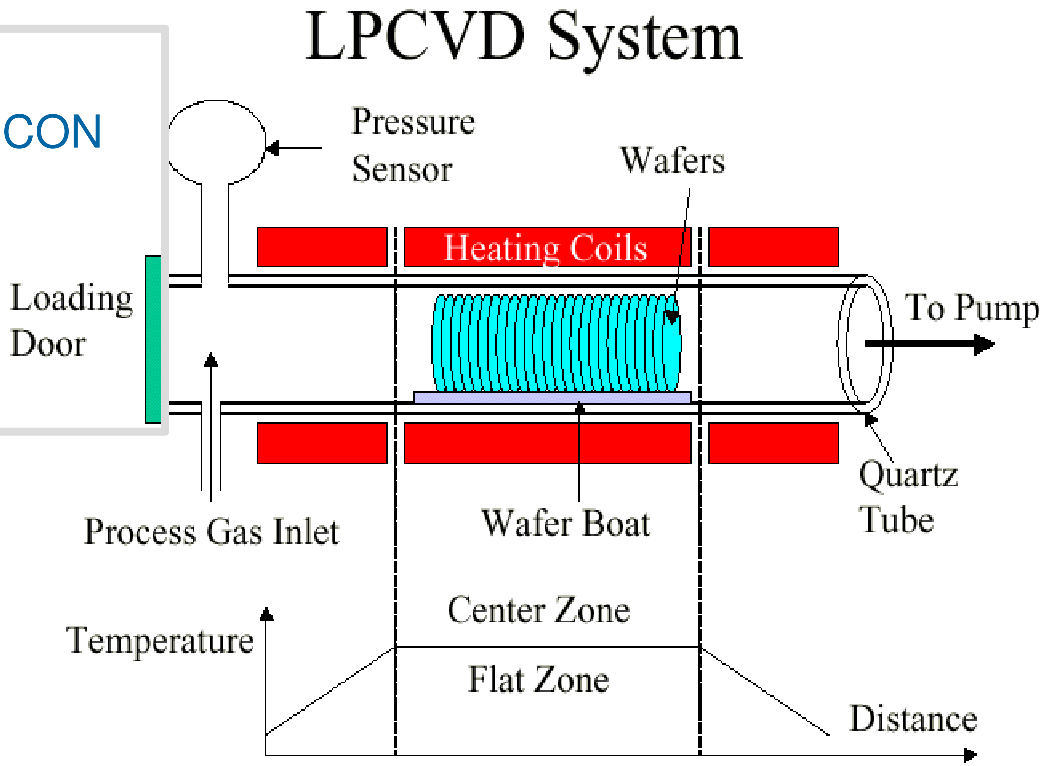
- Temperature
- Chemistry, wet or dry oxidation
- Thickness
- Pressure
- Wafer orientation (<100> vs. <111>)
- Silicon dopant

Oxidation Rate Wafer Orientation

- <111> surface has higher oxidation rate than <100> surface.
- More silicon atoms on the surface.

CHEMICAL VAPOUR DEPOSITION (LOW PRESSURE)

- DEPOSITION OF THIN FILM
- TYPICAL DEPOSITION ON SILICON
  - Polycrystalline silicon
  - Silicon dioxide, SiO_2
  - Silicon nitride, Si_3N_4



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CHEMICAL VAPOUR DEPOSITION (LOW PRESSURE)

LPCVD

- Longer MFP
- Good step coverage & uniformity
- Vertical loading of wafer
- Fewer particles and increased productivity
- Less dependence on gas flow
- Vertical and horizontal furnace

Dielectric CVD Precursors

- Silane (SiH_4)
- TEOS (tetra-ethyl-oxy-silane, $Si(OC_2H_5)_4$)

Sticking Coefficient

- The probability that precursor atom forms chemical bond with surface atom in one collision
- Can be calculated by comparing the calculated deposition rate with 100% sticking coefficient and the measured actual deposition rate

CHEMICAL VAPOUR DEPOSITION (LOW PRESSURE)

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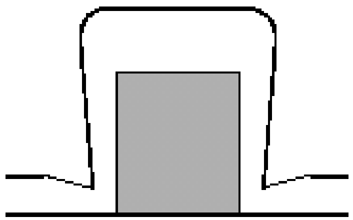
Sticking Coefficient

Precursors	Sticking Coefficient
SiH_4	3×10^{-4} to 3×10^{-5}
SiH_3	0.04 to 0.08
SiH_2	0.15
SiH	0.94
TEOS	10^{-3}
WF_6	10^{-4}

A lower value of sticking coefficient result in a higher surface mobility.

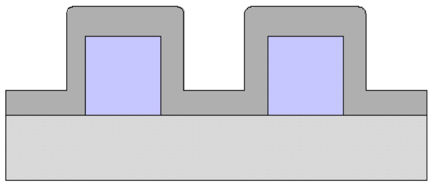
A high value of surface mobility gives a better step covering and a conformal deposition



LPCVD

No mobility

Conformal Deposition Gap Fill



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PLASMA DEPOSITION

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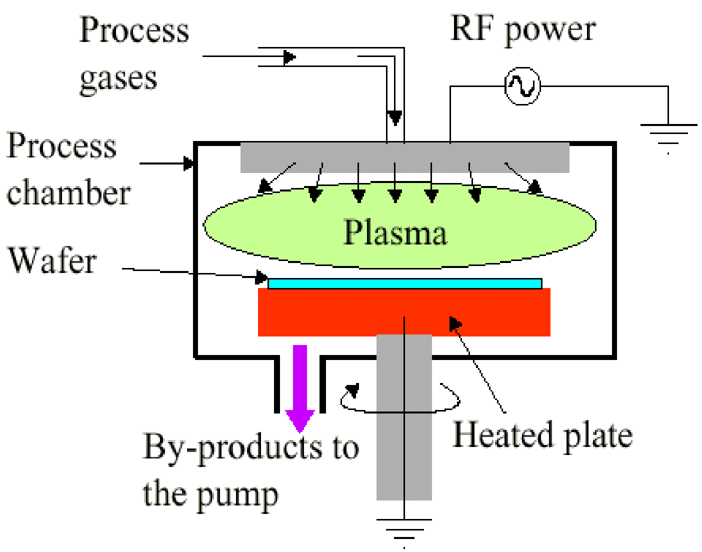
PECVD

- Developed when silicon nitride replaced silicon dioxide for passivation layer.
- High deposition rate at relatively low temp.
- RF induces plasma field in deposition gas
- Stress control by RF
- Chamber plasma clean.

Plasma Enhanced CVD System



Film contains trapped hydrogen, which alter the etching resistance, properties improves after annealing

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SEMICONDUCTOR SENSOR TECHNOLOGIES

- BASIC FABRICATION STEPS
  - –Lithography
    - Mask making
    - Alignment and Exposure
    - Lift-off
  - –Etching
    - Wet chemical etching
    - Dry etching

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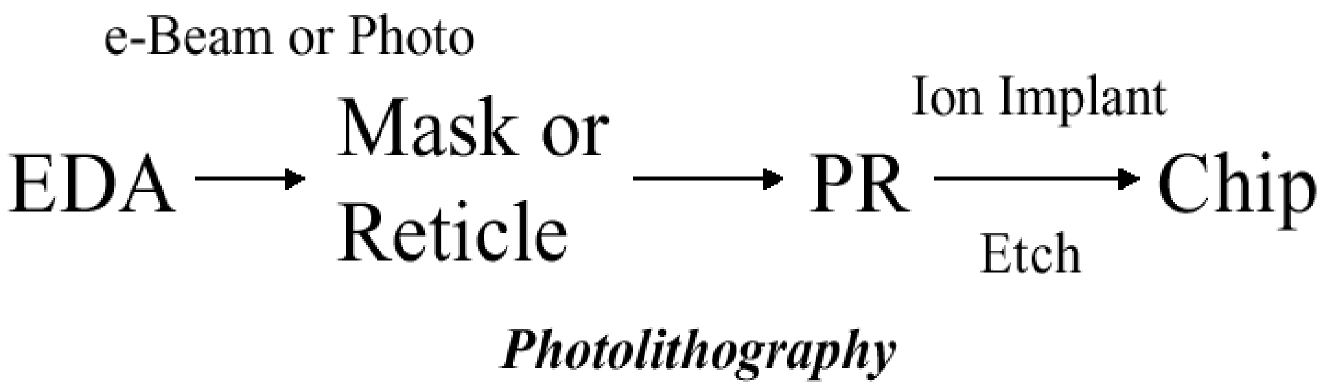
IC Fabrication



EDA: Electronic Design Automation

PR: Photoresist

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Photoresist

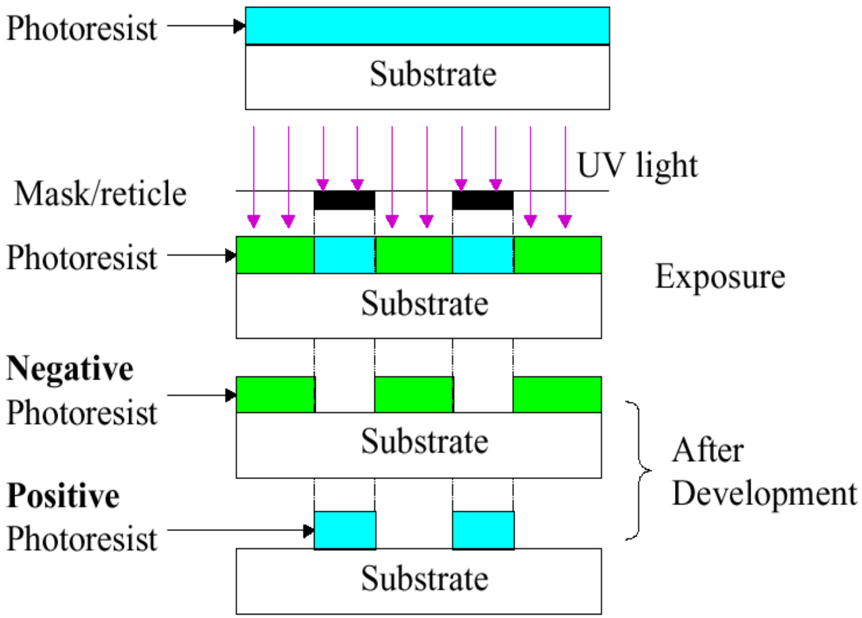
Negative Photoresist

- Becomes insoluble after exposure
- When developed, the unexposed parts dissolved.
- Cheaper

Positive Photoresist

- Becomes soluble after exposure
- When developed, the exposed parts dissolved
- Better resolution

Negative and Positive Photoresists



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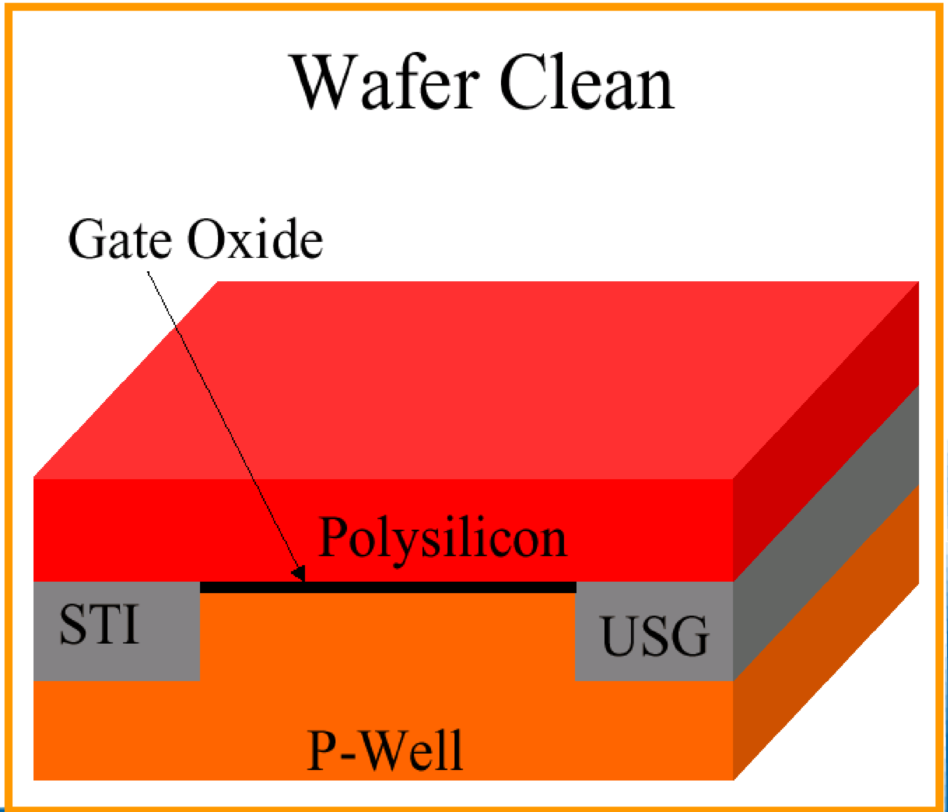
Basic Steps, Advanced Technology

Track-stepper integrated system:

- Wafer clean
- Pre-bake and primer coating
- Photoresist spin coating
- Soft bake
- Alignment and exposure
- Post exposure bake
- Development
- Hard bake
- Pattern inspection

(Wafer clean – Soft bake: PR coating; Post exposure bake – Hard bake: Development)



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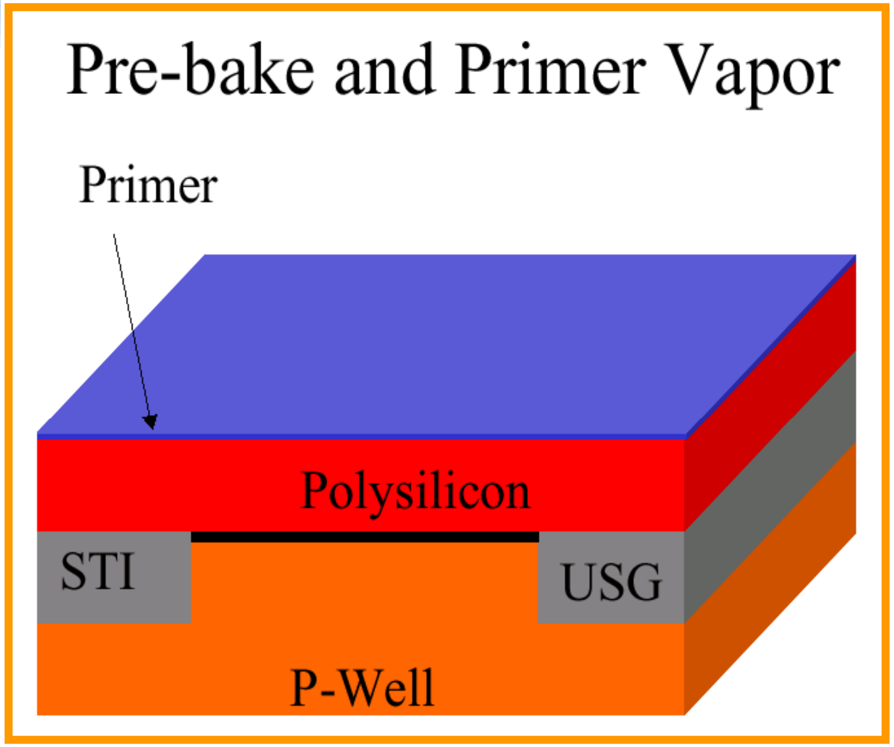

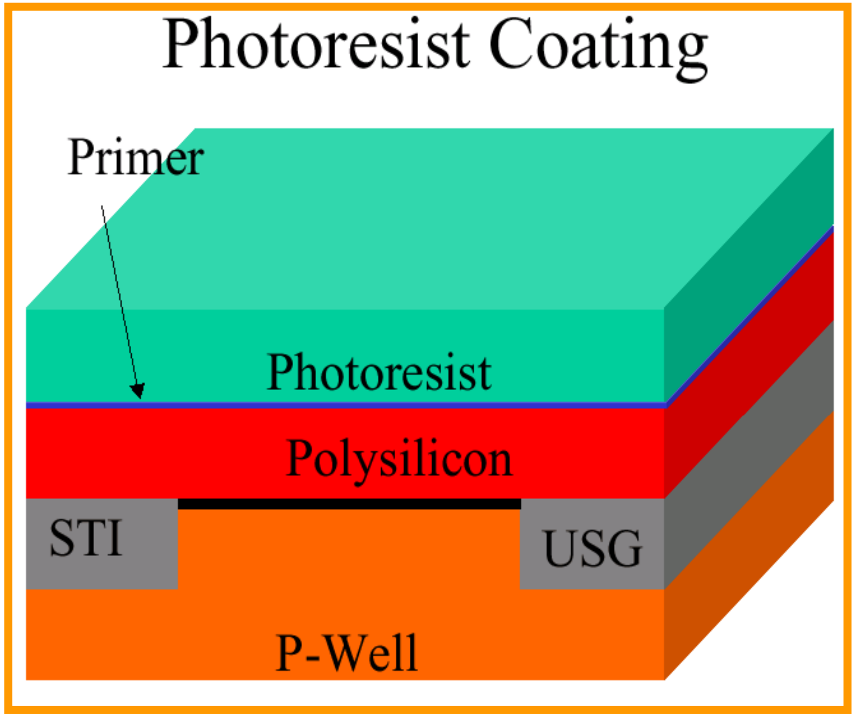

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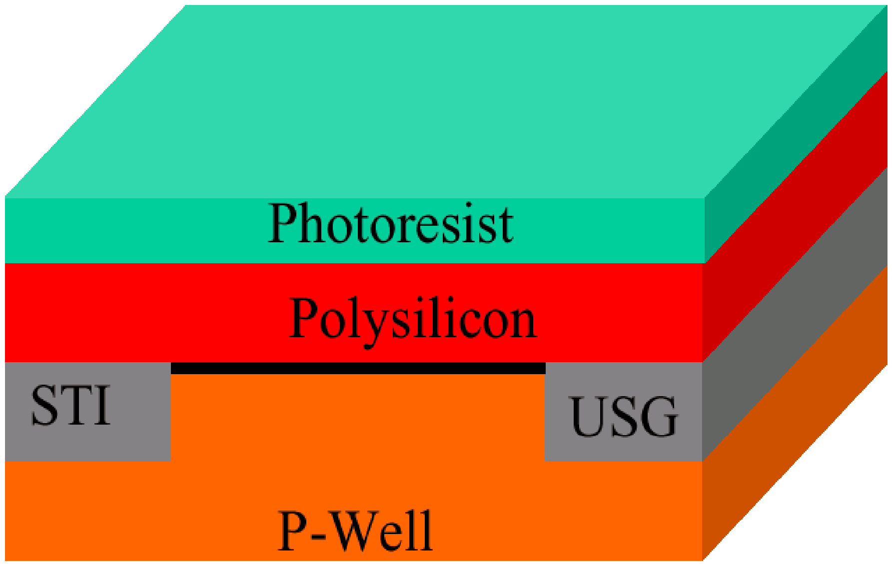
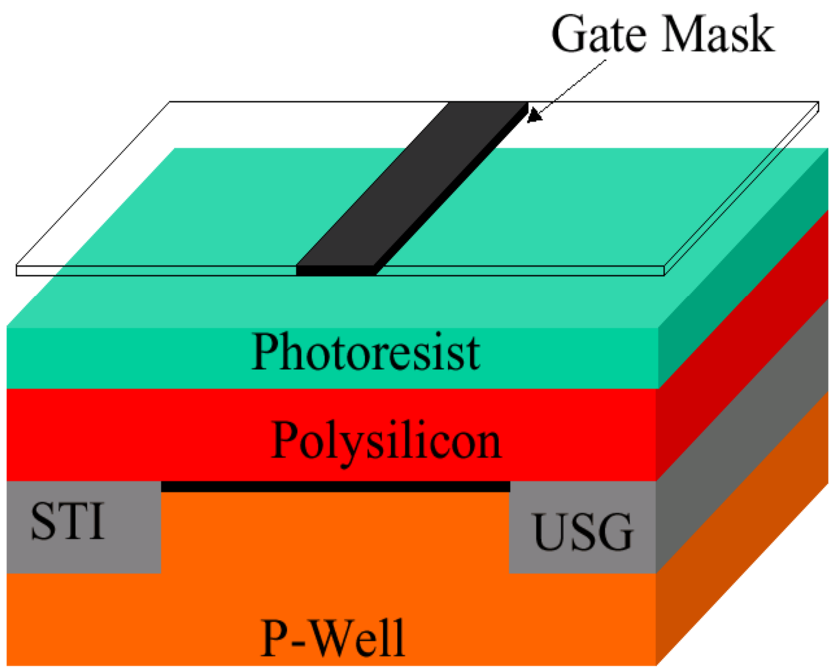
Soft Bake



Alignment and Exposure



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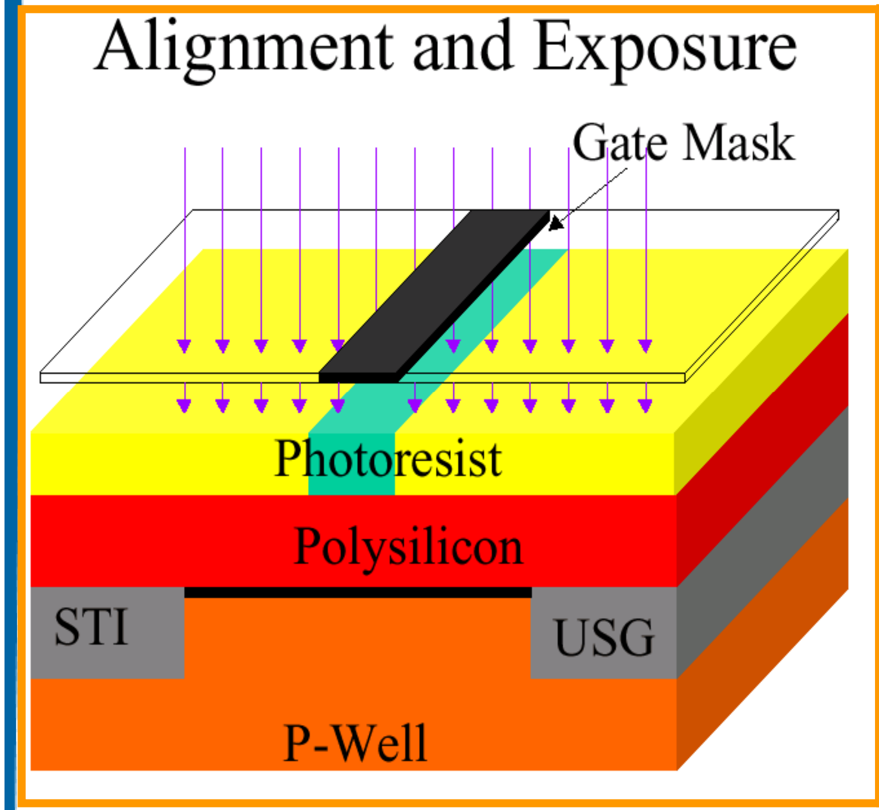

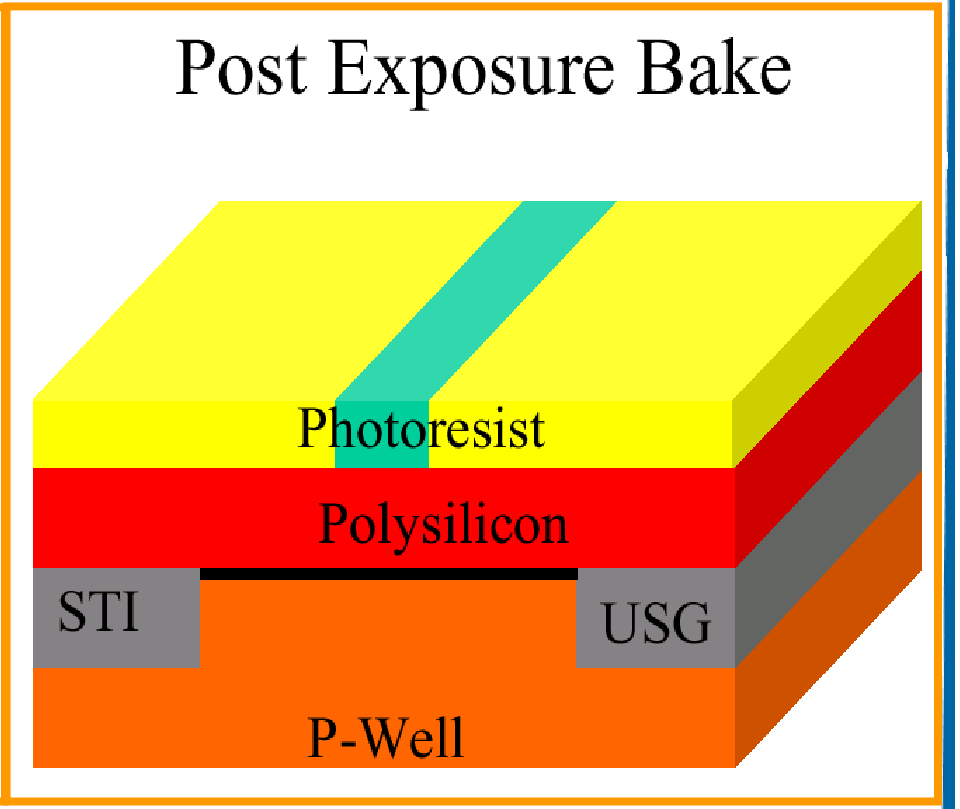

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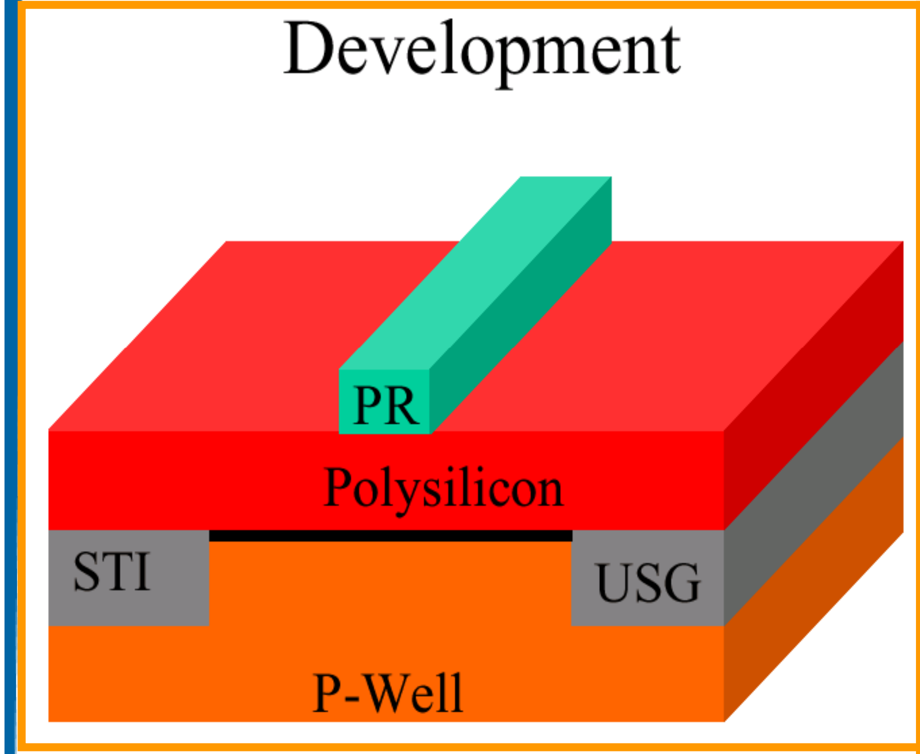

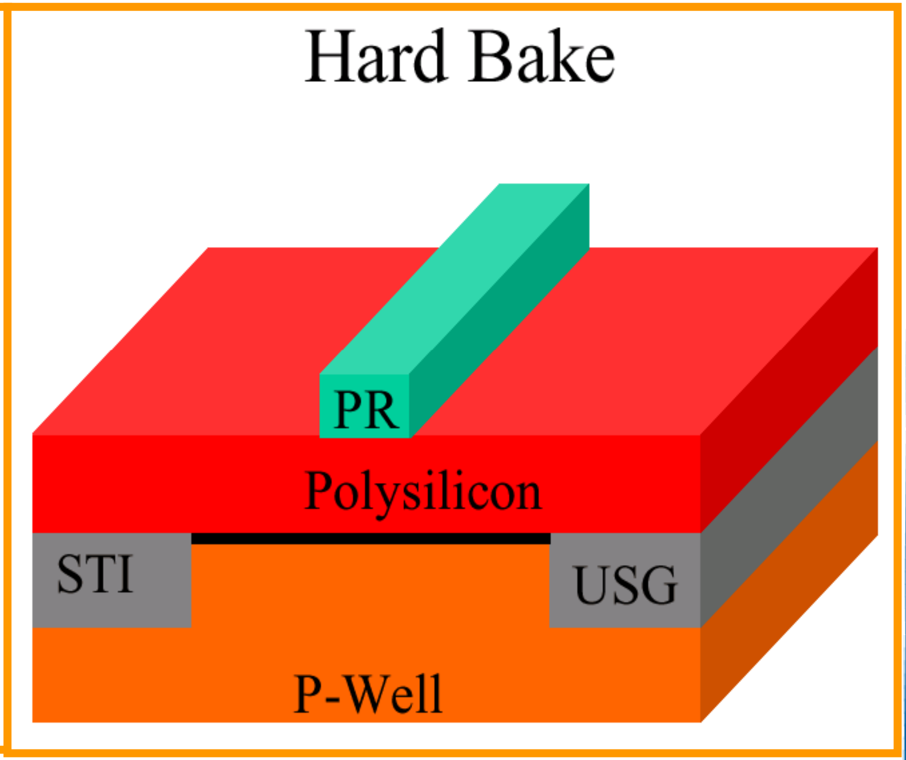

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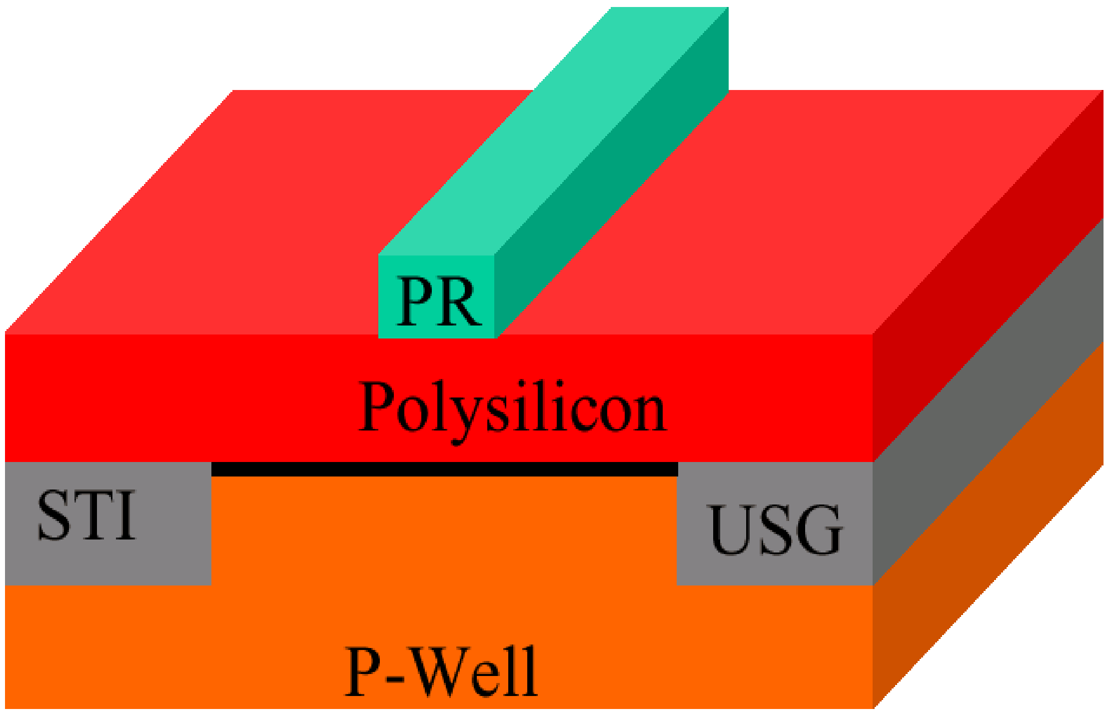
Pattern Inspection



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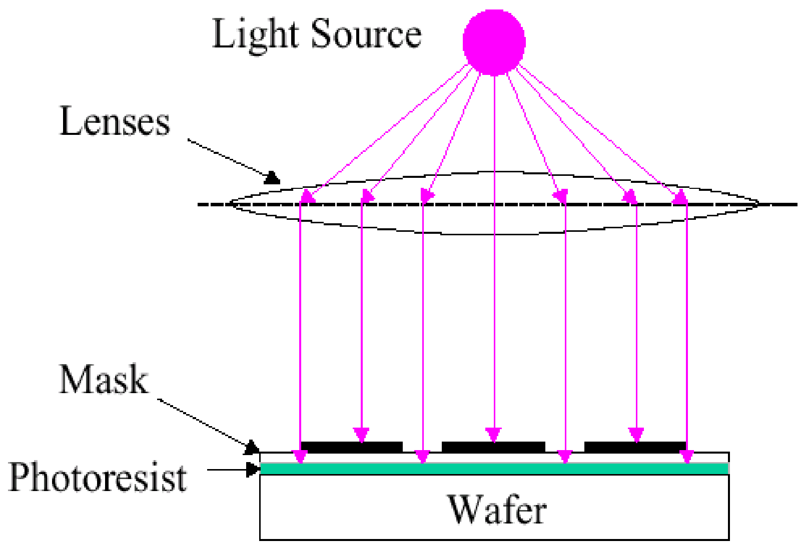
Alignment and Exposure Tools

- Contact printer
- Proximity printer
- Projection printer
- Stepper

Contact Printer



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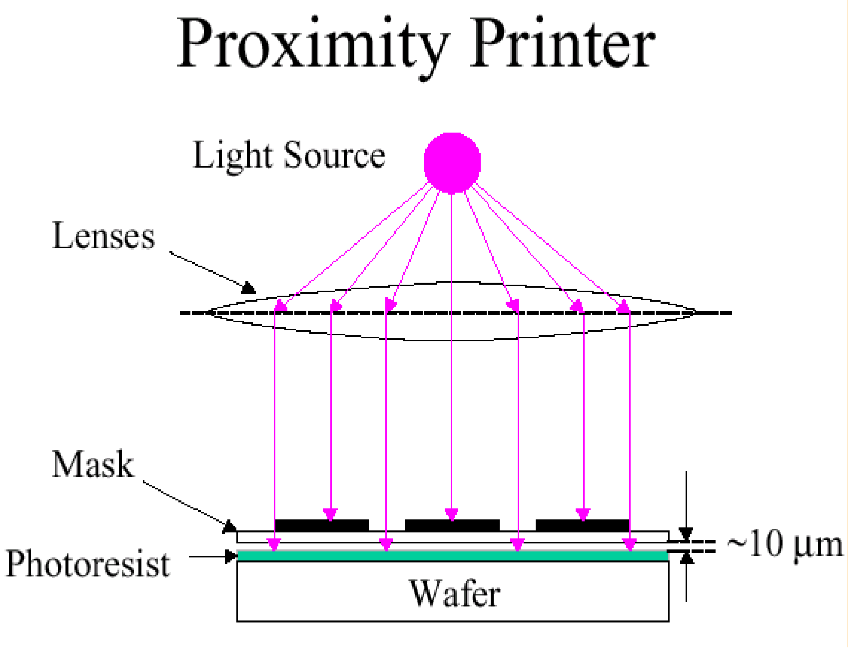

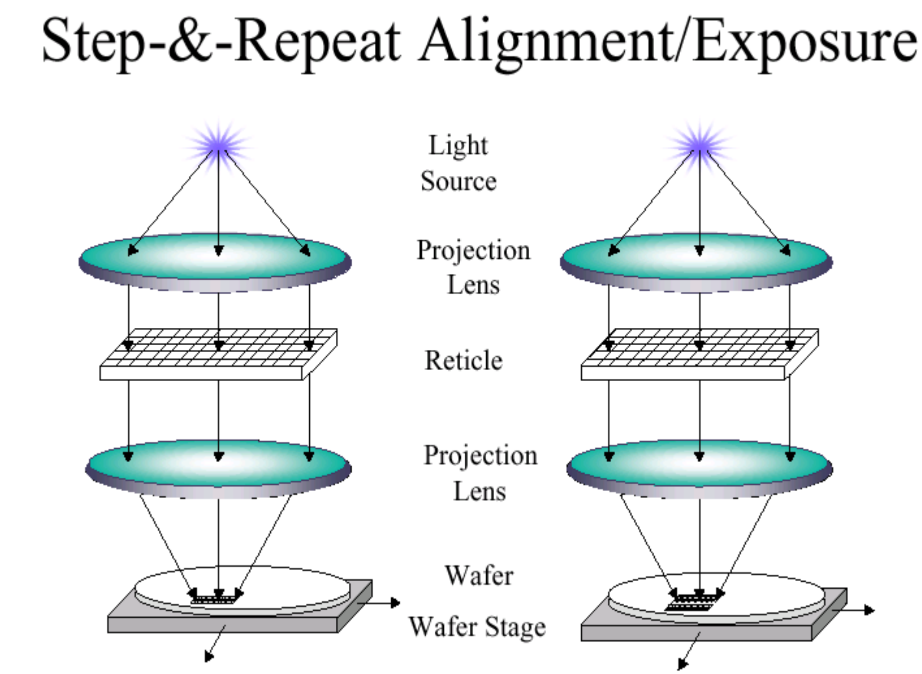

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Photolithography Light Sources

	Name	Wavelength (nm)	Application feature size (µm)
Mercury Lamp	G-line	436	0.50
	H-line	405	
	I-line	365	0.35 to 0.25
Excimer Laser	XeF	351	
	XeCl	308	
	KrF (DUV)	248	0.25 to 0.15
	ArF	193	0.18 to 0.13
Fluorine Laser	F_2	157	0.13 to 0.1

- Smaller objects need shorter wavelength
    - But this result in a worse depth of focus, therefore there is a requirement for surface planarization

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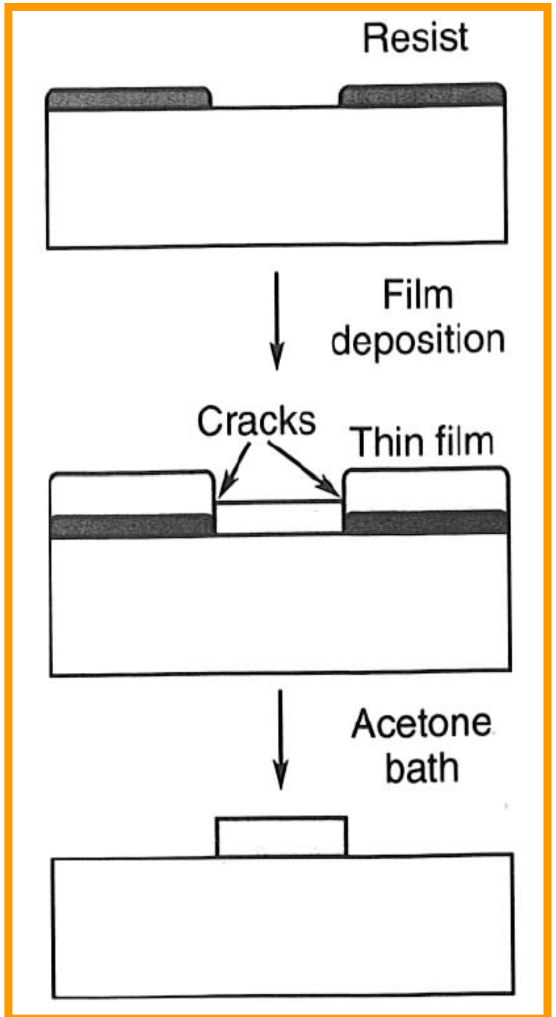
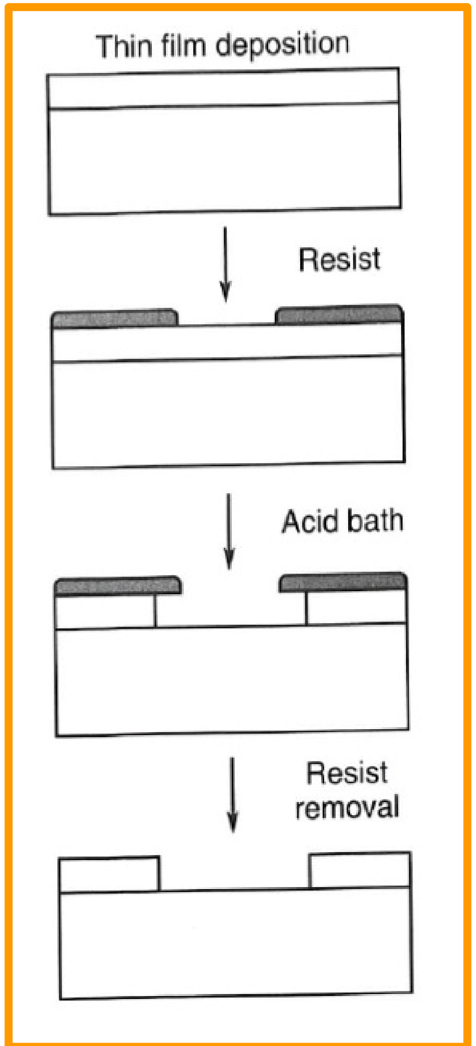
- Lift-off



- Etching



ETCHING

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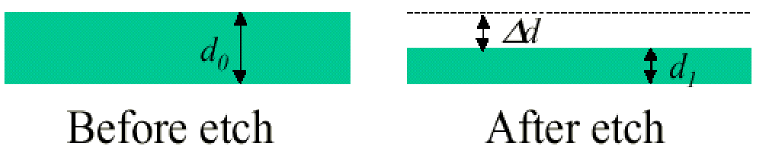
Etch Rate

Etch rate measures of the how fast the material is removed from wafer surface.

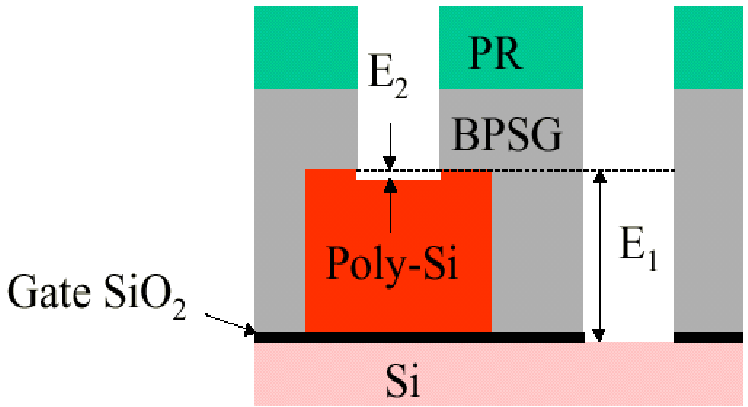


$$\text{Etch Rate} = \frac{\Delta d}{t} \quad (\text{Å/min})$$

$\Delta d = d_0 - d_1$ (Å) is thickness change and t is etch time (min)

Selectivity

- Selectivity of BPSG to Poly-Si: $S = \dfrac{E_1}{E_2}$



Boron Phosphorus silicate glass
BPSG

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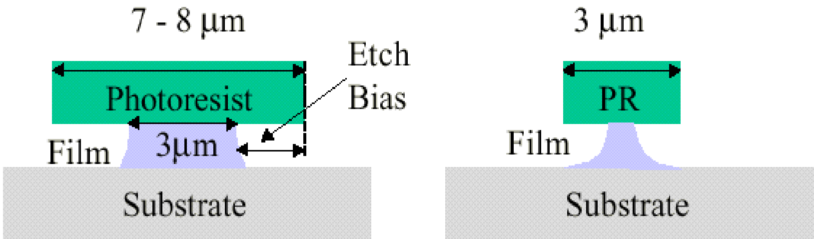
ETCHING

WET ETCHING

Wet Etch Profiles



•Can't be used for feature size is smaller than 3 μm

•Replaced by plasma etch for all patterned etch

Wet Etching Silicon Dioxide

- Hydrofluoric Acid (HF) Solution
- Normally diluted in buffer solution or DI water to reduce etch rate.

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$

- Widely used for CVD film quality control
- BOE: Buffered oxide etch
- WERR: wet etch rate ratio

ETCHING

DRY ETCHING (PLASMA)

Chemical Etch

- Purely chemical reaction
- By products are gases or soluble in etchants
- High selectivity
- Isotropic etch profile
- Examples:
  - Wet etch
  - Dry strip

Physical Etch

- Bombardment with inert ions such as Ar^+
- Physically dislodging material from surface
- Plasma process
- Anisotropic profile
- Low selectivity
- Example:
  - Argon sputtering etch

ETCHING

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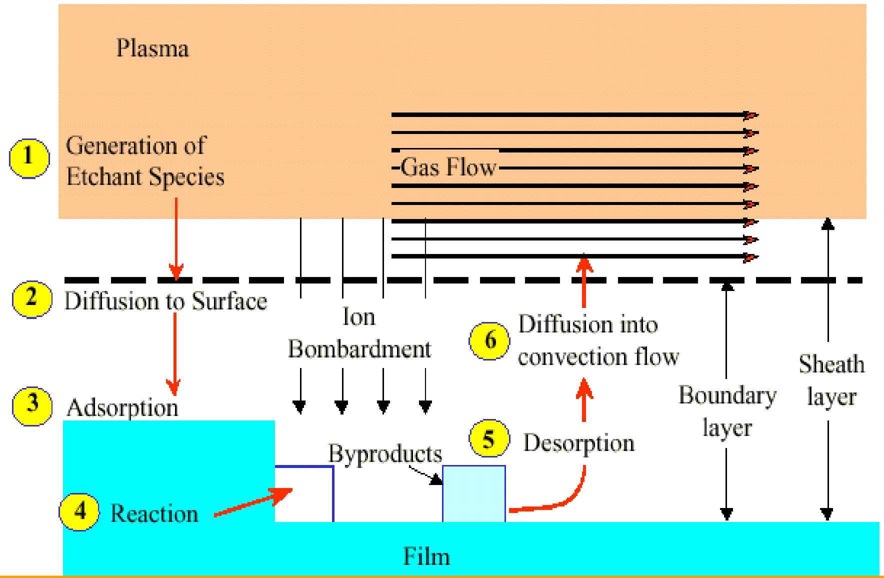
Reactive Ion Etch (RIE)

- Combination of chemical and physical etch
- Plasma process, ion bombardment plus free radicals
- Misleading name, should be called ion assistant etch (IAE)
- High and controllable etch rate
- Anisotropic and controllable etch profile
- Good and controllable selectivity
- All patterned etches are RIE processes in 8” fabs

Etch Process Sequence



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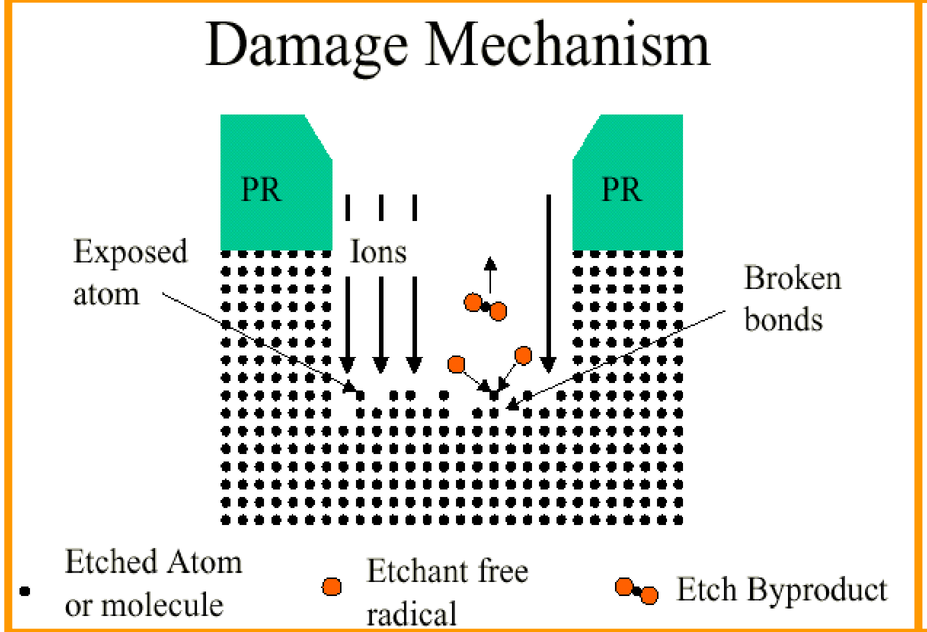
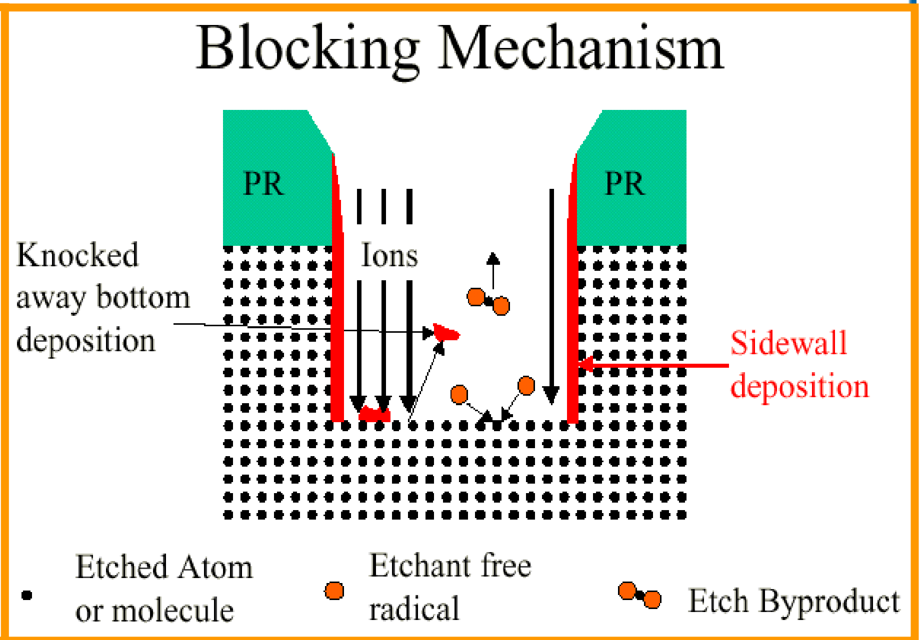
ETCHING

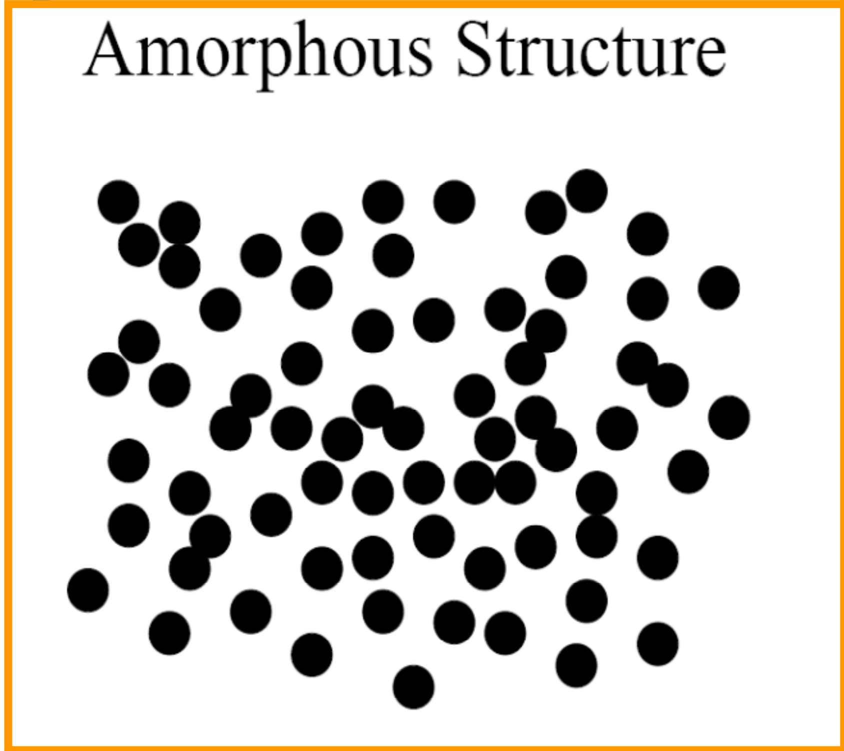

Damage Mechanism
PR
PR
Ions
Exposed
atom
Broken
bonds
Etched Atom
or molecule
Etchant free
radical
Etch Byproduct

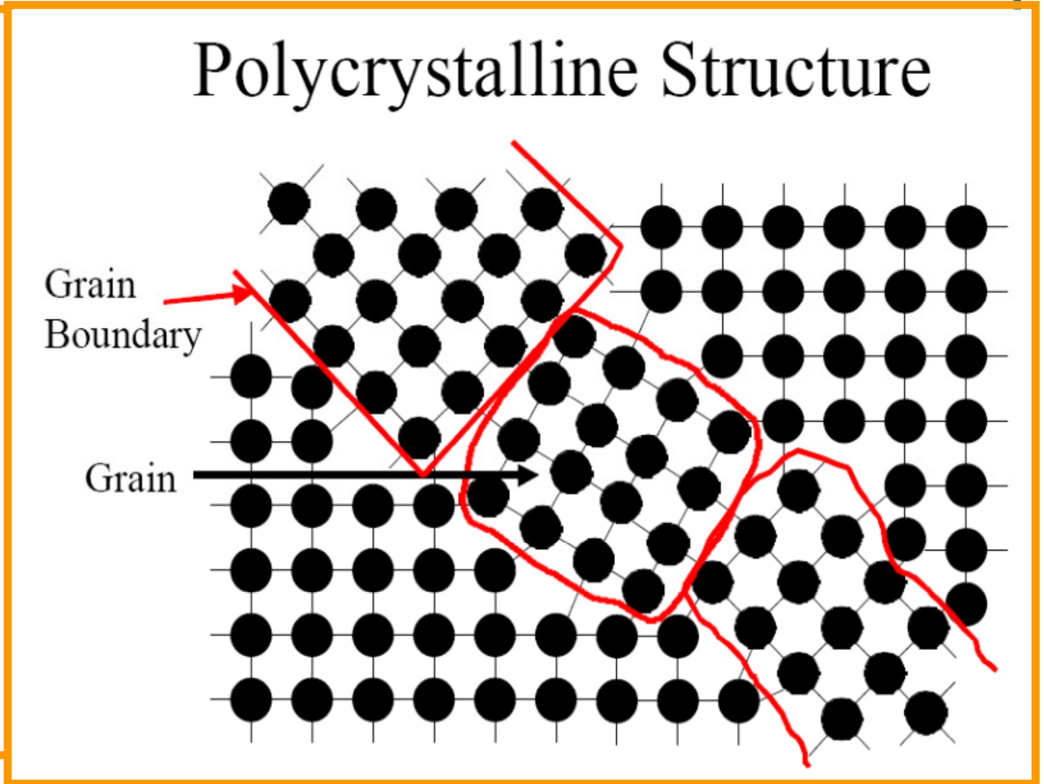

Blocking Mechanism
PR
PR
Ions
Knocked
away bottom
deposition
Sidewall
deposition
Etched Atom
or molecule
Etchant free
radical
Etch Byproduct

SEMICONDUCTOR SENSOR TECHNOLOGIES

- BULK MICROMACHINING
  - Bulk materials
  - Anisotropic silicon etching
  - Wafer bonding
- SURFACE MICROMACHINING
  - Thin film Materials
  - Thin film etching
  - Sacrificial etching

BULK MATERIALS





BULK MATERIALS

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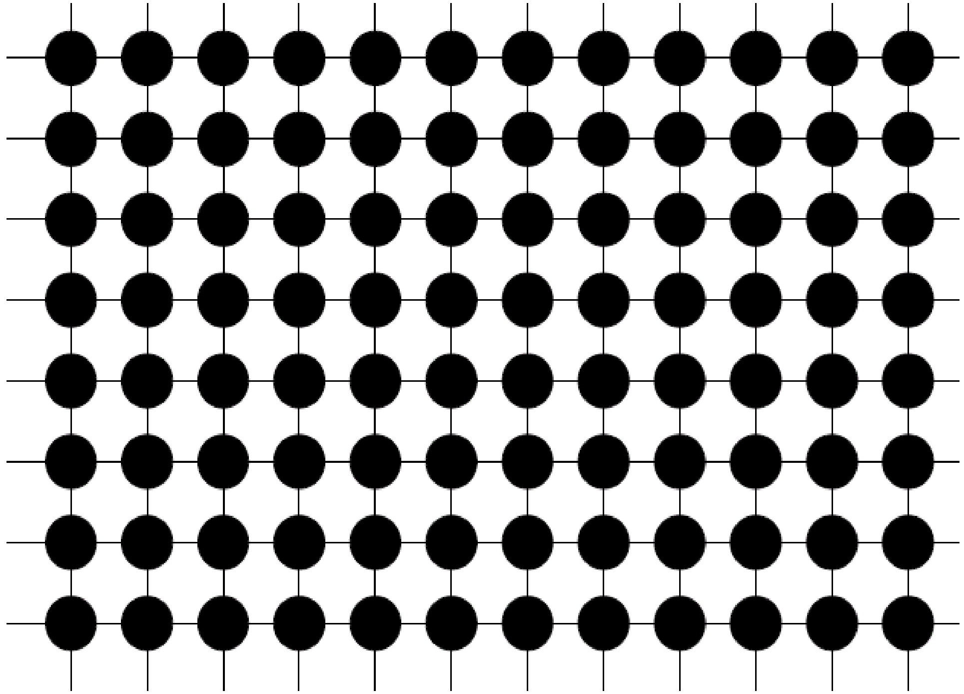
Single Crystal Structure



BULK MATERIALS

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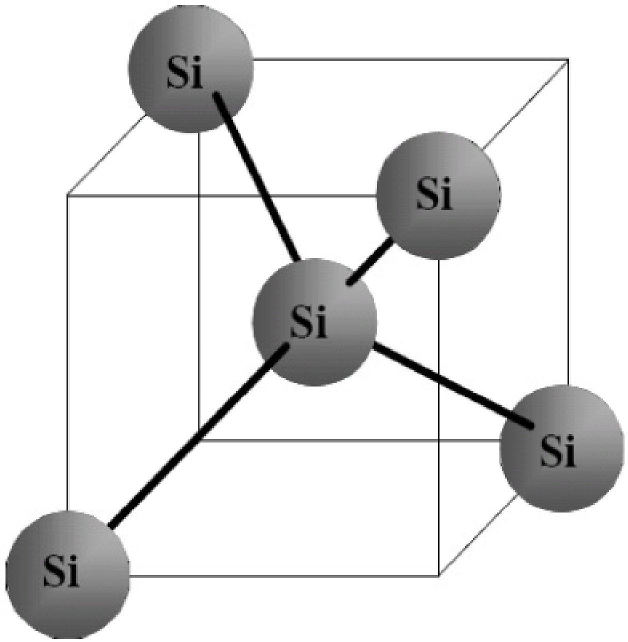
Unit Cell of Single Crystal Silicon



BULK MATERIALS

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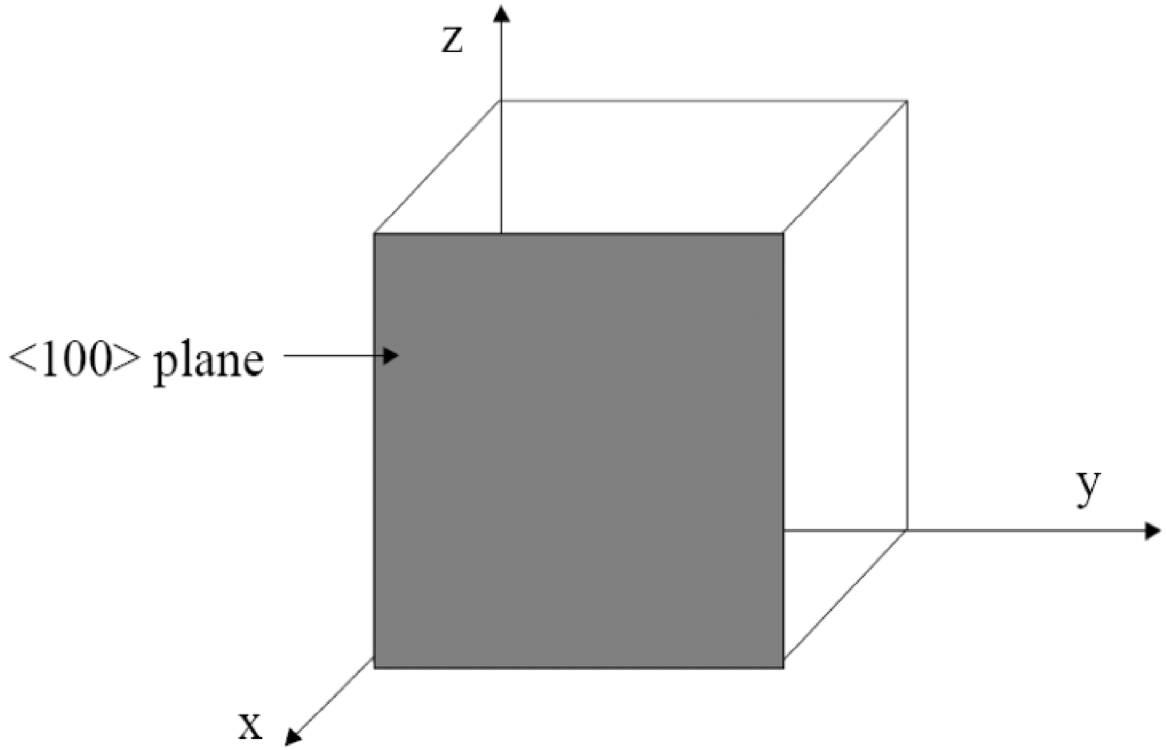
Crystal Orientations: <100>



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BULK MATERIALS

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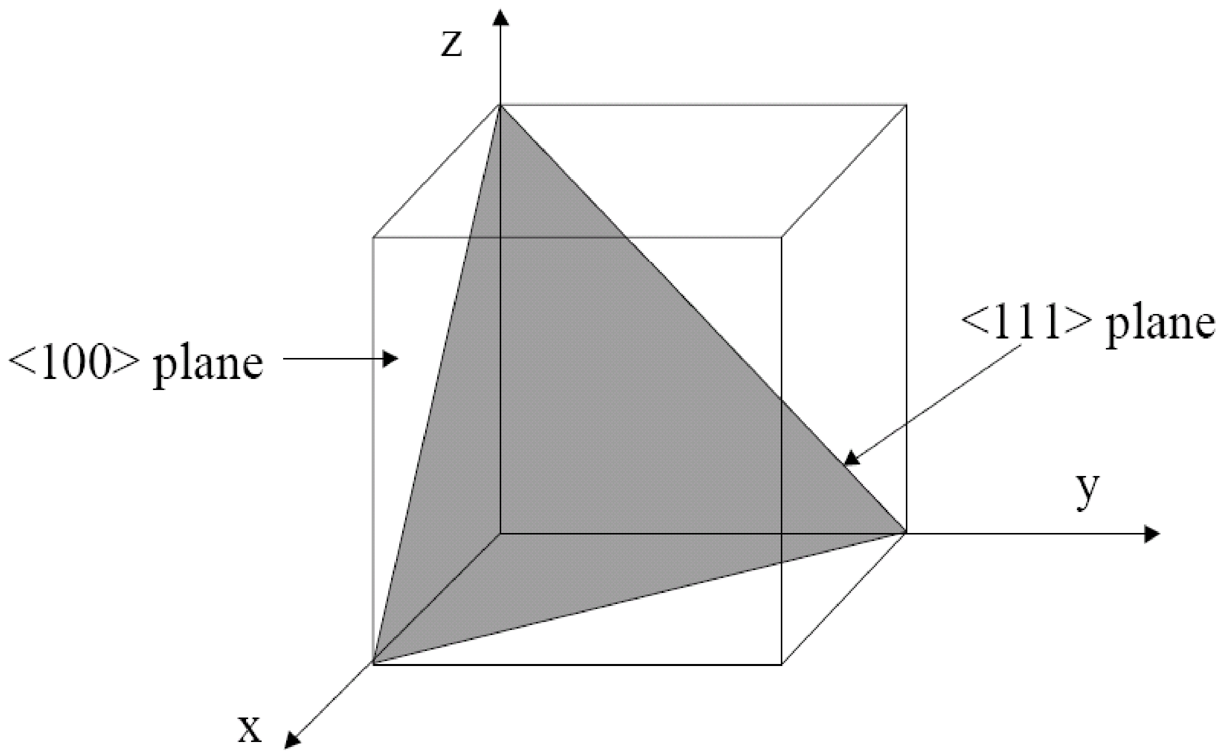
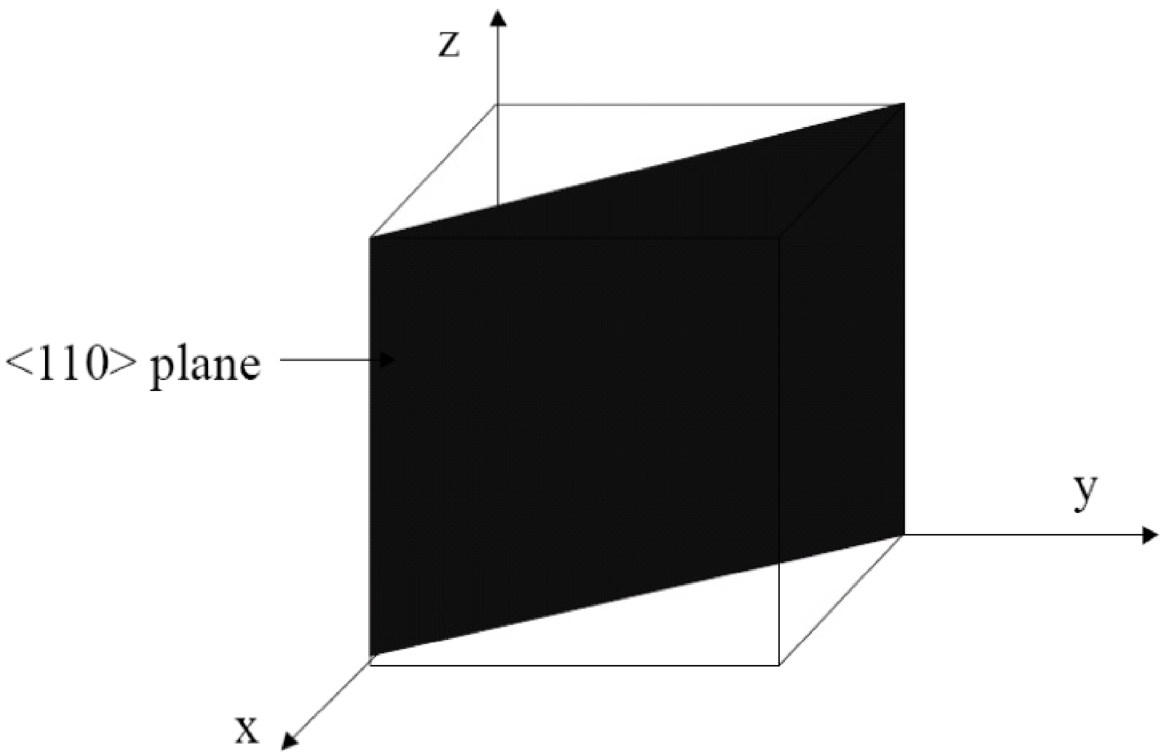
Crystal Orientations: <111>



BULK MATERIALS

Crystal Orientations: <110>



ANISOTROPIC SILICON ETCHING

Etching speed

(110) > (100) > (111)

Selectivity $S = \frac{(100)}{(111)}$

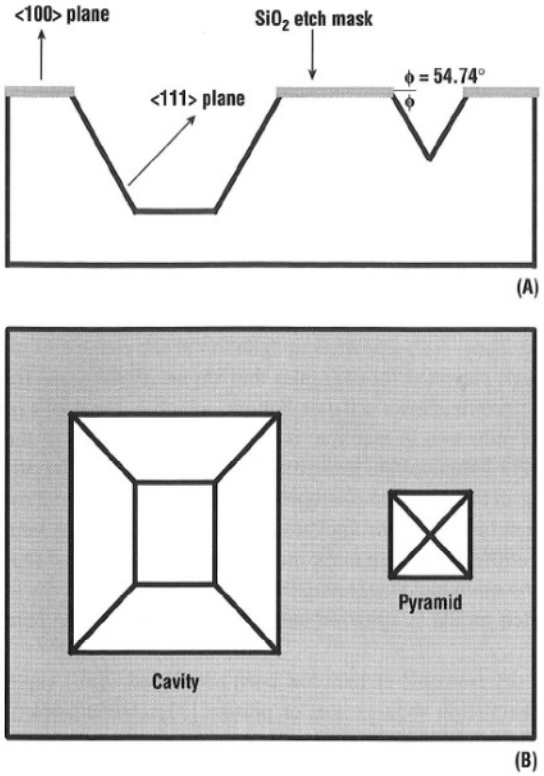


Figure 19.10 Cross section (A) and top view (B) of pyramidal holes and cavities formed in a (100) silicon wafer with an anisotropic etchant.

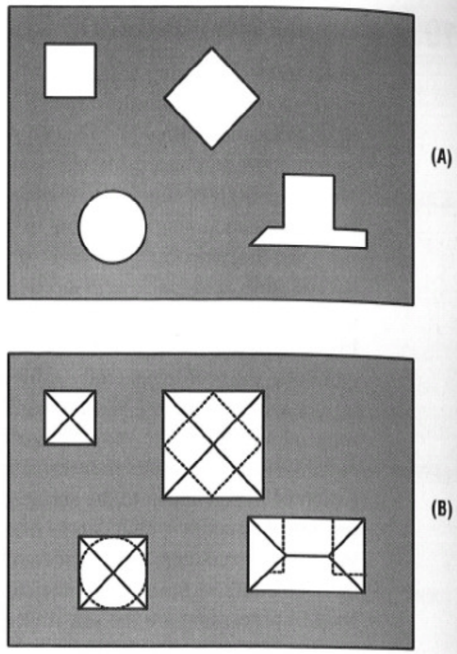
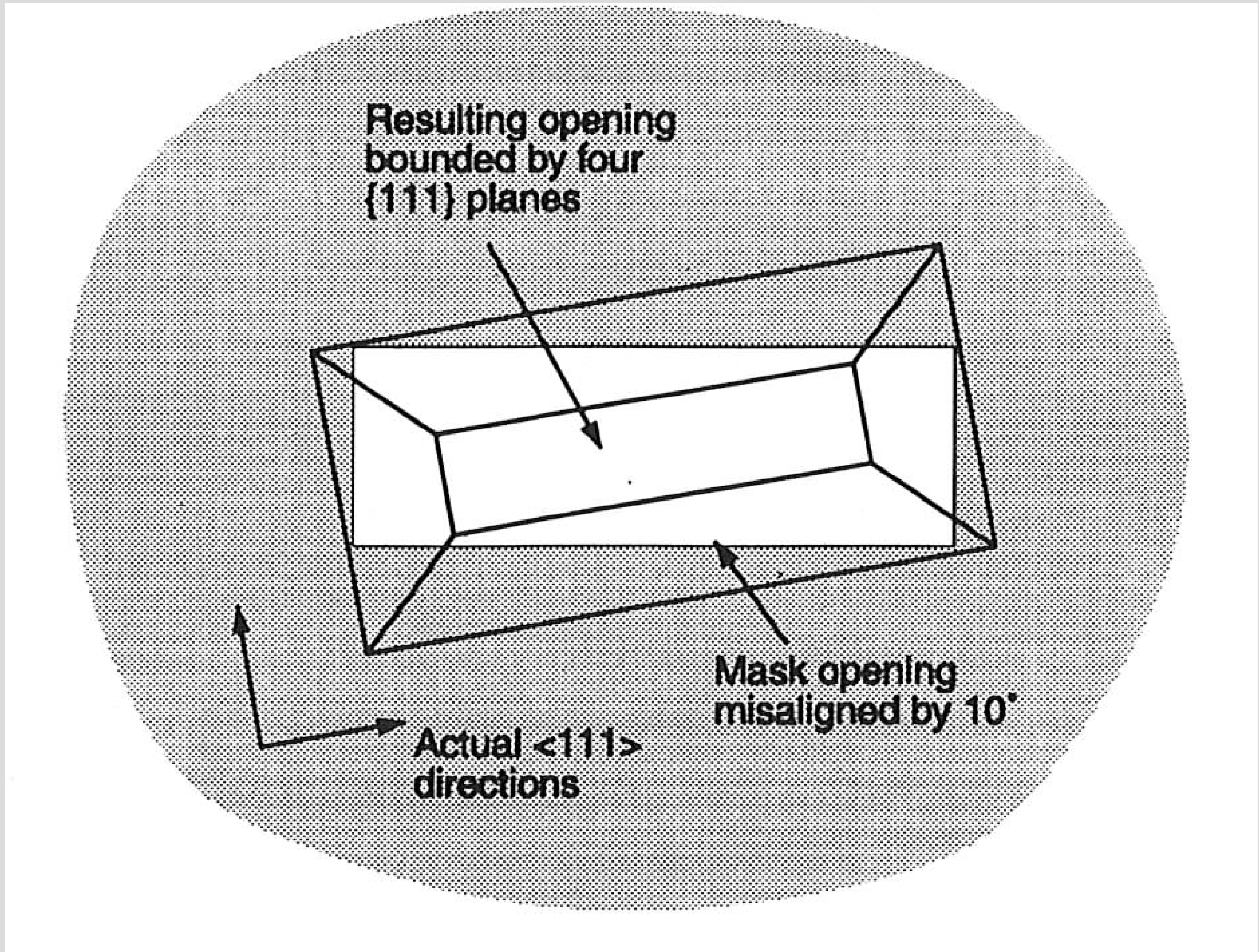


Figure 19.11 Effect of mask opening orientation on the etch profile. (A) Top view of mask openings as oriented to the <110> direction. (B) Etched structures resulting for an anisotropic etchant on (100) silicon.

ANISOTROPIC SILICON ETCHING



ANISOTROPIC SILICON ETCHING

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Example 19.4

Find the size of the mask opening that after anisotropic etching will yield a flat rectangular area of size 100 µm by 200 µm, 80 µm below the silicon (100) surface.

From the side view we find the length X to be

$$X = 100\ \mu\text{m} + 2Z$$

where Z is defined by the relation

$$\tan\phi = \tan 54.74° = \frac{80\ \mu\text{m}}{Z} = 1.41$$

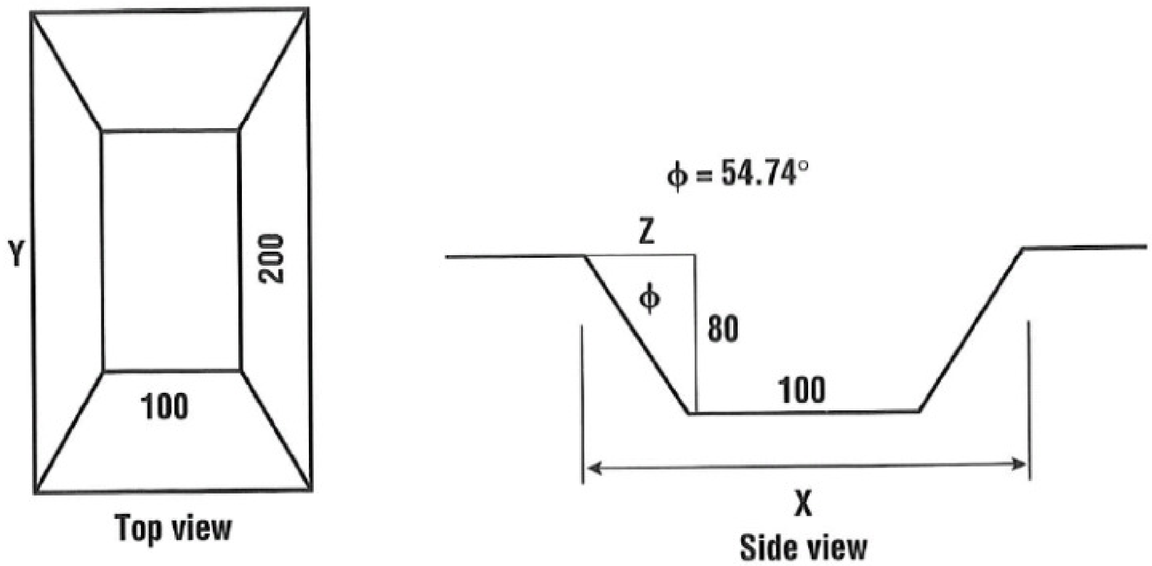
Solving for X gives

$$X = 100\ \mu\text{m} + 2\,\frac{80\ \mu\text{m}}{\tan 54.74°} = 213.2\ \mu\text{m}$$

ANISOTROPIC SILICON ETCHING

Similarly, solving for Y yields

$$Y = 200\ \mu\text{m} + 2\,\frac{80\ \mu\text{m}}{\tan 54.74°} = 313.2\ \mu\text{m}$$



ANISOTROPIC SILICON ETCHING

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Controlling of etch depth by;

1. Timed etches
2. Anisotropic etching of v grooves
3. P^{++} doping
4. Electrochemical etch stop.

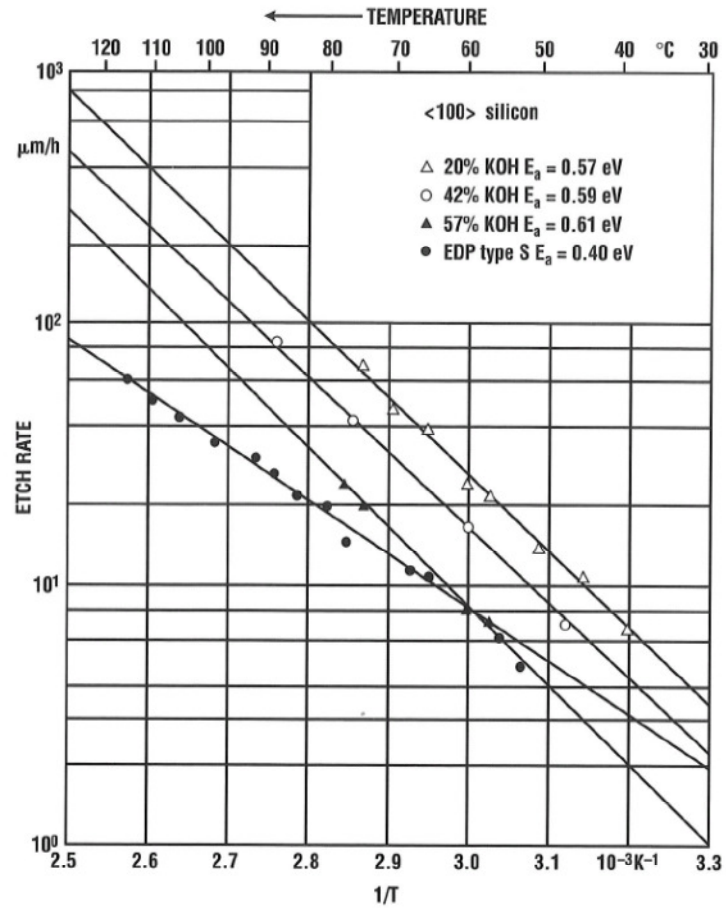

Figure 19.13 Arrenius plot of the vertical etching rate for (100) silicon wafers for EDP and KOH solutions *(after Seidel [33], reproduced by permission of The Electrochemical Society, Inc.)*.

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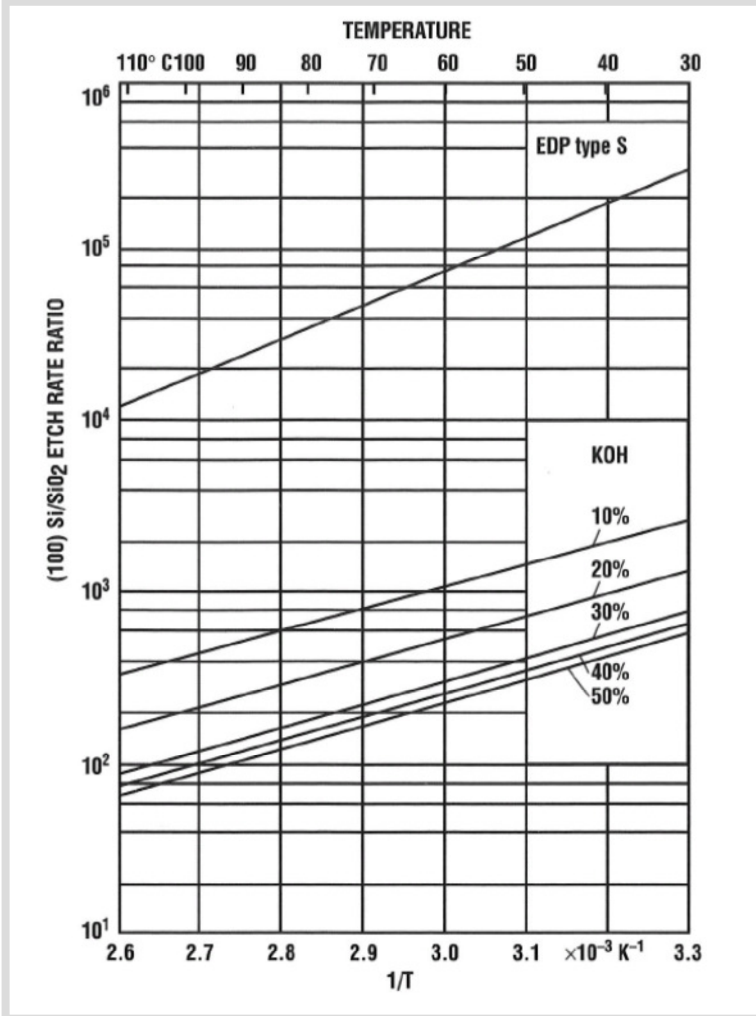
Selectivity SiO_2-Si(100)



ANISOTROPIC SILICON ETCHING

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Table 19.2 Principal characteristics of four different common anisotropic etchants[a]

Etchant/Diluent/ Additives/ Temperature	Etch Stop	Etch Rate (100) (mm/min)	Etch Rate Ratio (100)/(111)	Remarks	Mask (Etch Rate)
KOH/water, isopropyl alcohol additive, 85°C	Is $> 10^{20}$ cm^{-3} reduces etch rate by 20	1.4	400 and 600 for (110)/(111)	IC incompatible, avoid eye contact, etches oxide fast, lots of H_2 bubbles	Photoresist (shallow etch at room temperature); Si_3N_4 (not attacked); SiO_2 (28 Å/min)
Ethylene diamine pyrocatechol (water), pyrazine additive, 115°C	$\geq 5 \times 10^{10}$ cm^{-3} reduces the etch rate by 50	1.25	35	Toxic, ages fast, O_2 must be excluded few H_2 bubbles, silicates may precipitate	SiO_2 (2–5 Å/min); Si_3N_4 (1 Å/min); Ta, Au, Cr, Ag, Cu
Tetramethyl ammonium (TMAH) (water), 90°C	$> 4 \times 10^{20}$ cm^{-3} reduces etch rate by 40	1	From 12.5 to 50	IC compatible, easy to handle, smooth surface finish, few studies	SiO_2 etch rate is 4 orders of magnitude lower than (100) Si LPCVD Si_3N_4
N_2H_4/(water), isopropyl alcohol, 115°C	$> 1.5 \times 10^{20}$ cm^{-3} practically stops the etch	3.0	10	Toxic and explosive, okay at 50% water	SiO_2 (<2 Å/min) and most metallic films; does not attack Al according to some authors

[a] Given the many possible variables, the data in the table are only typical examples.

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TABLE 2 Experimentally Determined Activation Energies (E_a) and Pre-exponential Factors (R_0) for Etch Rate Calculation with the Arrhenius Equation: $R = R_0 \exp(-E_a/kT)$

Etchants	⟨100⟩ Si		⟨110⟩ Si		SiO_2	
	E_a (eV)	R_0 (μm h)	E_a (eV)	R_0 (μm h)	E_a (eV)	R_0 (μm h)
Type-S EDP	0.40	9.33×10^6	0.33	1.16×10^6	0.80	1.36×10^8
KOH, 20%	0.57	1.23×10^{10}	0.59	3.17×10^{10}	0.85	3.52×10^{11}
a-KOH, 20%	0.62	4.08×10^{10}	0.58	4.28×10^9	0.90	1.72×10^{12}
KOH, 34%	0.61	3.10×10^{10}	0.60	3.66×10^{10}	0.89	2.34×10^{12}
NaOH, 24%	0.65	1.59×10^{11}	0.68	7.00×10^{11}	0.90	3.20×10^{12}
LiOH, 10%	0.60	3.12×10^{10}	0.62	8.03×10^{10}	0.86	2.34×10^{11}

a-KOH contains isopropyl alcohol at 250 ml/l

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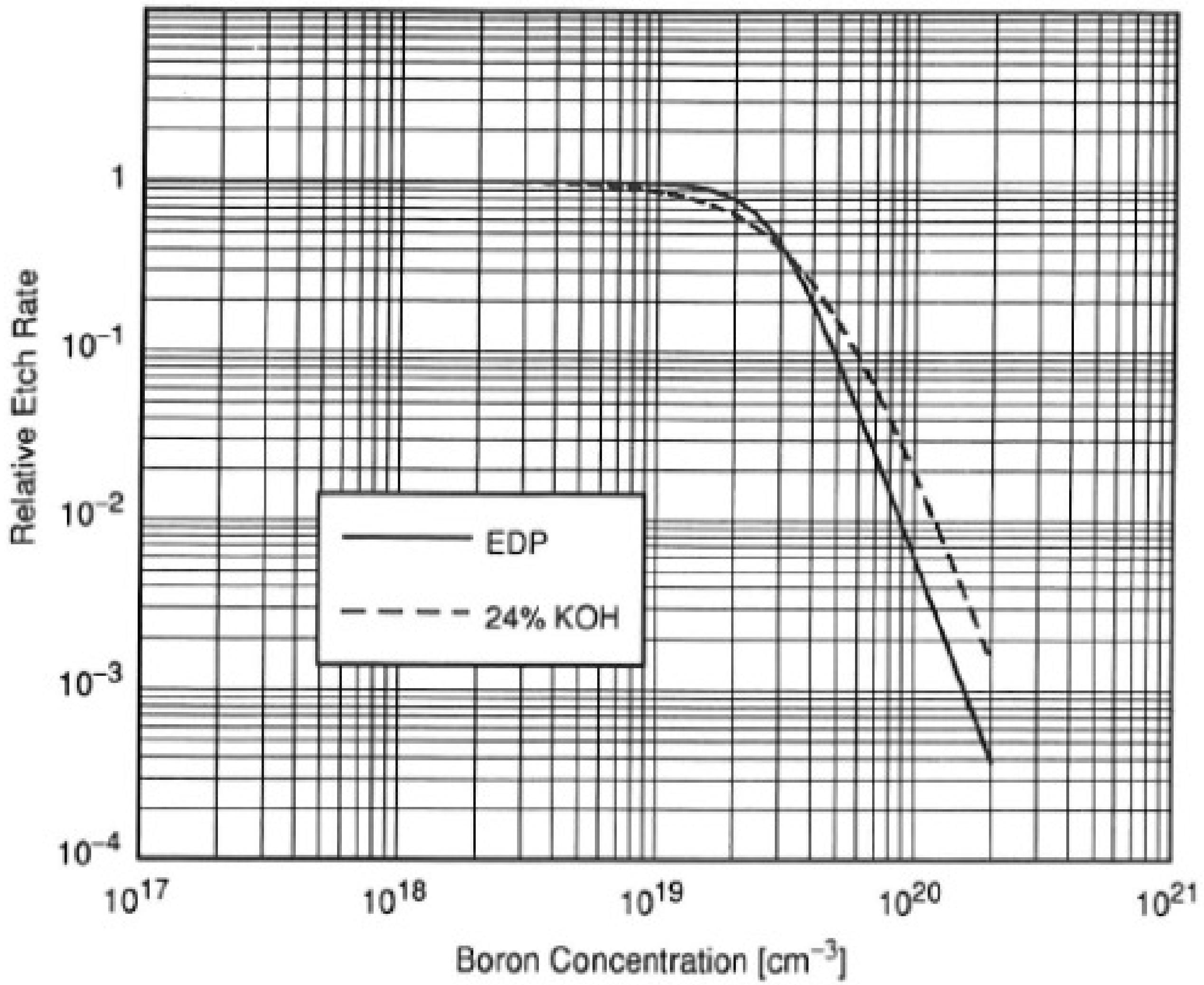

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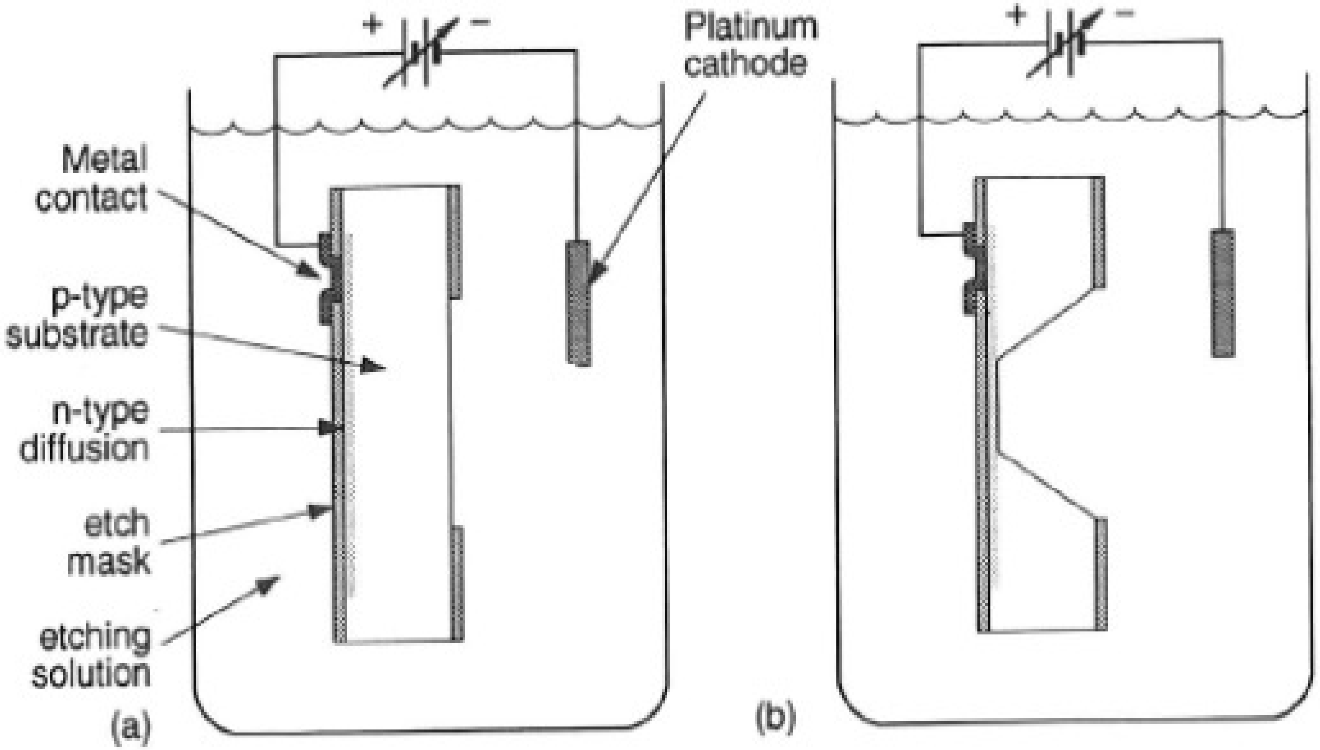


Fig. 27 The electrochemical etch-stop technique used to form a diaphragm.

WAFER BONDING

Anodic bondning

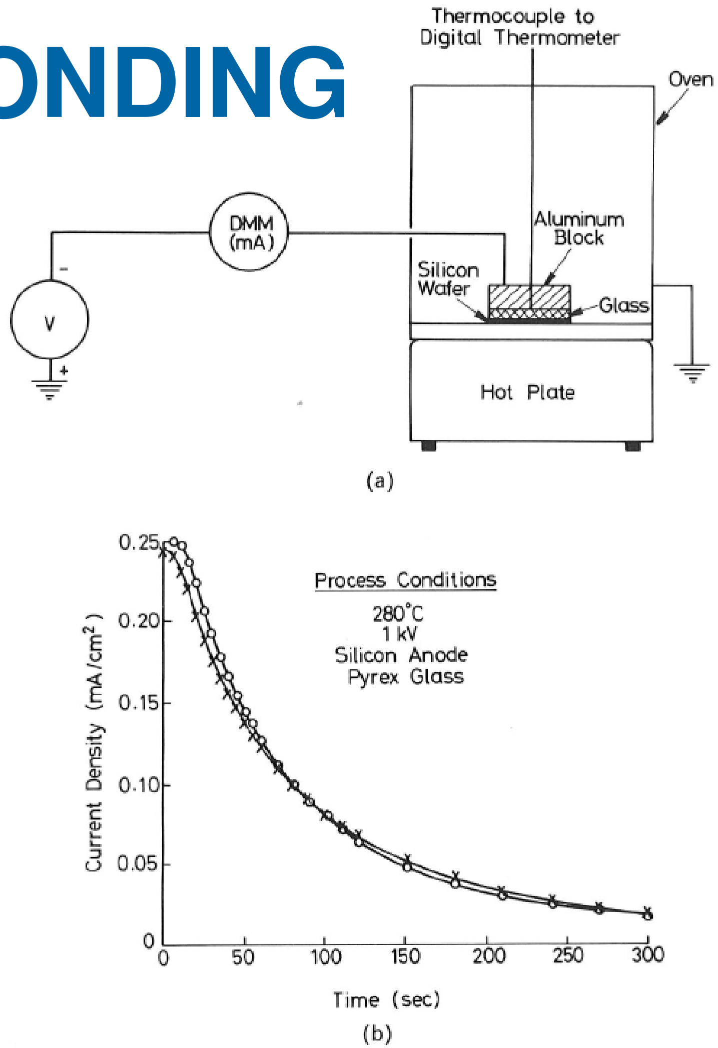
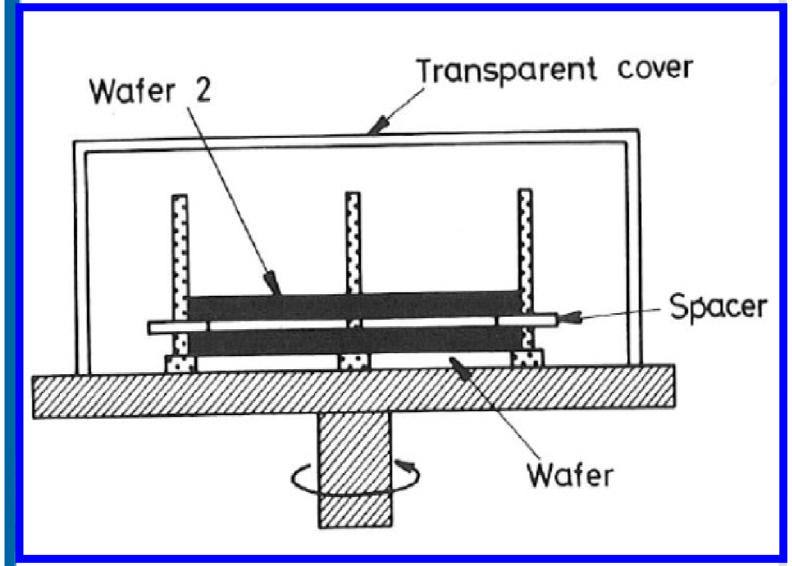


Fig. 28 (a) Schematic of an anodic bonding apparatus. The wafer assembly is pressed against a hot plate when the electric field is applied. (b) Typical current traces. The bond is complete when the current drops to about 10% of its peak value. (After Ref. 217)

WAFER BONDING

FUSION BONDING



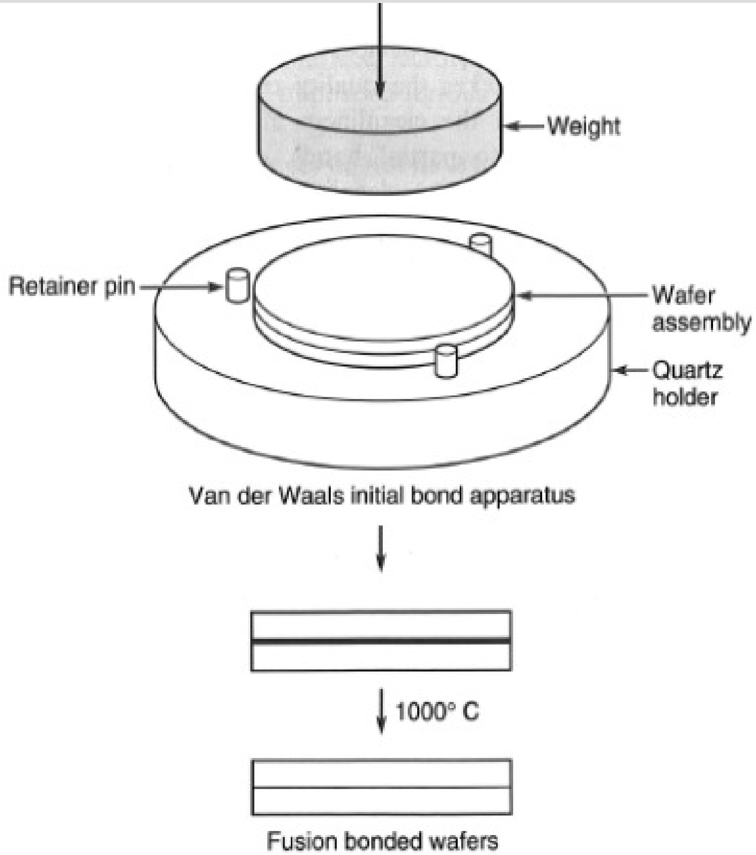


Fig. 29 Schematic of a fusion bonding apparatus. After pressing the wafers together, they are transferred to a high-temperature furnace to establish the bond.

SURFACE MICROMACHINING

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- THIN FILM MATERIALS
  - Poly silicon
  - Amorphous silicon
  - Epitaxi silicon
  - Silicon Nitride (LPCVD)
    - **300-500 MT 700-900 C**

$$3SiH_2Cl_2(g) + 4NH_3(g) \xrightarrow{\text{heat}} Si_3N_4(s) + 6HCl(g) + 6H_2(g).$$

  - Silicon dioxide

•Silicon dioxide

SURFACE MICROMACHINING

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- THIN FILM ETCHING
  - Silicon dioxide
    - Isotropic etching
      - **DILUTED HF OR BUFFERED HF (BUFFERED WITH AMMONIUM-FLUORIDE)**
    - Anisotropic etching
      - **REACTIVE ION ETCHING (RIE)**
        - » **1:1 C_2F_6 and CHF_3**
  - Silicon nitride
    - Isotropic etching
        - » **H_3PO_4 140-200 C**
    - Anisotropic etching *same as silicon dioxide*

SURFACE MICROMACHINING

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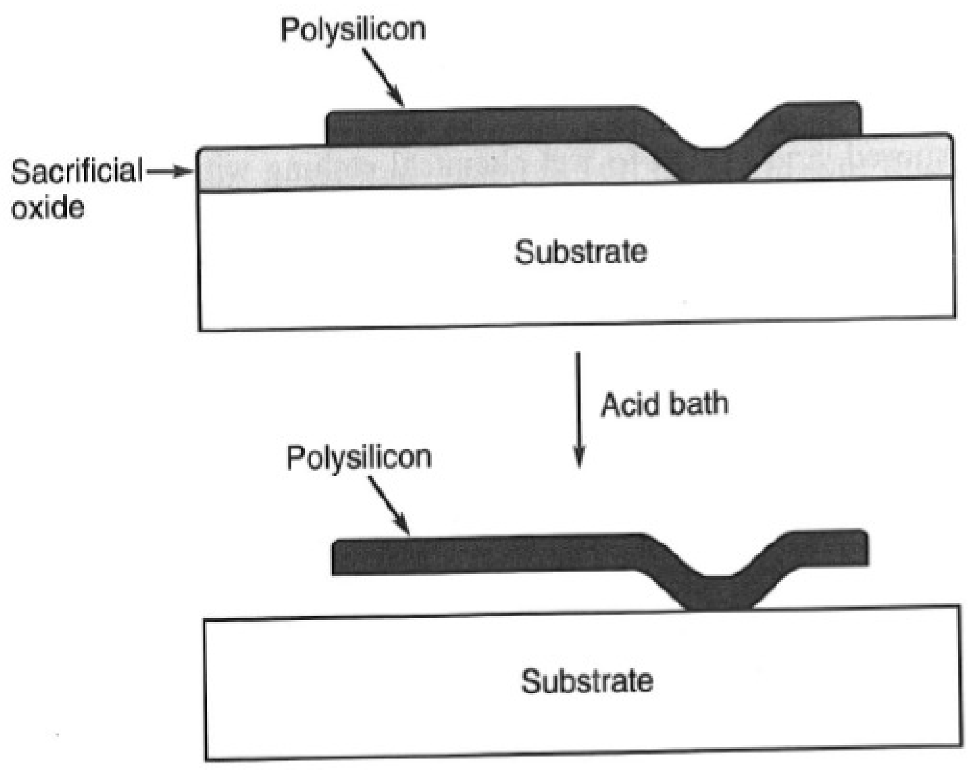
Sacrificial etching



(a)

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SURFACE MICROMACHINING

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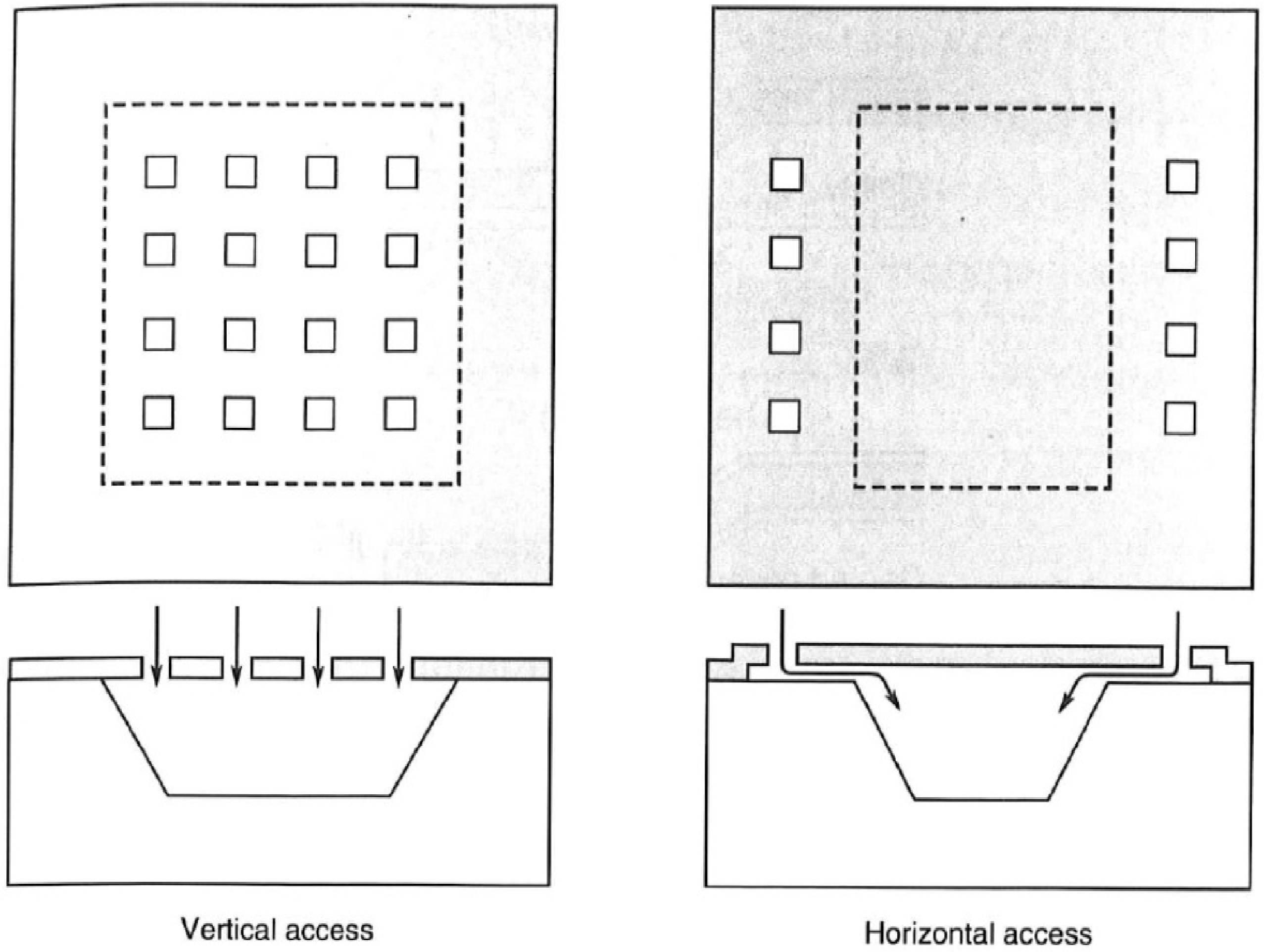

SURFACE MICROMACHINING

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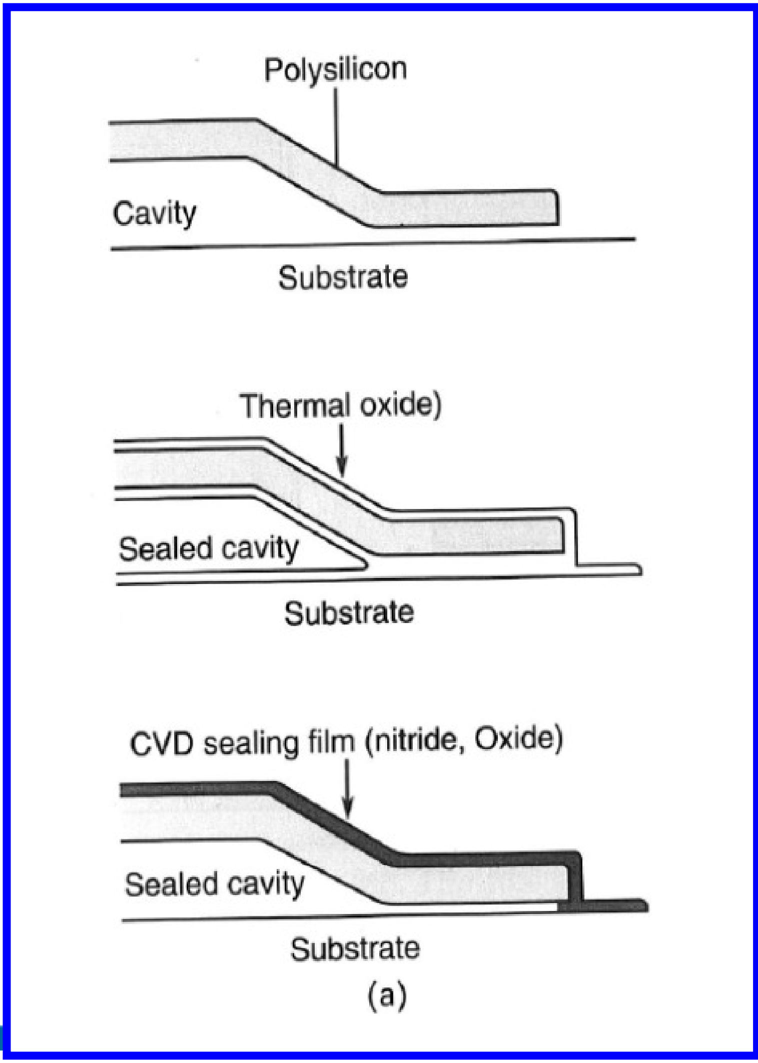
- Sealing



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LIGA

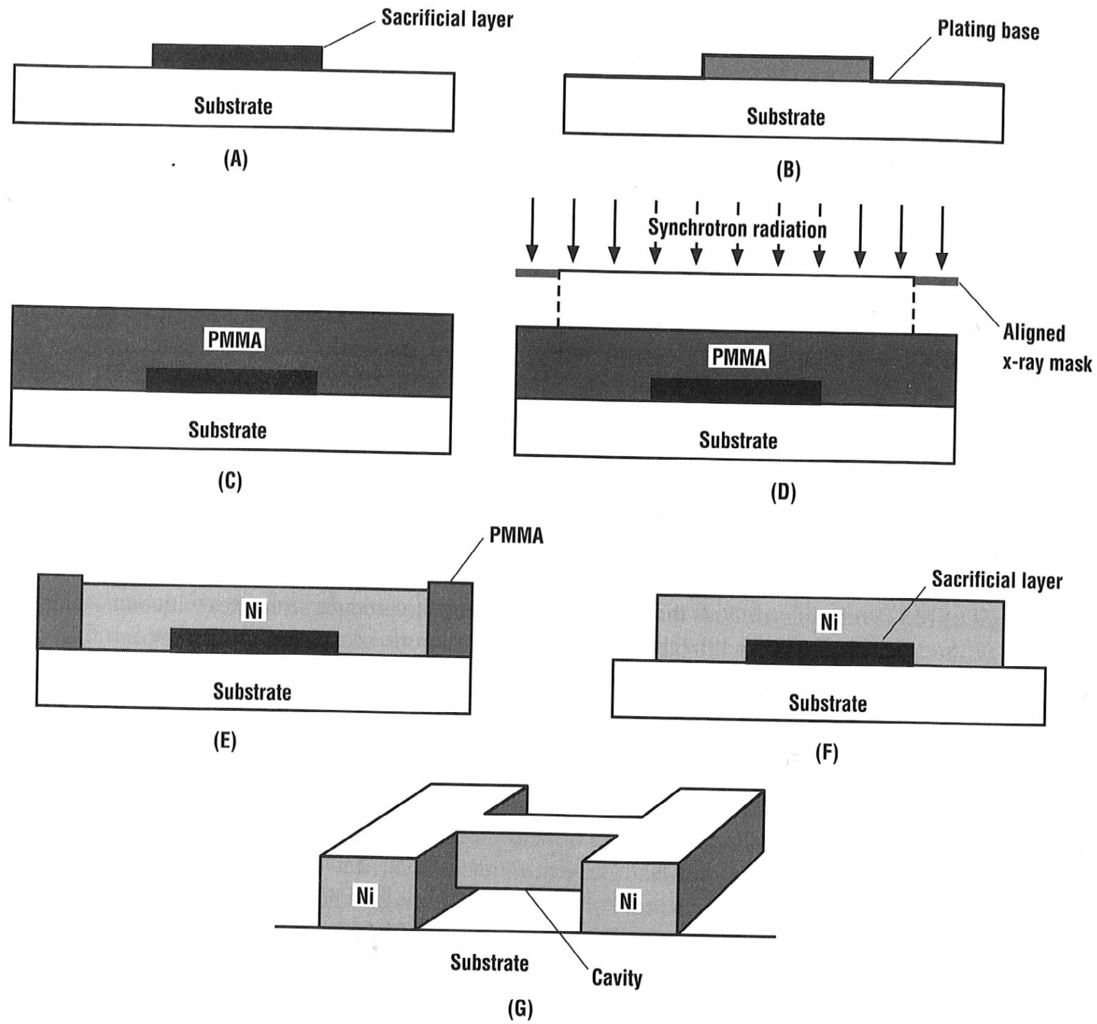
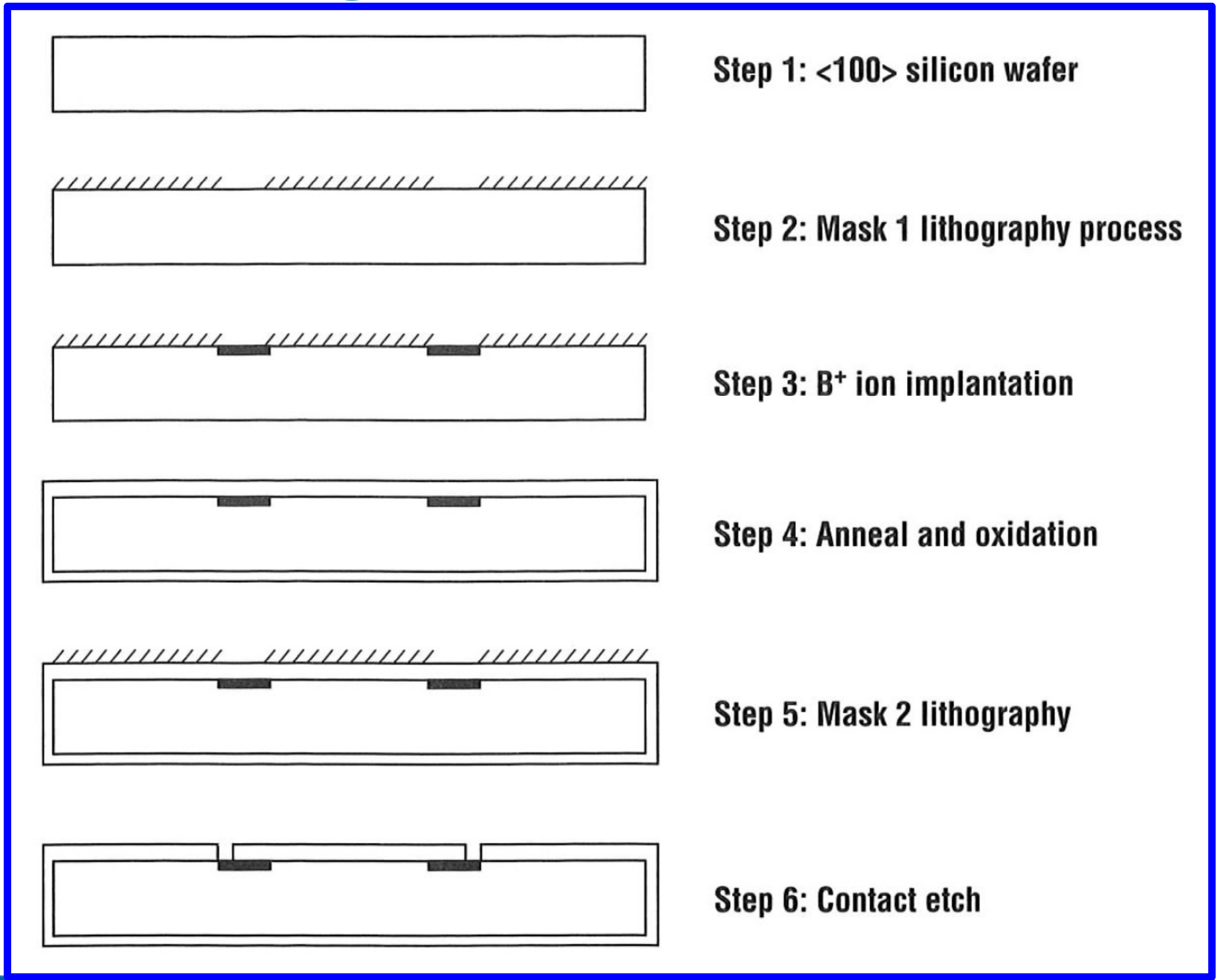


Figure 19.34 Cross-sectional view of LIGA with sacrificial layers. (A) Pattern sacrificial layer; (B) sputter plating base; (C) deposit PMMA; (D) align x-ray mask and expose PMMA; (E) develop PMMA and electroplate Ni; (F) remove PMMA and plating base to clear access to the sacrificial layer; (G) etch sacrificial layer, thereby undercutting and freeing the Ni structure *(from Guckel [75], © 1998 IEEE)*.

EXAMPLES


Step 1: <100> silicon wafer
Step 2: Mask 1 lithography process
Step 3: B^+ ion implantation
Step 4: Anneal and oxidation
Step 5: Mask 2 lithography
Step 6: Contact etch

EXAMPLES

Piezoresistive pressure sensor

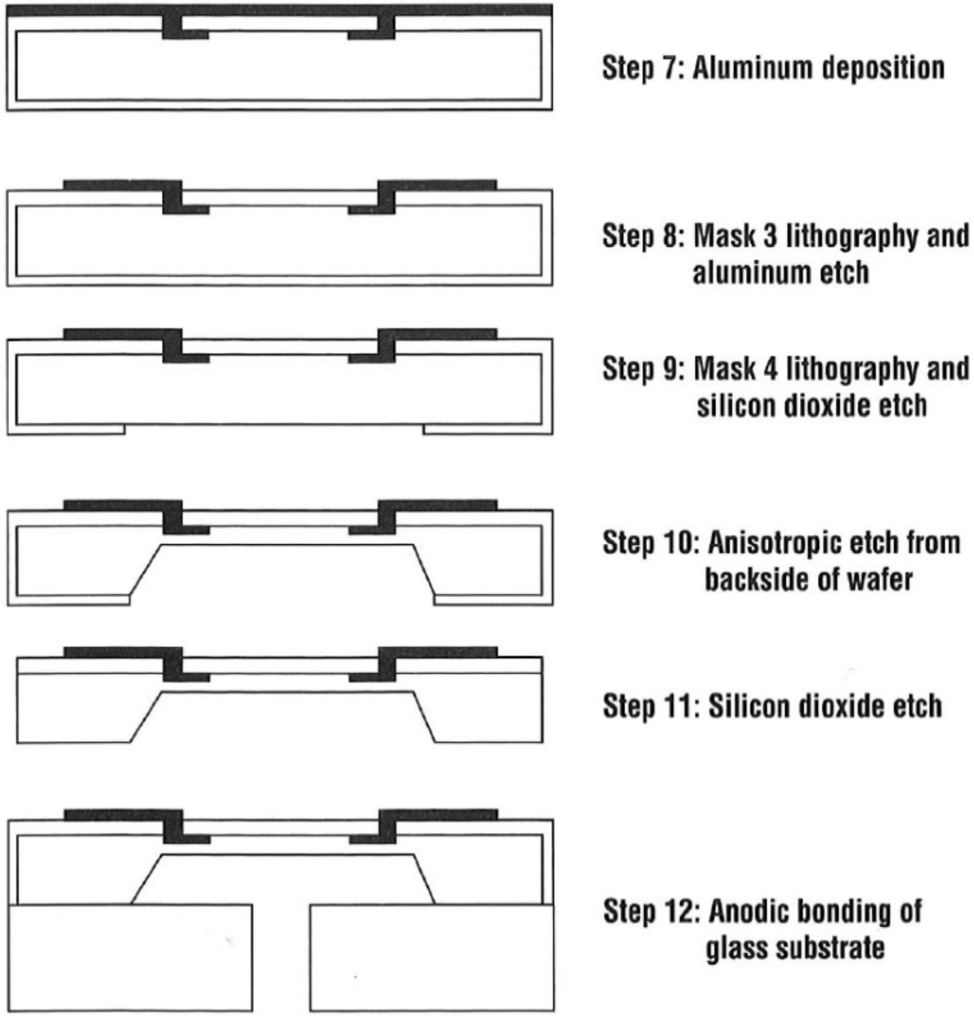
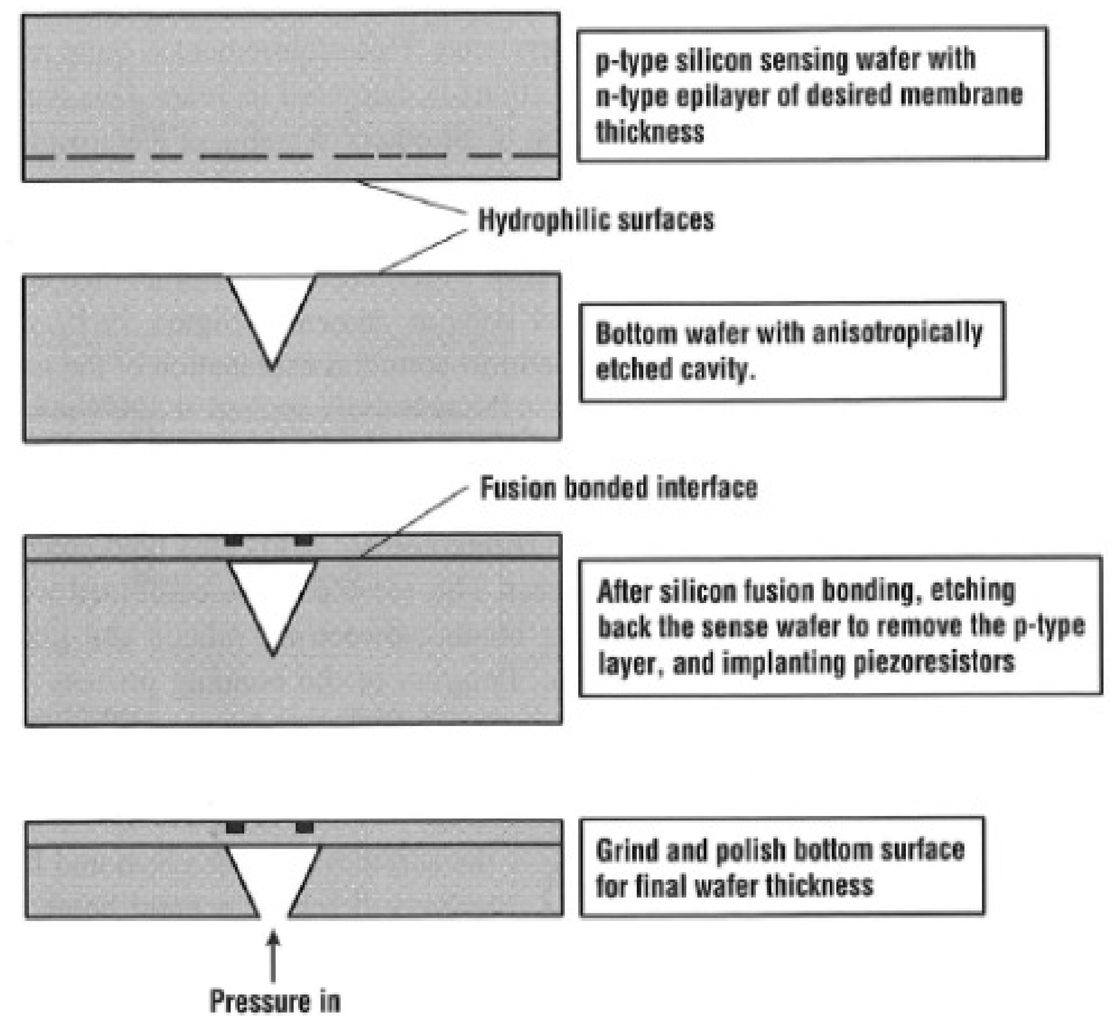


Figure 19.18 Bulk micromachining process for a piezoresistive pressure sensor.

EXAMPLES

Piezoresistive pressure sensor



EXAMPLES

Problem…

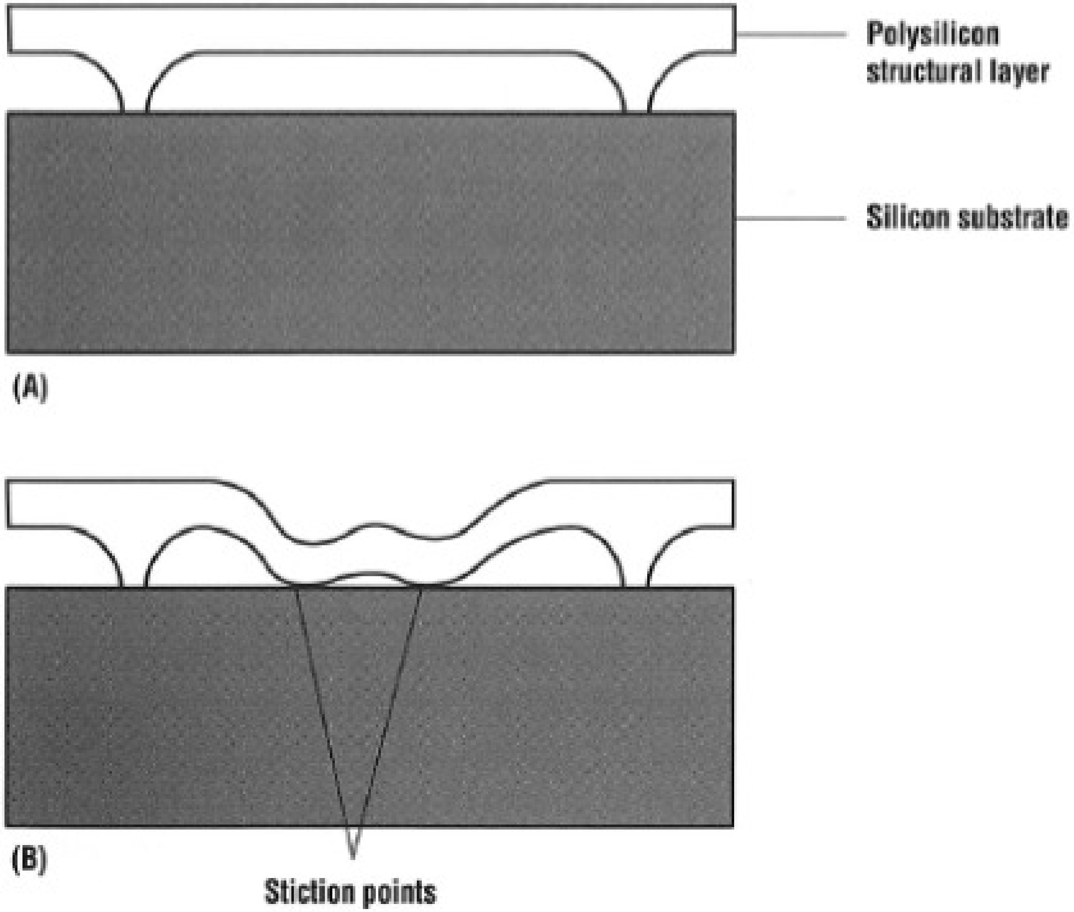


Figure 19.25 Side view of a released structure (A) without and (B) with stiction at two points.

EXAMPLES

Accelerometer