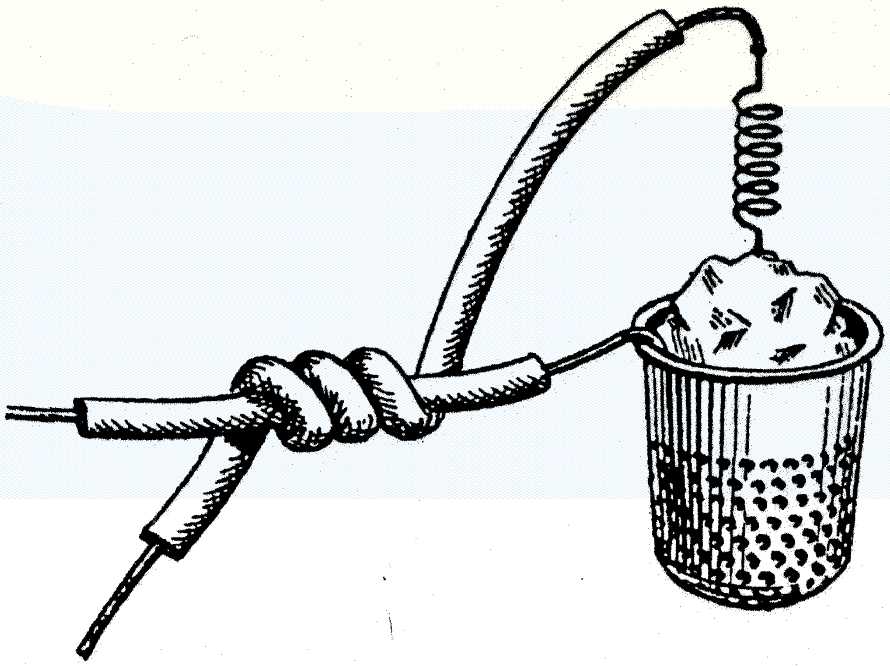
ELECTRONICS
Design Division

Sensor devices



Mittuniversitetet
MID SWEDEN UNIVERSITY

Outline

- Planning
- 1 Classification and terminology of sensors
- 2 Semiconductor Sensor Technologies

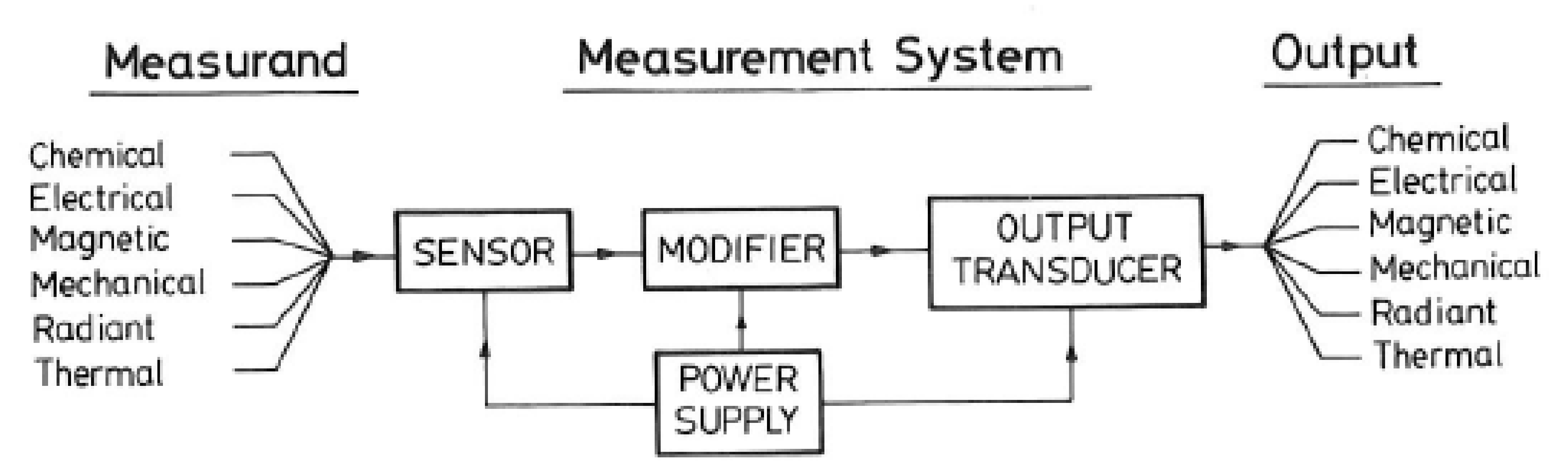
Planning

- 10 Lectures
- Laboratory work “Processing of silicon x-ray and ionised particle detector”
  - Processing in clean room , 3 groups
  - Characterisation with alpha source and x-ray
  - Written report
- “Home” written exam, hand in latest ,16 of January,
- ISBN 0-471-54609-7 “Semiconductor sensors” S.M.Sze
- http://apachepersonal.miun.se/~gorthu/sensor/

Planning Lectures

- 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
- L10 Integrated Sensors

Classification and terminology of sensors



The sensor produce in most case an electrical signal

Classification Scheme

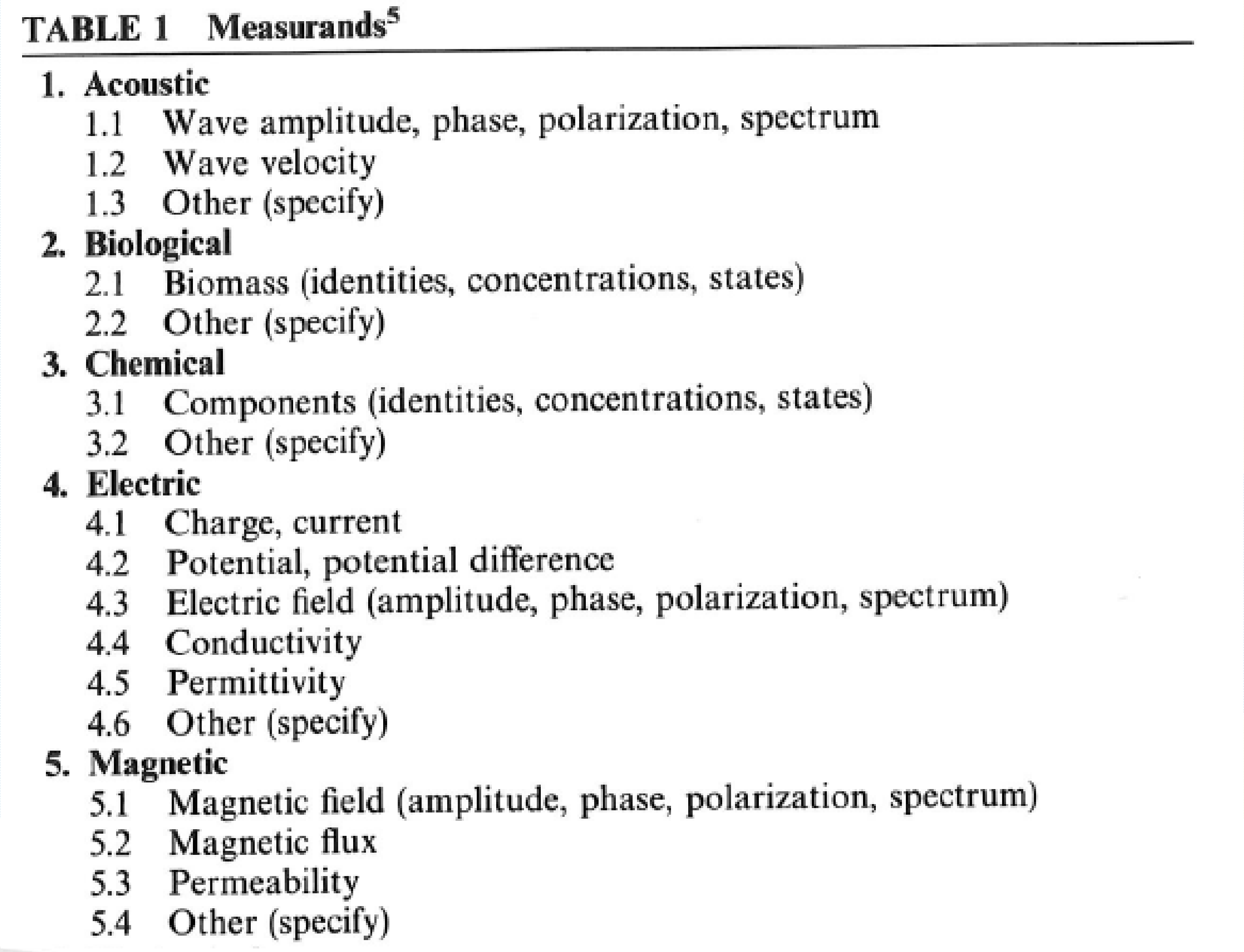
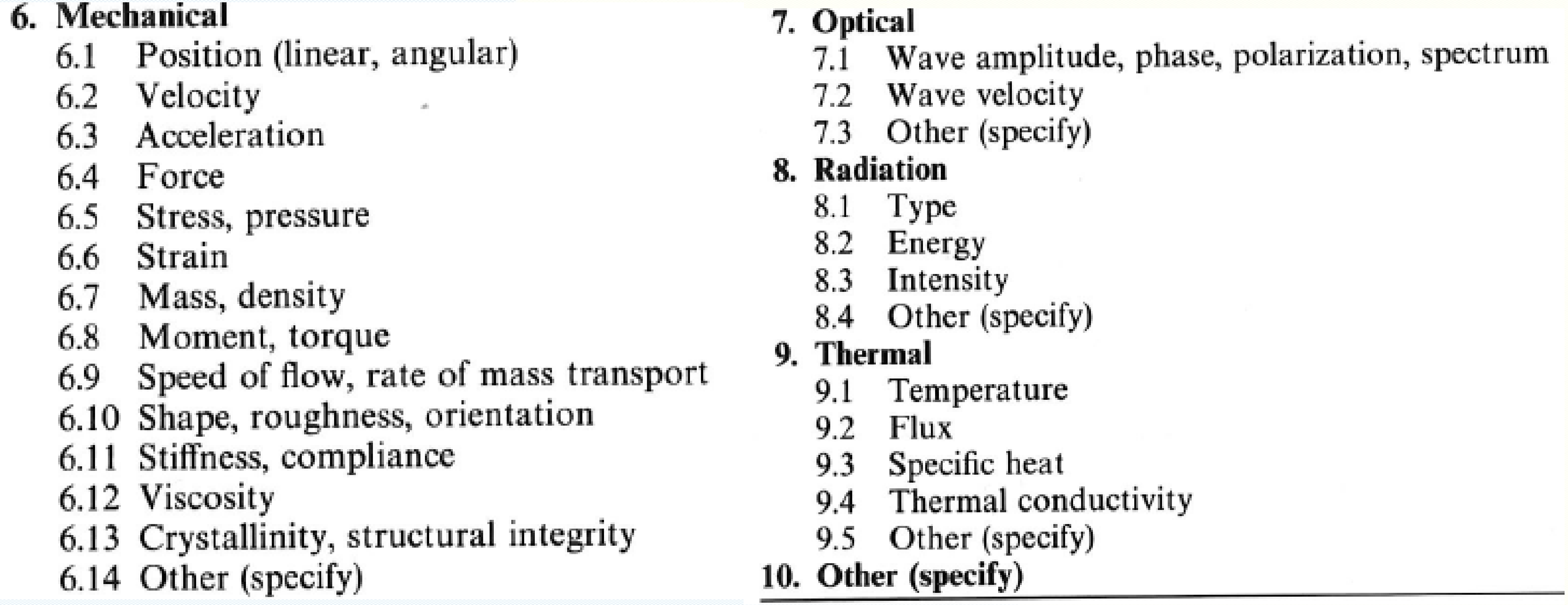


TABLE 1 Measurands[5]

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)

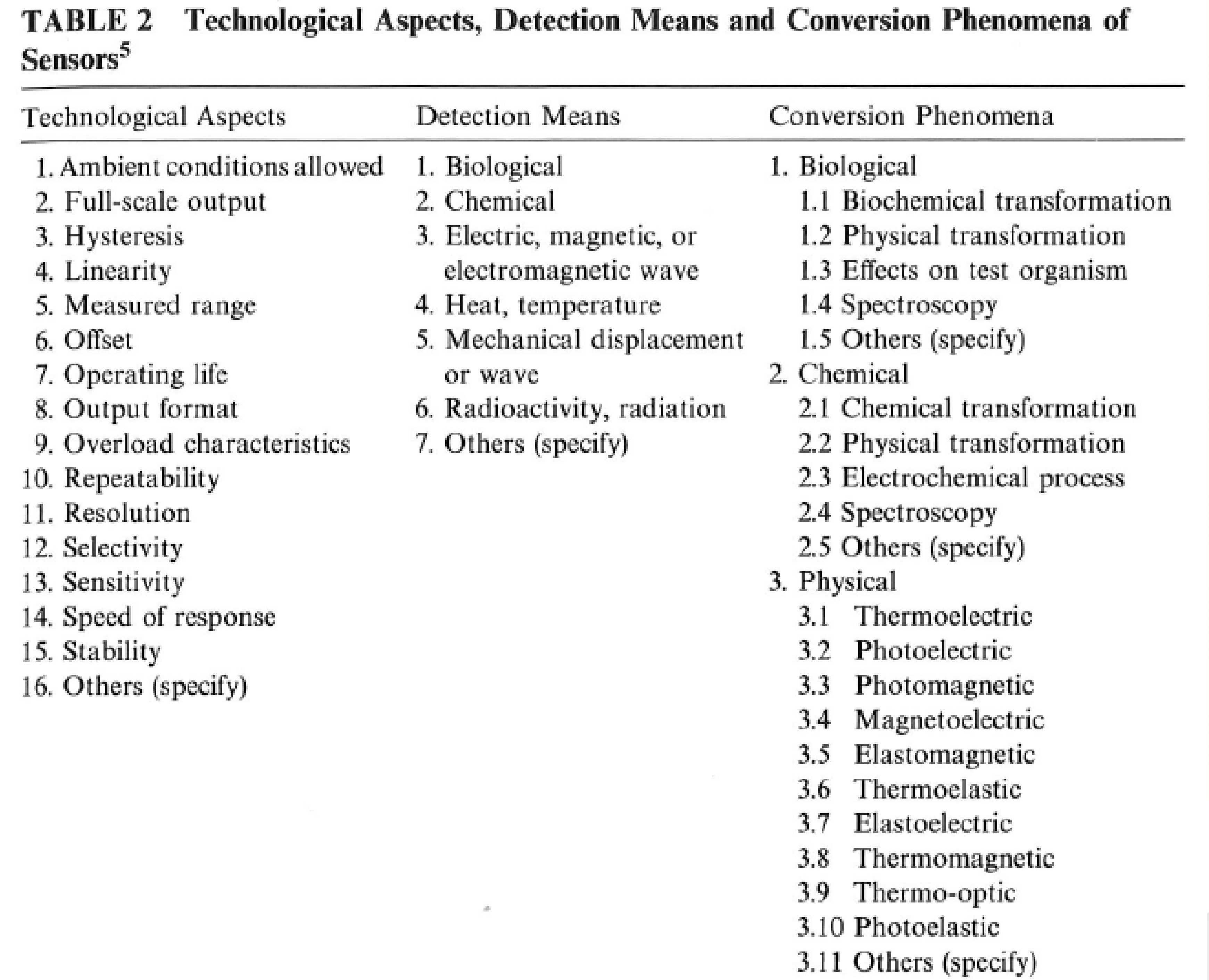
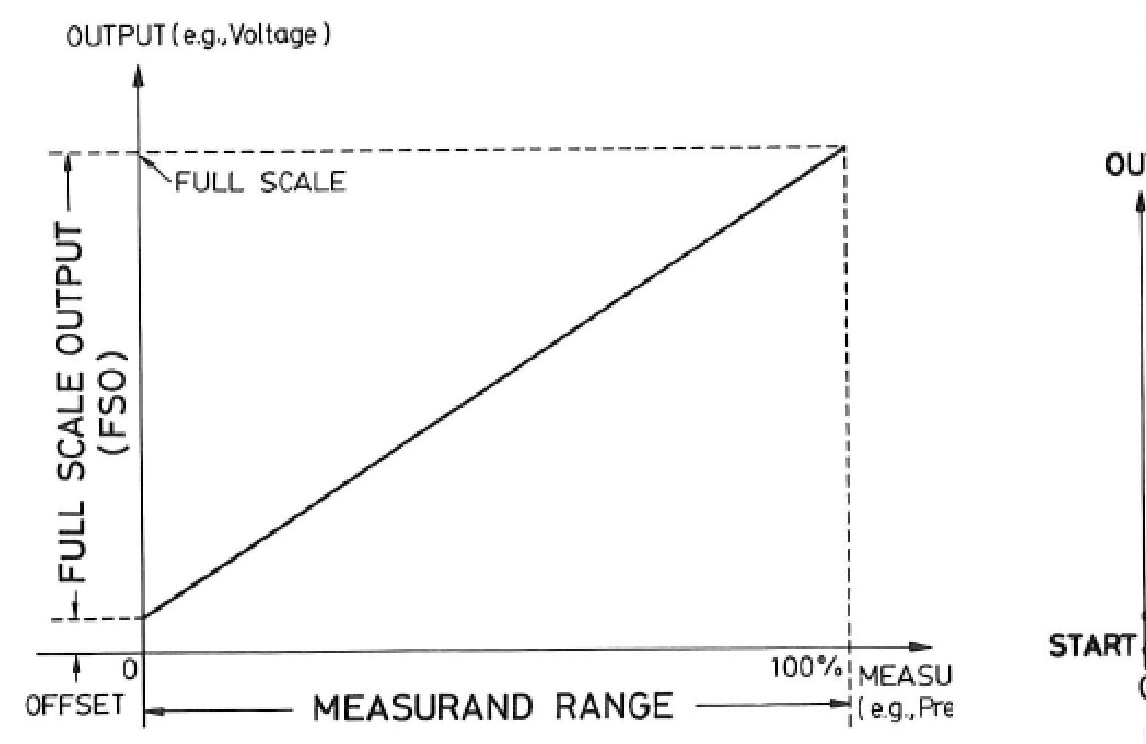
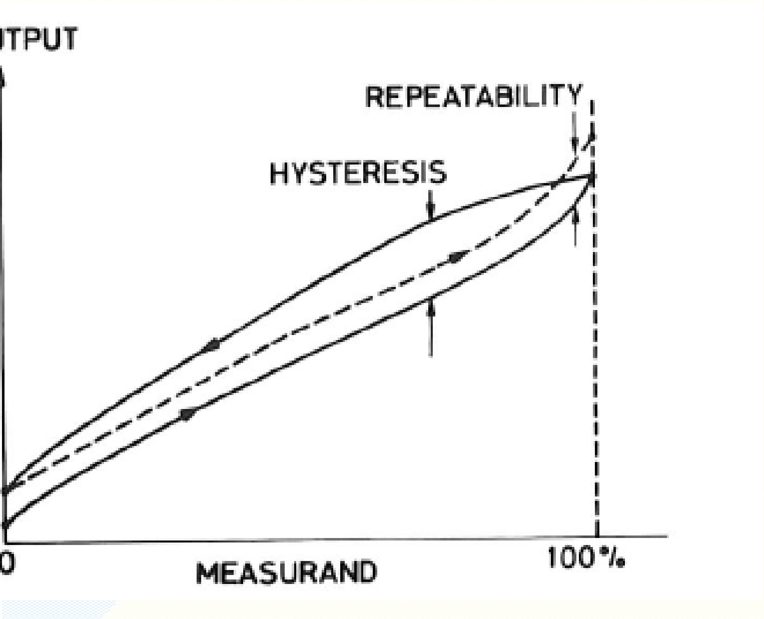


TABLE 2 Technological Aspects, Detection Means and Conversion Phenomena of Sensors[5]

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


OUTPUT (e.g.,Voltage)
FULL SCALE
FULL SCALE OUTPUT (FSO)
0
100%
MEASU
(e.g.,Pre
OFFSET
MEASURAND RANGE


OUTPUT
REPEATABILITY
HYSTERESIS
START
0
MEASURAND
100%

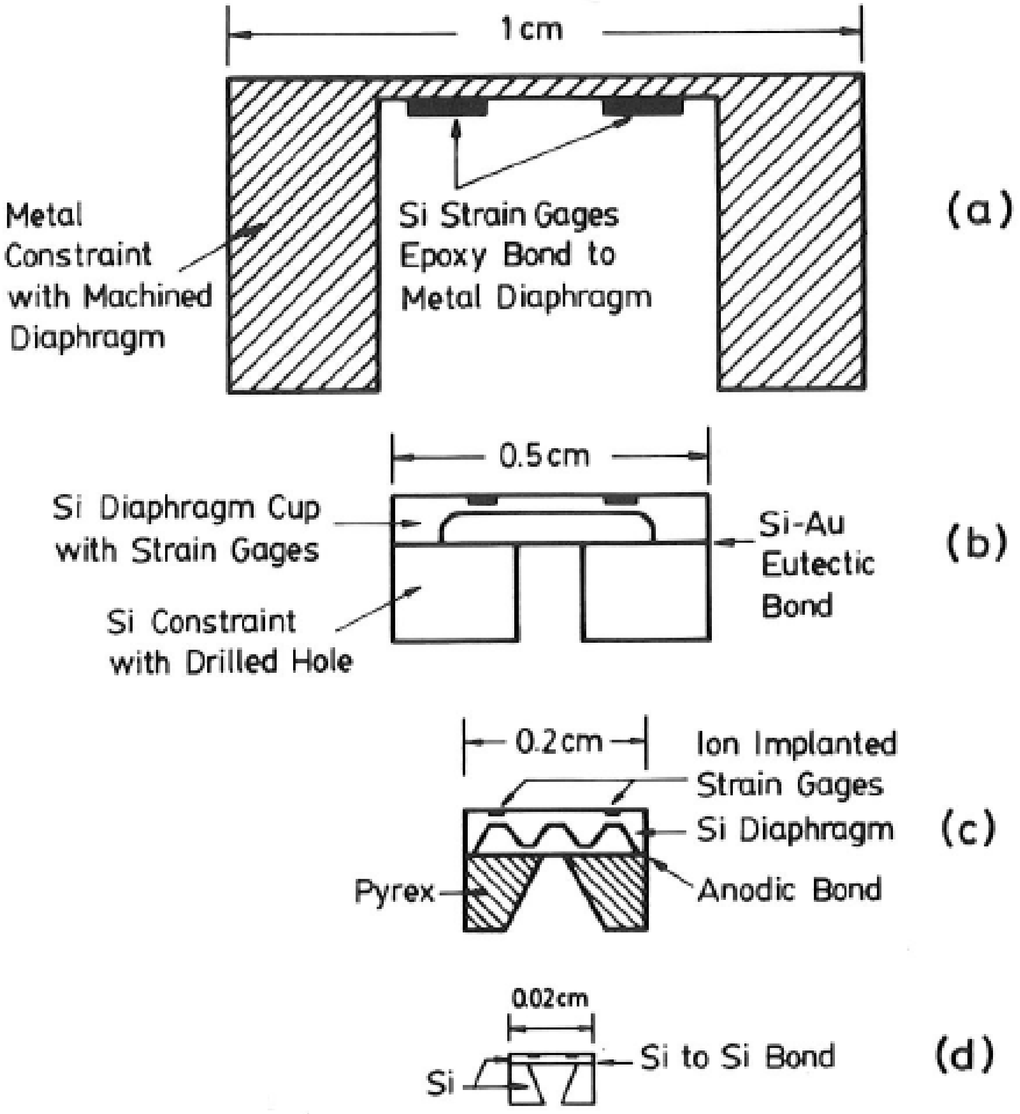


Fig. 5 Evolution of diaphragm pressure sensors. (After Ref. 11)

1958

1965

1975

1985

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

Advantage with silicon processing

Well developed processing technology, where the microprocessor end memory manufactures have pushed the technology to a sub um scale.

Batch processing result in a large number of sensors fabricated simultaneously at a low cost.

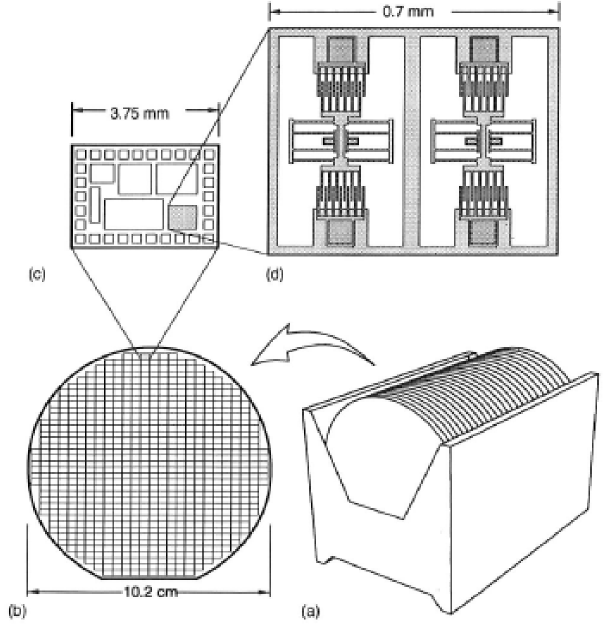


Fig. 2 Batch-fabrication process of microelectronic circuits.

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

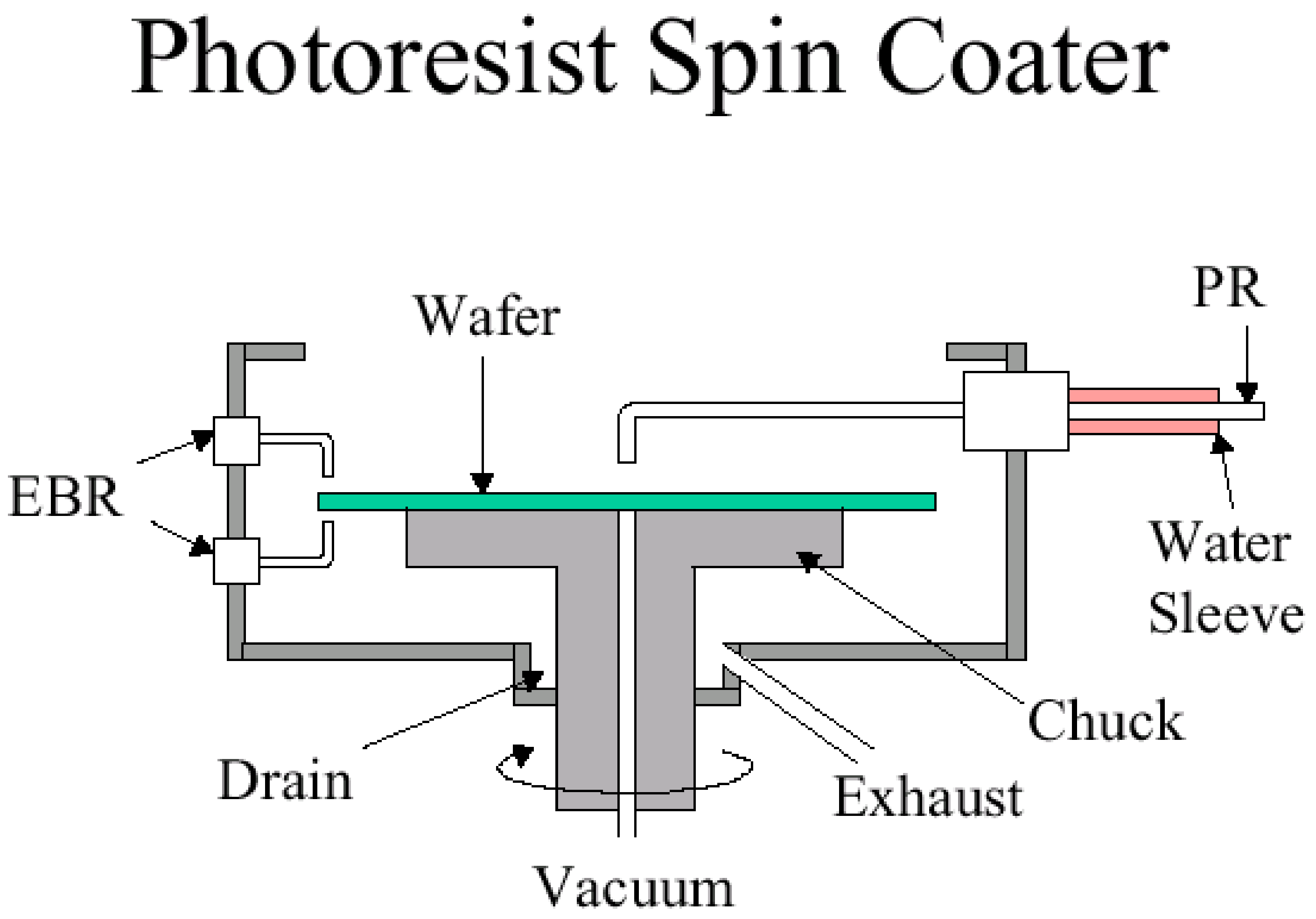
Semiconductor Sensor Technologies

- Important processing steps to fabricate a sensor are
  - **Deposition**
  - **Lithography**
  - **Etching**

Semiconductor Sensor Technologies

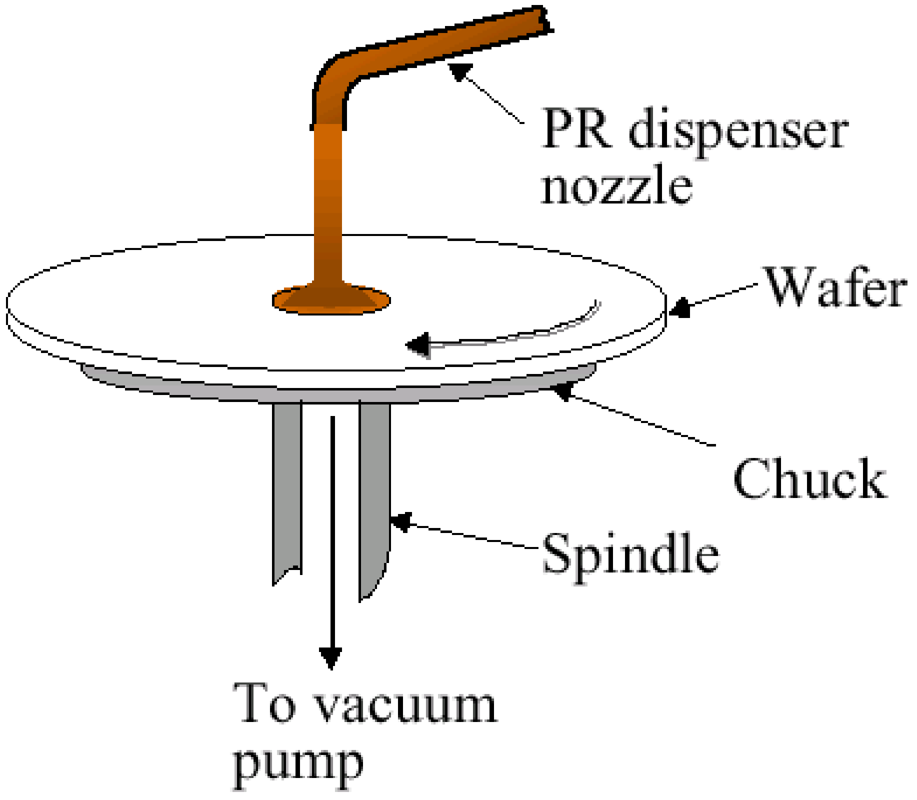
- Basic fabrication Steps
  - **Deposition**
    - Spin Casting
    - Evaporation
    - Sputtering
    - Reactive growth
    - Chemical Vapour deposition
    - Plasma deposition

Spin casting

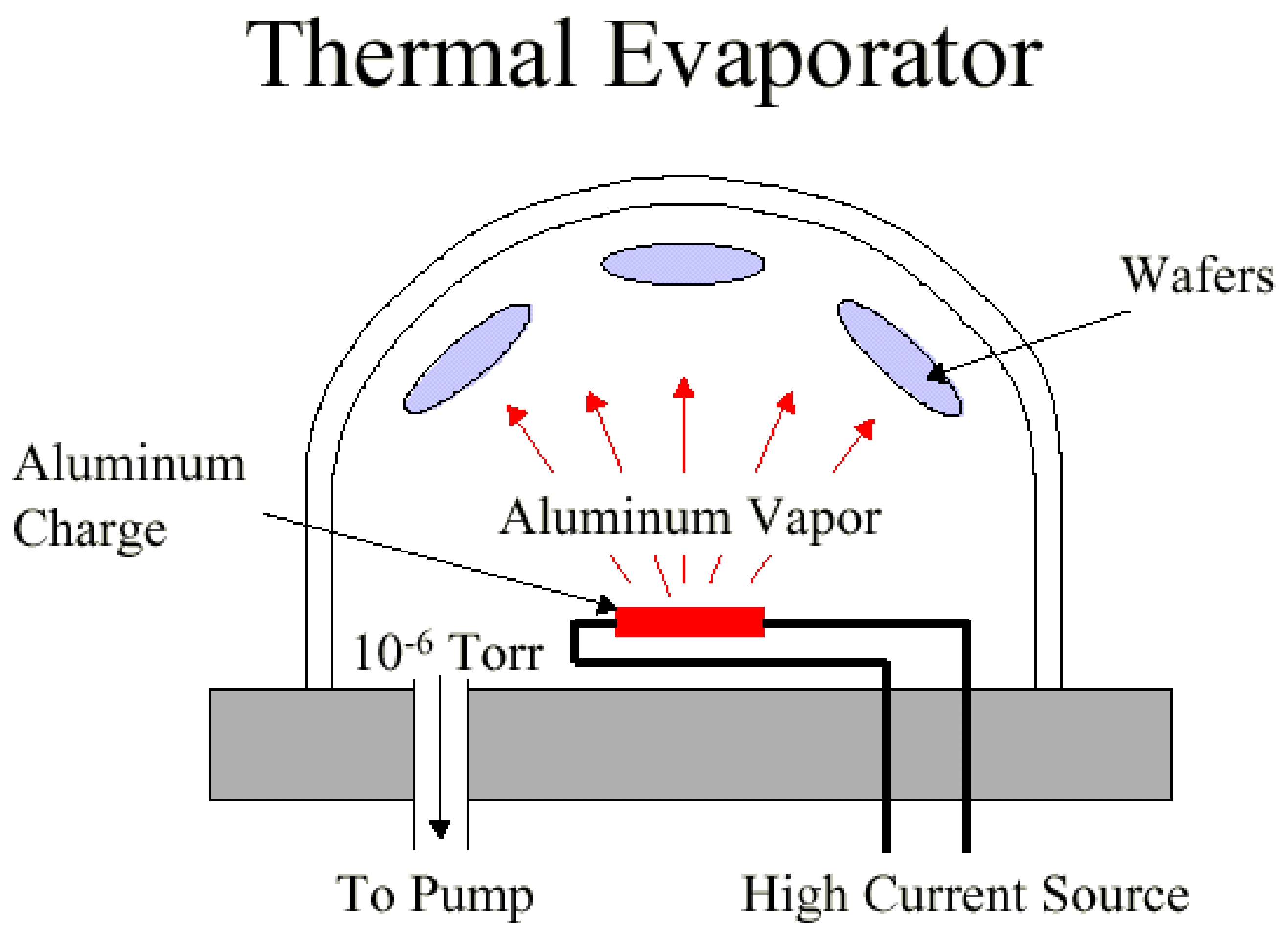


Spin casting

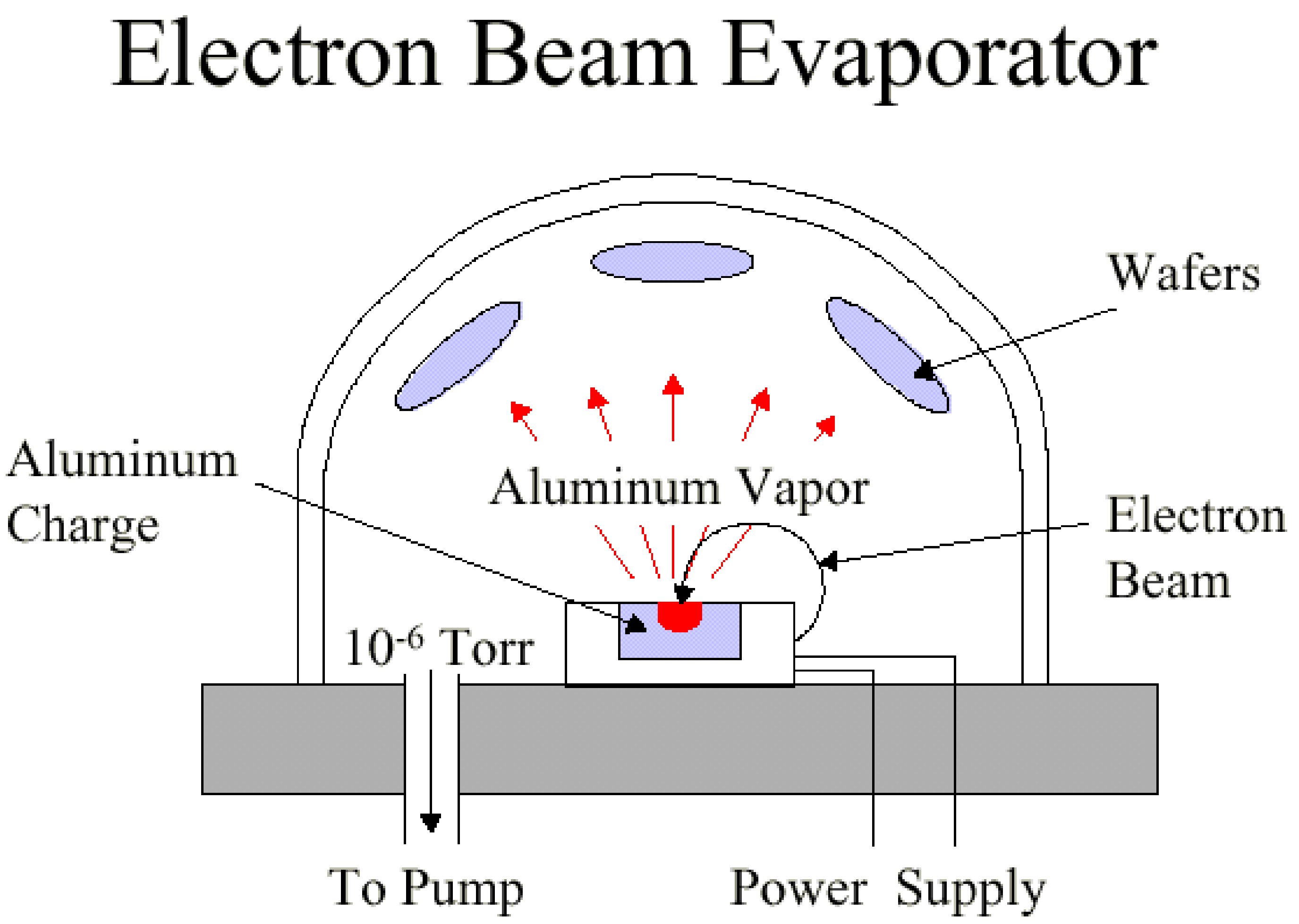
Photoresist Applying



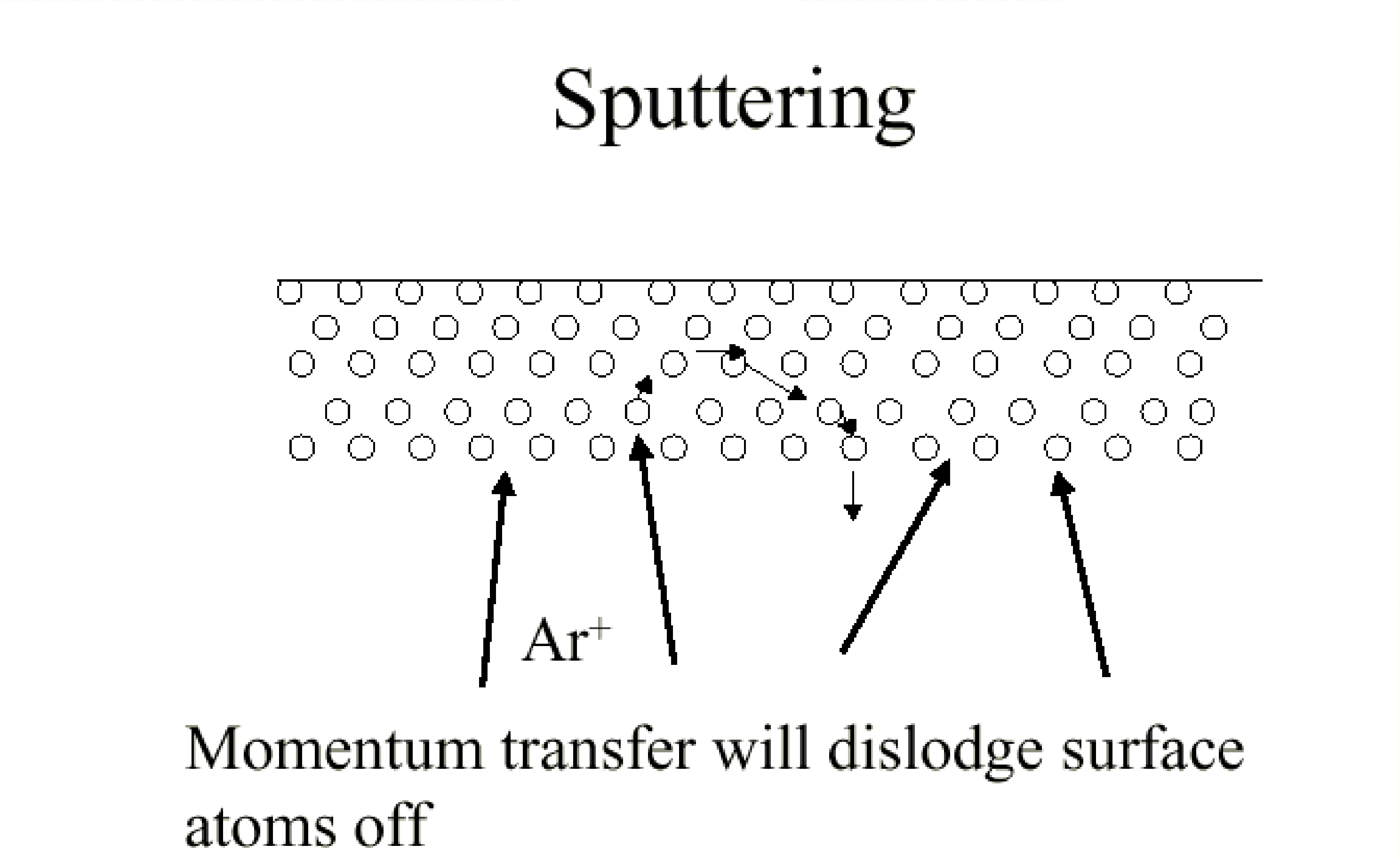
Evaporation



Evaporation



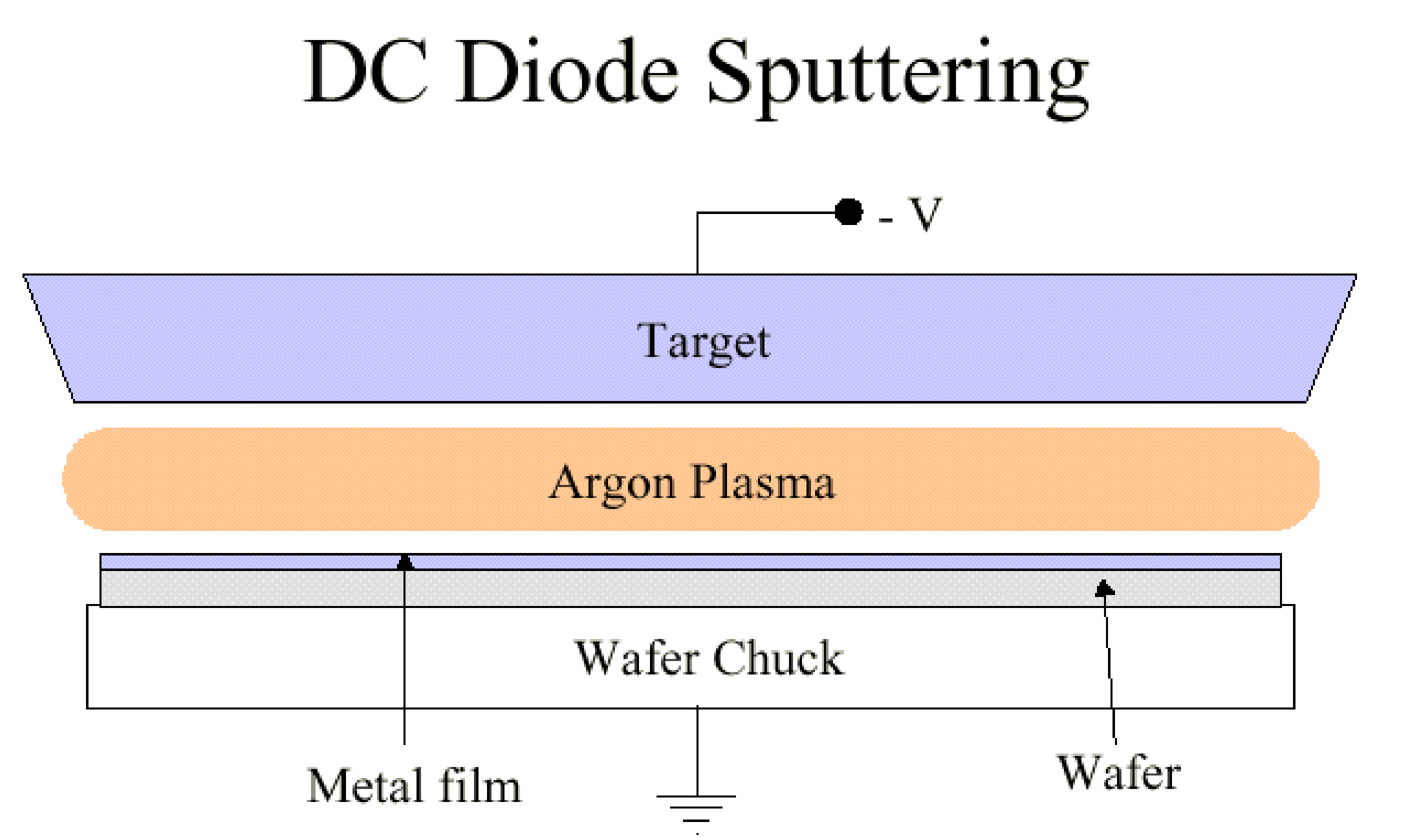
Sputtering



Sputtering

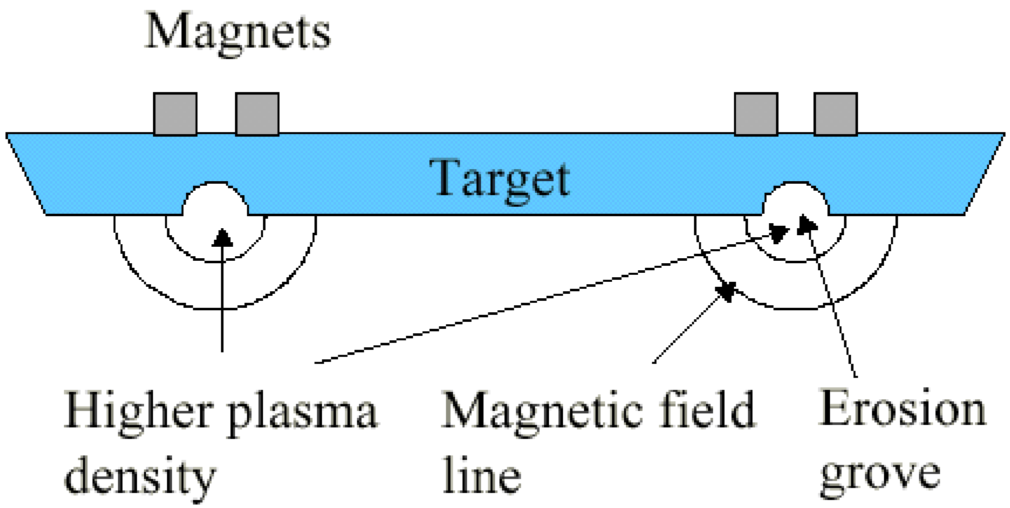
Momentum transfer will dislodge surface atoms off

Sputtering

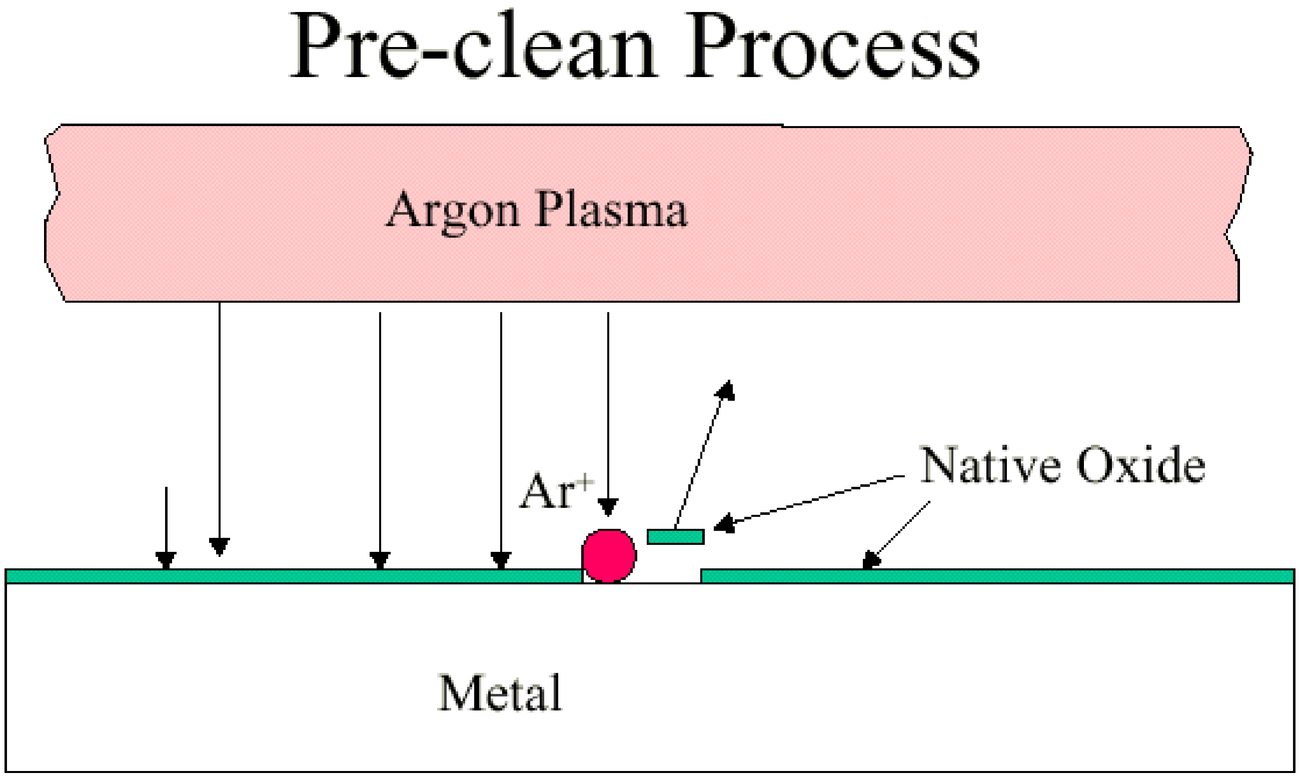

DC Diode Sputtering
- V
Target
Argon Plasma
Wafer Chuck
Metal film
Wafer

Sputtering

Schematic of Magnetron Sputtering



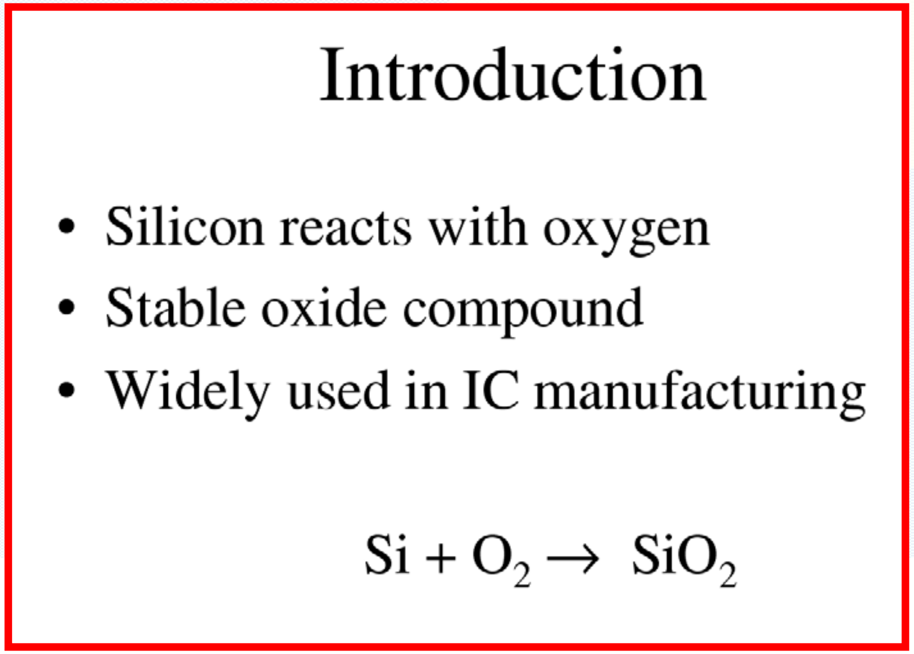
Sputtering



Reactive growth

Material: Silicon

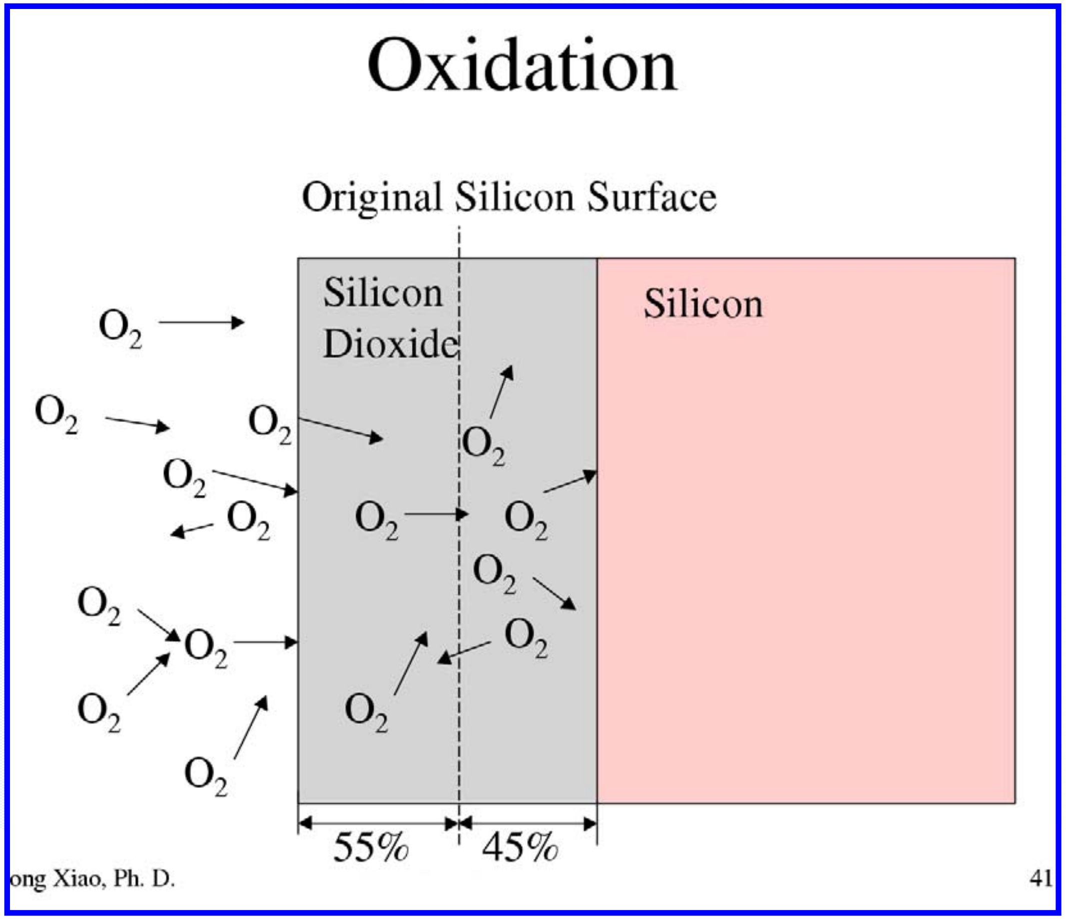
Growth of silicon dioxide, SiO_2



Introduction

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

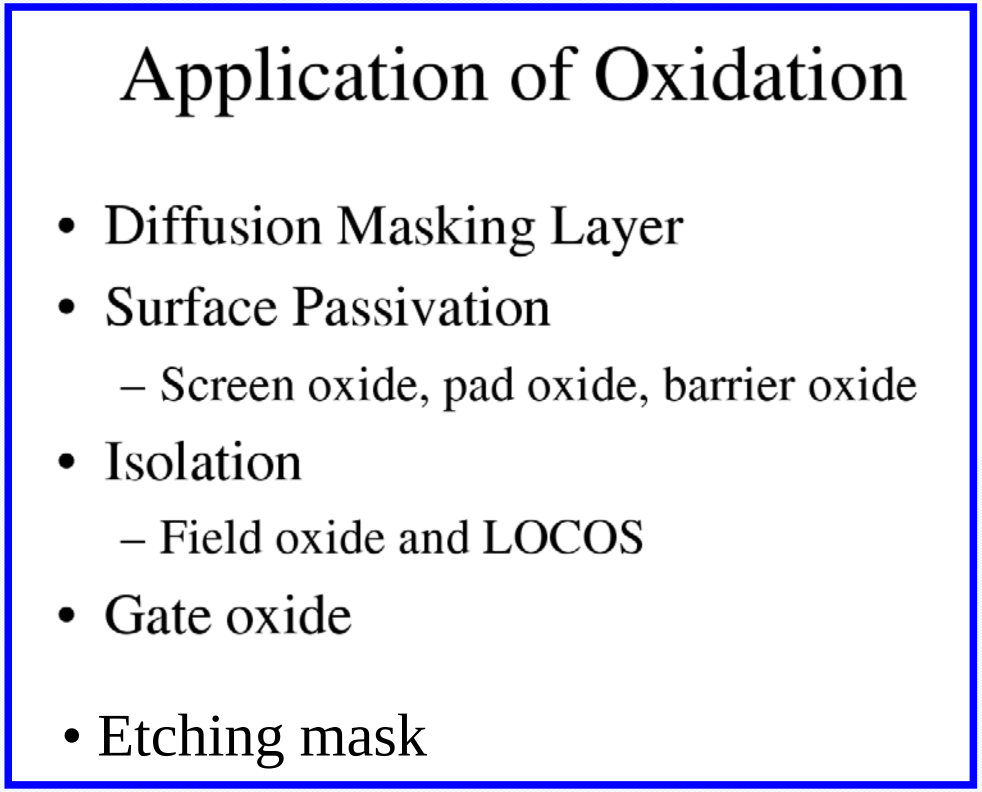
$$Si + O_2 \rightarrow SiO_2$$



Oxidation

ong Xiao, Ph. D.

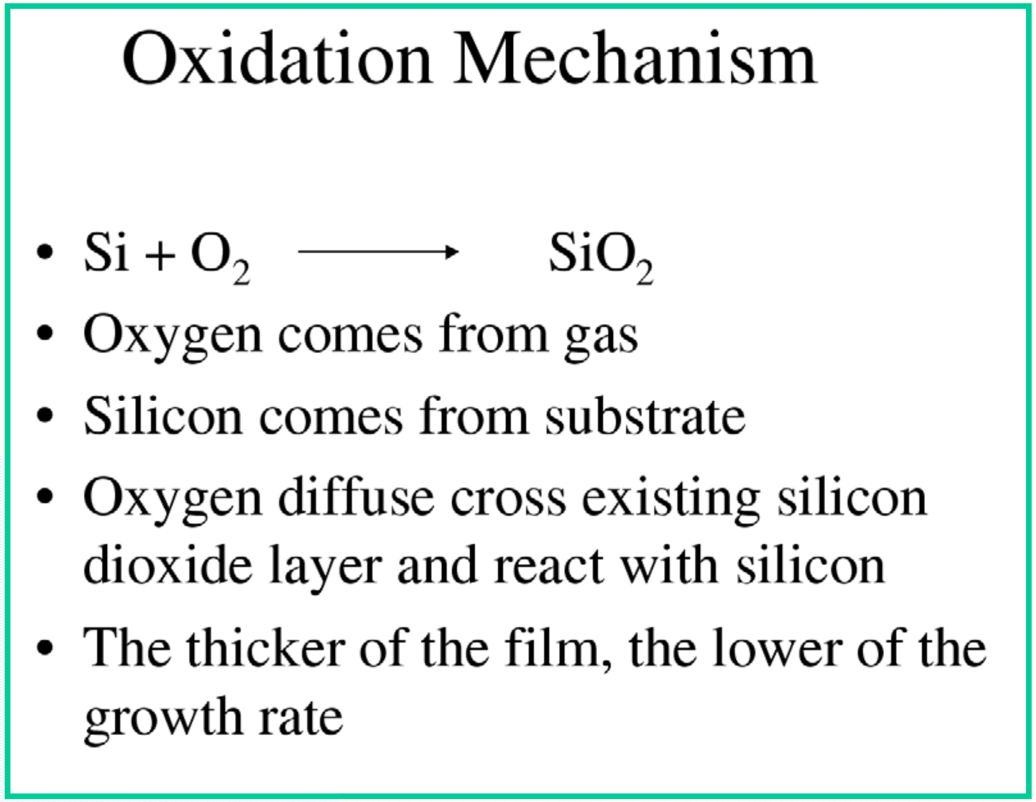
Reactive growth



Application of Oxidation

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

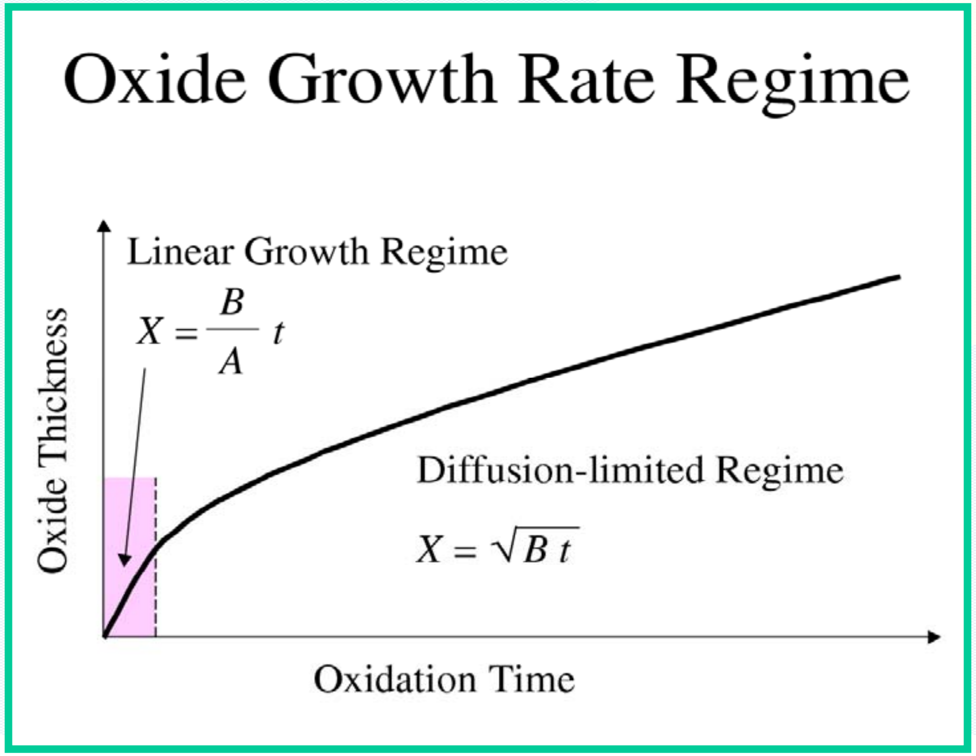
- Etching mask



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

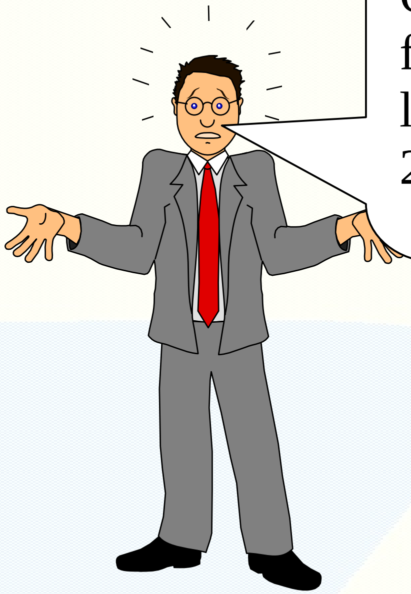
Result of the Deal-Grove model for growth of silicon dioxide

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

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

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

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



Only valid for film thicknesses larger than 200Å !!

Reactive growth

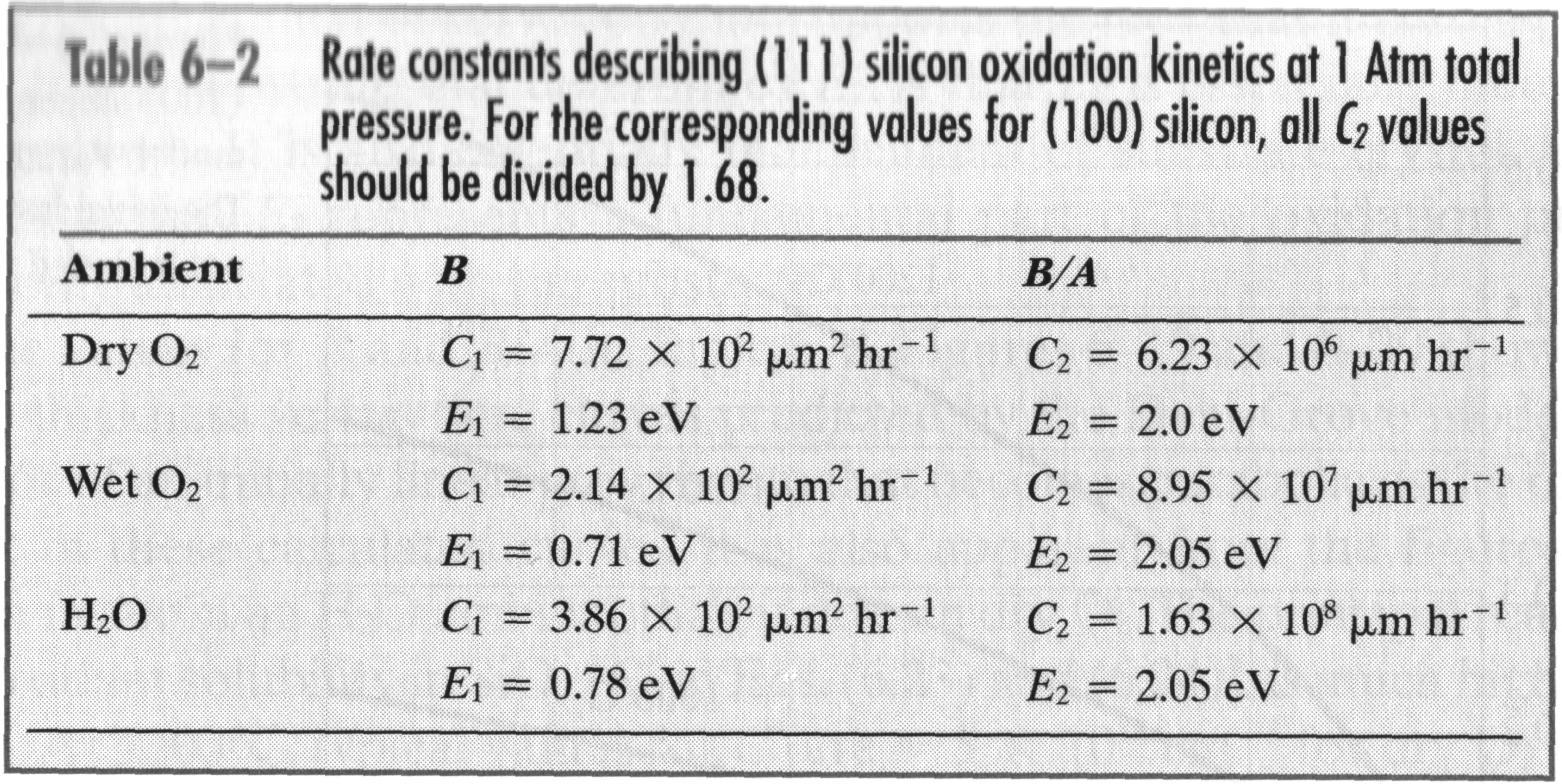
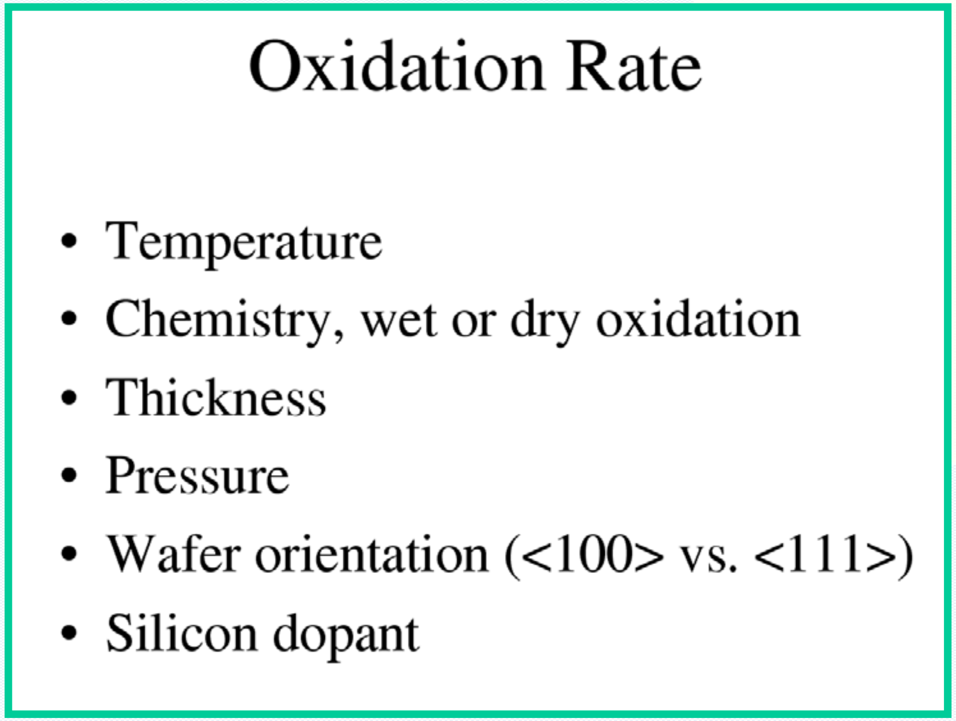


Table 6–2 Rate constants describing (111) silicon oxidation kinetics at 1 Atm total pressure. For the corresponding values for (100) silicon, all C_2 values should be divided by 1.68.

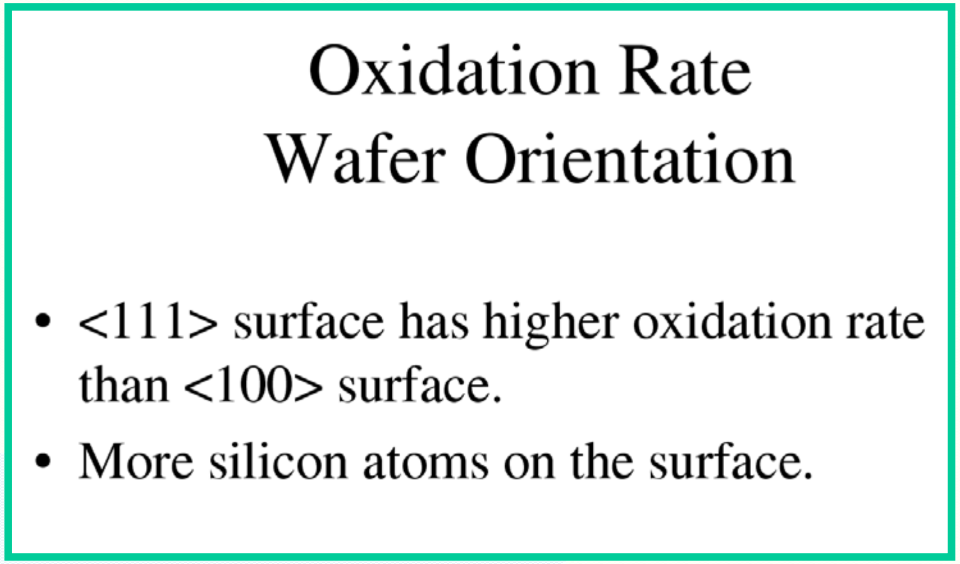
Ambient	***B***	***B/A***
Dry O_2	$C_1 = 7.72 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 6.23 \times 10^6\ \mu m\ hr^{-1}$
	$E_1 = 1.23$ eV	$E_2 = 2.0$ eV
Wet O_2	$C_1 = 2.14 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 8.95 \times 10^7\ \mu m\ hr^{-1}$
	$E_1 = 0.71$ eV	$E_2 = 2.05$ eV
H_2O	$C_1 = 3.86 \times 10^2\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

Reactive growth



Oxidation Rate

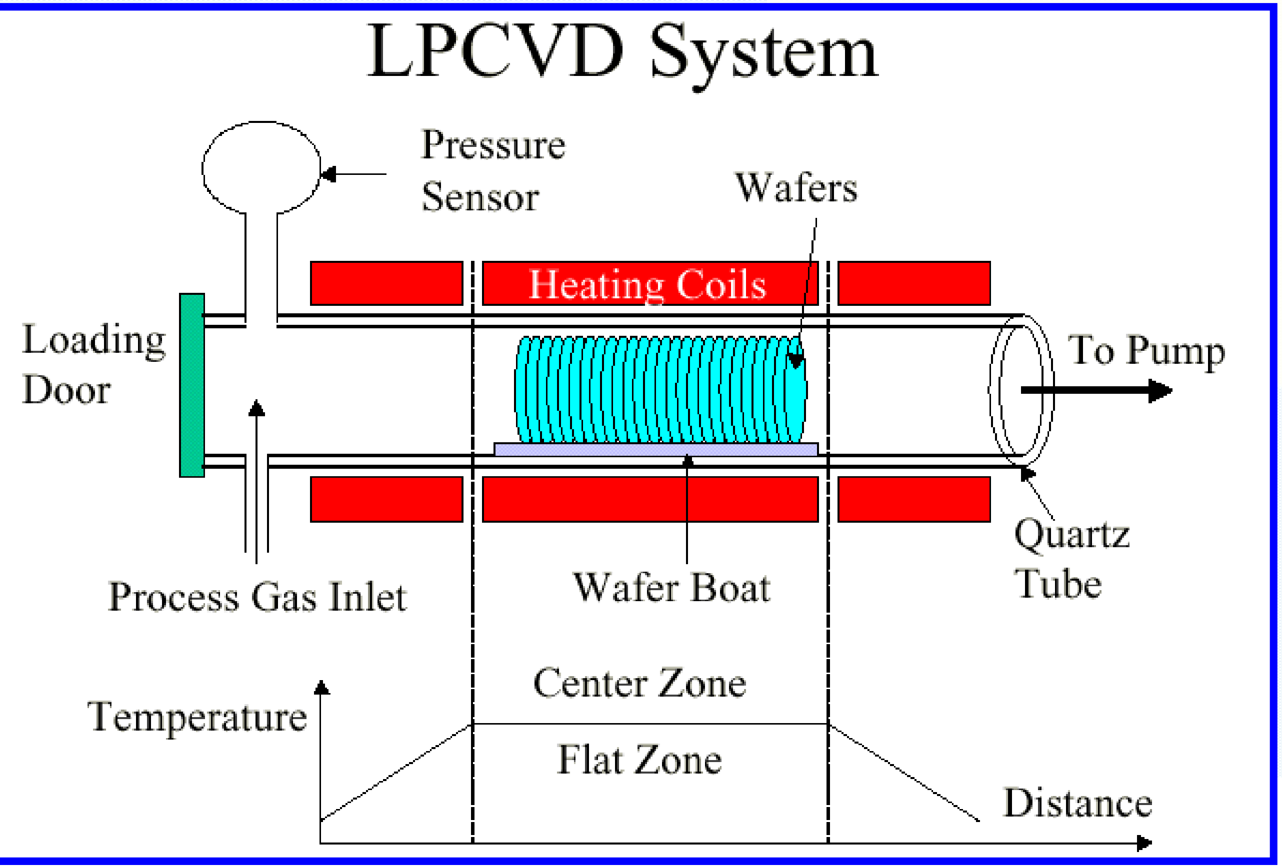
- Temperature
- Chemistry, wet or dry oxidation
- Thickness
- Pressure
- Wafer orientation (<100> vs. <111>)
- Silicon dopant



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

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

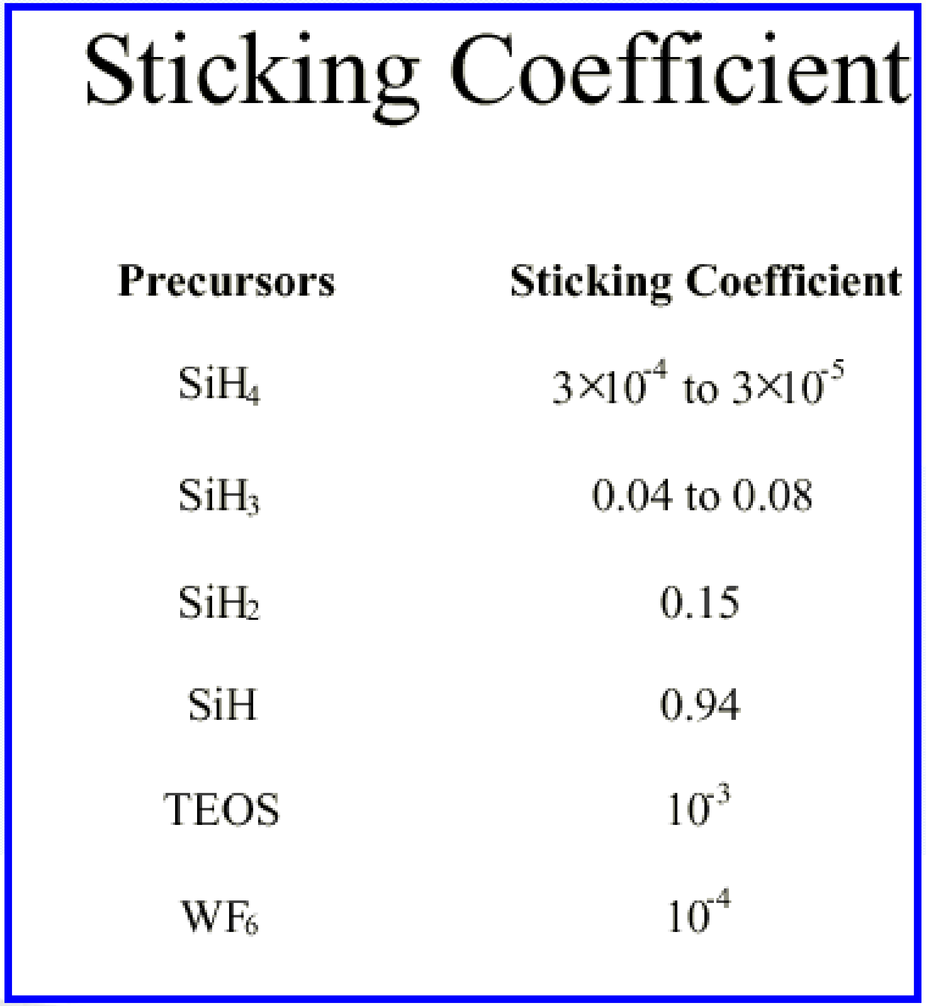
Dielectric CVD Precursors

- 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)

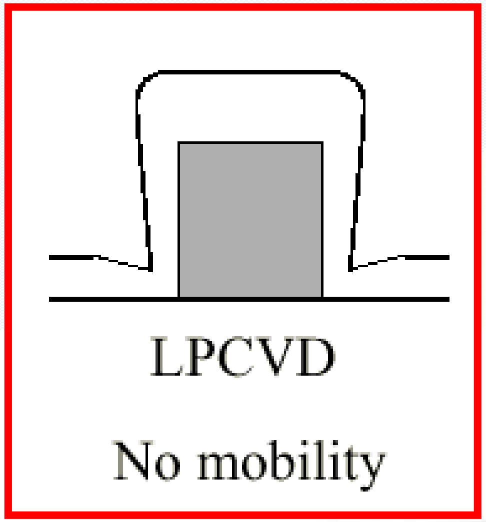


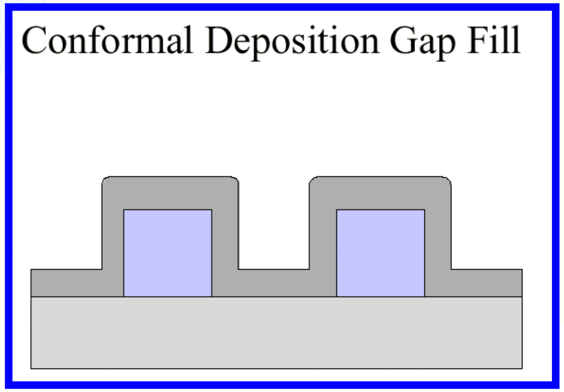
Sticking Coefficient

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



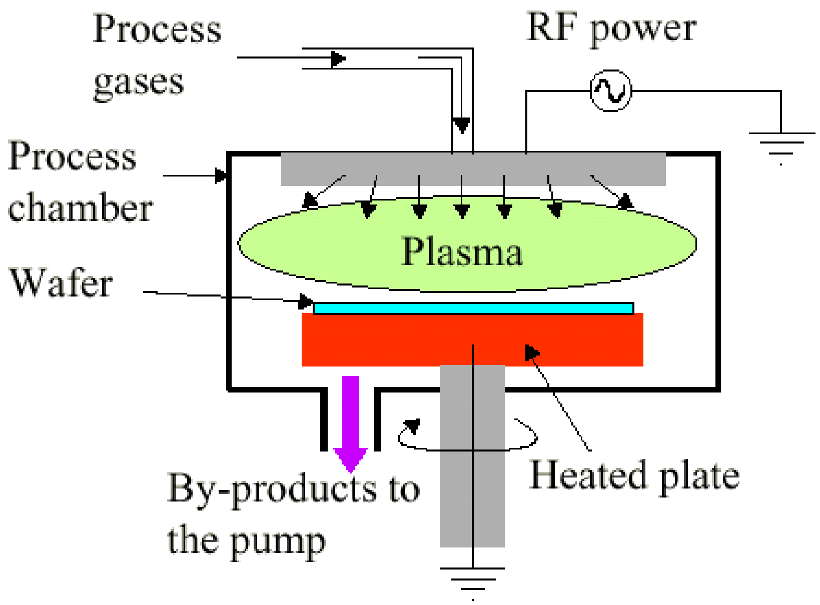

Conformal Deposition Gap Fill

Plasma deposition

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

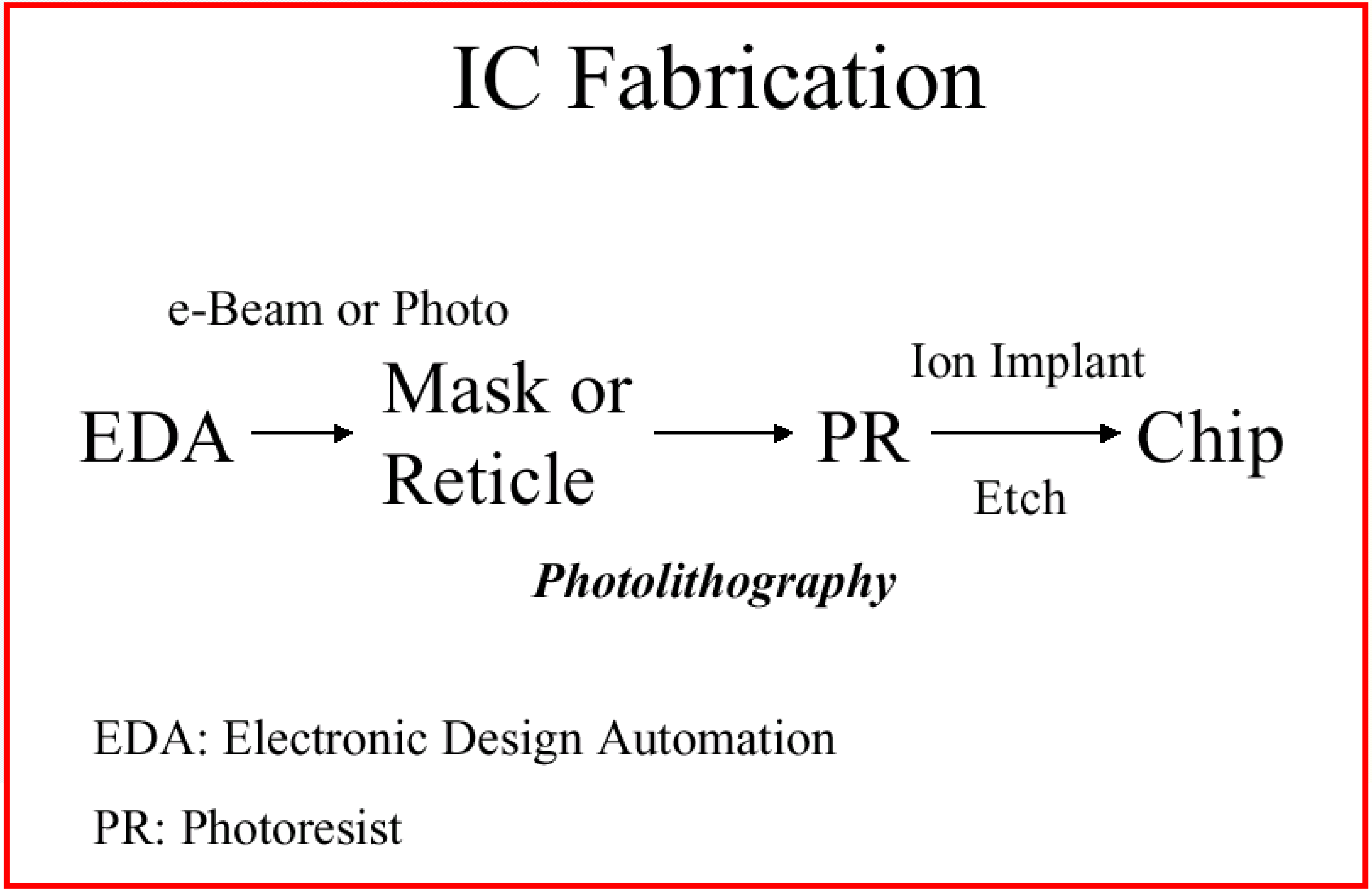


Film contains trapped hydrogen, which alter the etching resistance, properties improves after annealing

Semiconductor Sensor Technologies

- Basic fabrication Steps
  - **Lithography**
    - Mask making
    - Alignment and Exposure
    - Lift-off
  - **Etching**
    - Wet chemical etching
    - Dry etching

Lithography



IC Fabrication

e-Beam or Photo

EDA → Mask or Reticle → PR → Chip

Ion Implant

Etch

Photolithography

EDA: Electronic Design Automation

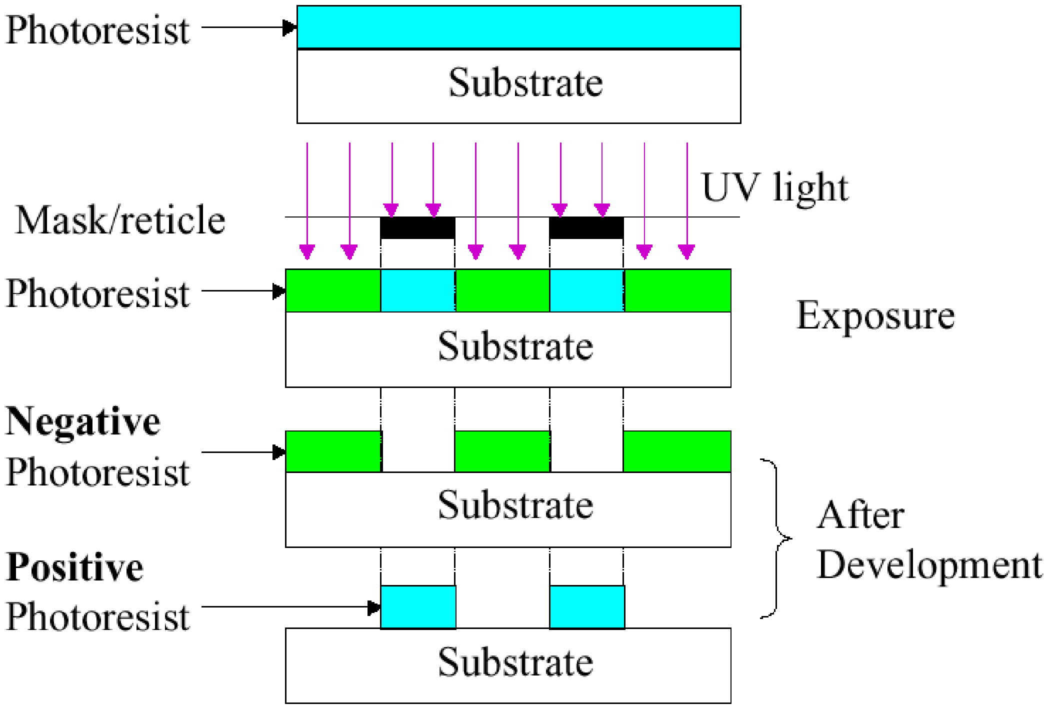
PR: Photoresist

Lithography

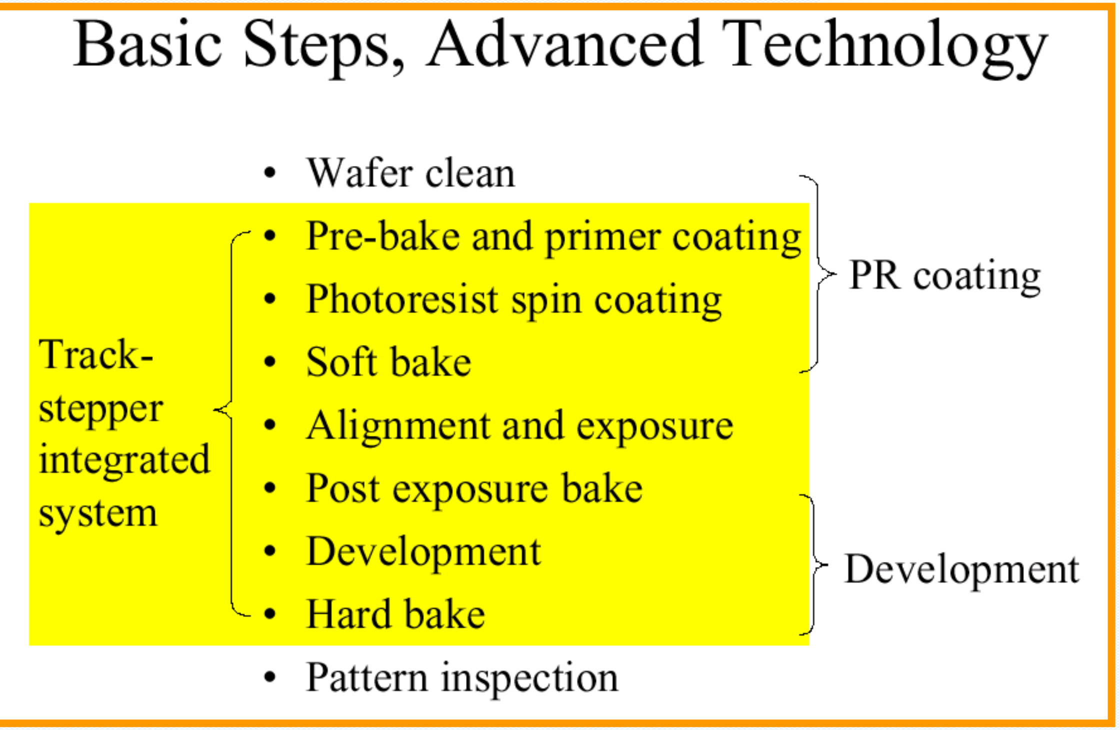
Photoresist

Negative Photoresist	**Positive Photoresist**
• Becomes insoluble after exposure	• Becomes soluble after exposure
• When developed, the unexposed parts dissolved.	• When developed, the exposed parts dissolved
• Cheaper	• Better resolution

Negative and Positive Photoresists



Lithography



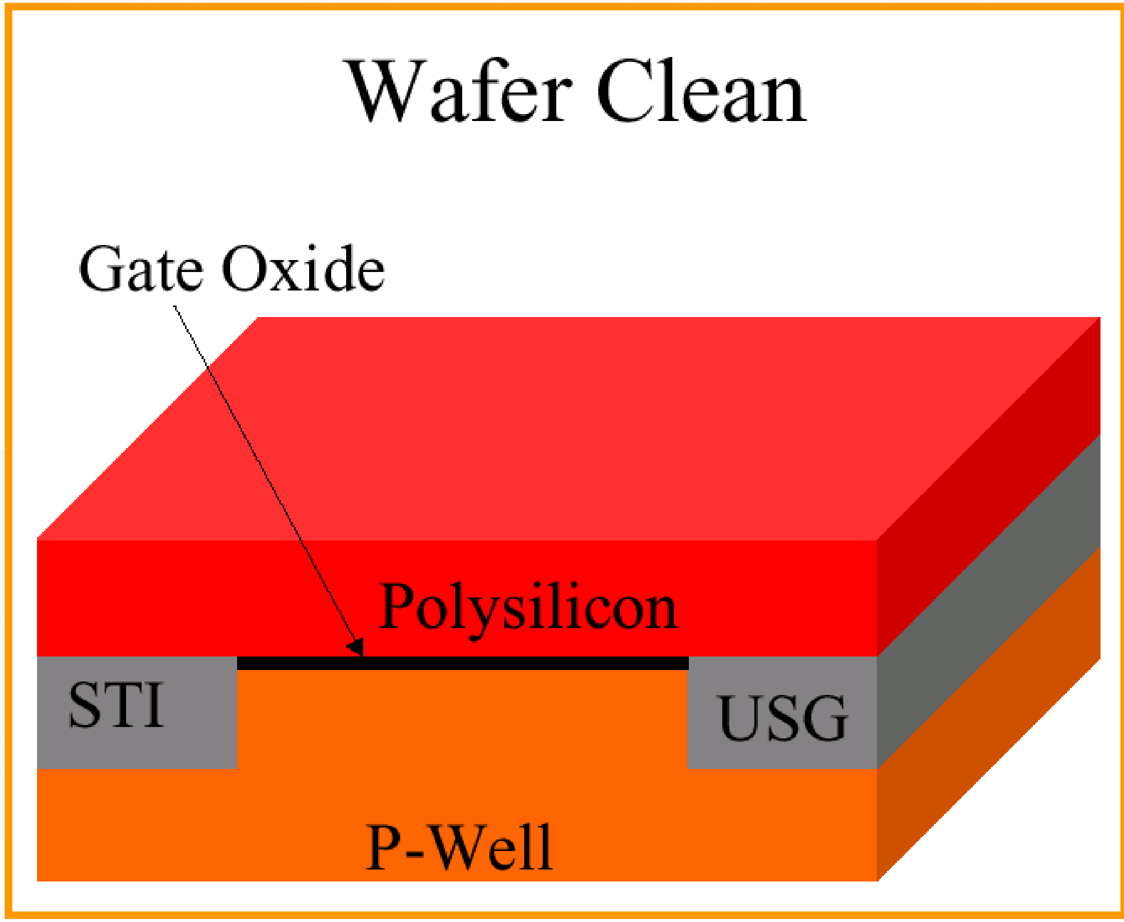
Basic Steps, Advanced Technology

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

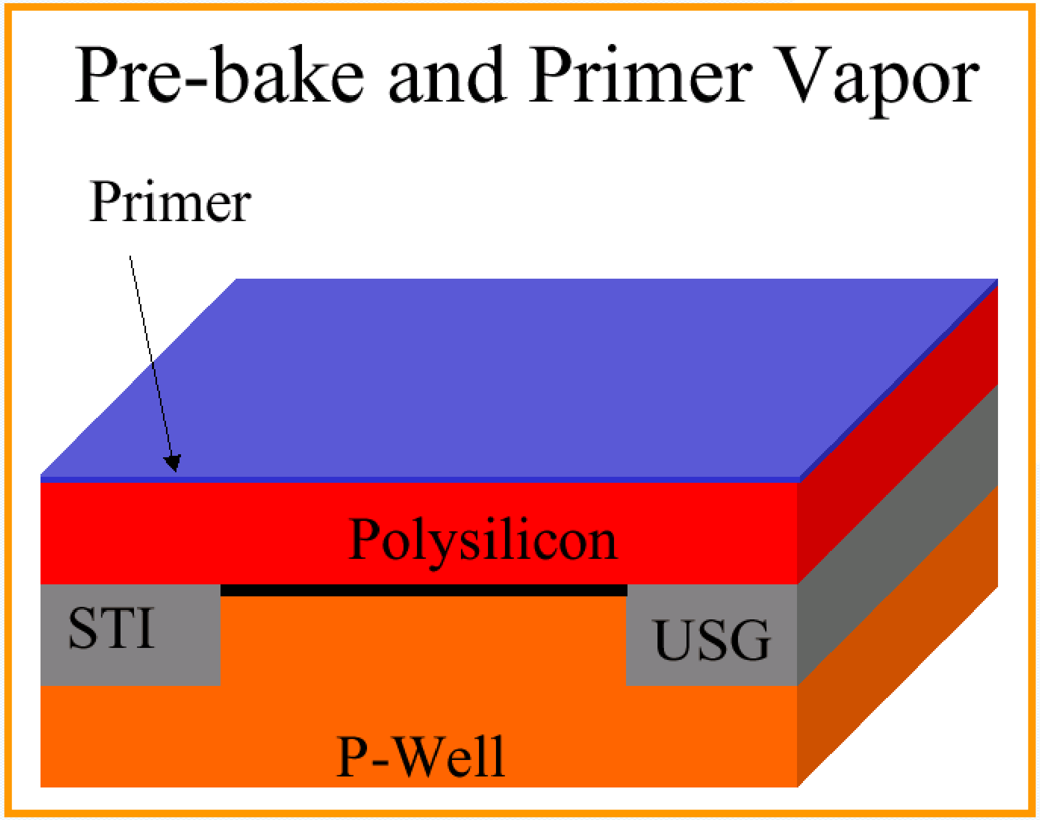
Track-stepper integrated system

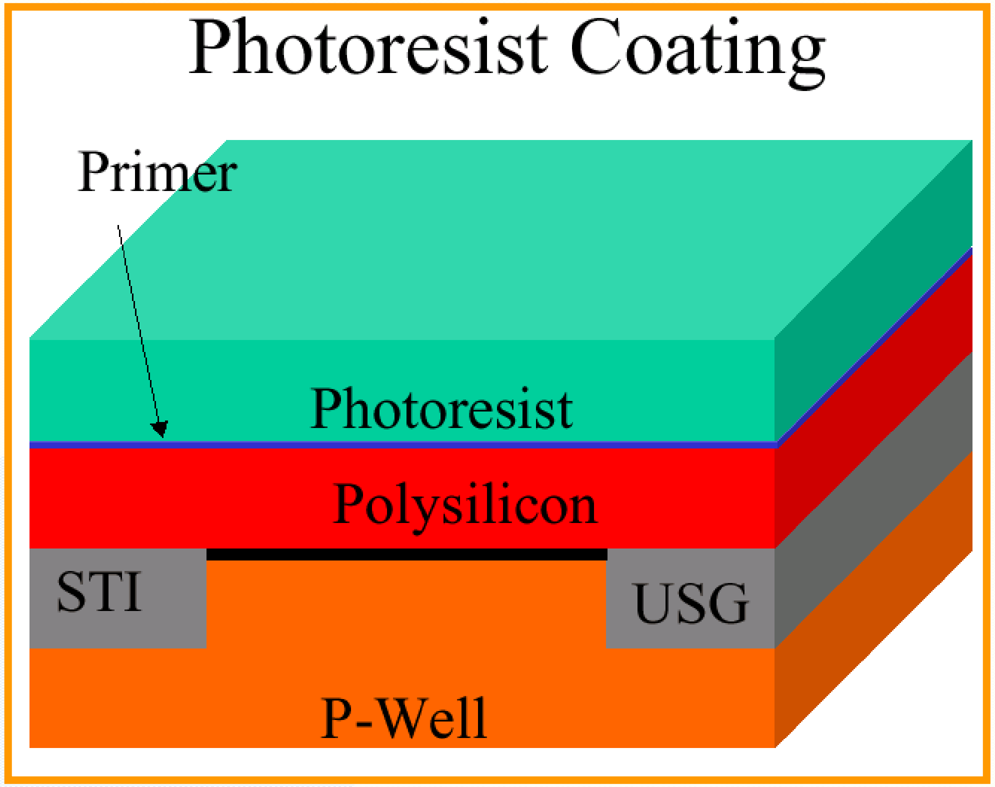
PR coating

Development



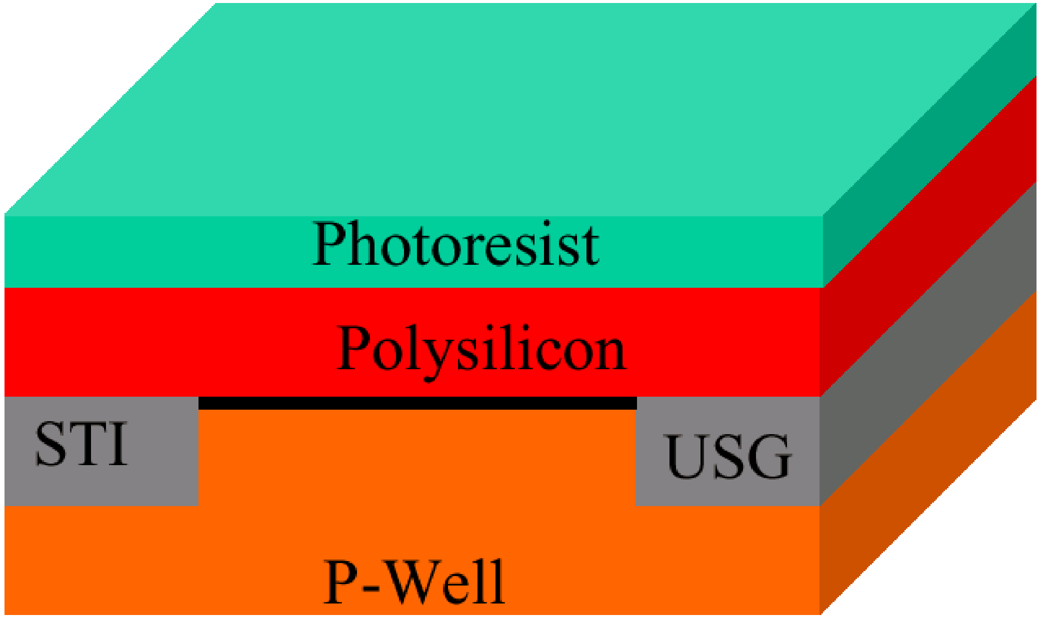
Lithography



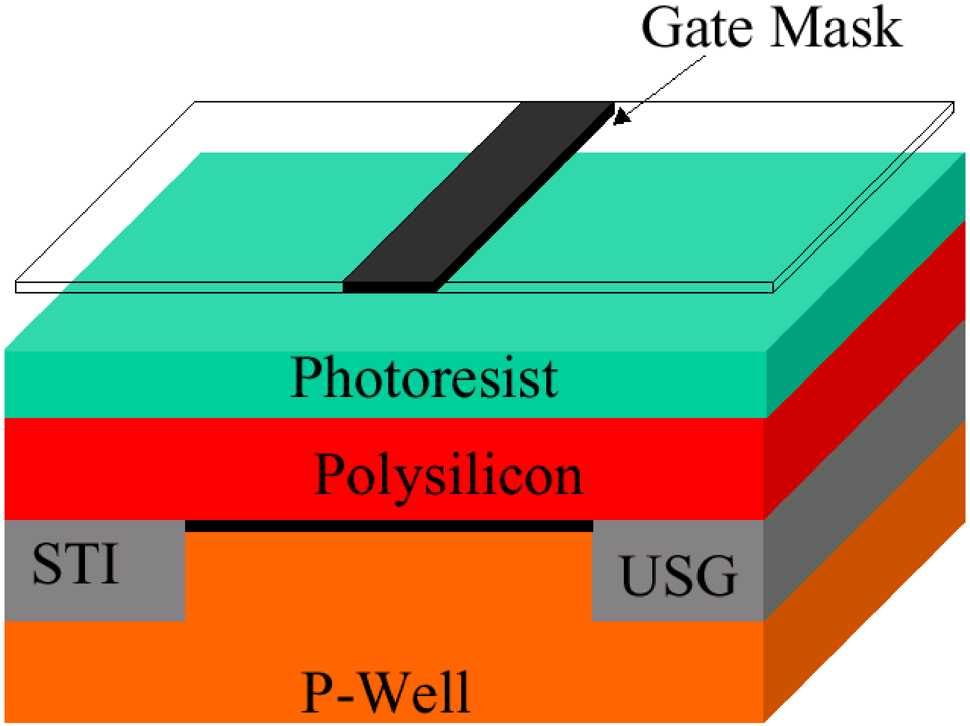


Lithography

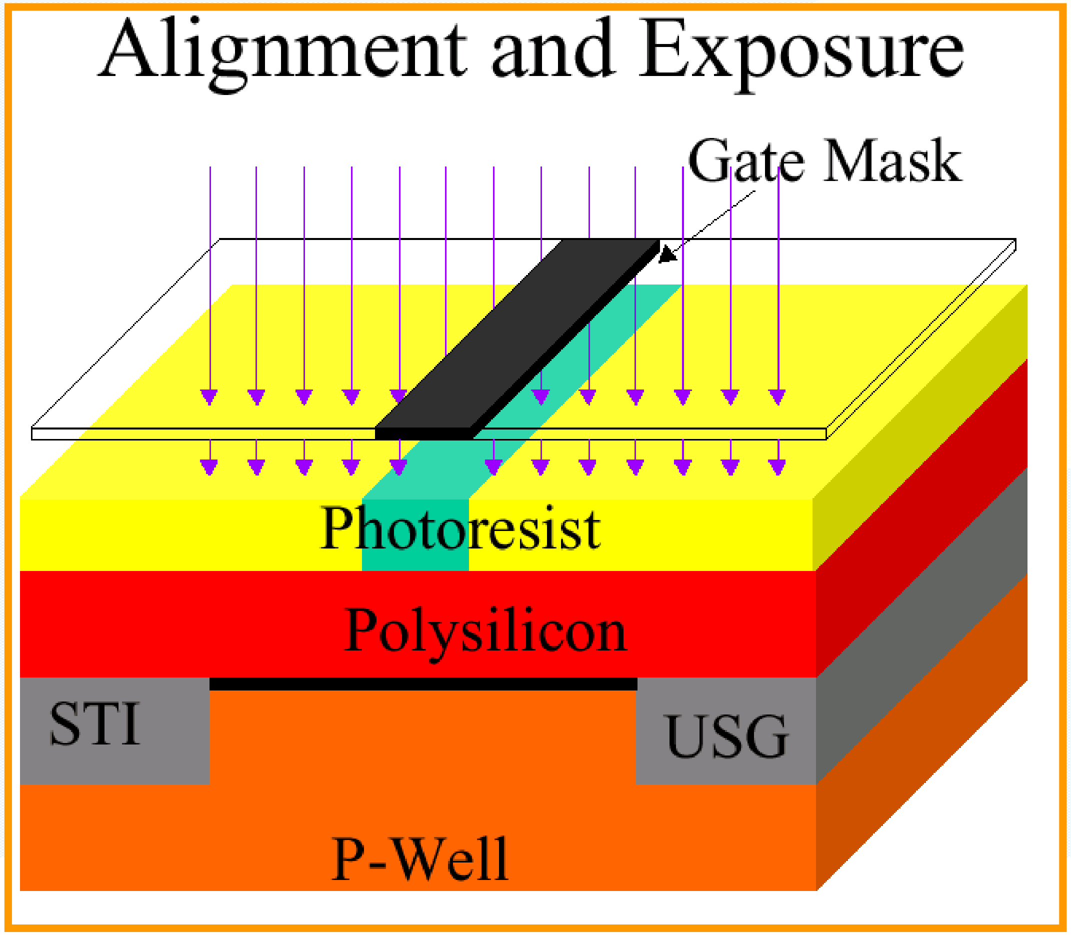
Soft Bake



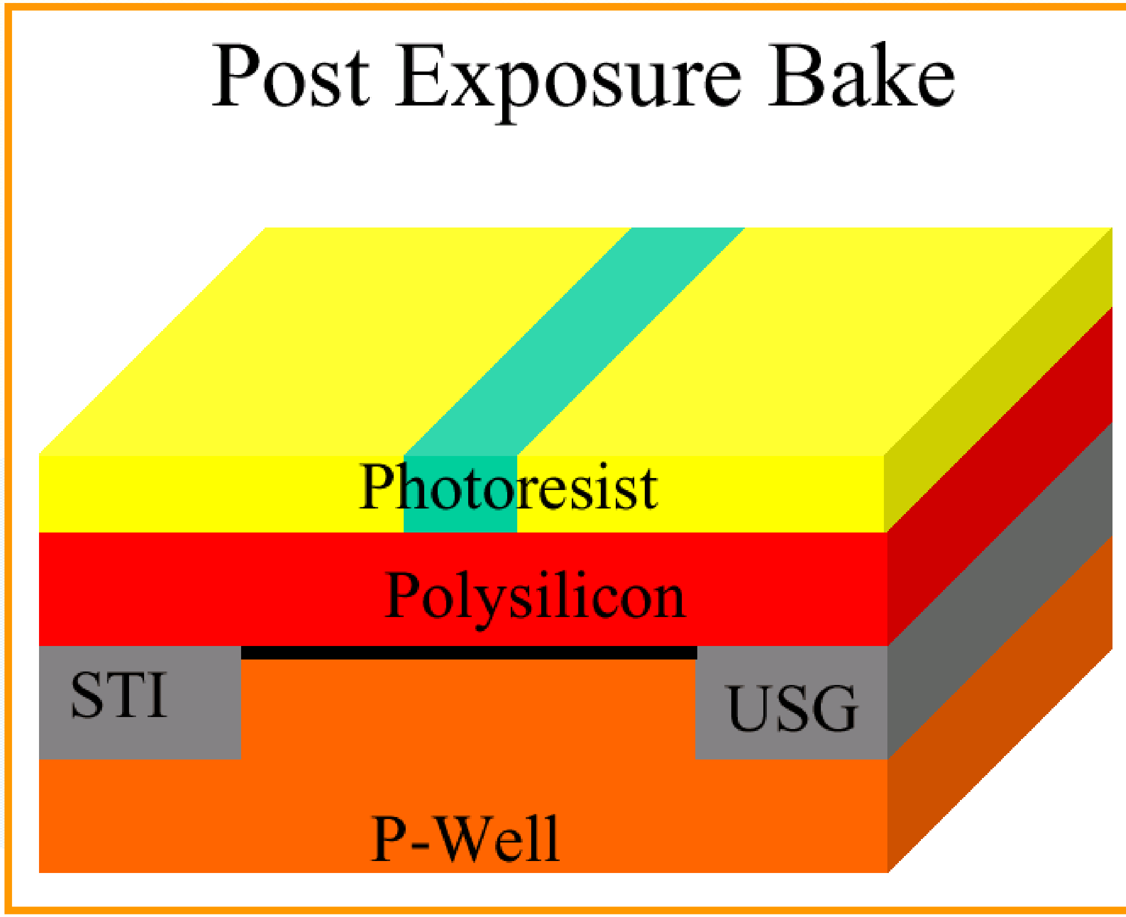
Alignment and Exposure



Lithography



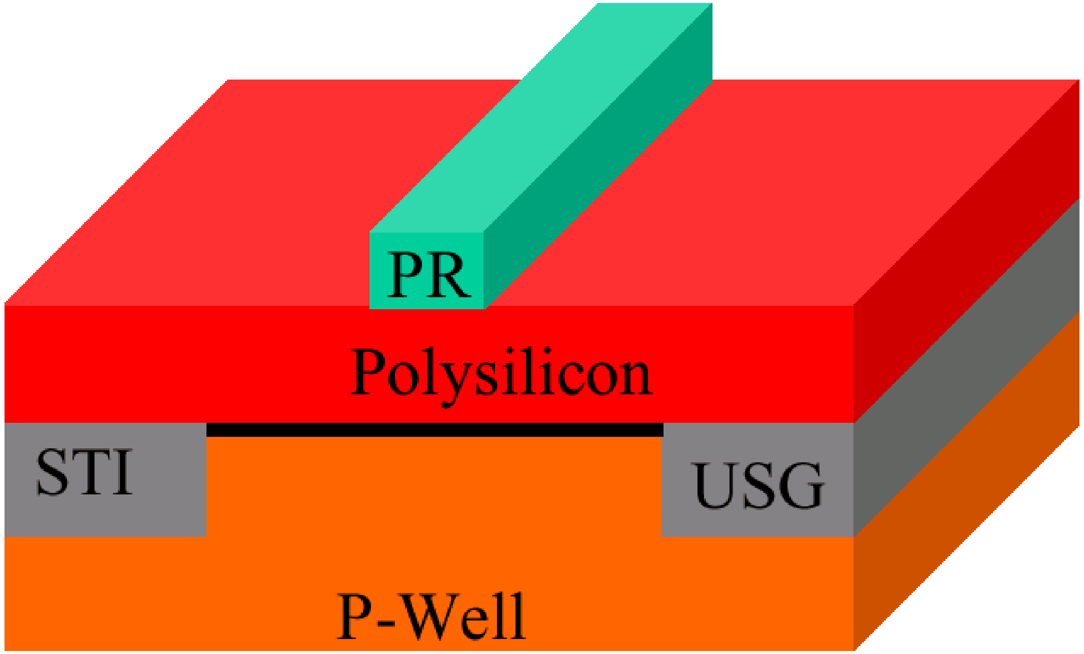
Alignment and Exposure



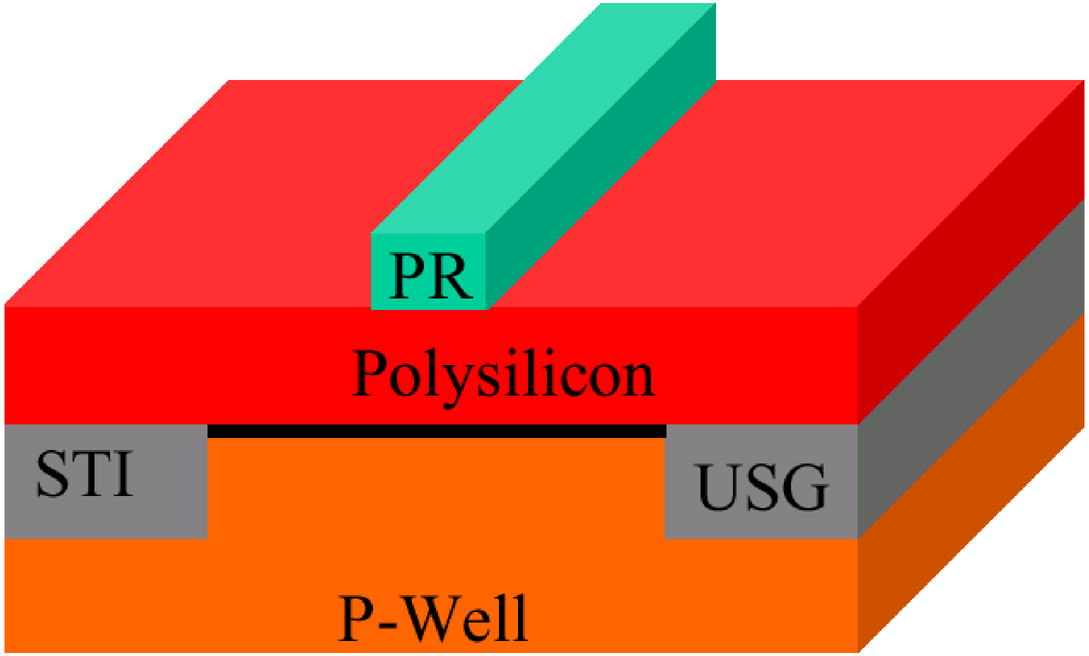
Post Exposure Bake

Lithography

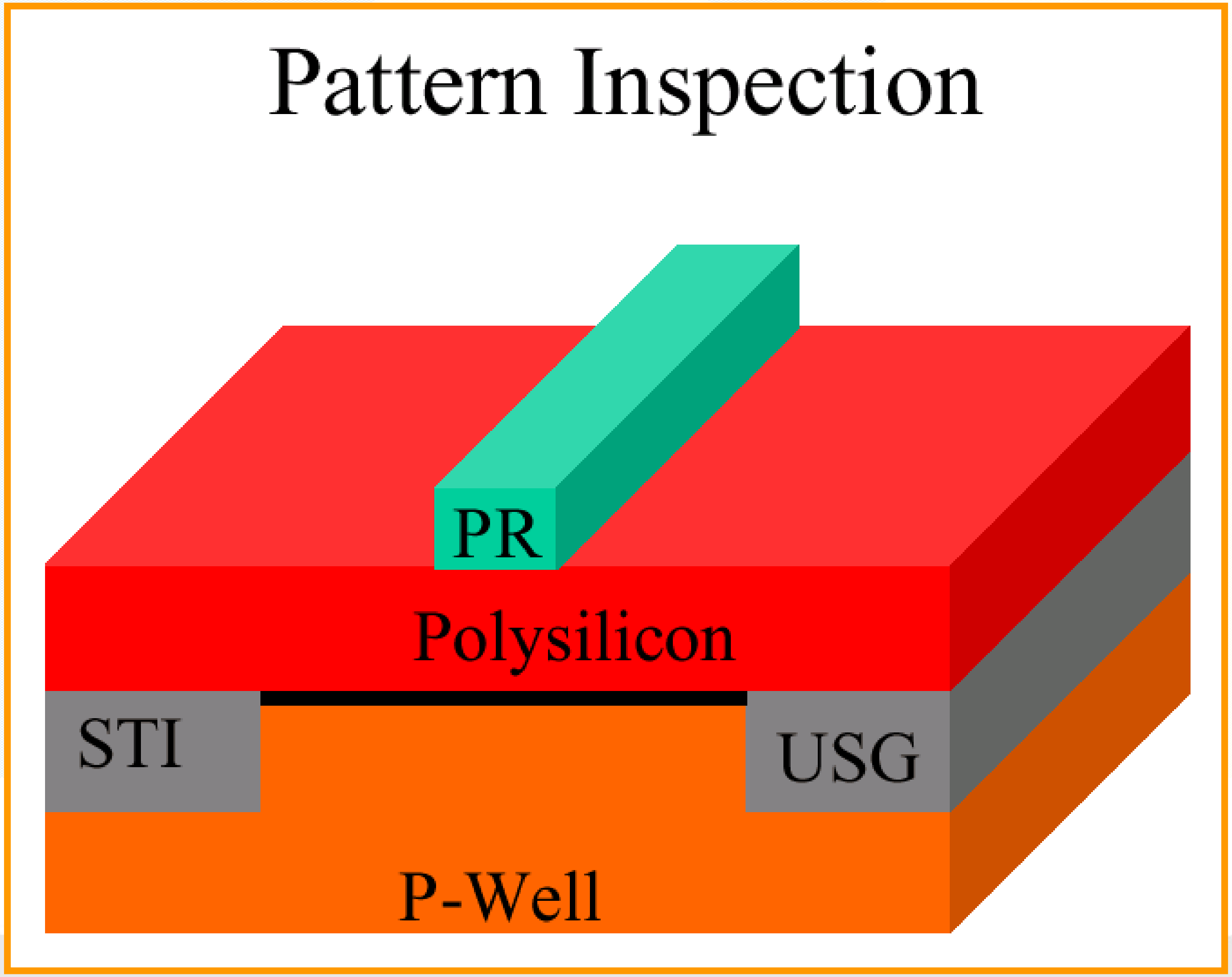
Development



Hard Bake



Lithography

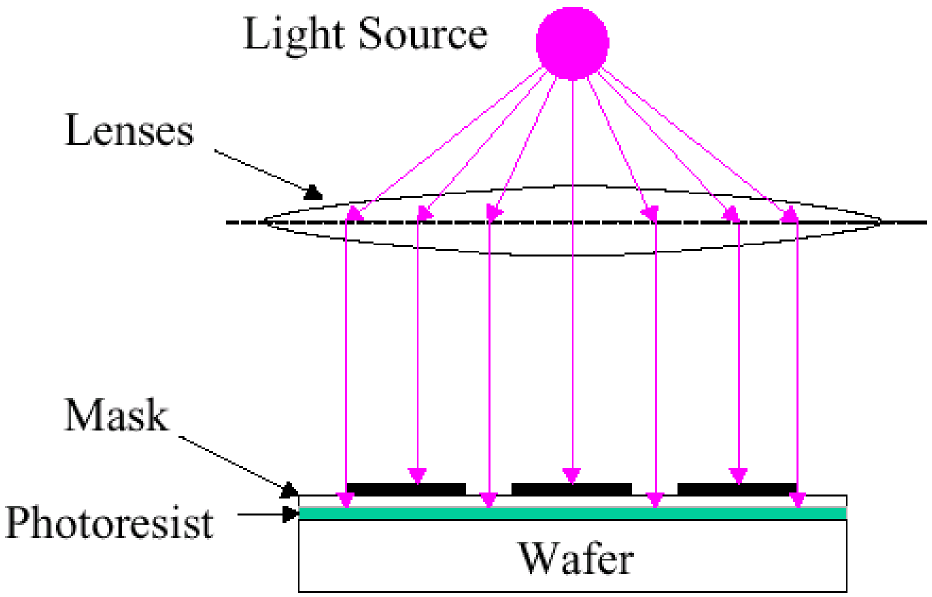


Lithography

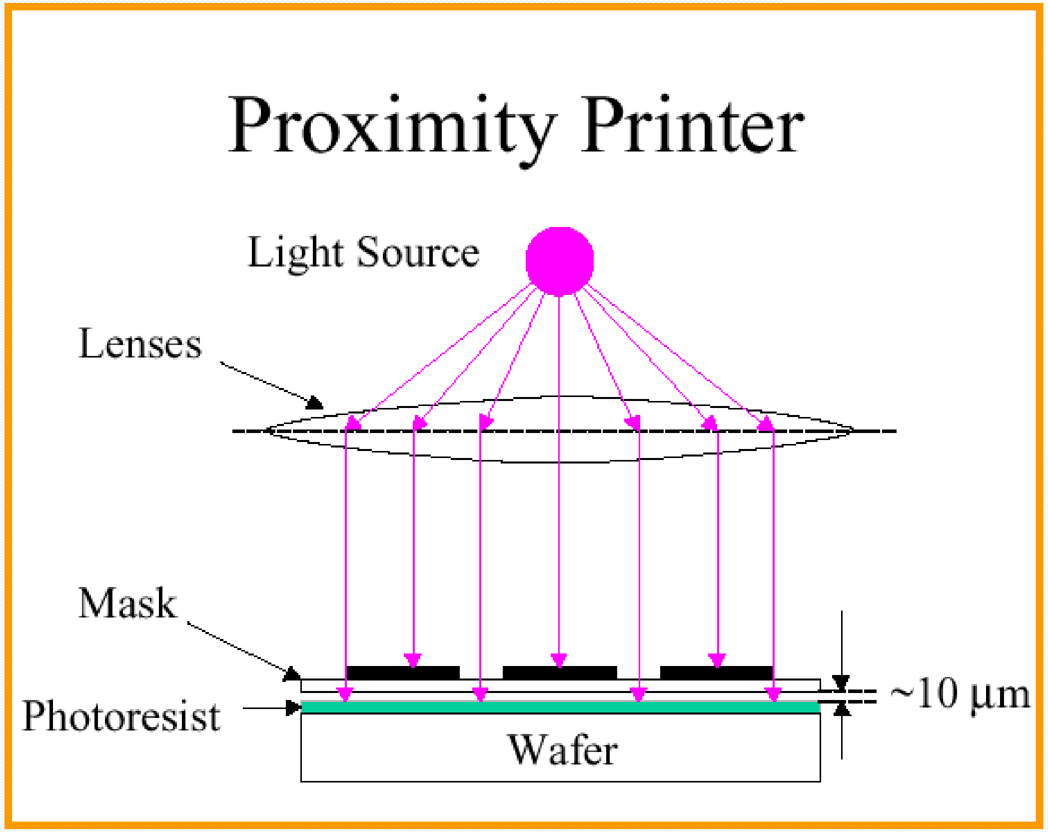
Alignment and Exposure Tools

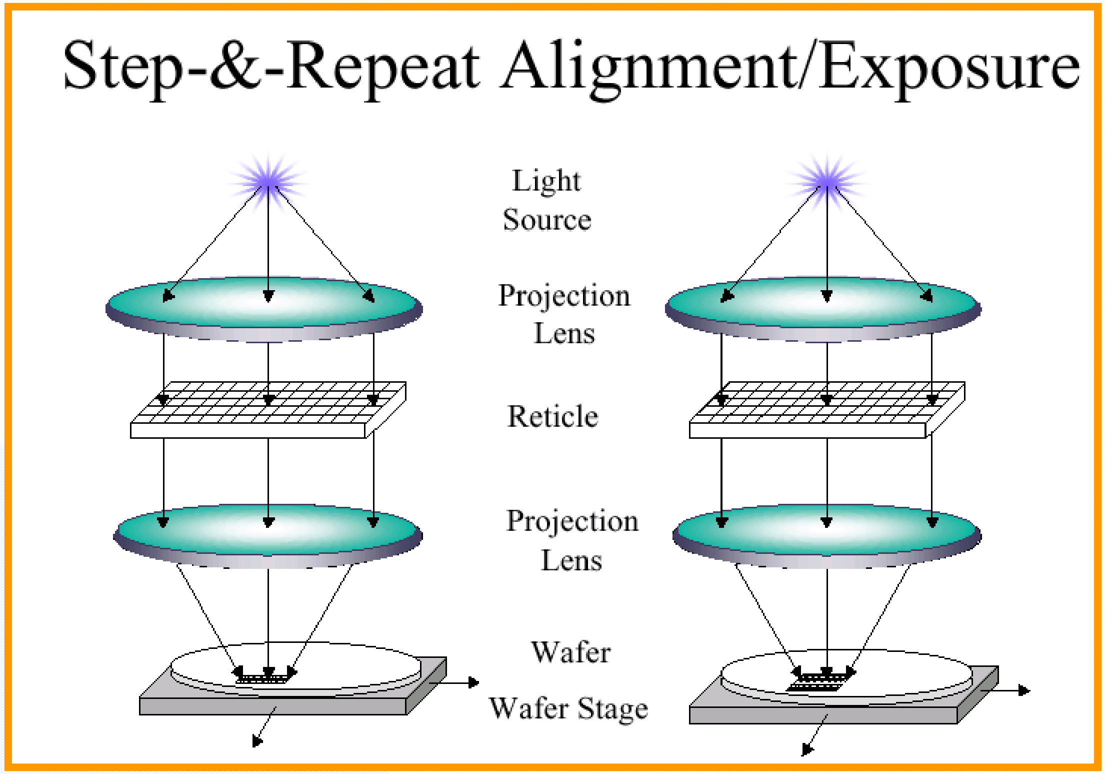
- Contact printer
- Proximity printer
- Projection printer
- Stepper

Contact Printer

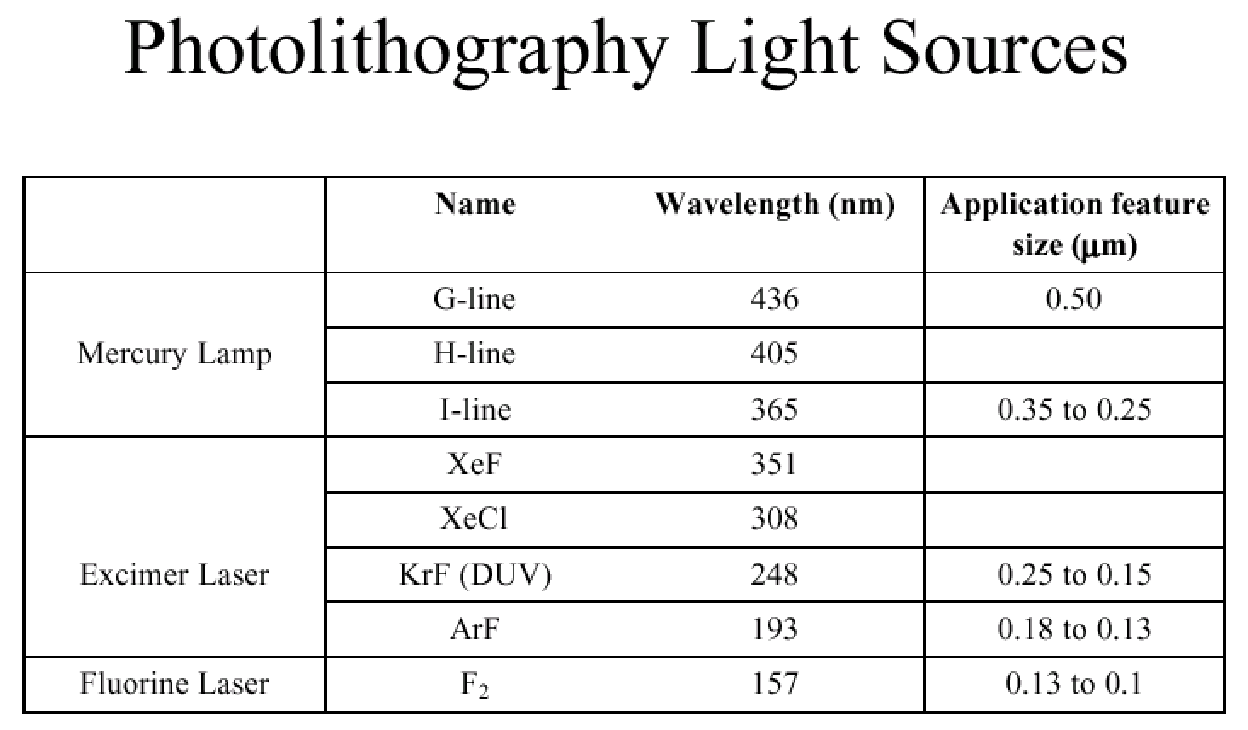


Lithography





Lithography



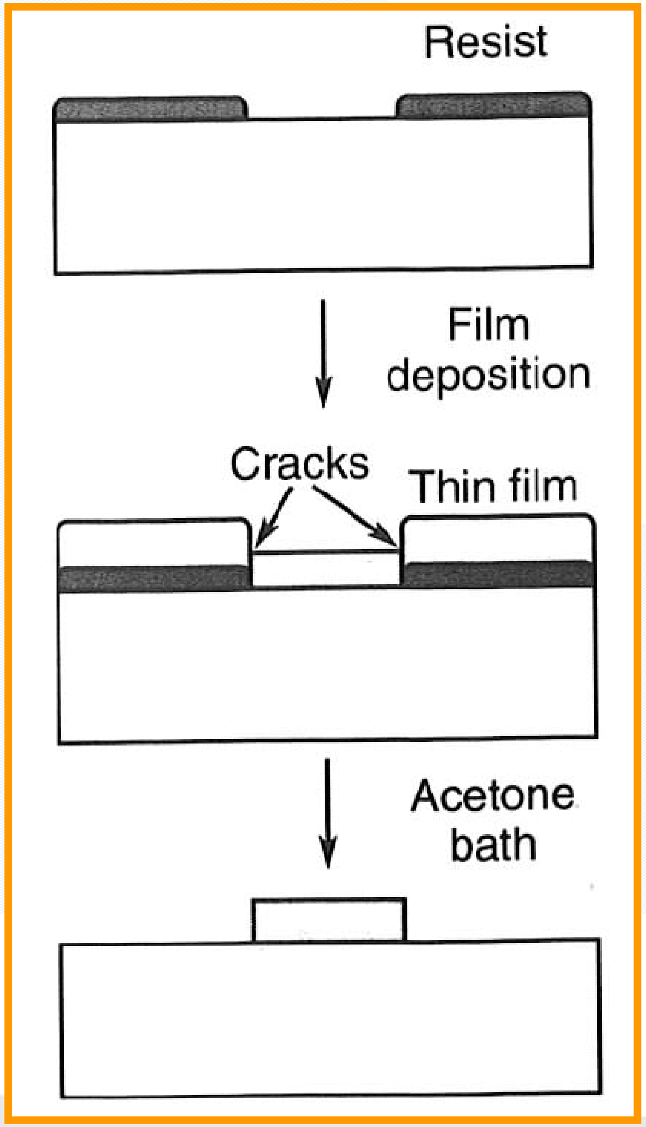
Photolithography Light Sources

	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

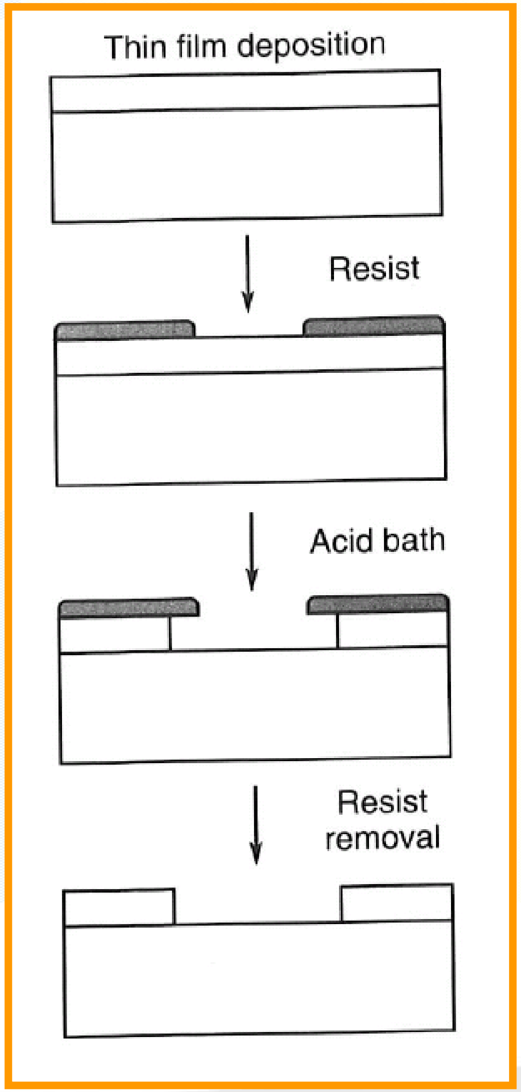
- Smaller objects need shorter wavelength
- But this result in a worse depth of focus, therefore there is a requirement for surface planarization

Lithography

- Lift-off



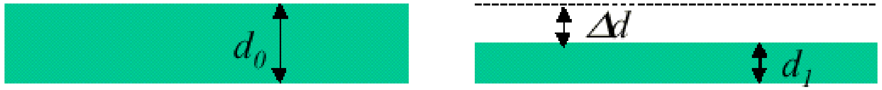
- Etching



Etching

Etch Rate

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



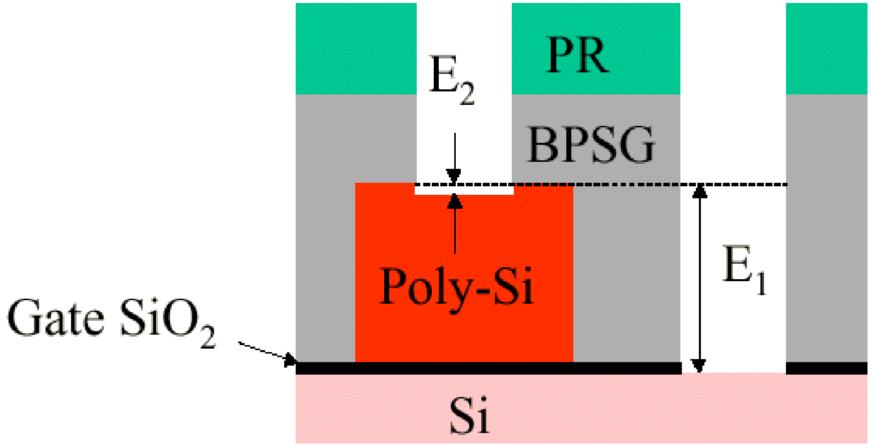
Before etch After etch

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

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

Selectivity

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

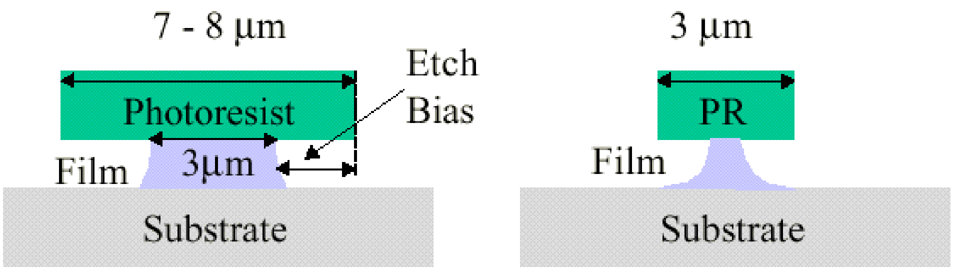


Boron Phosphorus silicate glass BPSG

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

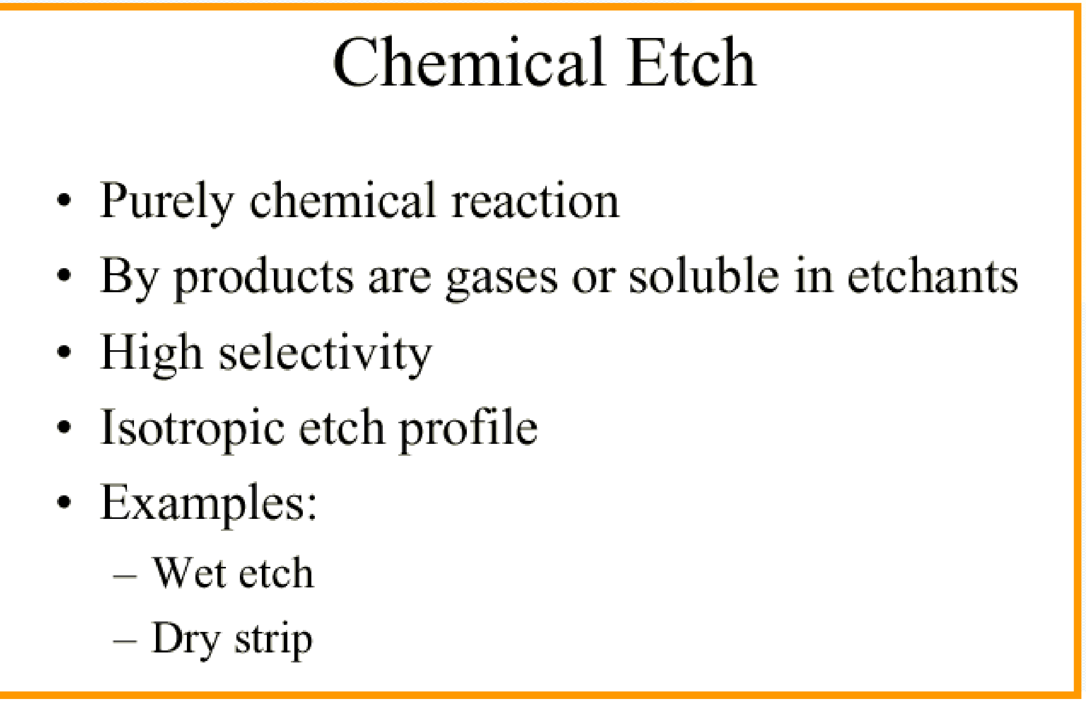
- Hydrofluoric Acid (HF) Solution
- Normally diluted in buffer solution or DI water to reduce etch rate.

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

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

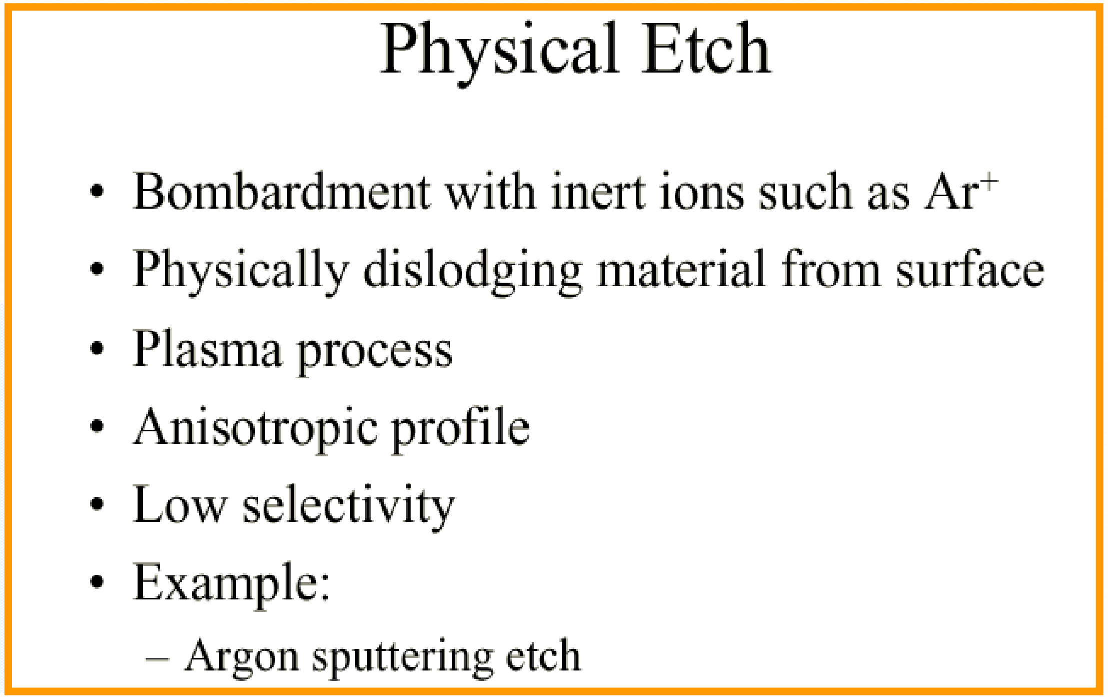
Etching

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

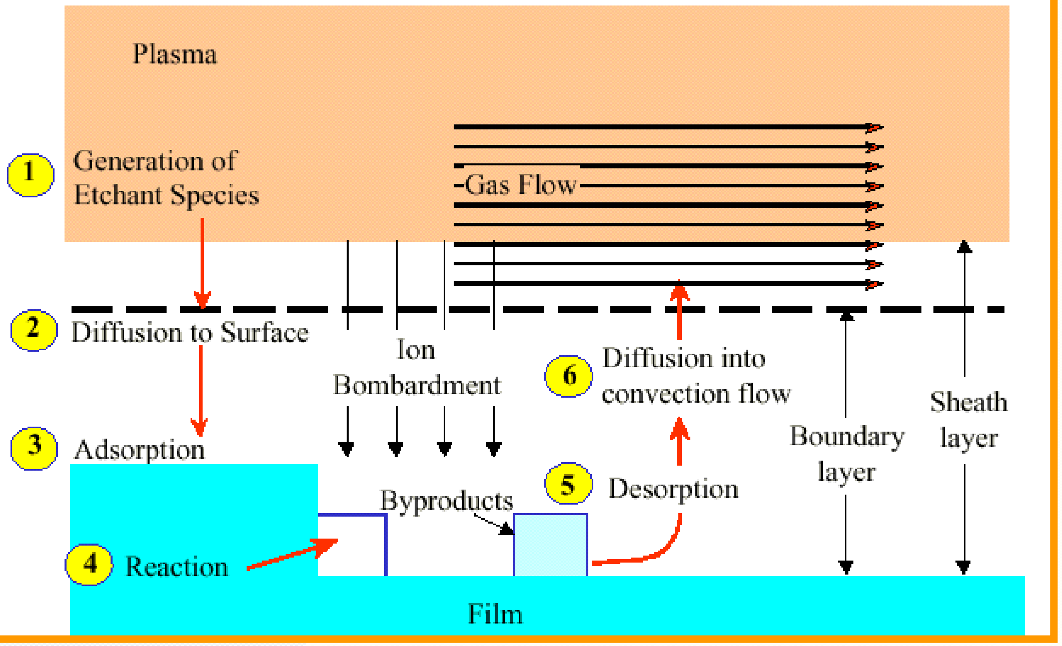
- Bombardment with inert ions such as Ar^+
- Physically dislodging material from surface
- Plasma process
- Anisotropic profile
- Low selectivity
- Example:
  - Argon sputtering etch

Etching

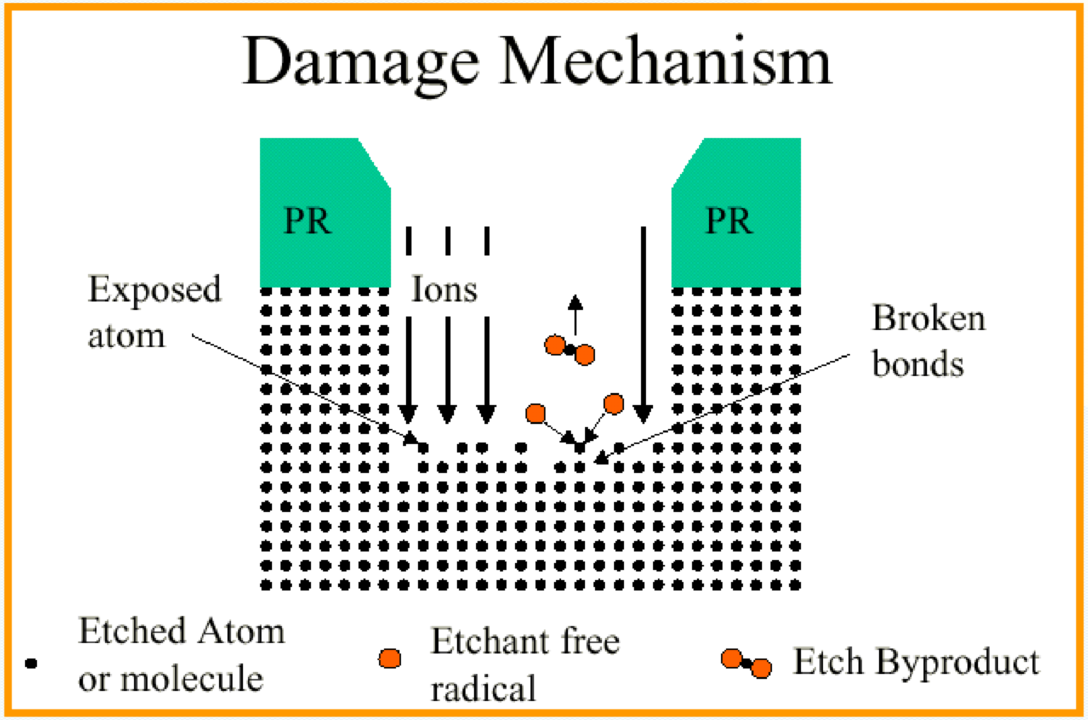
Reactive Ion Etch (RIE)

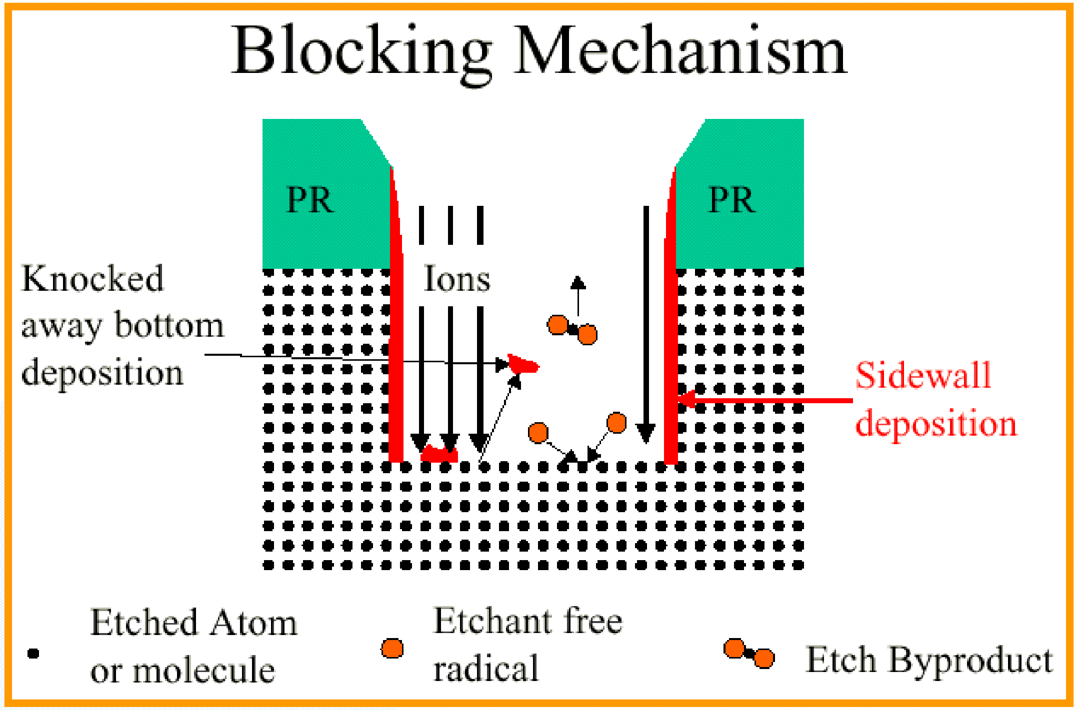
- Combination of chemical and physical etch
- Plasma process, ion bombardment plus free radicals
- Misleading name, should be called ion assistant etch (IAE)
- High and controllable etch rate
- Anisotropic and controllable etch profile
- Good and controllable selectivity
- All patterned etches are RIE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

Etch Process Sequence



Etching


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

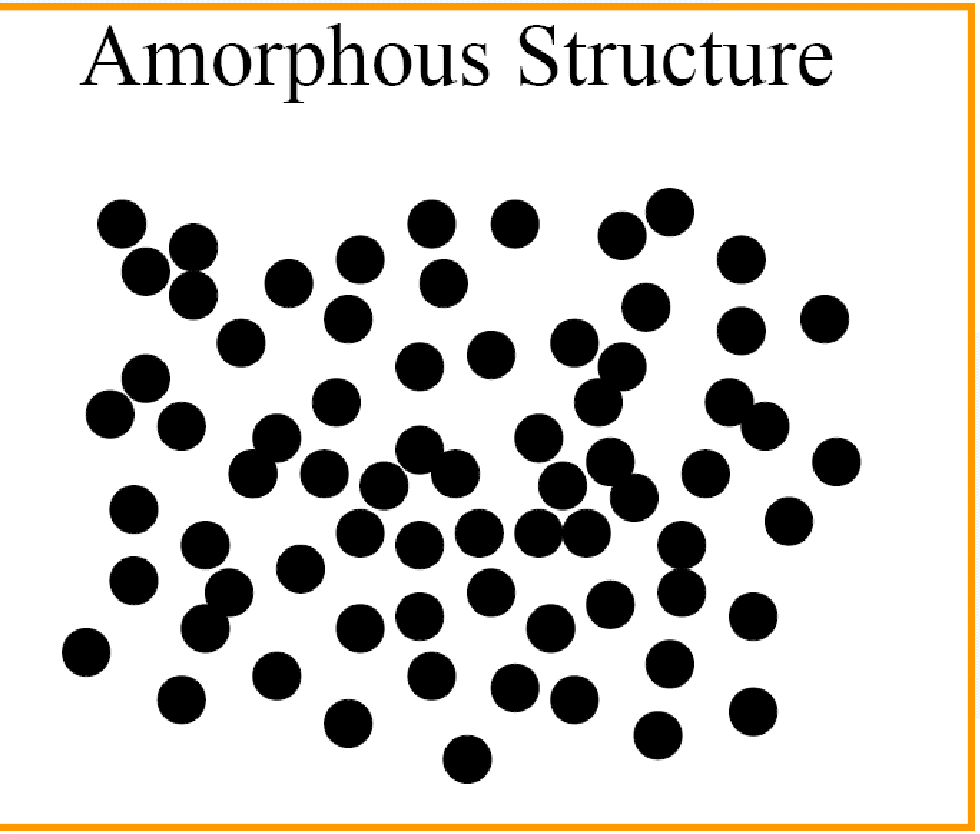

Blocking Mechanism
PR
PR
Ions
Knocked away bottom deposition
Sidewall deposition
Etched Atom or molecule
Etchant free radical
Etch Byproduct

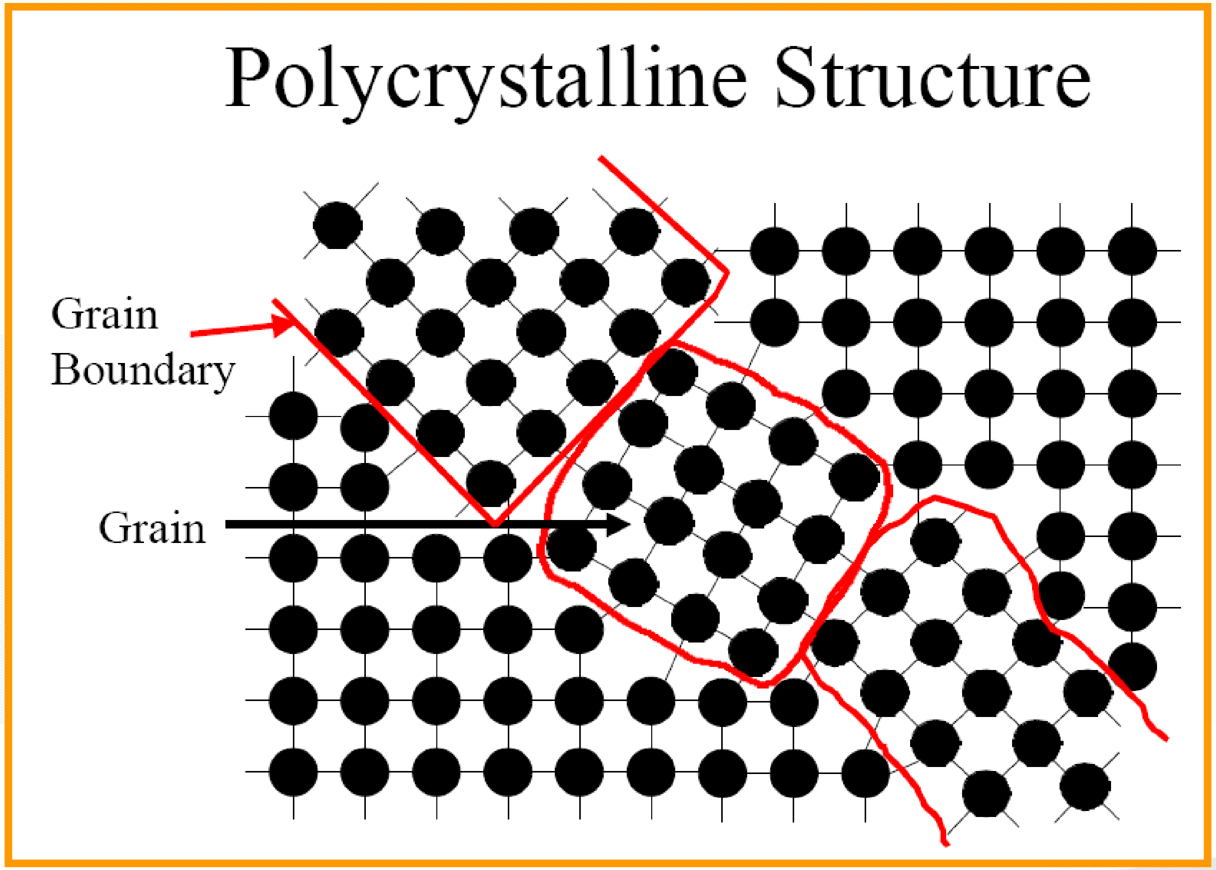
Semiconductor Sensor Technologies

- Bulk Micromachining
    - Bulk materials
    - Anisotropic silicon etching
    - Wafer bonding
- Surface Micromachining
    - Thin film Materials
    - Thin Film etching
    - Sacrificial etching

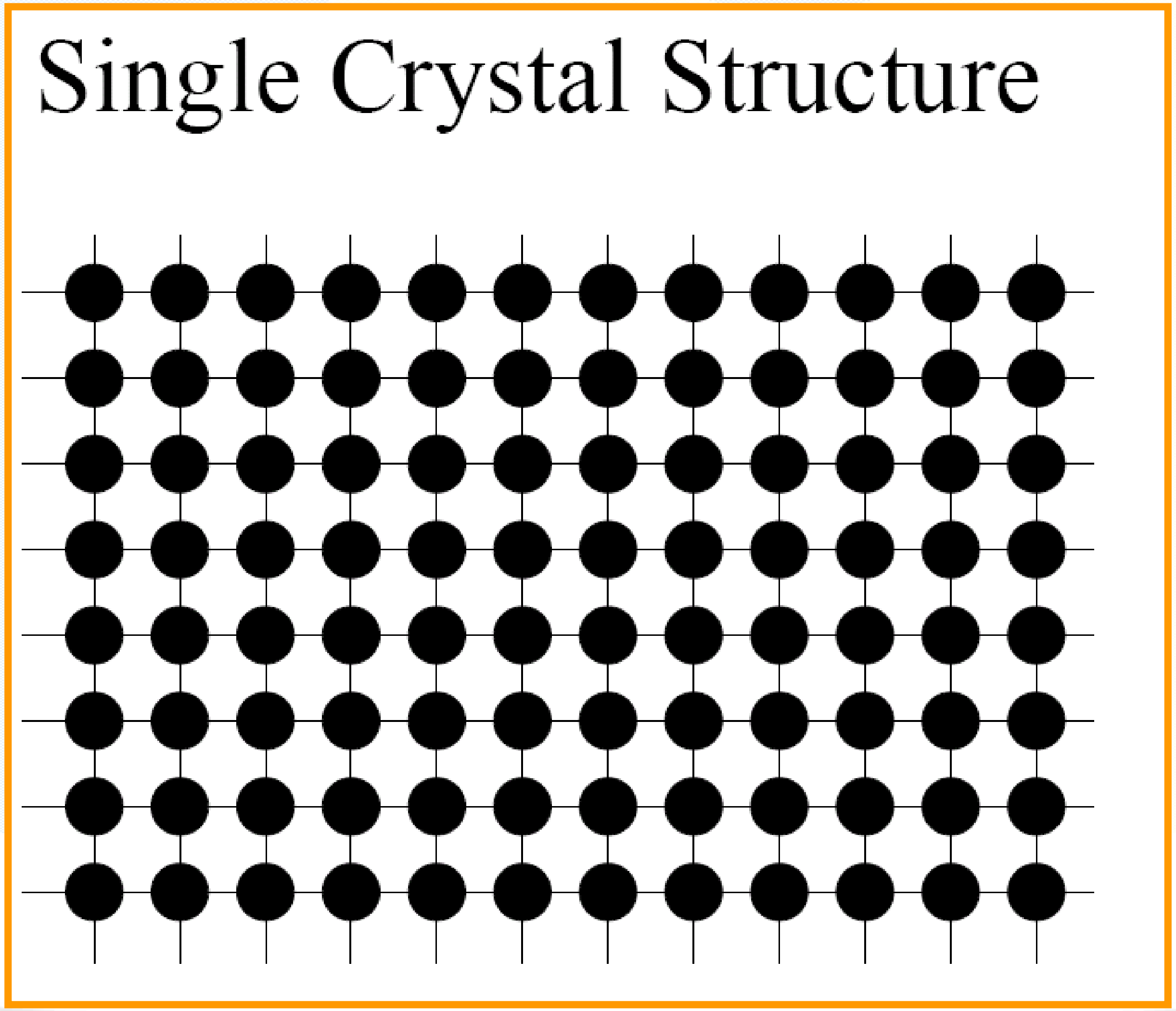
Bulk materials

Bulk materials



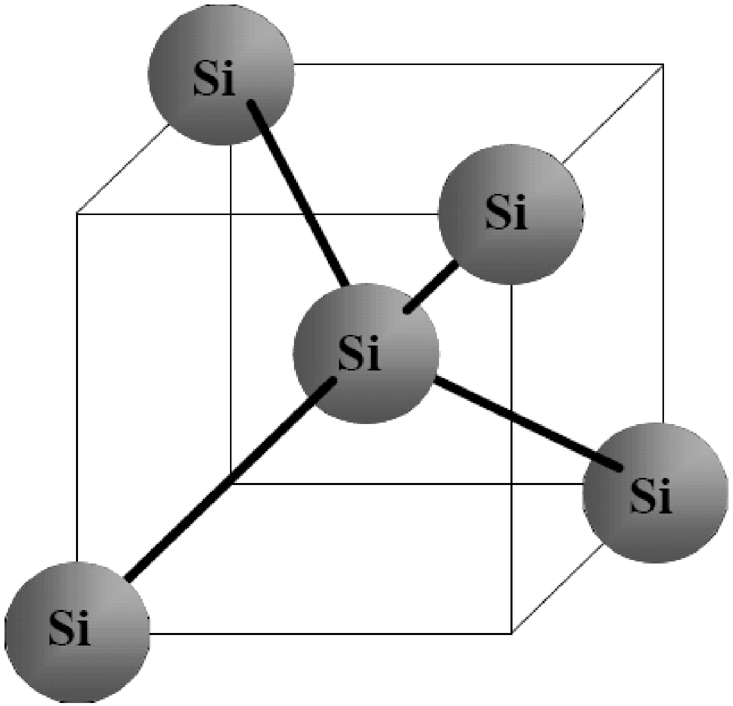


Bulk materials

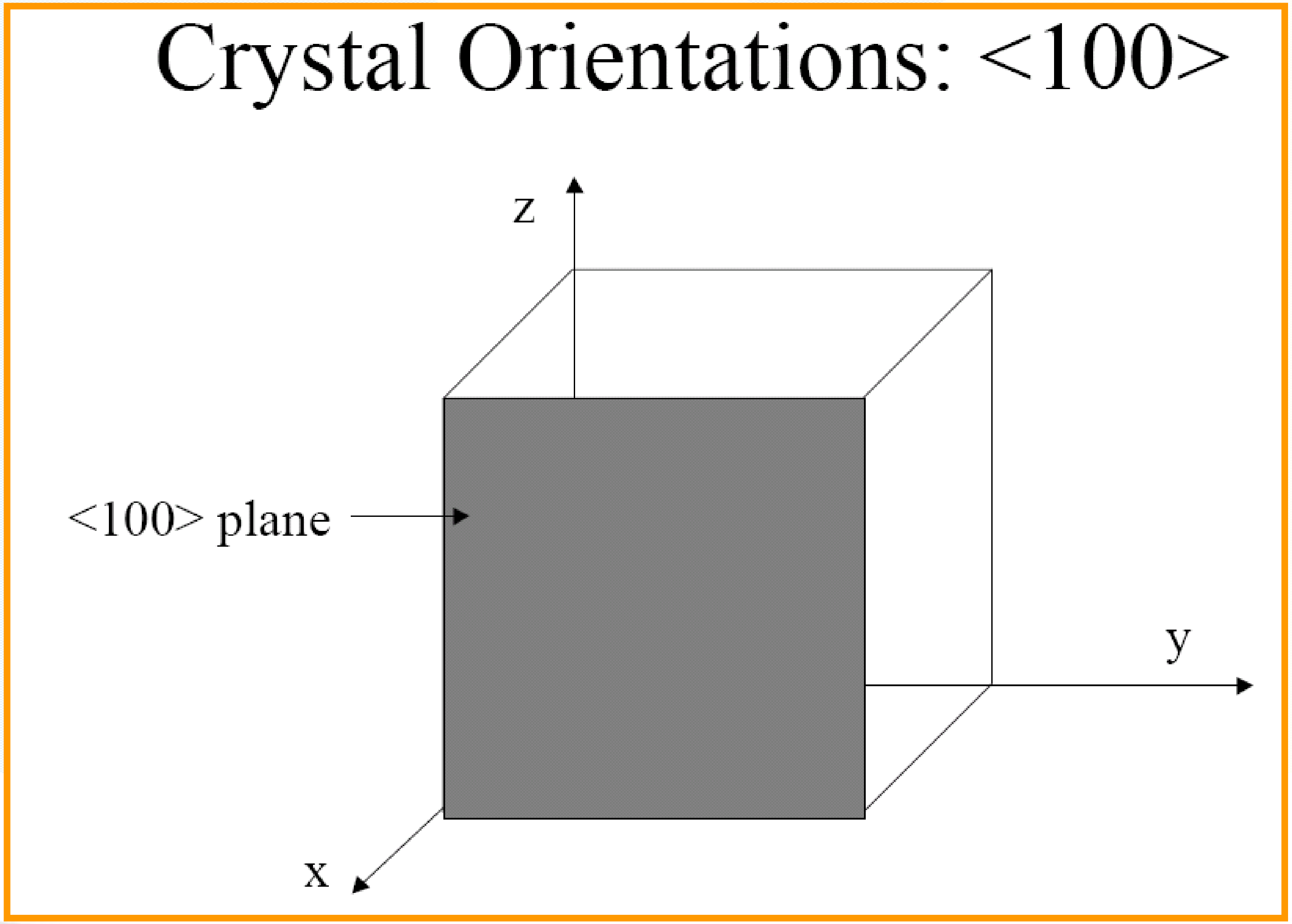


Bulk materials

Unit Cell of Single Crystal Silicon

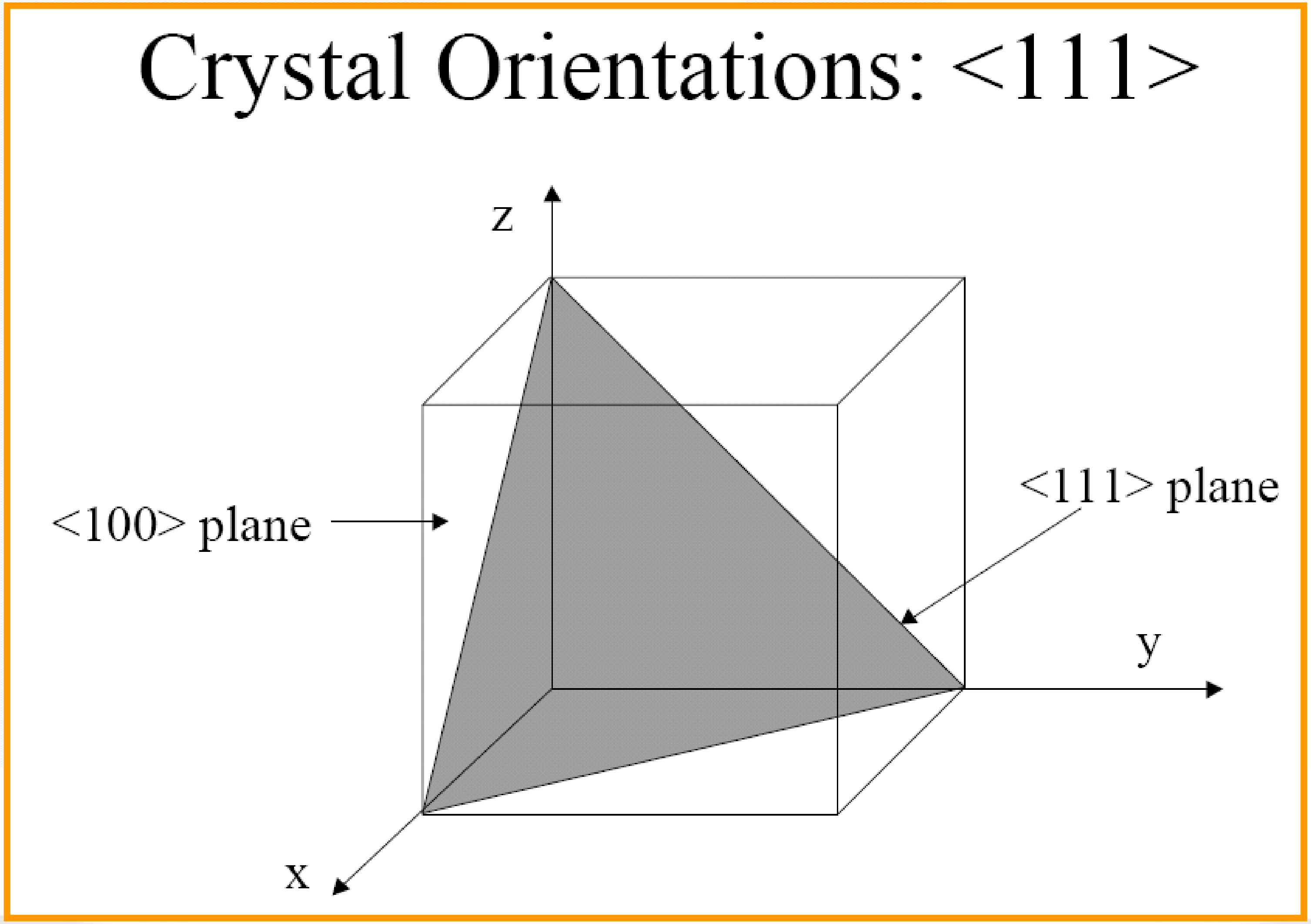


Bulk materials



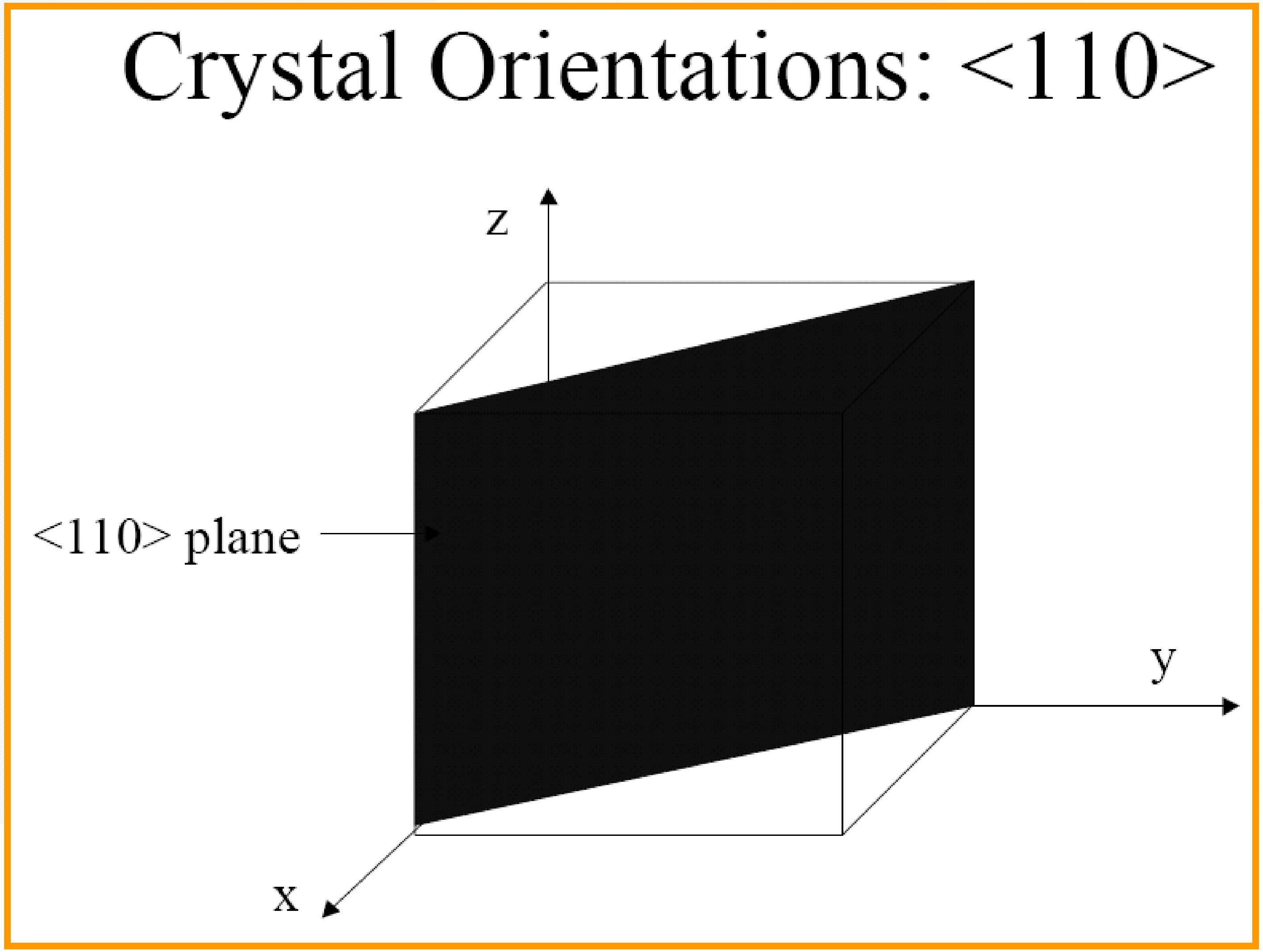
Crystal Orientations: <100>

Bulk materials



Crystal Orientations: <111>

Bulk materials



Anisotropic silicon etching

Etching speed

(110) > (100) > (111)

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

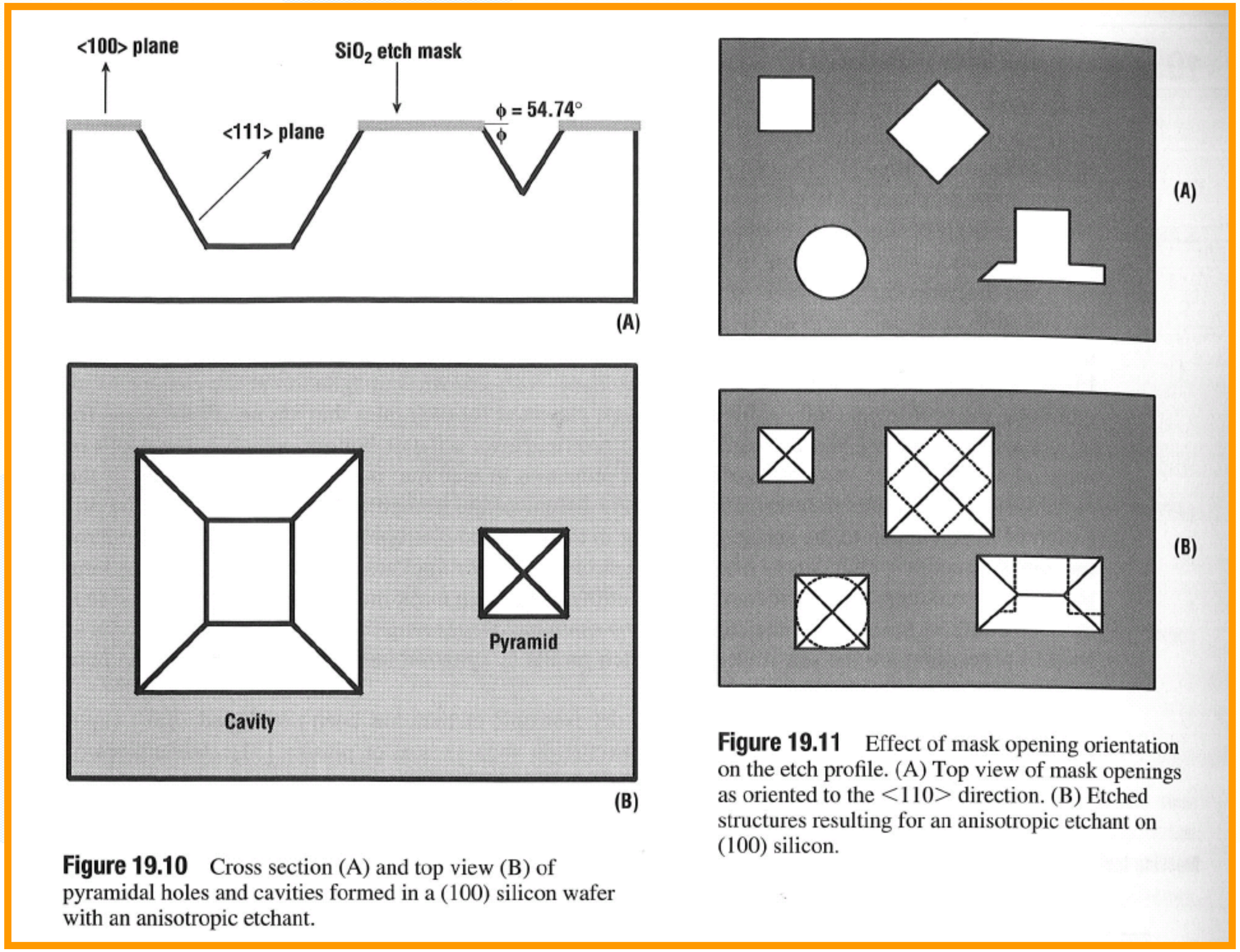
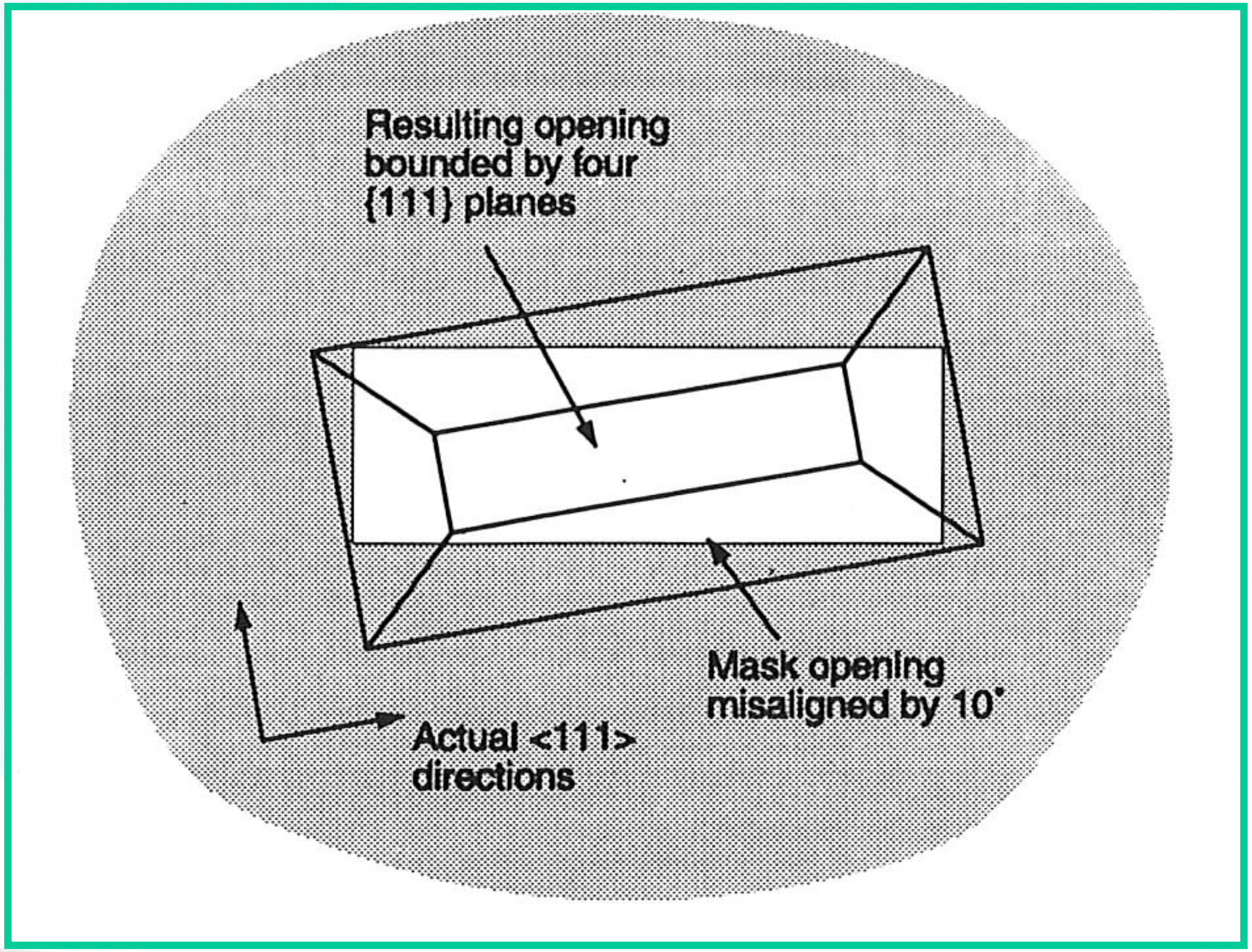


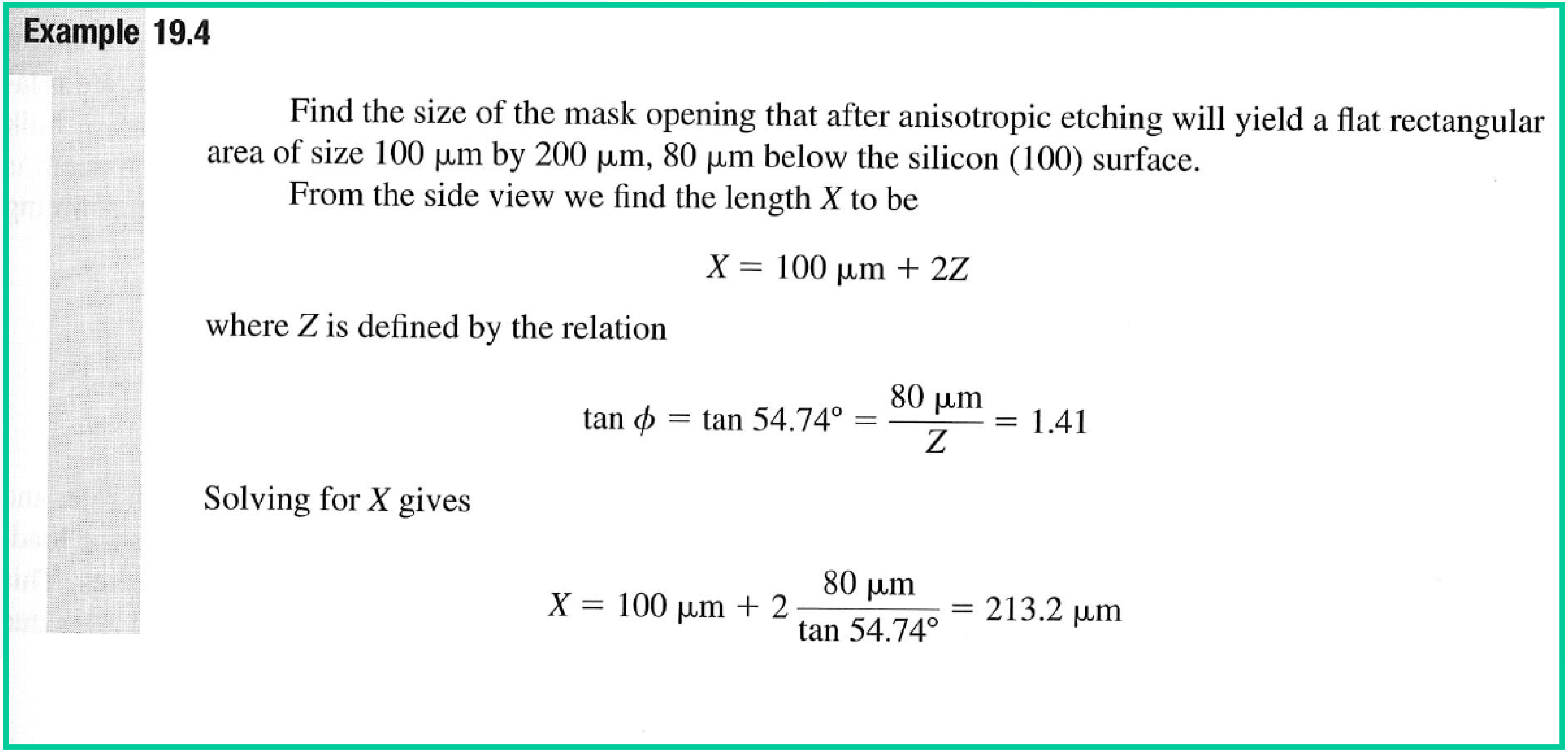
Figure 19.10 Cross section (A) and top view (B) of pyramidal holes and cavities formed in a (100) silicon wafer with an anisotropic etchant.

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



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

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

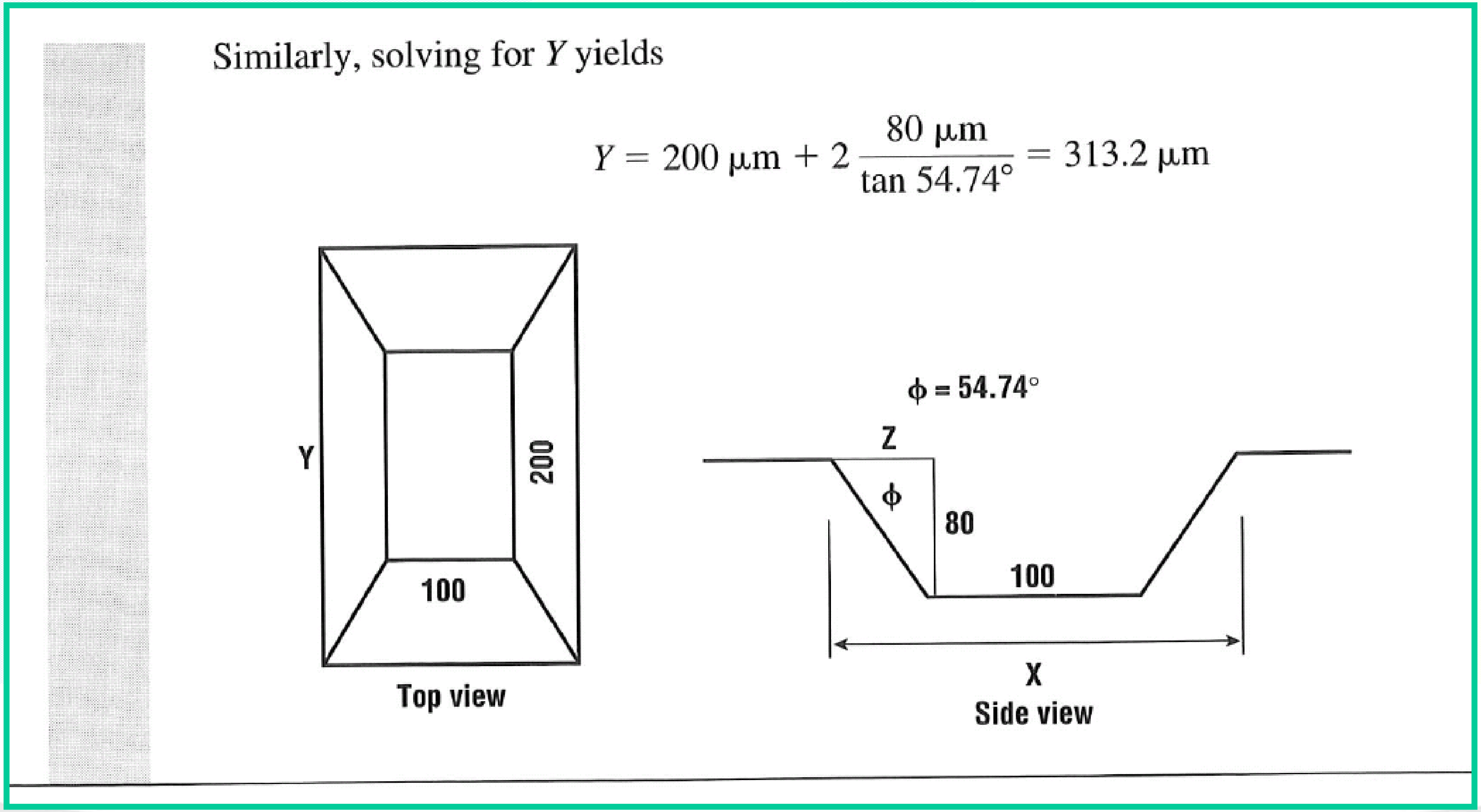
where Z is defined by the relation

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

Solving for X gives

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

Anisotropic silicon etching



Similarly, solving for *Y* yields

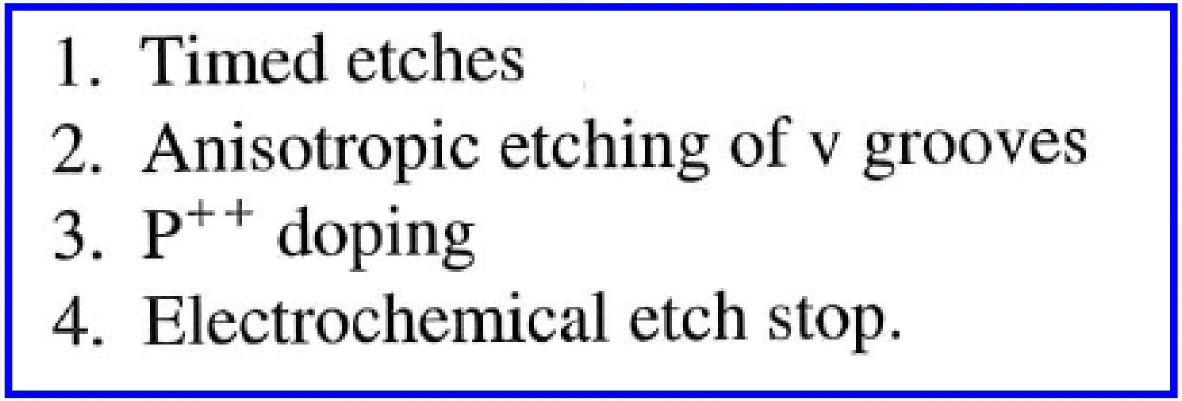
$$Y = 200\ \mu\text{m} + 2\,\frac{80\ \mu\text{m}}{\tan 54.74^\circ} = 313.2\ \mu\text{m}$$

Top view

Side view

Anisotropic silicon etching

Controlling of etch depth by;



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

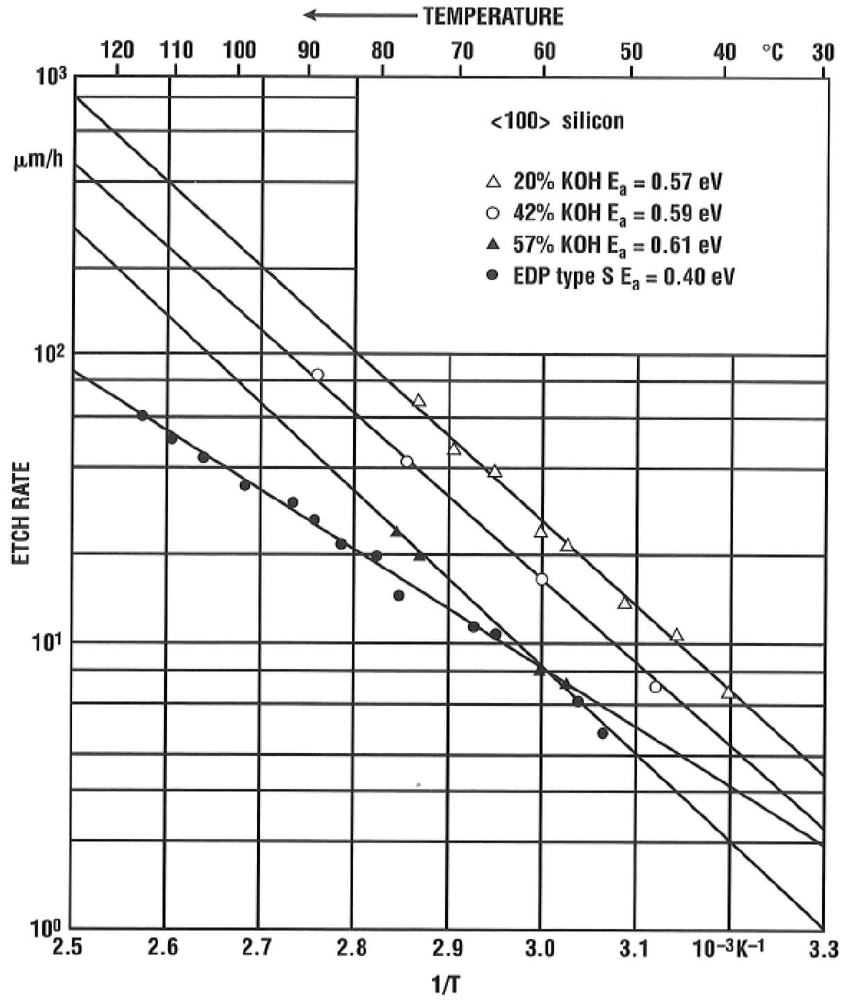
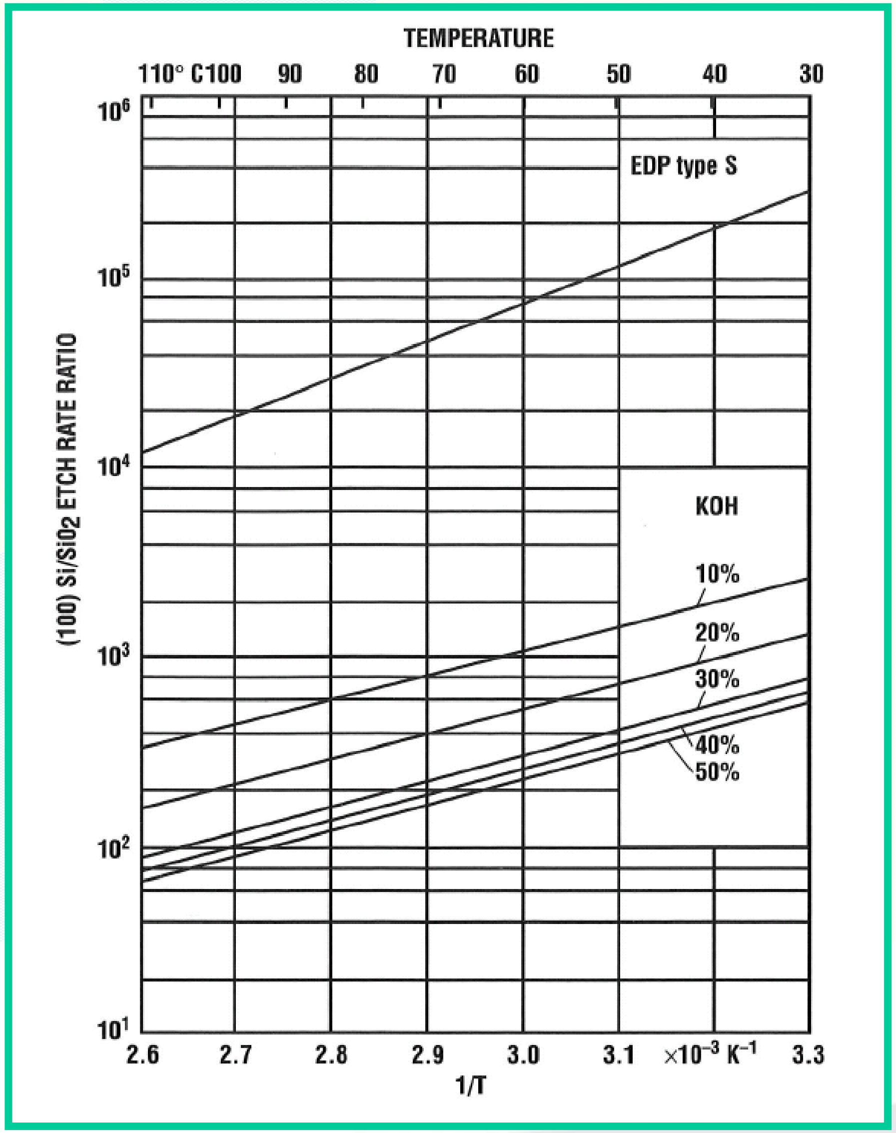


Figure 19.13 Arrenius plot of the vertical etching rate for (100) silicon wafers for EDP and KOH solutions *(after Seidel [33], reproduced by permission of The Electrochemical Society, Inc.).*

Anisotropic silicon etching

Selectivity SiO_2-Si(100)



Anisotropic silicon etching

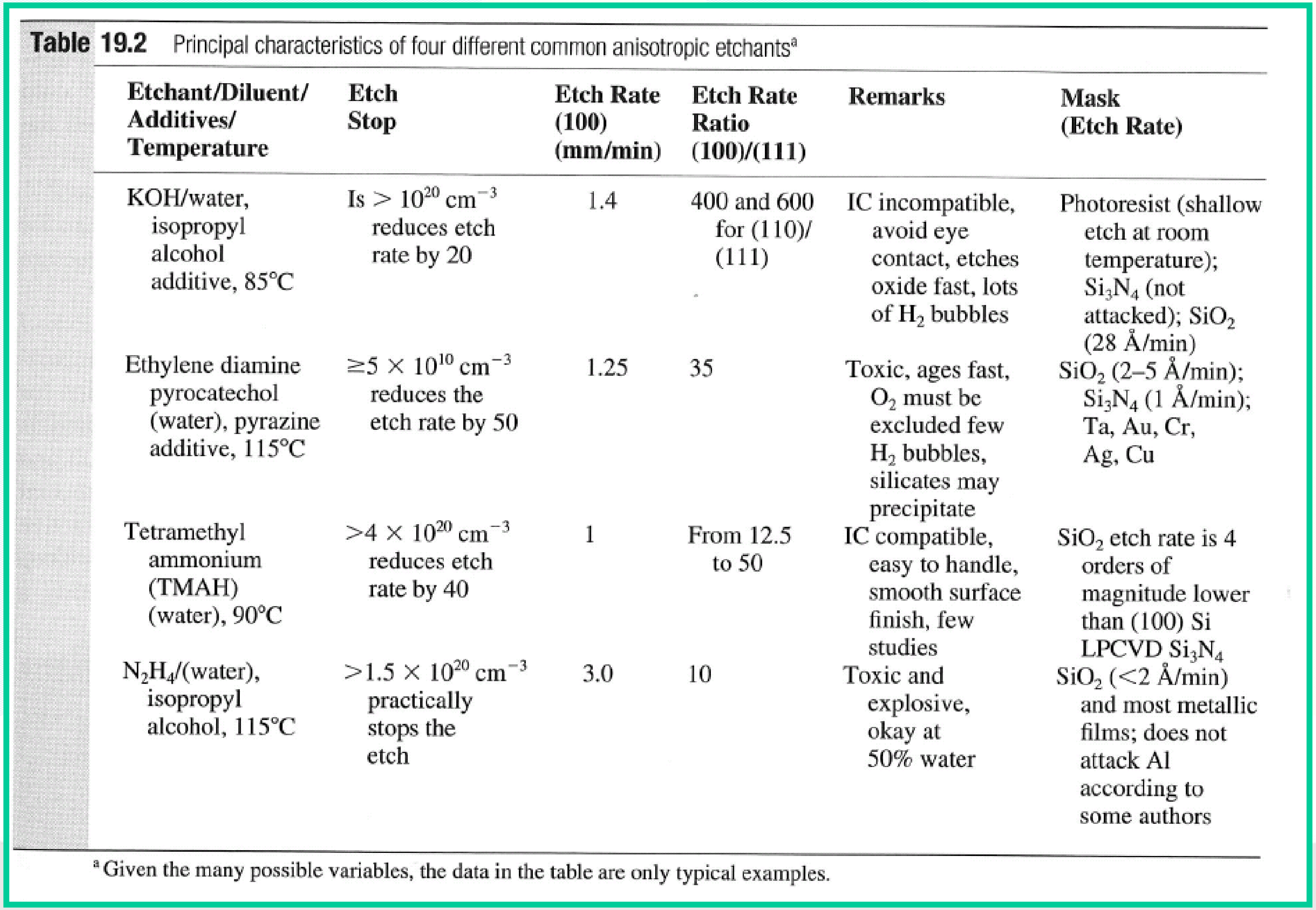


Table 19.2 Principal characteristics of four different common anisotropic etchants[a]

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.

Anisotropic silicon etching

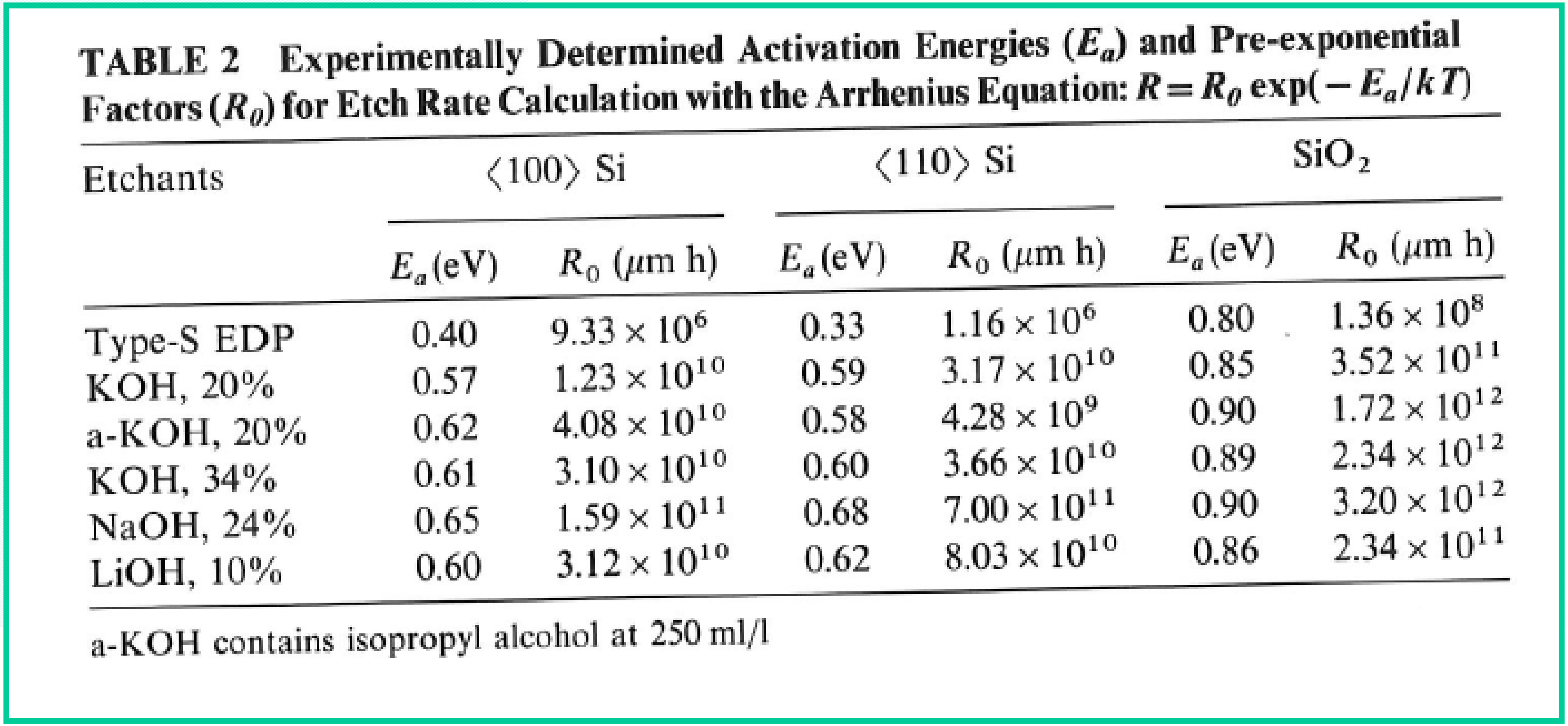
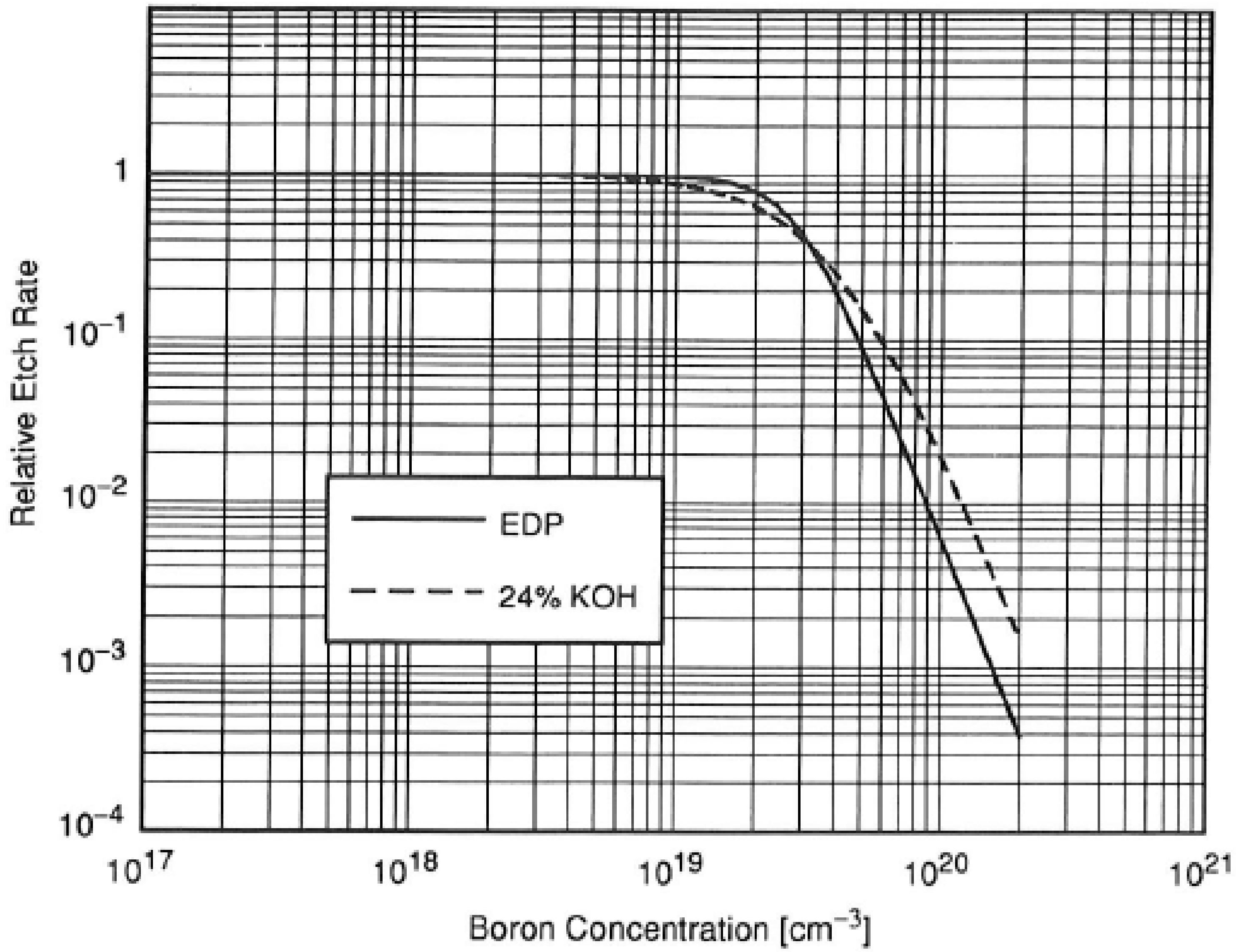


TABLE 2 **Experimentally Determined Activation Energies (E_a) and Pre-exponential Factors (R_0) for Etch Rate Calculation with the Arrhenius Equation: $R = R_0 \exp(-E_a/kT)$**

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

Anisotropic silicon etching



Anisotropic silicon etching

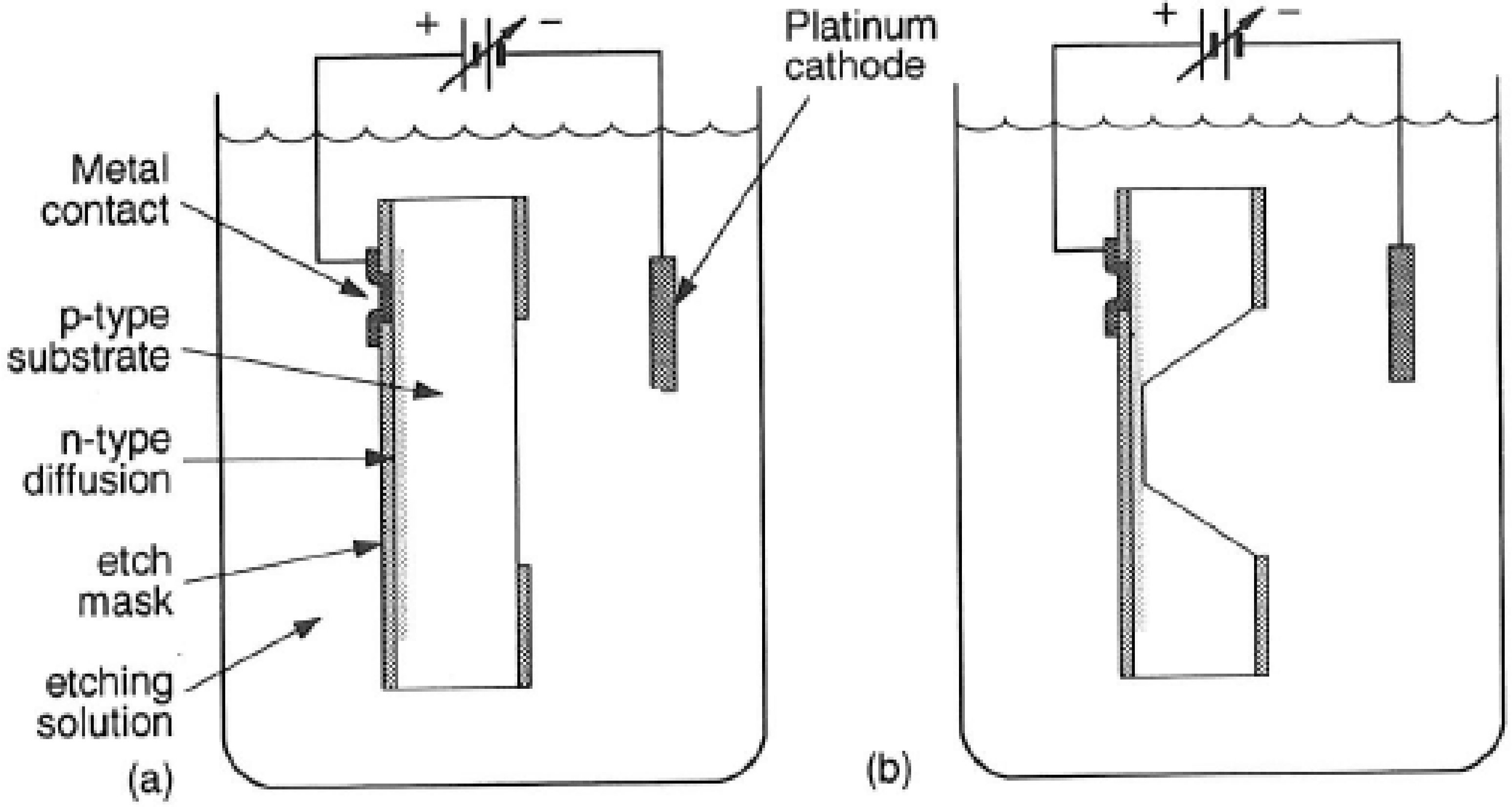


Fig. 27 The electrochemical etch-stop technique used to form a diaphragm.

Wafer bonding

Anodic bondning

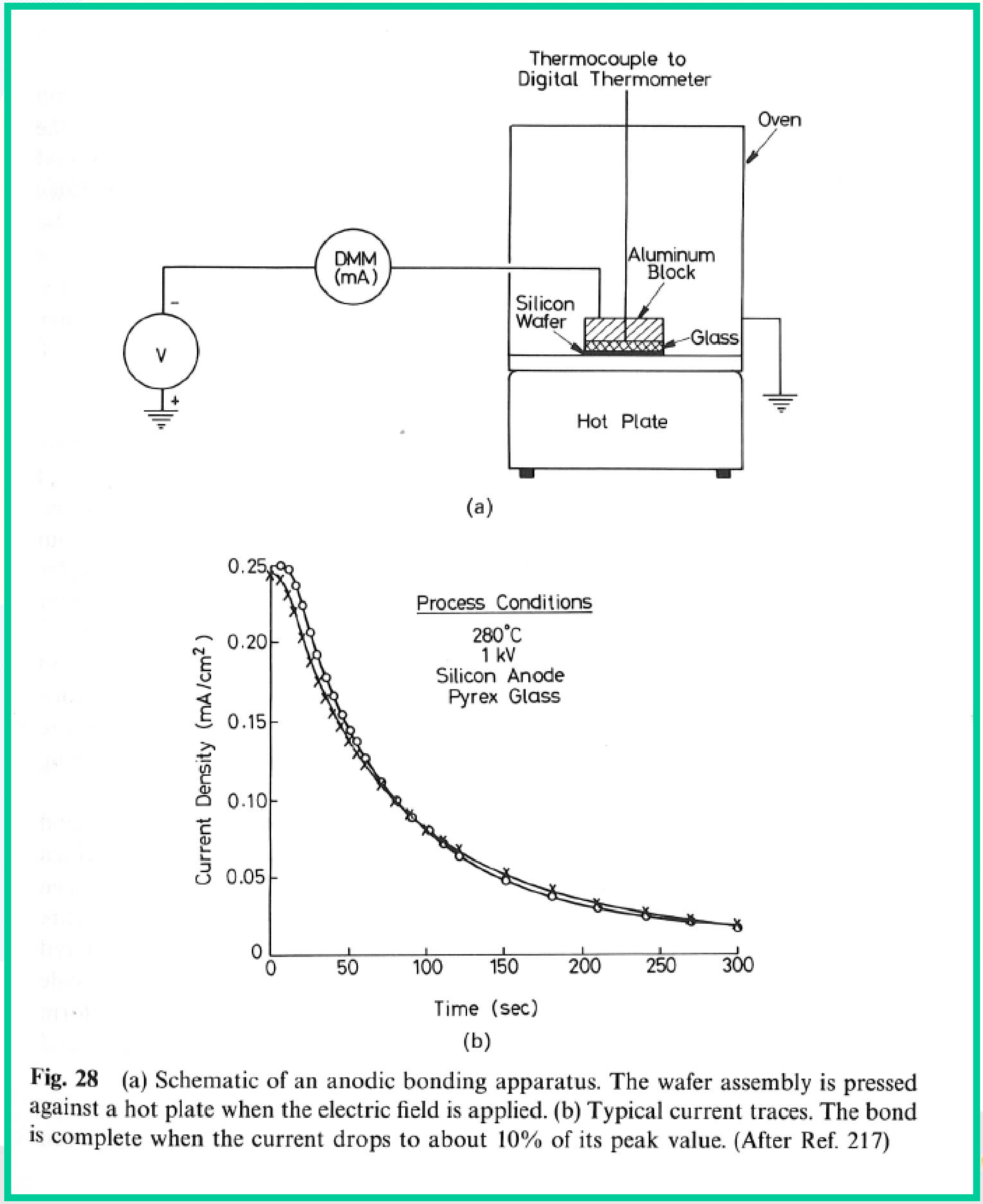
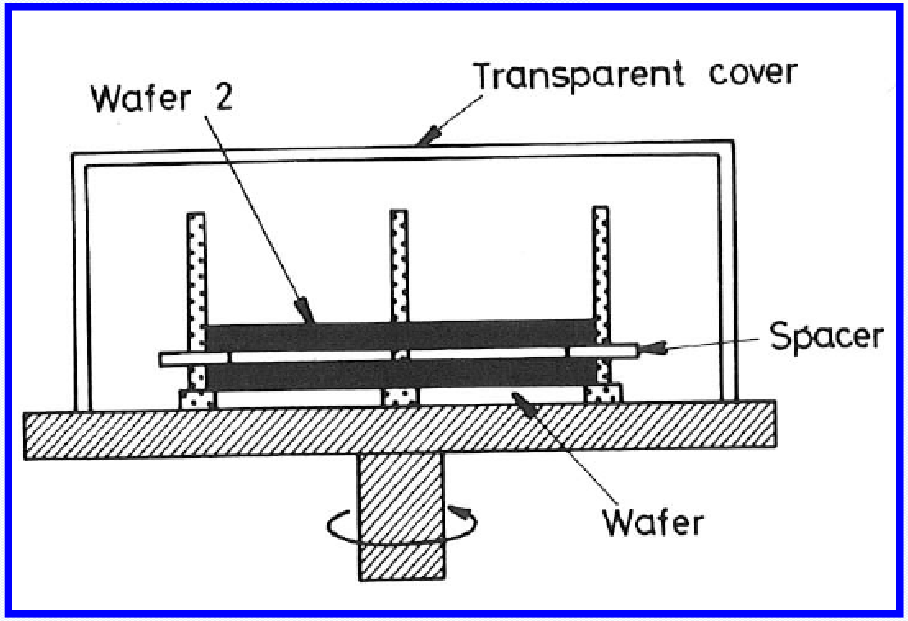


Fig. 28 (a) Schematic of an anodic bonding apparatus. The wafer assembly is pressed against a hot plate when the electric field is applied. (b) Typical current traces. The bond is complete when the current drops to about 10% of its peak value. (After Ref. 217)

Wafer bonding

Fusion bonding



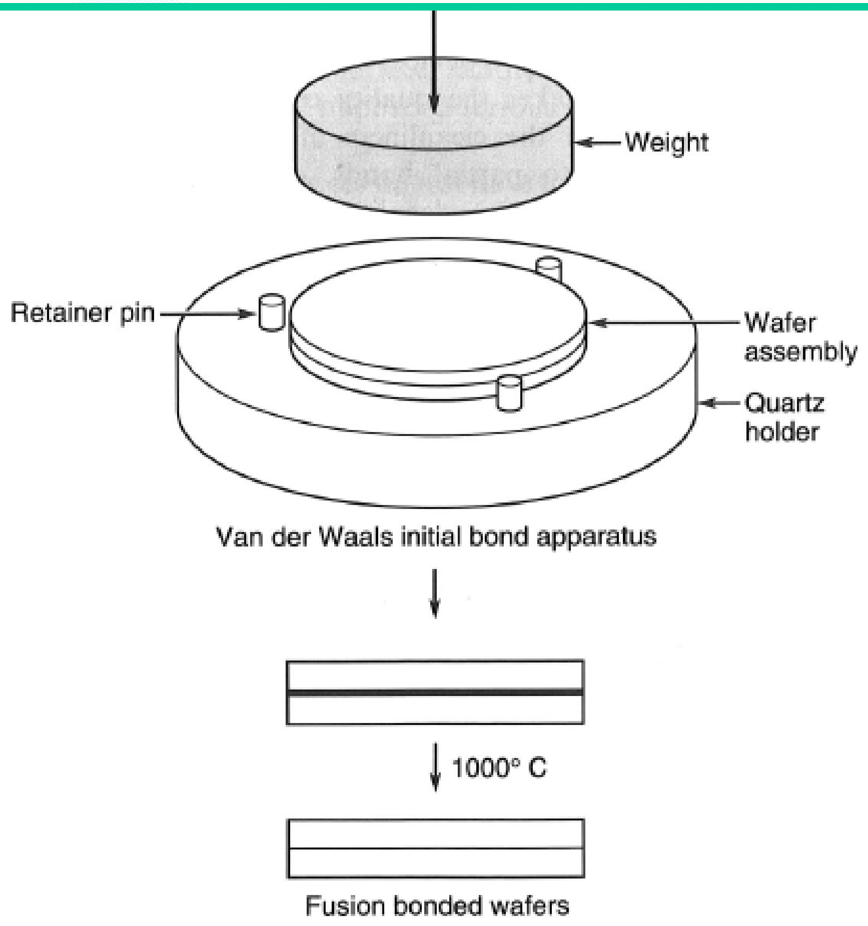


Fig. 29 Schematic of a fusion bonding apparatus. After pressing the wafers together, they are transferred to a high-temperature furnace to establish the bond.

Surface Micromachining

- Thin Film materials
    - Poly silicon
    - Amorphous silicon
    - Epitaxi silicon
    - Silicon Nitride (LPCVD)
        - 300-500 mT 700-900 C

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

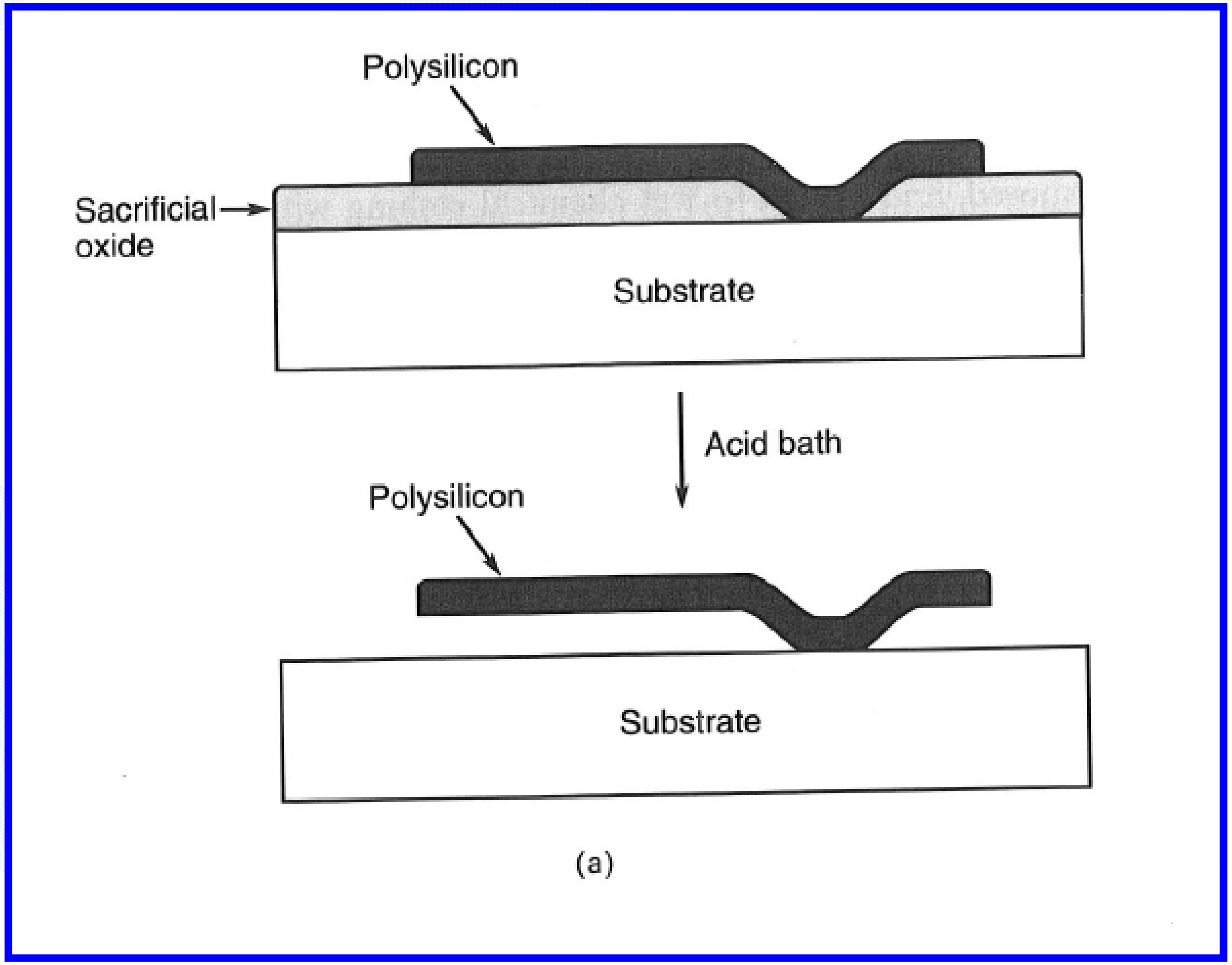
- Silicon dioxide

Surface Micromachining

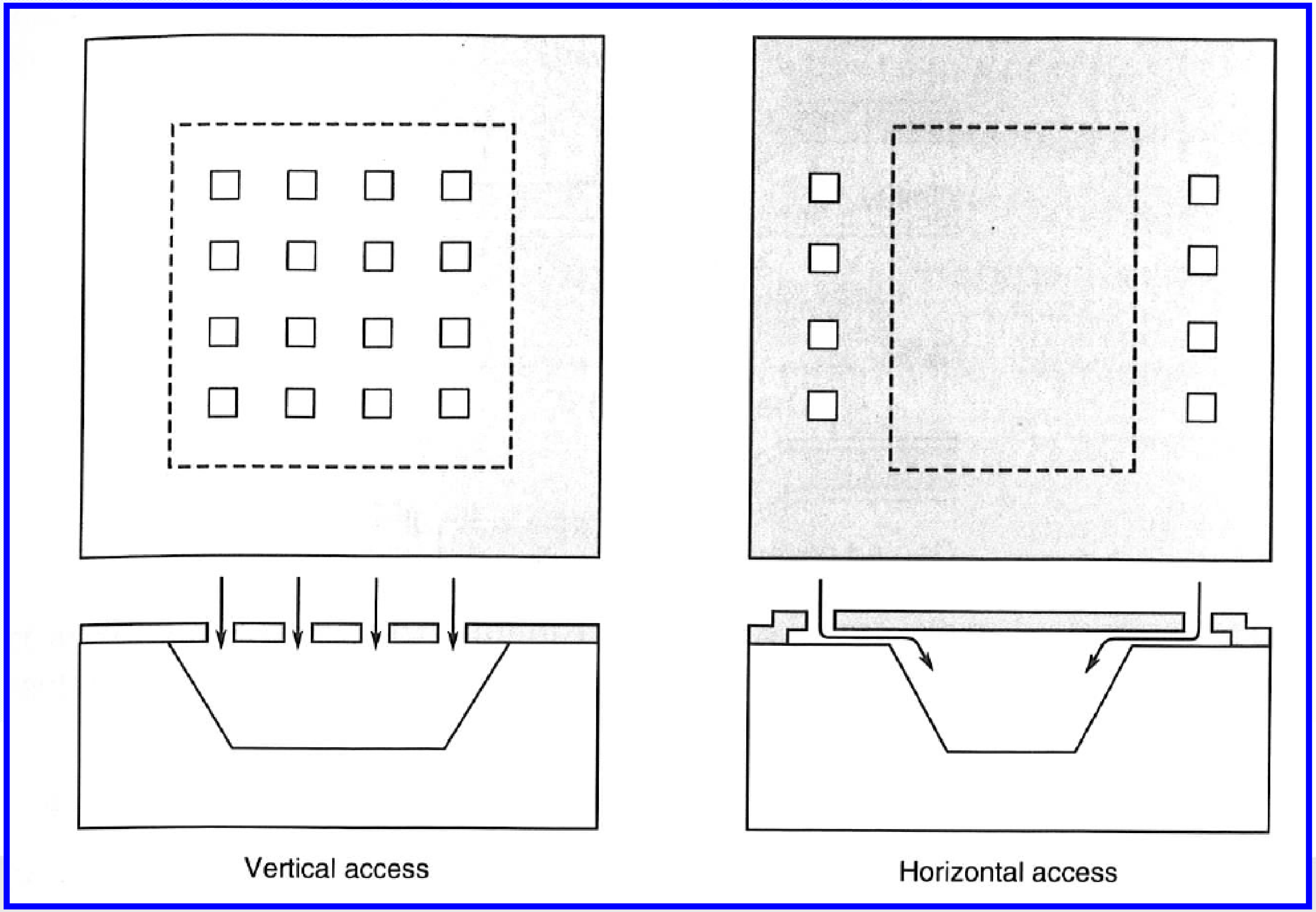
- Thin Film etching
  - **Silicon dioxide**
    - Isotropic etching
      - Diluted HF or Buffered HF (buffered with Ammonium-fluoride)
    - Anisotropic etching
      - Reactive Ion Etching (RIE)
        - » 1:1 C_2F_6 and CHF_3
  - **Silicon nitride**
    - Isotropic etching
        - » H_3PO_4 140-200 C
    - Anisotropic etching *same as silicon dioxide*

Surface Micromachining

Sacrificial etching



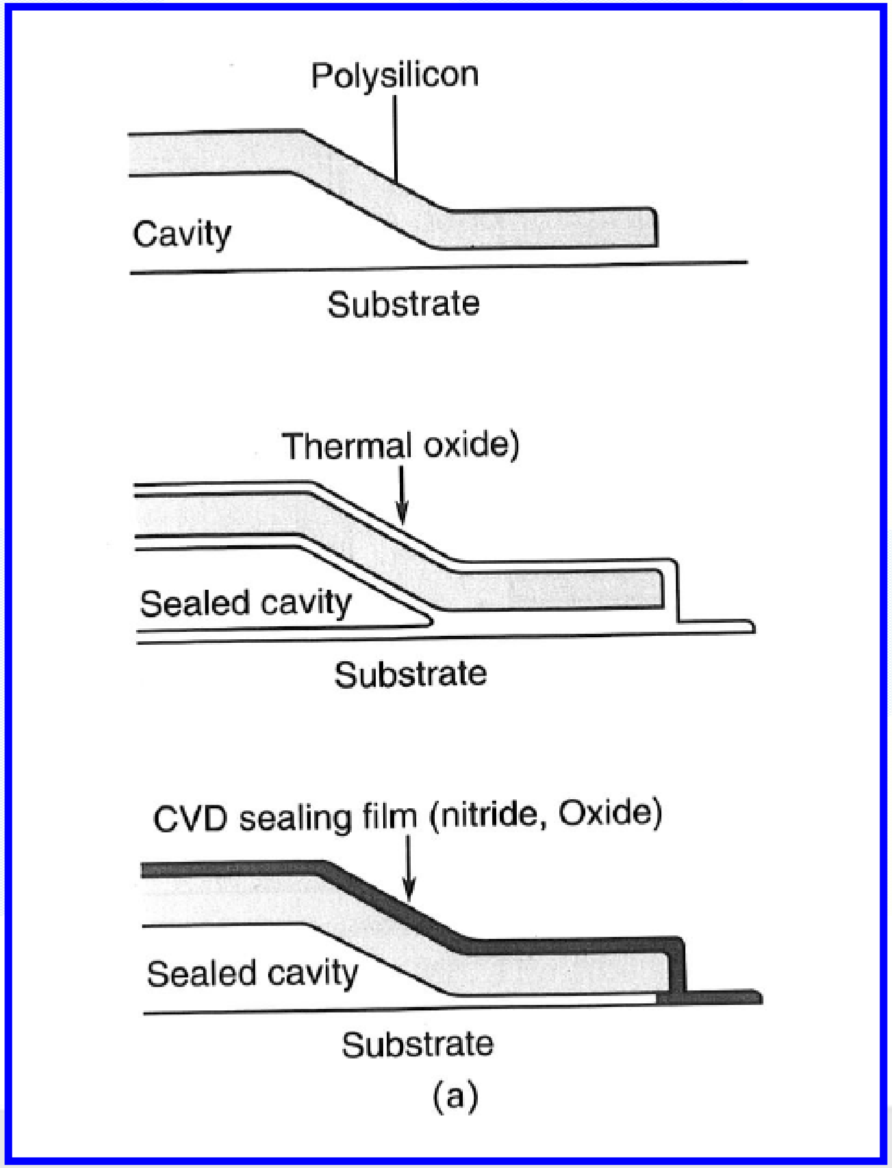
Surface Micromachining


Vertical access

Horizontal access

Surface Micromachining

- Sealing



LIGA

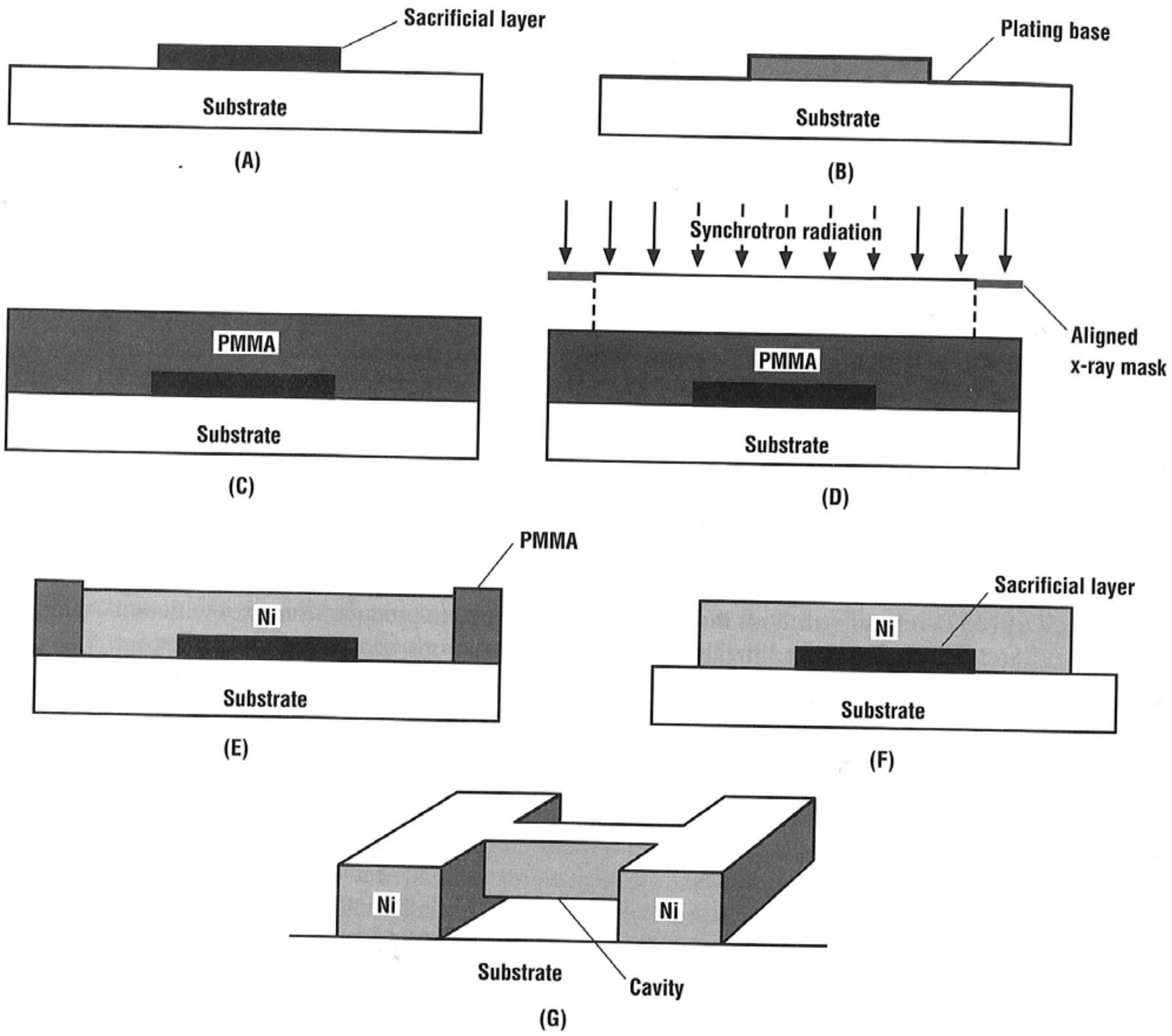
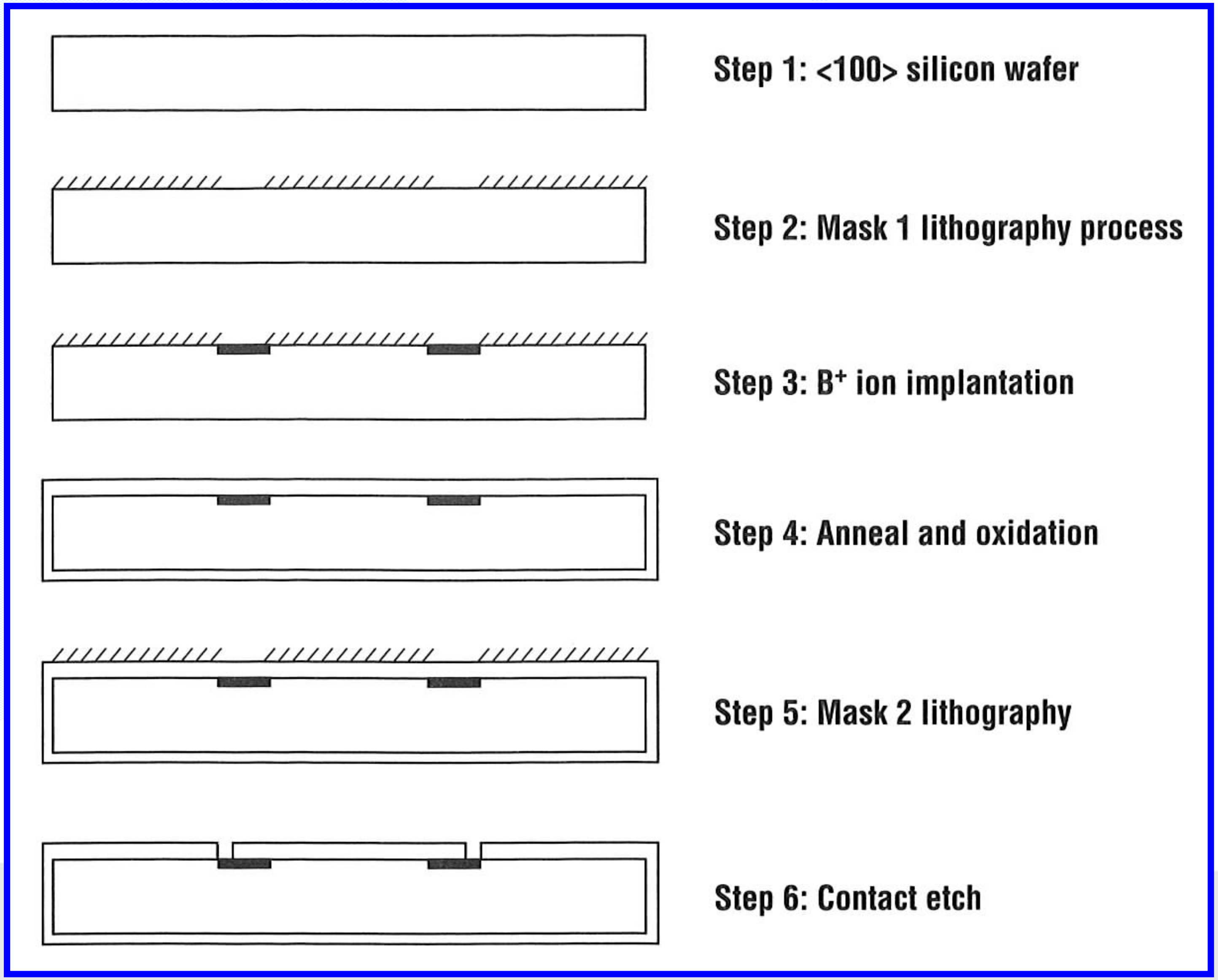


Figure 19.34 Cross-sectional view of LIGA with sacrificial layers. (A) Pattern sacrificial layer; (B) sputter plating base; (C) deposit PMMA; (D) align x-ray mask and expose PMMA; (E) develop PMMA and electroplate Ni; (F) remove PMMA and plating base to clear access to the sacrificial layer; (G) etch 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

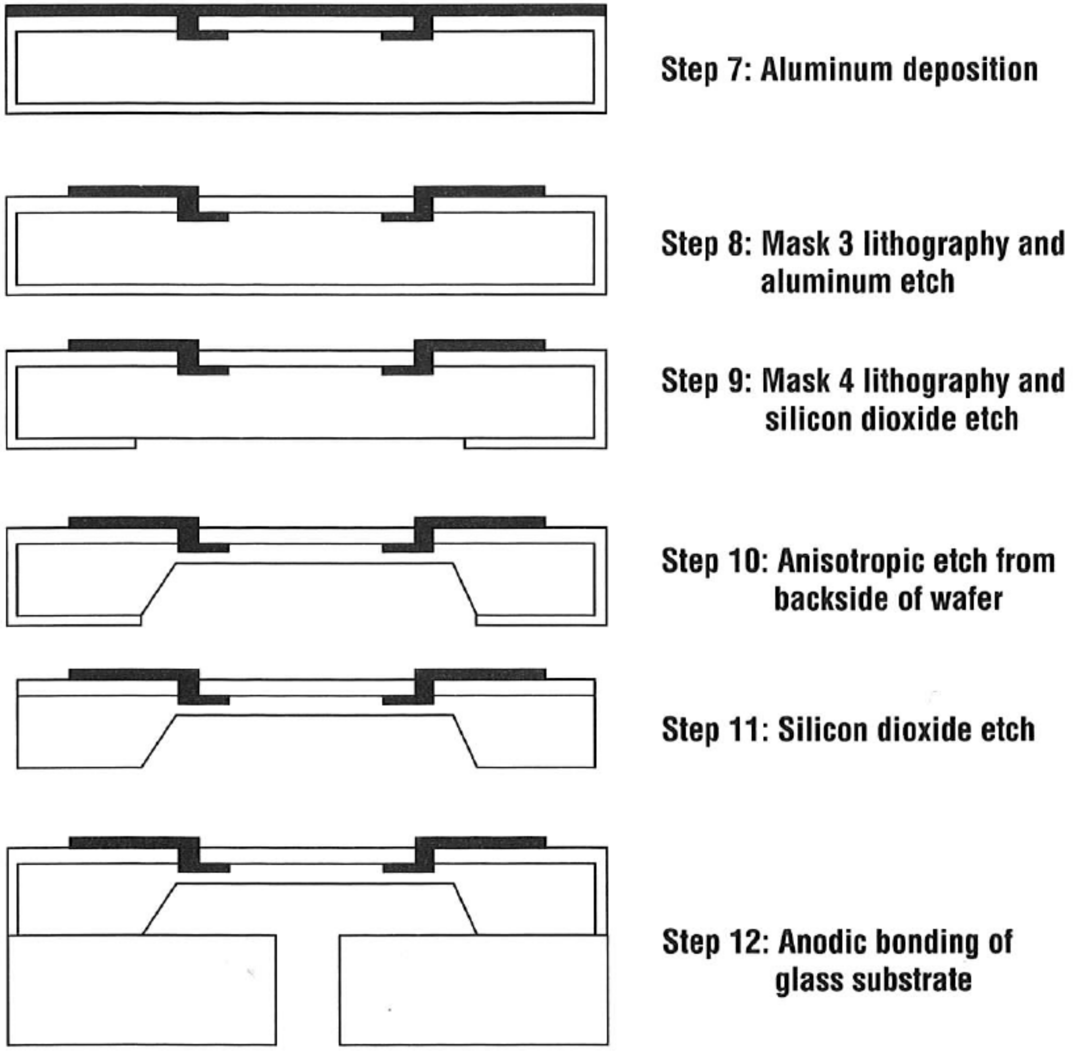
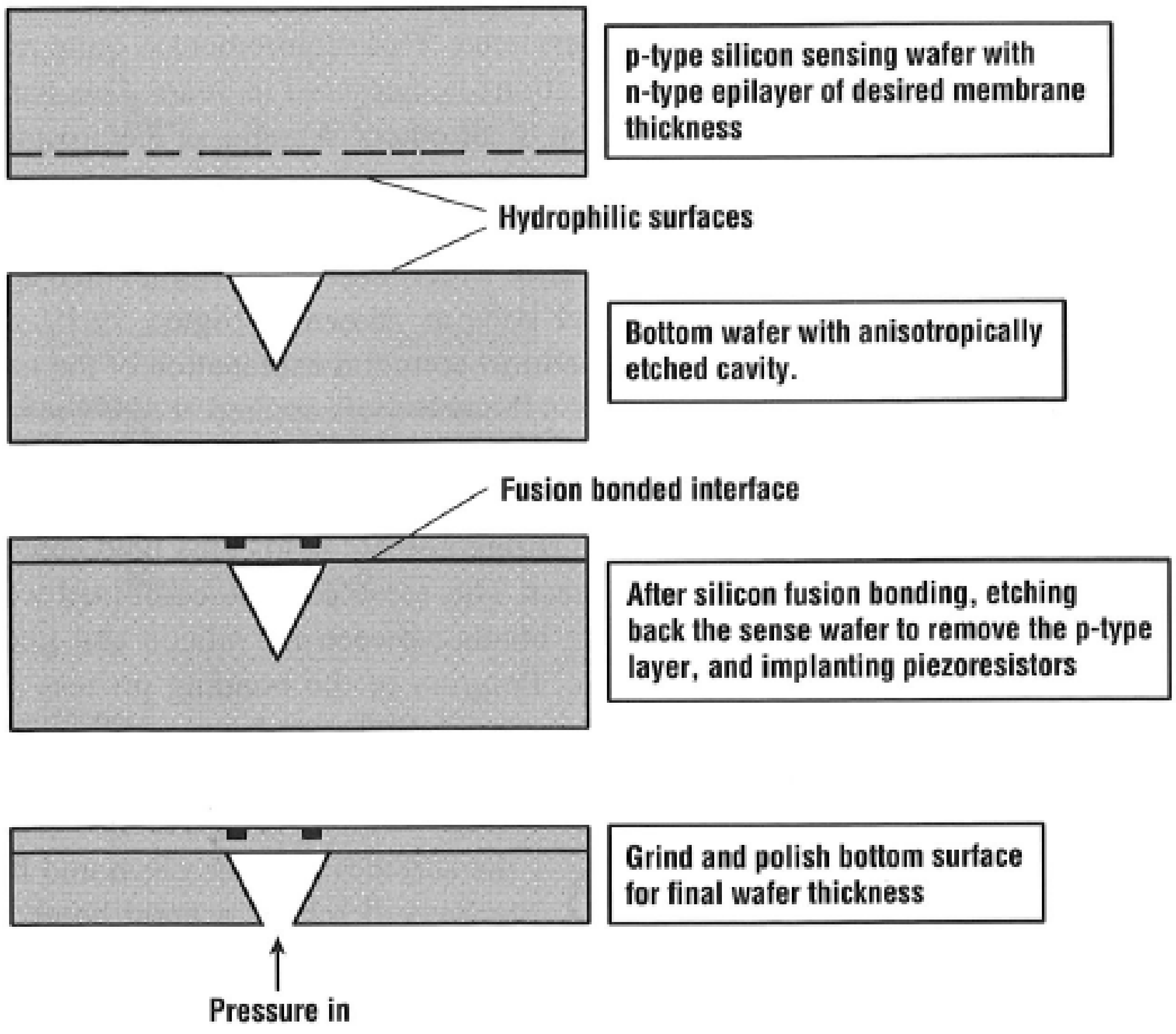


Figure 19.18 Bulk micromachining process for a piezoresistive pressure sensor.

Examples


p-type silicon sensing wafer with n-type epilayer of desired membrane thickness
Hydrophilic surfaces
Bottom wafer with anisotropically etched cavity.
Fusion bonded interface
After silicon fusion bonding, etching back the sense wafer to remove the p-type layer, and implanting piezoresistors
Grind and polish bottom surface for final wafer thickness
Pressure in

Examples (Trouble)

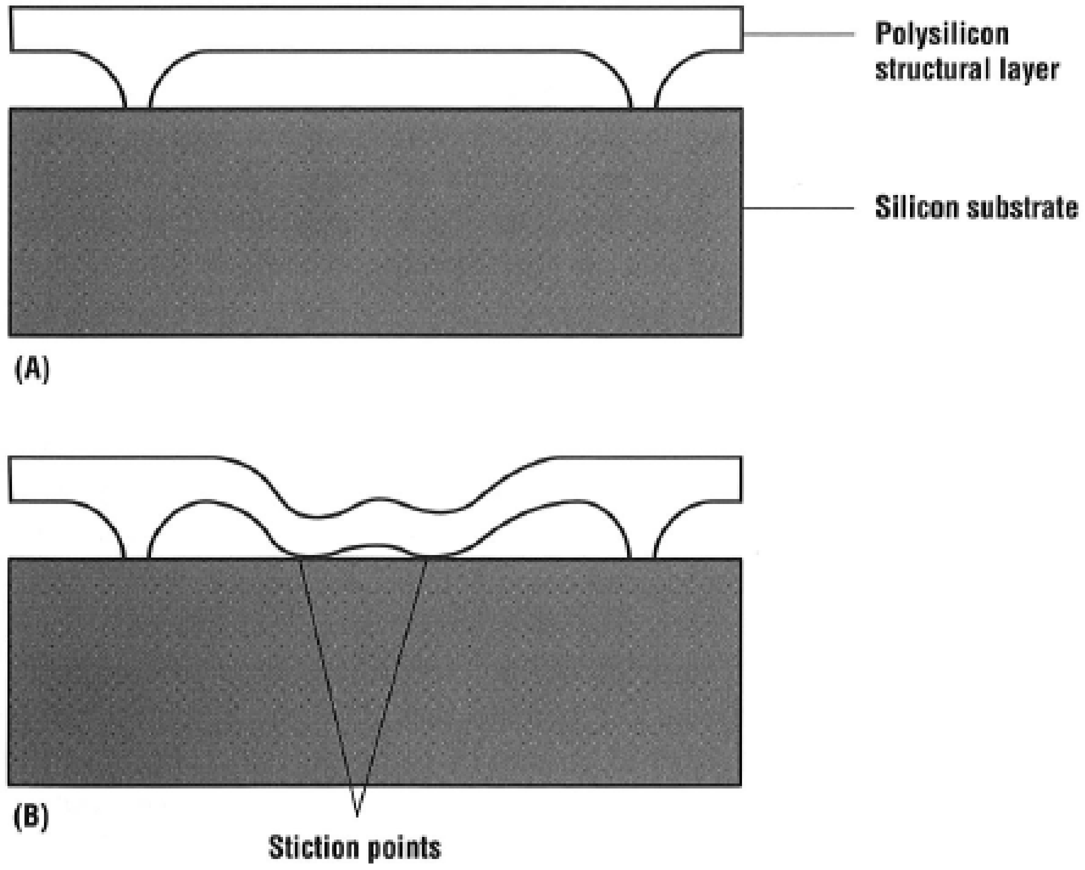
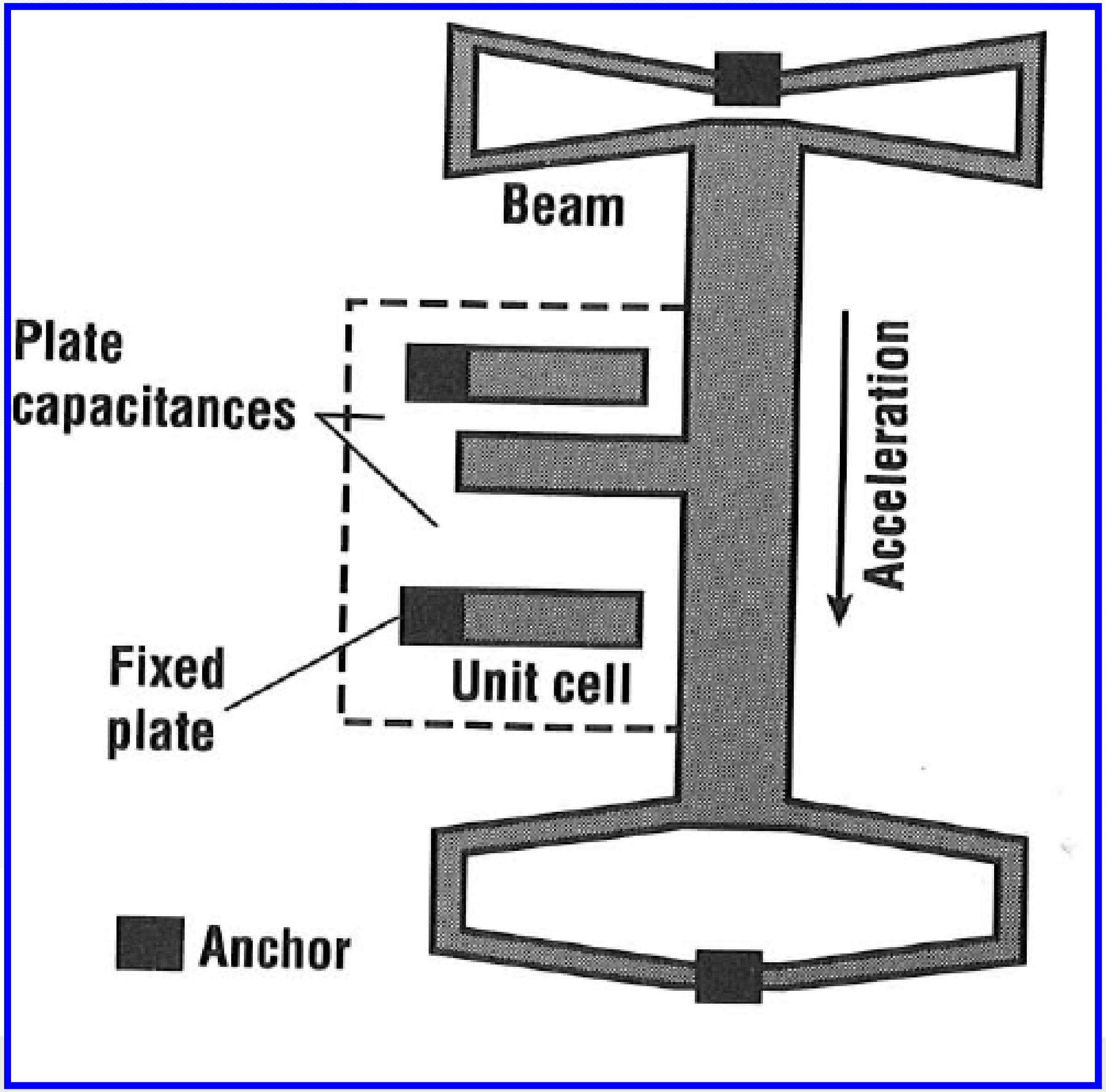


Figure 19.25 Side view of a released structure (A) without and (B) with stiction at two points.

Examples


Beam
Plate capacitances
Acceleration
Fixed plate
Unit cell
Anchor