

**Lectures on
MEMS and MICROSYSTEMS DESIGN and MANUFACTURE**

**Chapter 3
Engineering Science for
Microsystems Design and Fabrication**

In this Chapter, we will present overviews of the principles of physical and chemical processes that are used in fabricating MEMS and microsystems components.

Design engineers must have good knowledge in micro fabrication processes for successful design of these products.

Chapter content

Atomic structure of matter

Ions and ionization

Molecular theory of matter and intermolecular forces

Doping of semiconductors

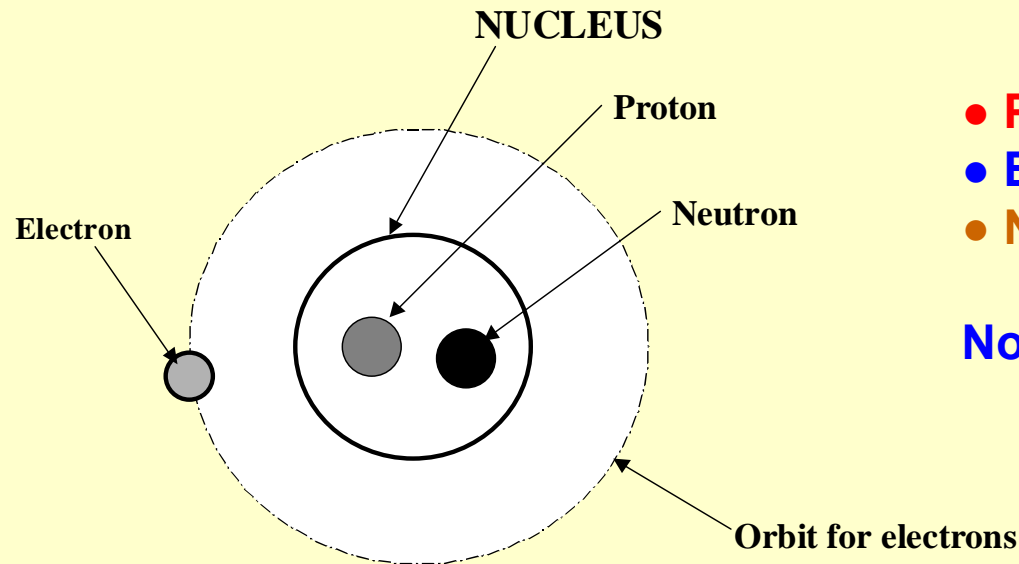
Diffusion process

Plasma physics

Electrochemistry

Atomic Structure of Matter

Basic atomic structure



- **Protons** carry +ve charge
- **Electrons** carry -ve charge
- **Neutrons** carry no charge

No. of protons = No. of electrons

- **Nucleus contains protons and neutrons**

NOTE: There is no neutron in the nucleus of H₂ atoms.

- **The diameter of outer orbit:** 2 to 3×10^{-8} cm, or 0.2 to 0.3 nm.
- **Mass of protons:** 1.67×10^{-24} g
- **Mass of electrons:** 9.11×10^{-28} g

Atomic Structure of Matter-Cont'd

The periodic table of elements

Every thing on the Earth is made by 96 stable and 12 unstable elements.

Atomic Number =
No. of protons in nucleus

Group III to VIII
elements

I																VIII															
1	II											2	He																		
3	4															5	6	7	8	9	10										
Li	Be															B	C	N	O	F	Ne										
11	12															13	14	15	16	17	18										
Na	Mg															Al	Si	P	S	Cl	Ar										
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36														
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr														
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54														
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe														
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86														
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn														
87	88	89																													
Fr	Ra	Ac																													
			58	59	60	61	62	63	64	65	66	67	68	69	70	71															
			Ce	Pr	Nd		Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu															
			90	91	92	93	94	95	96	97	98	99	100	101	102	103															
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr															

Ions and Ionization

What is an ion?

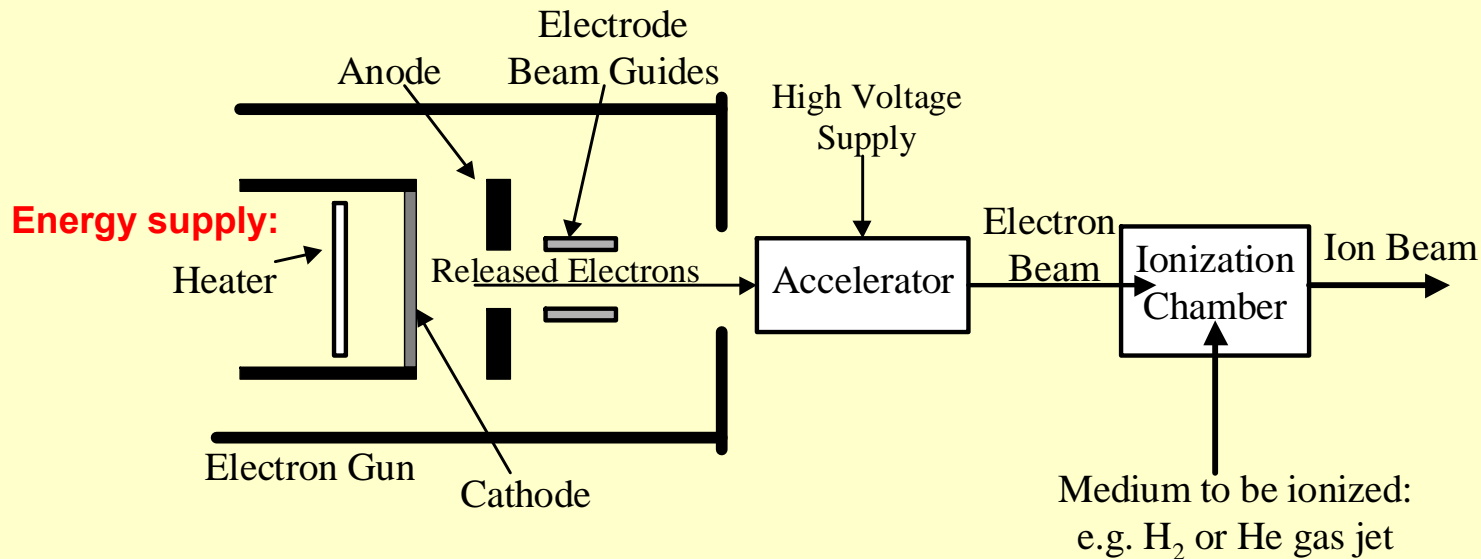
An ion is an electrically charged atom or molecule.

+ve charged ions = atoms with more protons than electrons.

-ve charged ions = atoms with more electrons than protons.

Ionization = The process of producing ions.

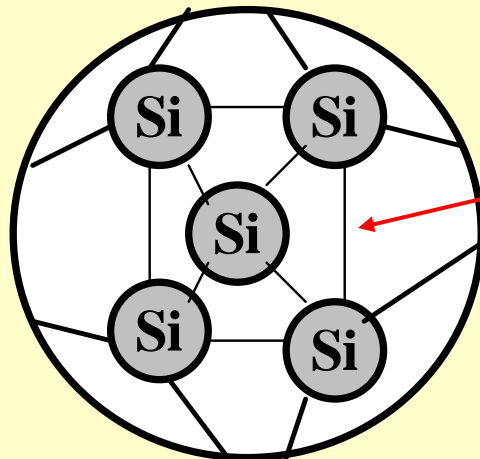
Schematic diagram of ionization by electron beams:



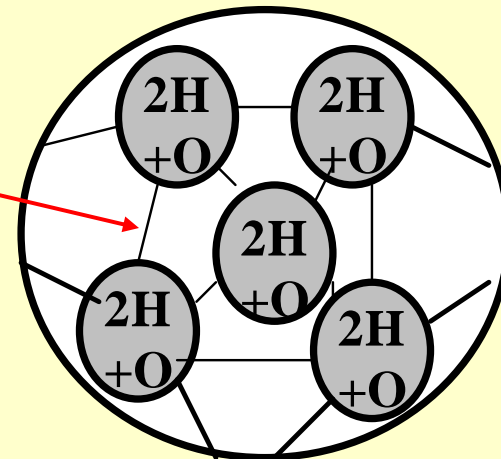
Molecular Theory of Matter

- All matters are made of large number of “**particles**” interconnected by **deformable** bonds.
- These “particles” are called **molecules**.
- By nature, some molecules are made by single atoms and some others involve multiple kinds of atoms.

Single atom molecule (silicon)



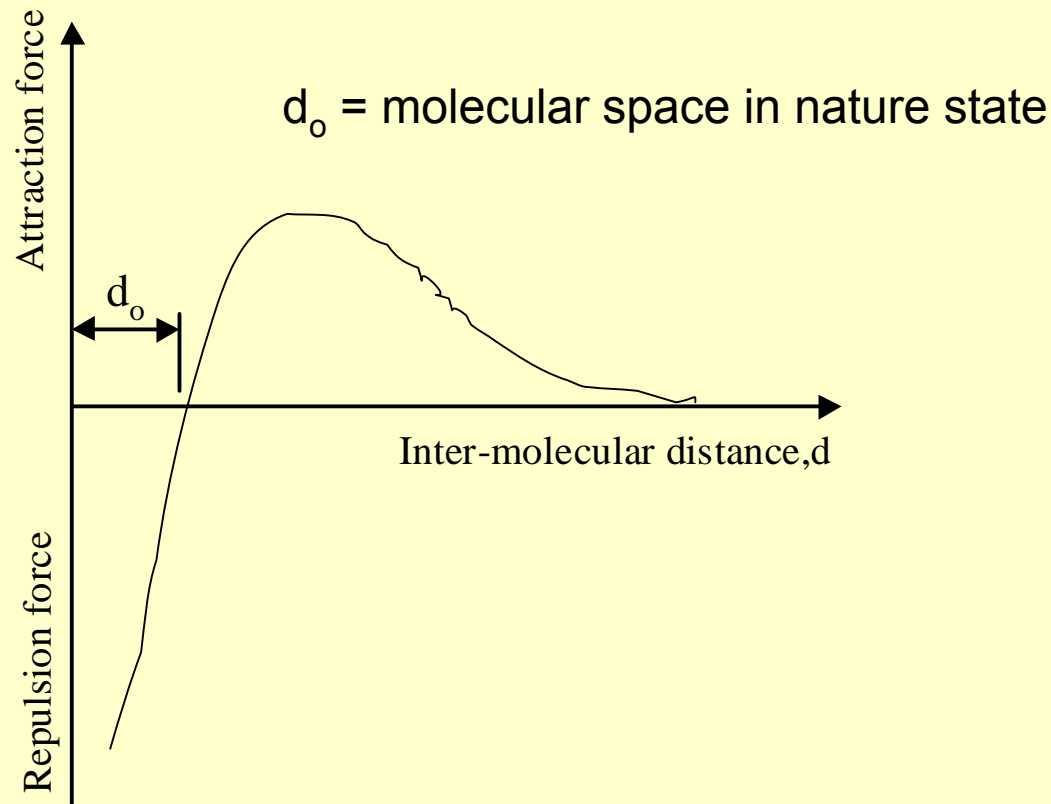
Bi-atom molecules (water)



Chemical
bonds

Inter-molecular Forces

- The fact that molecular bonds are deformable indicates the existence of forces between molecules in a matter.
- These inter-molecular forces can be “**attractions**” or “**repulsions**”- determined by the **distances** between the molecules.
- Inter-molecular forces are often referred to as **van der Waals forces**.



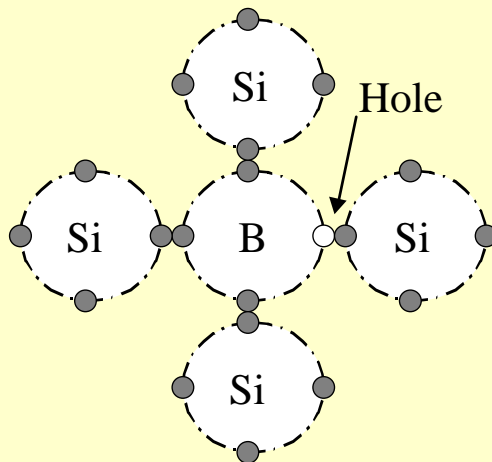
Doping of Semiconductors

- The process “**doping**” is a key process for producing transistors in microelectronics industry.
- **Semiconducting materials** are characterized by their electrical resistivity to be between electrically conductive and electrically insulators (or dielectric).
- They can be made electrically conductive by proper “**doping**” processes.
- Three classes of electrically conducting materials are:

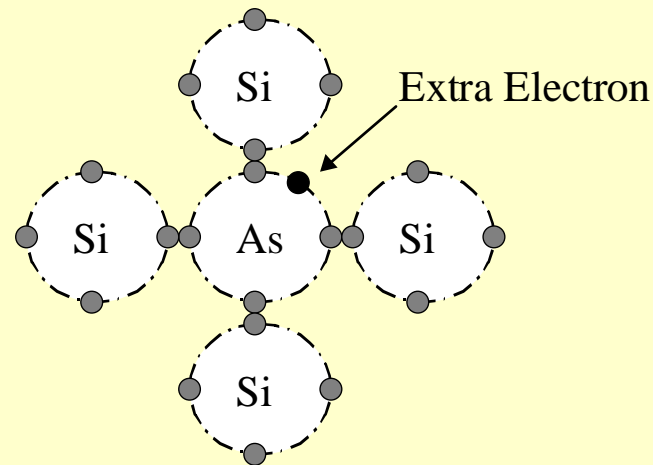
Materials	Approximate Electrical Resistivity, ρ (Ω -cm)	Classifications
Silver (Ag) Copper (Cu) Aluminum (Al) Platinum (Pt)	10^{-6} $10^{-5.8}$ $10^{-5.5}$ 10^{-5}	Conductors
Germanium (Ge) Silicon (Si) Gallium Arsenide (GaAs) Gallium Phosphide (GaP)	$10^{1.5}$ $10^{4.5}$ $10^{8.0}$ $10^{6.5}$	Semiconductors
Oxide Glass Nickel (pure) Diamond Quartz (fused)	10^9 $10^{10.5}$ 10^{13} 10^{14} 10^{18}	Insulators

Doping of Semiconductors-Cont'd

- Doping for common semiconductor, e.g. silicon (Si) involves adding atoms with **different number of electrons** to create **unbalanced number of electrons** in the base material (e.g. Si)
- The base material, after doping, with **excessive electrons** will carry **-ve charge**.
- The base material, after doping, with **deficit in electron** will carry **+ve charge**.
- Doping of silicon can be achieved by “**ion implantation**” or “**diffusion**” of **Boron (B) atom for +ve charge** or of **Arsenide (As) or Phosphorous (P) for -ve charge**.



P-type doping

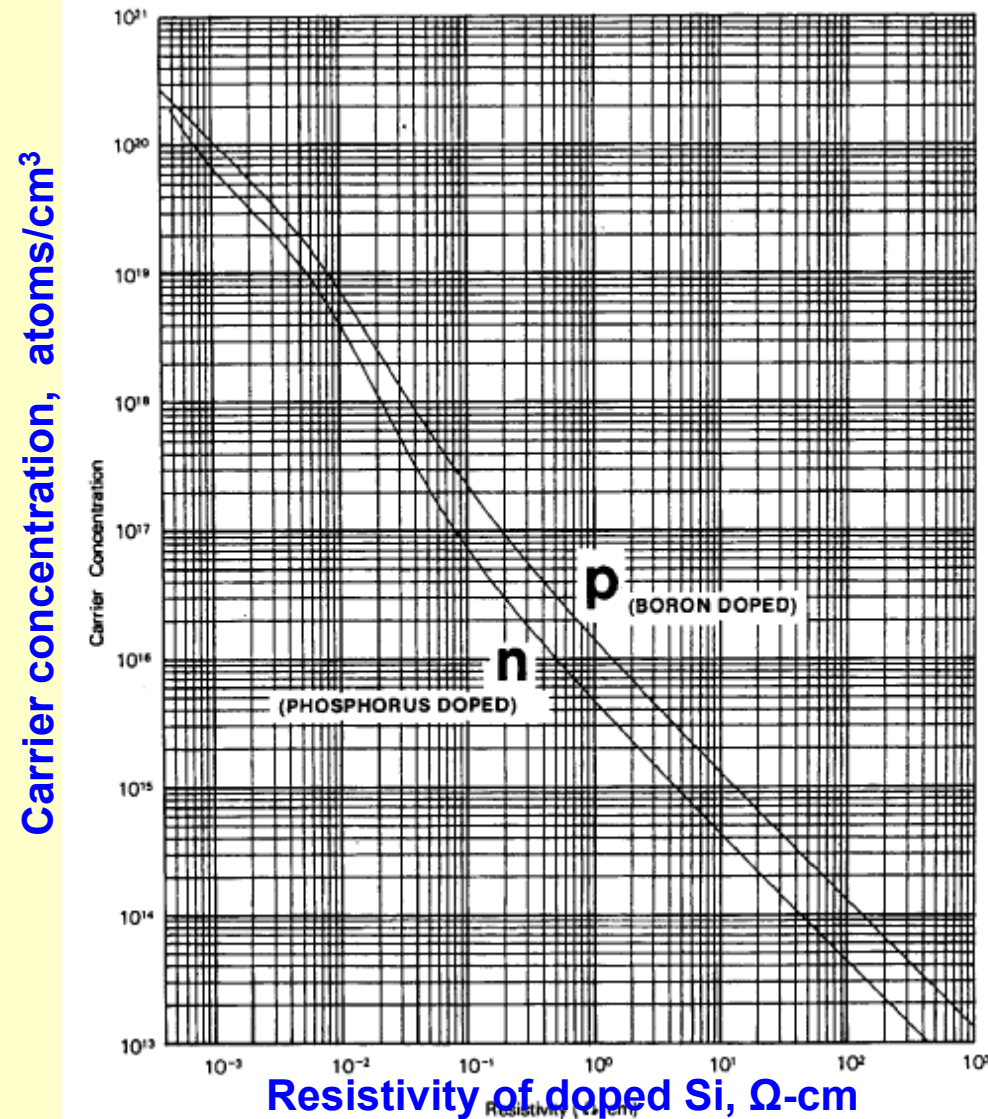


N-type doping

Doping of Semiconductors-Cont'd

Doping strength

It is determined by the concentration of atoms in the Dopants. Example for doping of silicon:



Diffusion Process

Diffusion process = Introducing a controlled amount of foreign material into selected regions of another material.

Diffusion processes may take place in:

Gas – gas (e.g. gas mixing and air pollution)

Liquid – liquid (e.g. spread of drop of ink in a pot of clear water)

Gas – solids (e.g. oxidation of metal)

Liquid – solids (e.g. corrosion of metal in water)

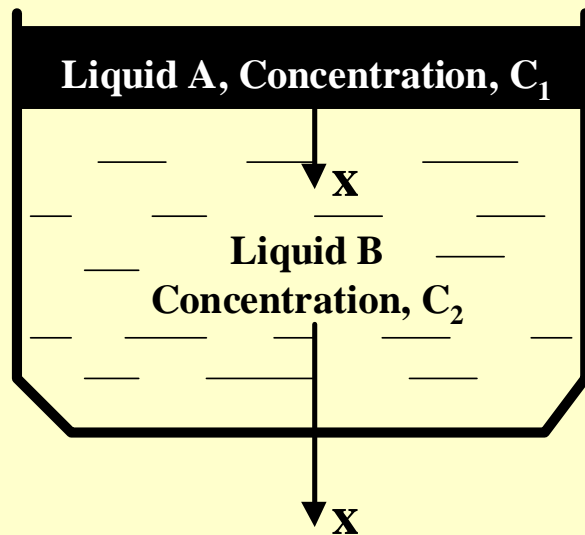
Three major applications of diffusion in microfabrication
- a very important process:

- **Doping of semiconducting materials to produce p-n junctions and the production of piezoresistors.**
- **Oxidation of semiconducting materials.**
- **Chemical vapor deposition processes.**

Diffusion Process-Cont'd

Mathematical modeling by Fick's law:

A diffusion of liquid A into liquid B:



For the case $C_1 > C_2$:

$$C_a \propto \frac{C_{a,x_0} - C_{a,x}}{x_0 - x} = -\frac{\Delta C}{\Delta x}$$

C_a = Concentration of A at a distance x away from the initial contacting surface/m²-s

x_0 = position of the initial interface of A and B.

C_{a,x_0} , C_{ax} = respective concentrations of A at x_0 and x .

The above expression may be expressed in a different form of equation:

$$C_a = -D \frac{\Delta C}{\Delta x}$$

in which D = diffusivity of A into B - a material constant for specific pair of materials in the process.

The value of D usually increases with temperature → higher efficiency at elevated temperature

Diffusion Process-Cont'd

Solid-solid diffusion e.g. in doping of silicon with B or As or P

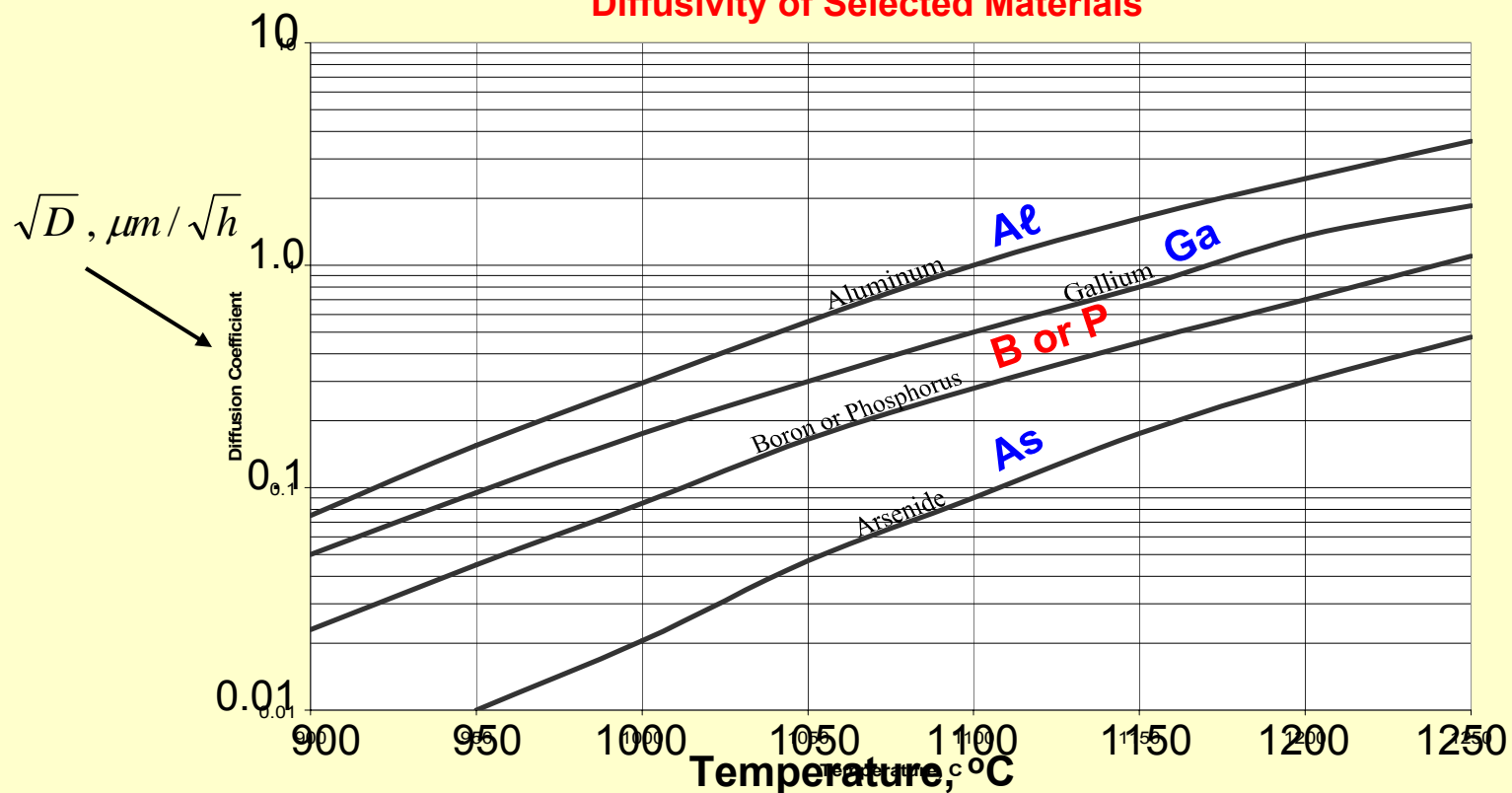
Let J = the atoms (or molecules) of the foreign materials (B, As or P) to be diffused into base substrate material (e.g. Si) can be computed by:

$$J = -D \frac{\partial C}{\partial x} \quad \text{atoms/m}^2\text{-s}$$

where D = diffusivity, or diffusion coefficient of the foreign material in the substrate material, m^2/s .

C = concentration of the foreign material in the substrate, atoms/m^3 .

Diffusivity of Selected Materials



Diffusion Process-Cont'd

Solid Solubility

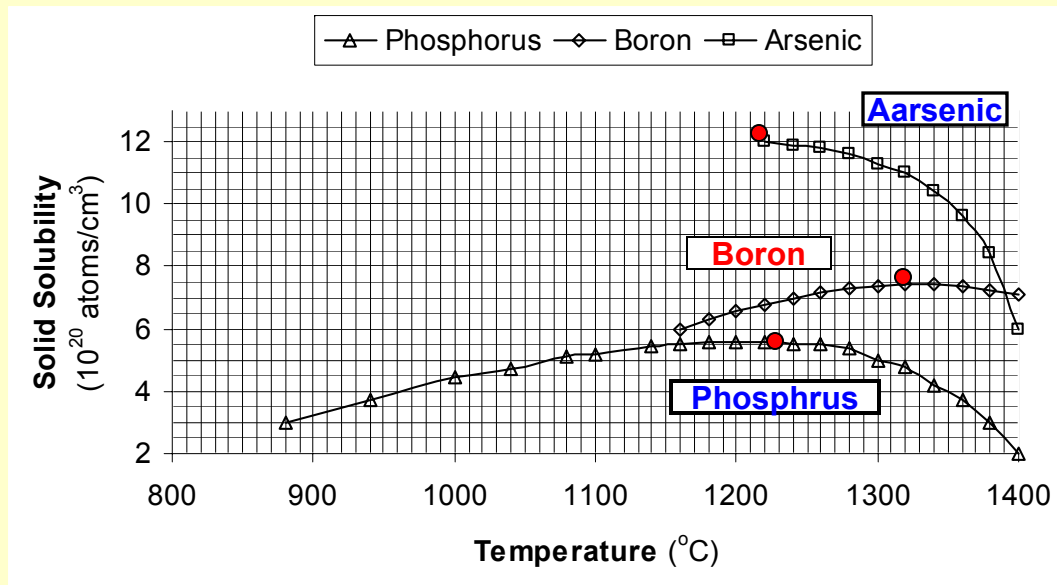
The theory of “Higher temperature → Higher diffusion efficiency” does not always hold for solid-solid diffusion.

The “solubility” diagram below indicates, for example the temperatures at which maximum diffusion can take place are:

≈ 1220°C for As (-ve Si)

≈ 1350°C for B (+ve si)

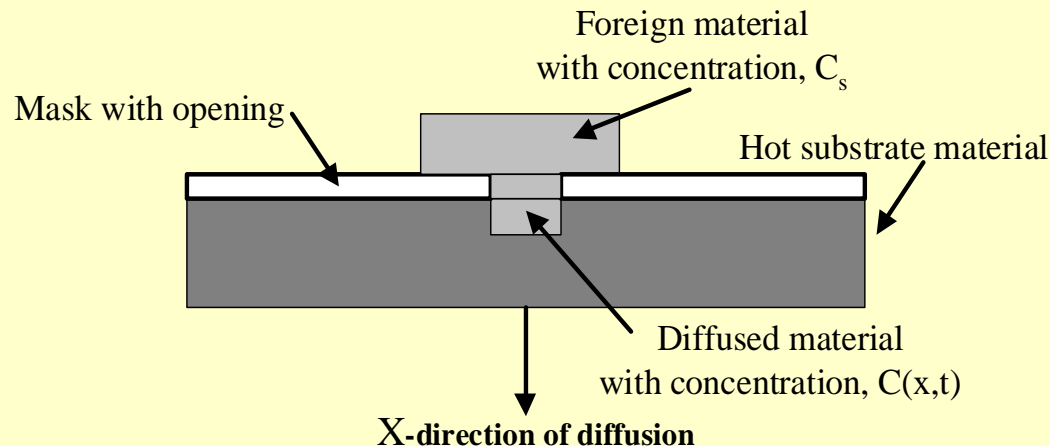
≈ 1230°C for P (-ve Si) in doping silicon substrates



Diffusion Process-Cont'd

The Diffusion Equation

This equation is used to predict the concentration of the foreign material (e.g. B) in the substrate (e.g. Si) at given depth and time in a one-dimensional diffusion process.



$$\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2}$$

with the following conditions:

$$C(x,0) = 0; C(0,t) = C_s; C(\infty,t) = 0$$

The solution of the partial differential equation satisfying the specific conditions is:

$$C(x,t) = C_s \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$$

where $\operatorname{erfc}(X)$ is the **complementary error function**, $\operatorname{erfc}(X) = 1 - \operatorname{erf}(X)$ in which $\operatorname{erf}(X)$ is the **error function** with values available from mathematical handbooks.

Diffusion Process-Cont'd

The Error functions

X	erf(X)	X	erf(X)	X	erf(X)	X	erf(X)
0.0	0.0						
0.05	0.0564	0.55	0.5633	1.05	0.8624	1.55	0.9716
0.10	0.1125	0.60	0.6039	1.10	0.8802	1.60	0.9763
0.15	0.1680	0.65	0.6420	1.15	0.8961	1.65	0.9804
0.20	0.2227	0.70	0.6778	1.20	0.9103	1.70	0.9838
0.25	0.2763	0.75	0.7112	1.25	0.9229	1.75	0.9867
0.30	0.3286	0.80	0.7421	1.30	0.9340	1.80	0.9891
0.35	0.3794	0.85	0.7707	1.35	0.9438	1.85	0.9911
0.40	0.4284	0.90	0.7969	1.40	0.9523	1.90	0.9923
0.45	0.4755	0.95	0.8209	1.45	0.9597	1.95	0.9942
0.50	0.5205	1.00	0.8427	1.50	0.9661	2.00	0.9953

Example: $\text{erf}(1.25) = 0.9229$

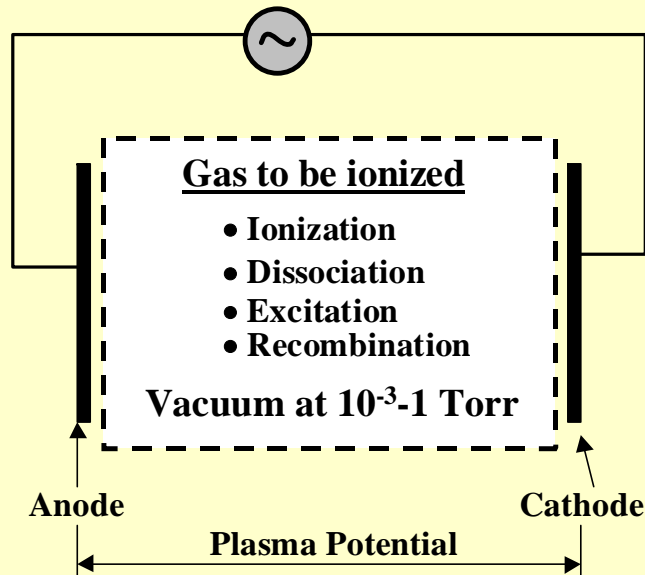
Plasma Physics

Plasma

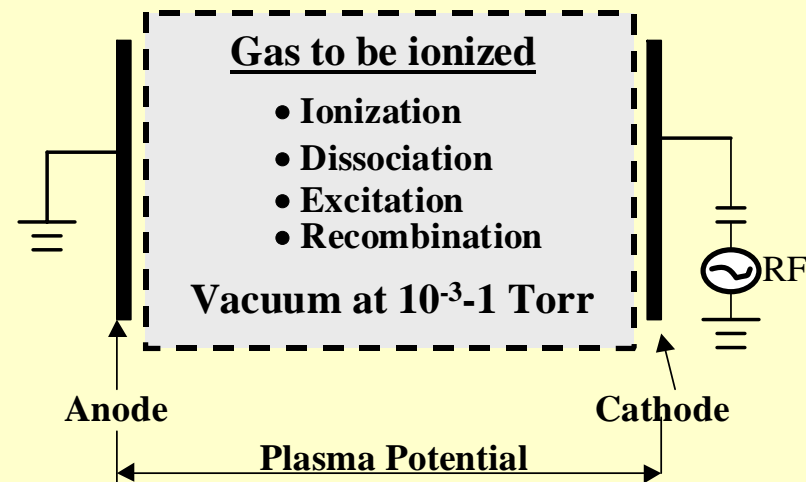
- It is a **gas** containing **high energy ions** that carries electronic charges.
- Plasma is used to “knock out” substrate materials at desired localities - in a “**dry etching process**”, or is used to carry chemicals in **chemical vapor deposition (CVD) process**.

Production of plasma

by high electric voltage:



by high energy RF:



Electrochemistry

There are two principal applications of electrochemistry in microfabrication:

- **Electrolysis** in electroplating of polymers, and
- **Electrohydrodynamics** for pumping fluids in micro fluidics.

Electrolysis

It is the process that produces **chemical changes in a chemical compound** by **oppositely charged constituents** moving in opposite direction toward the electrodes under an **electric potential difference**.

The **desired element** (or chemical) from the chemical compound can thus be **isolated** and **collected at the electrodes**.

Electrochemistry-Cont'd

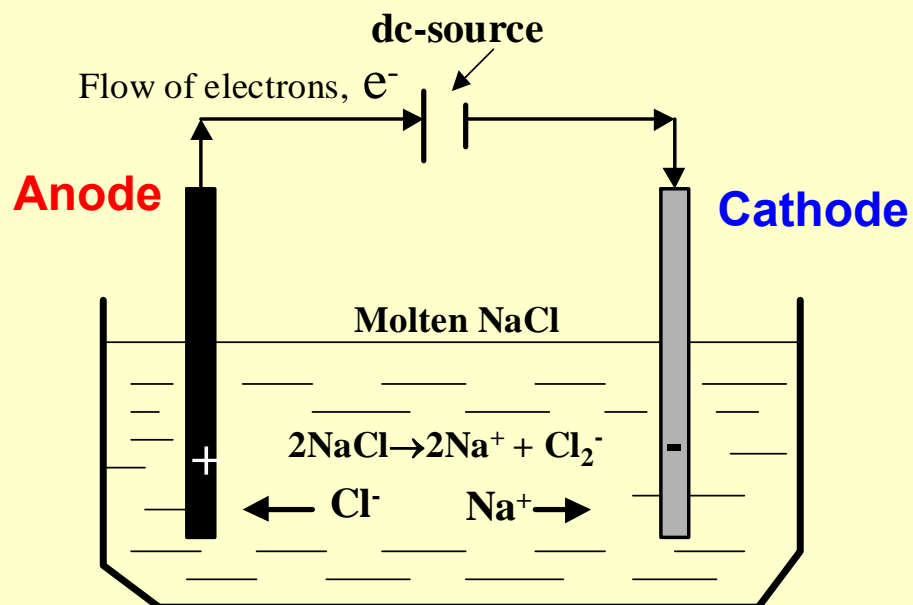
Example of electrolysis

Production of sodium (Na) from chemical compound NaCl.

Chemical reaction: $2\text{NaCl} \rightarrow 2\text{Na}^+ + \text{Cl}_2^-$

+ve charged Na ions move towards the -ve electrode (cathode)

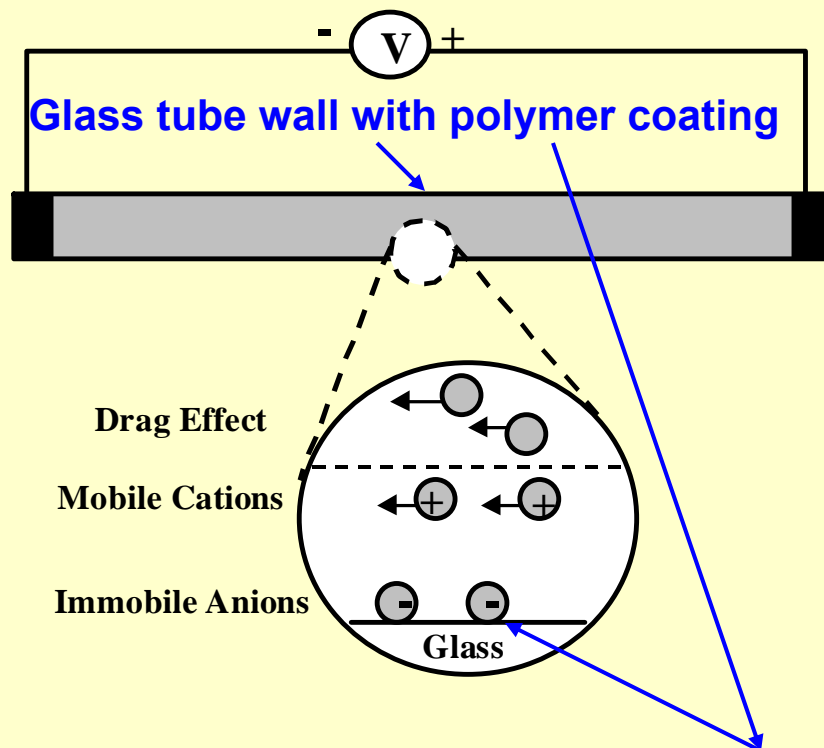
-ve charged Cl ions move towards the +ve electrode (anode)



Electrohydrodynamics

The principle of moving fluids in micro channels or passages is similar to electrolysis, i.e. by “ionizing” the fluid first using electric potential. The ionized fluid will move in the direction of the preferred electrodes
- achieving the pumping effect.

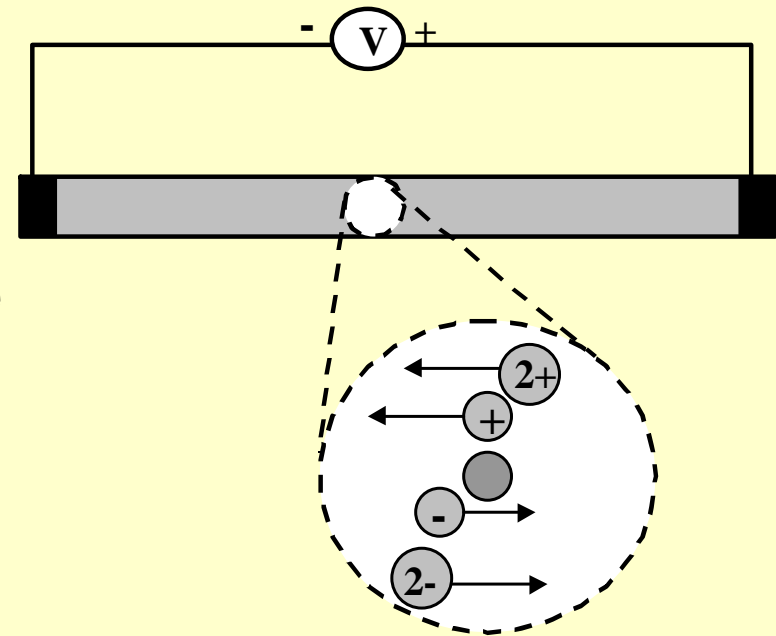
Electro-osmotic pumping - Moving the entire fluid in micro passages.



- Fluid near the tube wall is ionized into +ve ion (cations) and -ve ions (anions).
- the special polymer coating on the tube wall “immobilize” the local anions.
- The free cations will move towards the -ve electrode.
- The moving cations carry the neutral fluid and result in motion.

Electrophoretic pumping

- Move various **species** in fluid (e.g. biological samples) through micro channels.
- The heterogeneous fluid is ionized.
- The ions of contained species have their own respective “**electro osmotic mobility**”.
- Distinct “electro-osmotic mobility” of the species make them moving at **different velocities under the influence of the applied electric field**.
- **Separation of species** in micro samples thus be achieved by the difference in velocities in motion.



Electrophoretic pumping is widely used in biomedical and pharmaceutical Industries. It is usually used in conjunction with electro-osmotic pumping.

End of Chapter 3