*** Direct Recombination of Electrons and Holes:-** Electrons of conduction band recombine with Holes in the valence band either directly or indirectly. In the direct recombination electrons falling from the conduction band to empty states (holes) in the valence band. The energy lost by an electron in making the transition is given up as a photon. Direct recombination is spontaneous.

The probability of recombining of an electron and a hole is constant in time,

$$\frac{d(n(t))}{dt} = \alpha_r n_i^2 - \alpha_r n(t)\, p(t) \quad \text{---- (i)}$$

← rate of change of conduction band electrons

$\alpha_r n_i^2$ → rate of generation. (Thermal generation)

$\alpha_r n(t) p(t)$ → rate of recombination.

We know that.

Rate of recombination $\propto n(t)\, p(t)$

$= \alpha_r n(t)\, p(t)$

Where α_r = Recombination Coefficient.

Let assume Excess EHP is at $t=0$, . Initial electron - Hole Concentrations Δn and Δp are equal.

The instantaneous concentrations of excess carriers $= \delta n(t), \delta p(t)$.

Now we can write equation (i) in the terms of equilibrium values n_0 and p_0 and excess carrier concentrations $\delta n(t) = \delta p(t)$.

$$\frac{d[\delta n(t)]}{dt} = \alpha_r n_i^2 - \alpha_r [n_0 + \delta n(t)][p_0 + \delta p(t)]$$

$$= -\alpha_r [(n_0 + p_0)\delta n(t)] + \delta n^2(t)]$$

$$= -\alpha_r [(n_0 + p_0)\delta n(t) + \delta n^2(t)] \quad \text{---- (ii)}$$

The equation (ii) is nonlinear and it is difficult to solve it. We simplified for the case of Low-level Injection. So,

If excess carrier concentrations small then we neglect δn^2.
If material is extrinsic then we can neglect the term representing equilibrium minority carriers.

Suppose P type then $P_o >> n_o$

$$\therefore \frac{d[\delta n(t)]}{dt} = -\alpha_r P_o \delta n(t)$$

The solution of this equation is an exponential decay from the original excess carrier concentration Δn.

$$\delta n(t) = \Delta n e^{-\alpha_r P_o t} = \Delta n e^{-t/\tau_n}$$

Where, $\tau_n = (\alpha_r P_o)^{-1}$, called decay constant or recombination life time.

$$\tau_p = (\alpha_r n_o)^{-1}$$
$$\tau_n = (\alpha_r P_o)^{-1}$$

• **Problem:-** A sample of GaAs is doped with $10^{15}/cm^3$ (acceptor). The intrinsic carrier concentration of GaAs [illegible] $10^6/cm^3$, the minority electron concentration is n_o [illegible]. The minority 10^{14} EHP/cm³ are created at $t = 0$, & τ_n [illegible] find α_r (Recombination Coefficient).

Solution:-

$$P_o \simeq N_A = 10^{15}/cm^3$$
$$n_i = 10^6/cm^3$$
$$n_o = \frac{n_i^2}{P_o} = \frac{(10^6)^2}{10^{15}} = 10^{-3}$$

$$P_o >> n_o$$

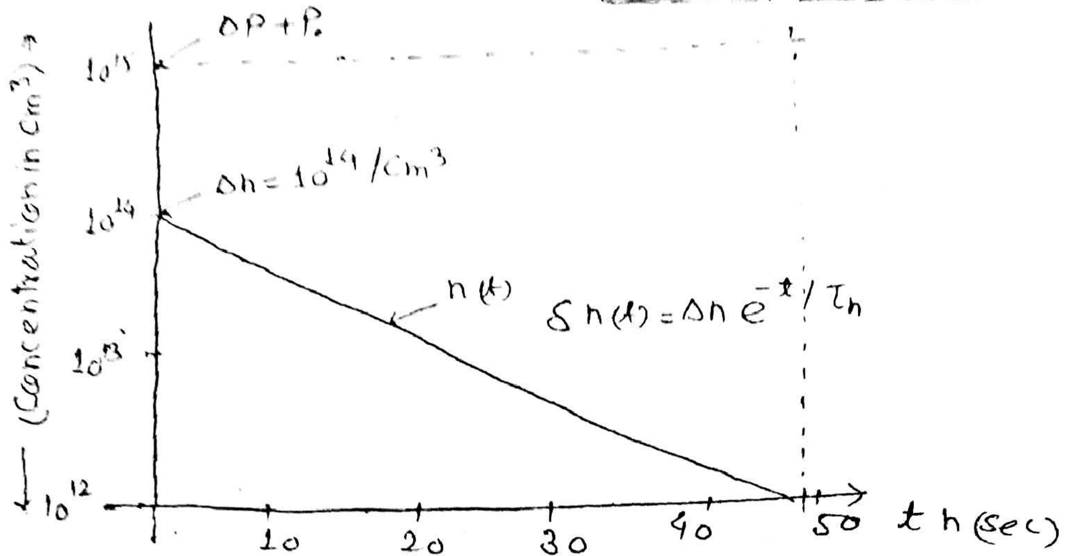
$\therefore$ τ [illegible]

$$= \frac{1}{10^{-8}\,sec \times 10^{15}/cm^3}$$

$$= 10^{-7}\ cm^3/sec$$

$\alpha_r = 10^{-7}\ cm^3/sec$

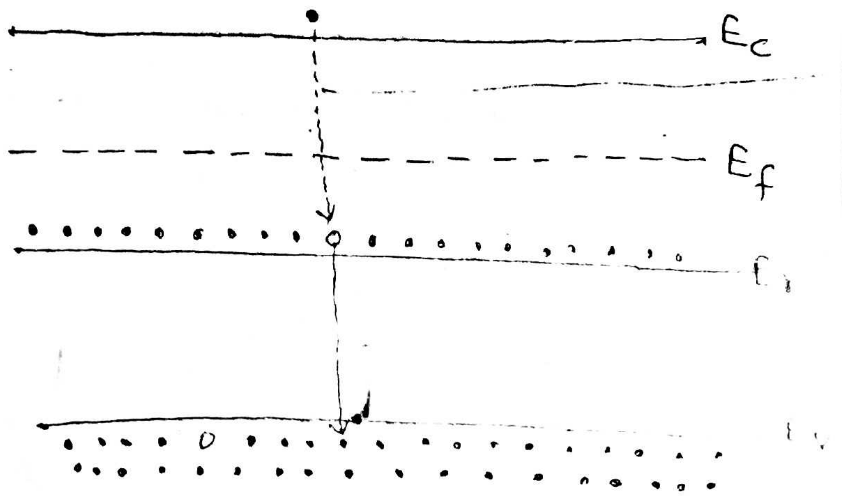
The exponential decay of $\delta n(t)$ is circular in GaAs.



Indirect Recombination or Trapping:- The figure shows - Indirect Recombination.

E_r is recombination level which is bellow E_f at equilibrium and filled with electrons. When excess electrons and holes are created in this material each EHP recombines at E_r in two steps-

- → Hole Capture and
- → Electron Capture,



Since the recombination centres are filled at Equilibrium, the first event in the recombination process is Hole Capture. This process is equivalent an electron of valence band falling at E_r, falling to valence band. and leaving behind an empty state in the recombination level. Thus in Hole Capture, energy is given to heat to the Lattice.

Failing of electron from E_r to valence band ⟶ Hole capture
Conduction band electron falling to E_r ⟶ Electron capture,

electron capture must follow the Hole capture means if Hole capture occur the electron capture will occur. Energy is leaving as a heat in both steps.

When both events are occure then recombination centre is back to it's original state (filled with an electron) but an EHP is missing. Thus one recombination has taken place and the centre is ready to participate in another recombination event by capturing of a hole.

Unequal time required for capturing of each type of carrier. It mean the electron capture does not follow hole capture immediately after hole capture.

When a carrier is trapped temporarily at a centre and then is reexcited without recombination taking place, the process is called temporarily trapping.

The effects of recombination and trapping can be measured by an photoconductive decay experiment. The conductivity of the sample during decay is -

$$\sigma(t) = q\,[n(t)\,\mu_n + p(t)\,\mu_p]$$

→ Electron capture,

→ Recombination level, or, trapping centre or, defect level.

→ Hole capture

<u>Steady state Carrier Generation</u> :— The steady state electron and holes concentrations are given in the terms of fermi levels. The fermi level E_f is meaningful only when no excess carriers are present. We can write steady state electron and holes concentrations as expressions in the equilibrium by defining quasi-fermi levels F_n and F_p for electrons and holes

$$n = n_i e^{(F_n - E_i)/kT}$$

$$p = n_i e^{(E_i - F_p)/kT}$$

The thermal generation of EHPs -

$$g(T) = g_i \quad \text{for intrinsic Semiconductor,}$$

$$g(T) = \alpha_i n_i^2 = \alpha_r n_o p_o \quad \text{------------(i)}$$

where. α_r = recombination Coefficient.
n_i = Intrinsic Carrier Concentration.
n_o, P_o = electron, Hole Concentrations at thermal Equilibrium.

a light is shown on the Sample, an optical generation rate g_{op} will be added to the thermal generation -

$$g(T) + g_{op} = \alpha_r n p$$

$$= \alpha_r (n_o + \delta n)(P_o + \delta P) \quad \text{-------(ii)}$$

Here. n_o and. P_o are equilibrium Concentrations and. δn, δp are departures, for no trapping $\delta n = \delta p$.
Eqs (ii) becomes

$$g(T) + g_{op} = \alpha_r [n_o P_o + \delta n (n_o + P_o) + \delta n^2]$$

$$\cancel{g(T)} + g_{op} = \cancel{\alpha_r n_o P_o} + \alpha_r \delta n (n_o + P_o) + \alpha_r \delta n^2$$

$$g_{op} = \alpha_r (n_o + P_o) \delta n$$

$$g_{op} = \frac{\delta n}{\tau_n}$$

δn^2 is neglected for Low level Injection.

Hence excess carrier concentration written as-

$$\boxed{\delta n = \delta p = g_{op} \tau_n}$$

The photoconductivity.

$$\boxed{\sigma = q g_{op} (\tau_n \mu_n + \tau_p \mu_p)}$$

Similar to Conductivity of Semiconductor.

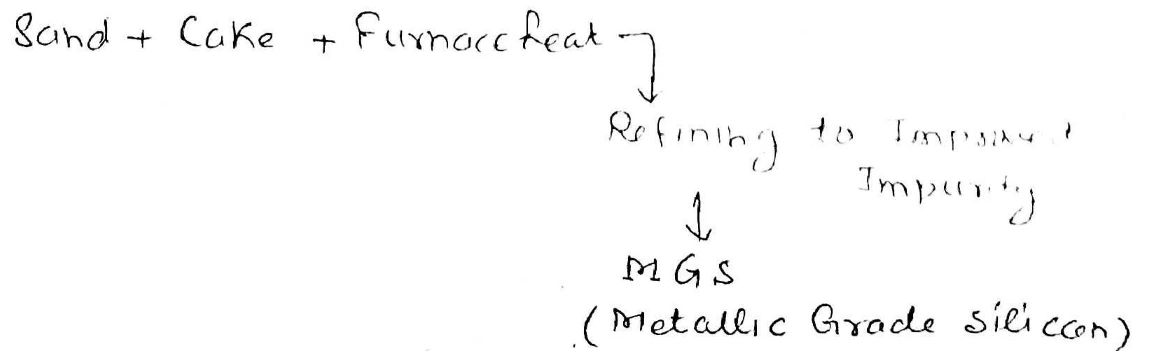
3

Junctions:-

Fabrication of Junctions:- Mainly following techniques are used for fabrication of junctions-

→ 1. Grown junctions.
→ 2. alloyed junctions
→ 3. Diffused junctions
→ 4. Ion Implantation
→ 5. Epitaxyle Junctions.

Grown junctions :- Grown junctions are fabricated by using Crystal growth process. In this process a single crystal of silicon is obtained. As we already know that silicon achieved from sand. under following steps-



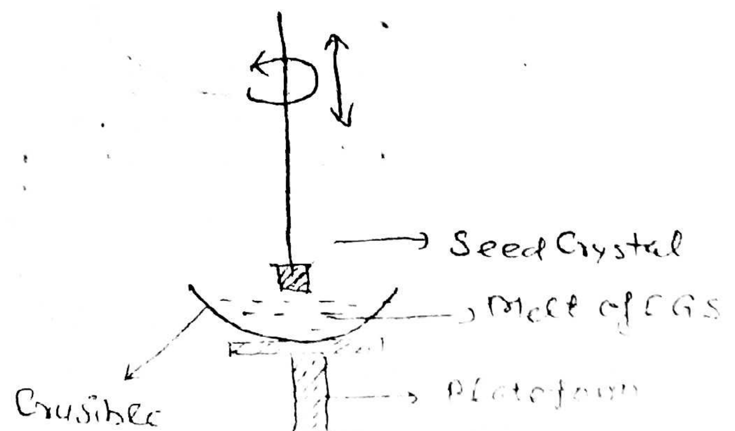
This metallic grade silicon is impure and polly crystalline.

Metallic Grade Silicon —under treatment→ Electron Grade Silicon (EGS)
Pure crystalline
But polycrystalline

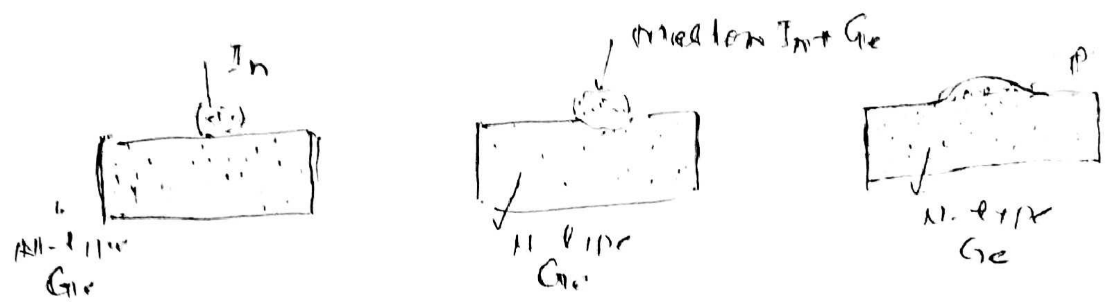
CZ process:- CZ process is used for converting this EGs into single crystal silicon.

Required amount of Impurity is added for N type & P type semiconductor.

firstly Boron is added and groth process is stop and-fir further phosphorous is added.



Alloyed junctions : Alloyed junctions are fabricated by using alloying technique. In this technique a metal is alloyed on a semiconductor with the opposite type of dopant.

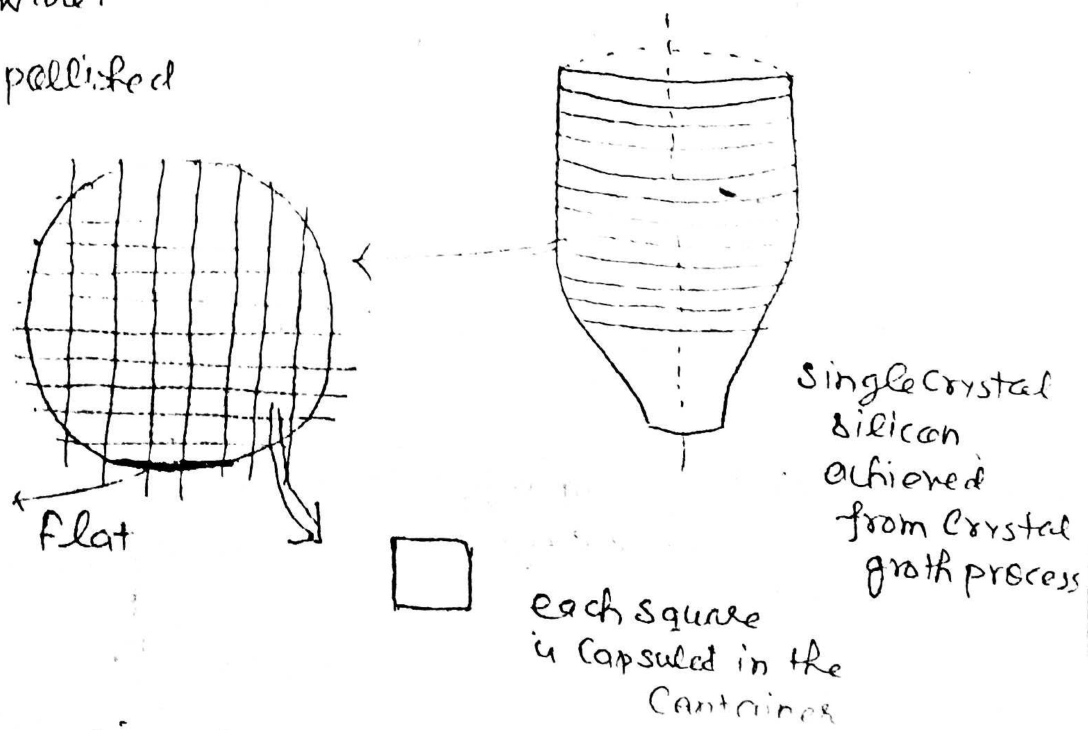


(a) Pellet of In in contact with N type Ge. (b) Molten phase of In & Ge mixture during heating (c) Crossection view of alloyed junction.

This process was used in the 1950 to produce diode and transistors. For example in the figure above, a sample of Ge can be heated with a pellet of In on it.

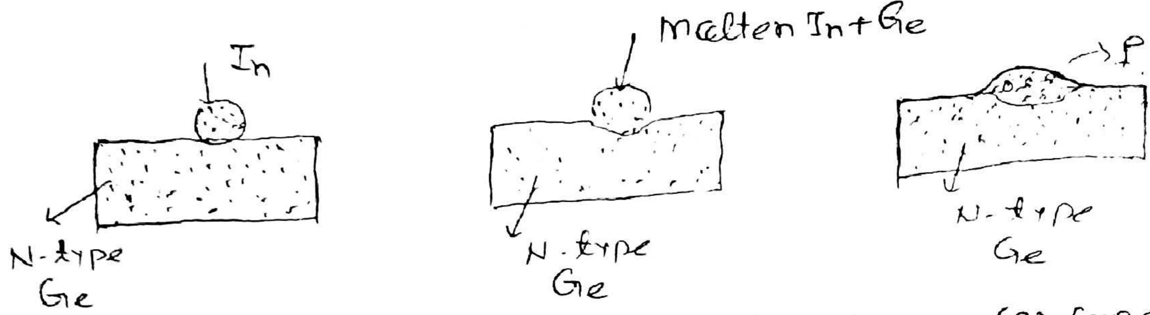
> **Diffused junctions :-** Diffused junctions are fabricated for IC technology purpose. In the IC fabrication technology.- After CZ process a single crystal Silicon is obtained in the form of Cylinder as shown in the figure. we cut it in equal sharp parts. Each part is circular and called Si-ware.

Now wafer is pollished and d and



To make diffused junctions photolithography ... used. photolithography process is a selective ... process to control junction Geometry.

__Alloyed junctions__ :- Alloyed junctions by using alloying technique. In this technique a metal is alloyed on a semiconductor with the so. opposite type of dopant.

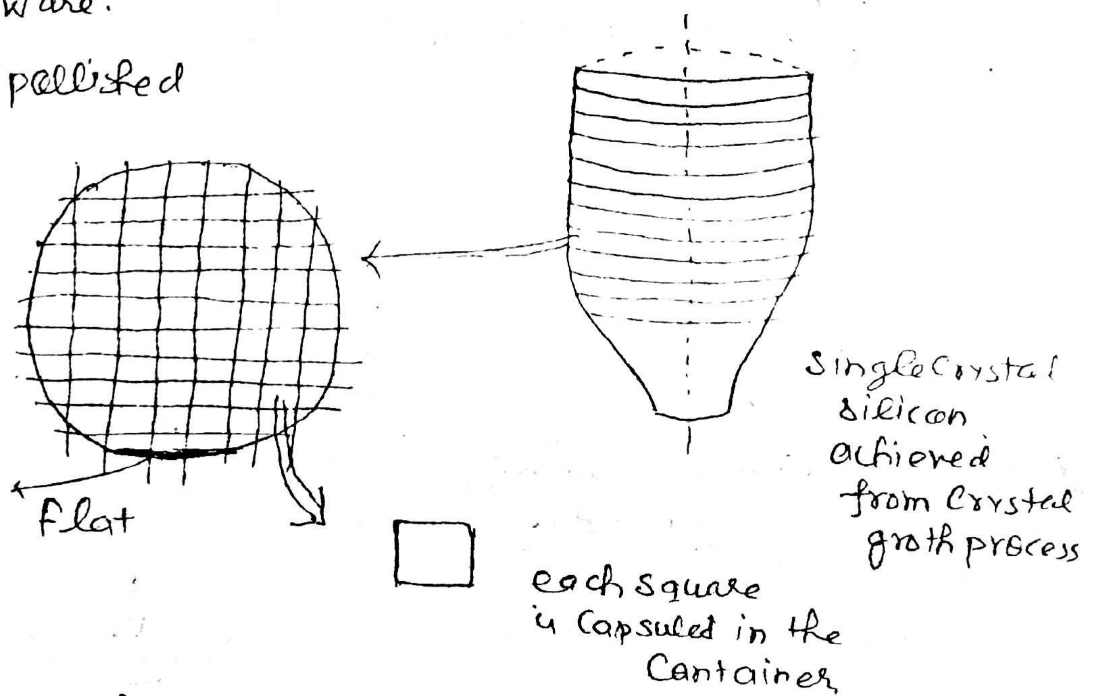


(a) Pellet of In in contact with n type Ge. (b) Molten phase of In & Ge mixture during Heating. (c) Crossection view of alloyed junction.

This process was used in the 1950 to produce diode and transistors. for example in the figure above, a sample of Ge can be heated with a pellet of In on it.

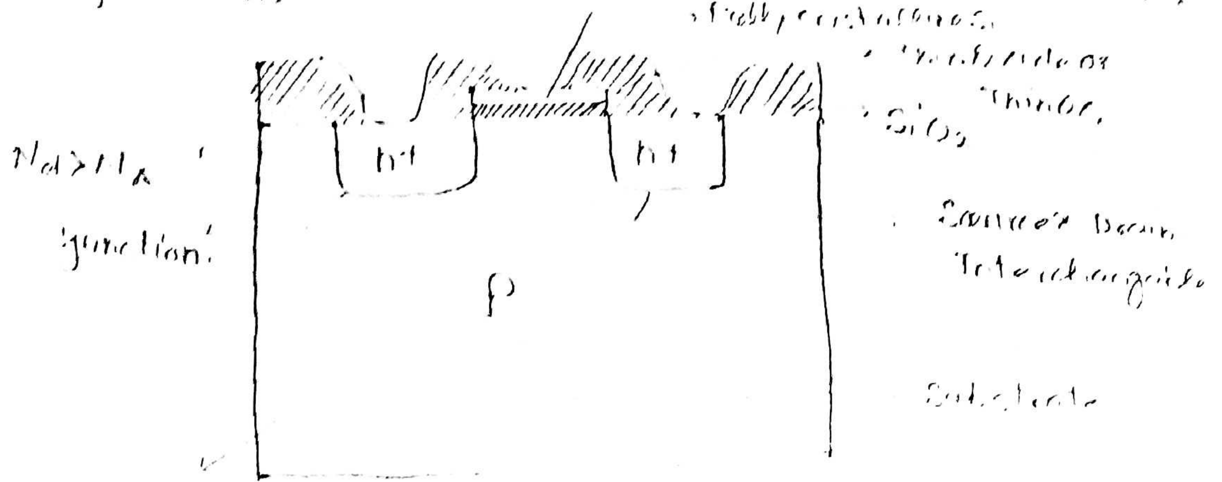
→ __Diffused junctions__ :- Diffused junctions are fabricated for IC technology purpose. In the IC fabrication technology.- After CZ process a single crystal silicon is obtained in the form of cylinder as shown in the figure. we cut it in equal shap parts. Each part is circular and called Si-ware.

New wafer is pollished and d and



To make diffused junctions photolithography process is used. photolithography process is a selective diffusion process to control junction Geometry

Figure shows structure of n-mos where junctions are diffused junctions.



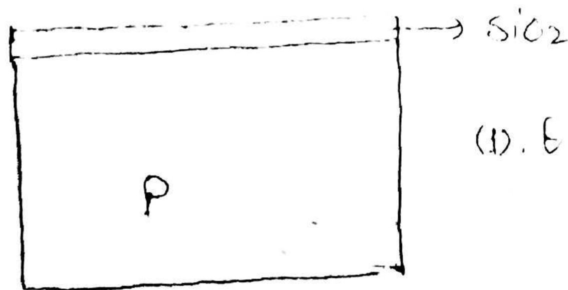
In this Region NA > ND

: Structure of n-mos :-

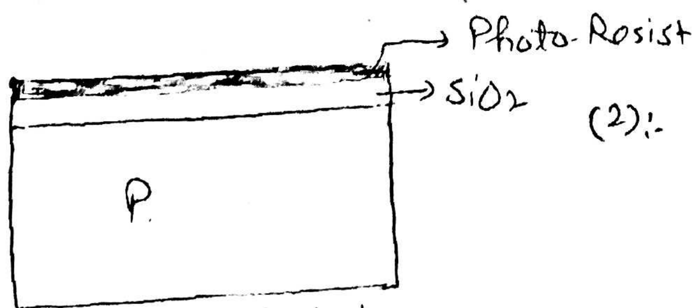
(actually cross section view of n-mos)

while 3 Diementional view of n-mos it looks as well.

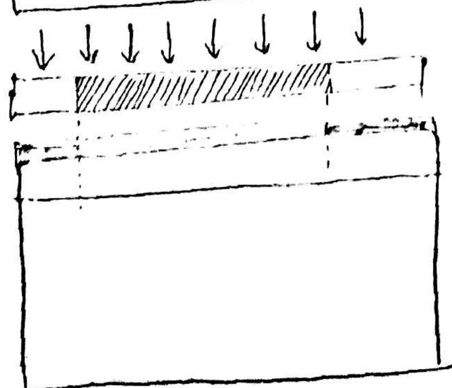
Making a n-mos following steps are used -



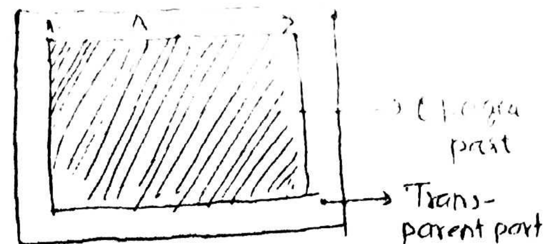
(1). Exidised Si Sample



(2):- Apply a Layer of Photoresist.



(3) :- Expose PR through Photomask A.



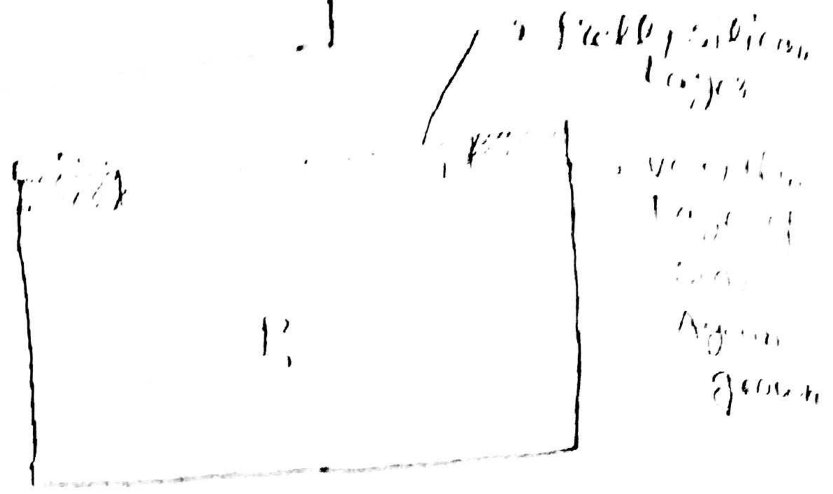
Glass Photomask

→ (Top view of Glass photomask)

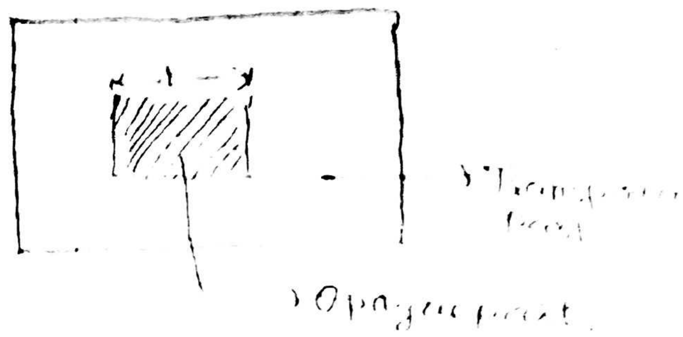
4. Opening of the window for diffusion.

5. polly silicon is coated using chemical vapour deposition.

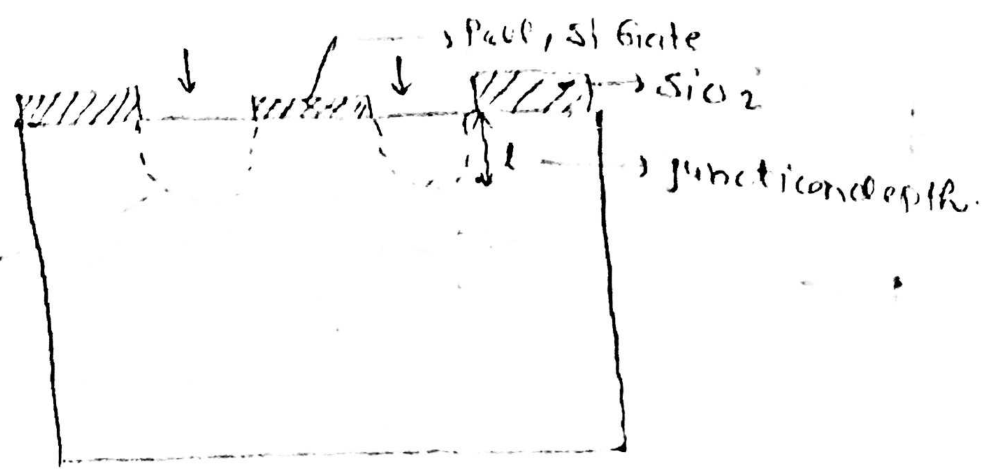
Pollysilicon is Gate layer.



6. After forming gate, Again making Mask and repeat all previous steps again



7.



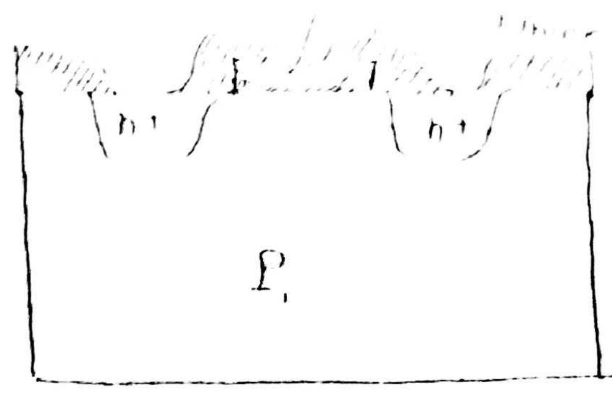
Now these two windows ↓ ↓ are ready to make n+ region.

The depth of junction depends upon following parameters →

Diffusion time,

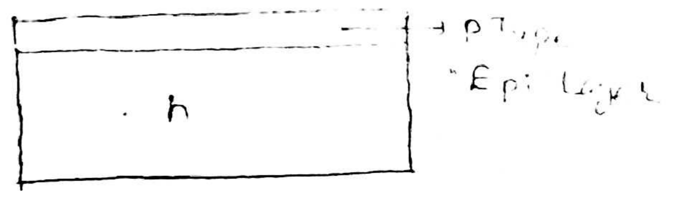
Pressure, and other parameters.

→ For making n+ regions, Ion implantation is used.

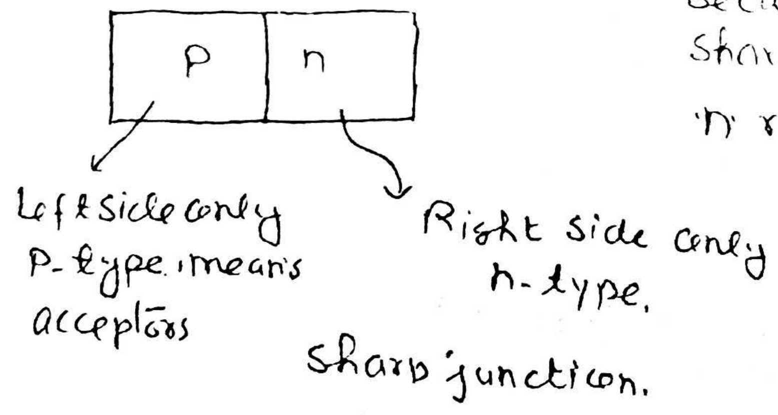


Depletion type.
n-MOS.

- **Epitaxyle Junction:** Epitaxyle junctions are formed by using epitaxy process. In the epitaxy process a layer is deposited by using chemical vapour deposition process. The epitaxyle layer sometimes called "epi" layer.



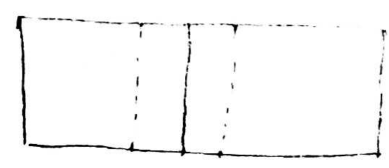
Epitaxyle junctions &
Alloyed junctions are modeled as ⇒ step junction
⇓
Because there is sharp 'P' region and 'n' region.



Sharp junction.

On other Hand, diffused junctions are called ⇒ Graded junctions
Because.

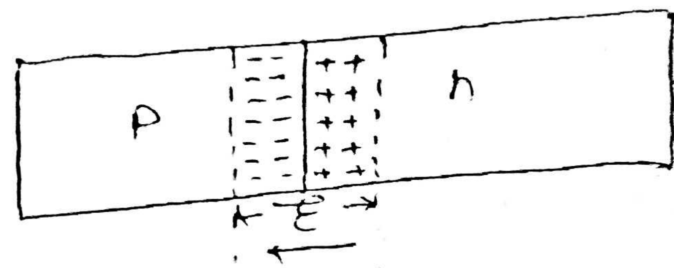
Na - Nd varies across the junction.

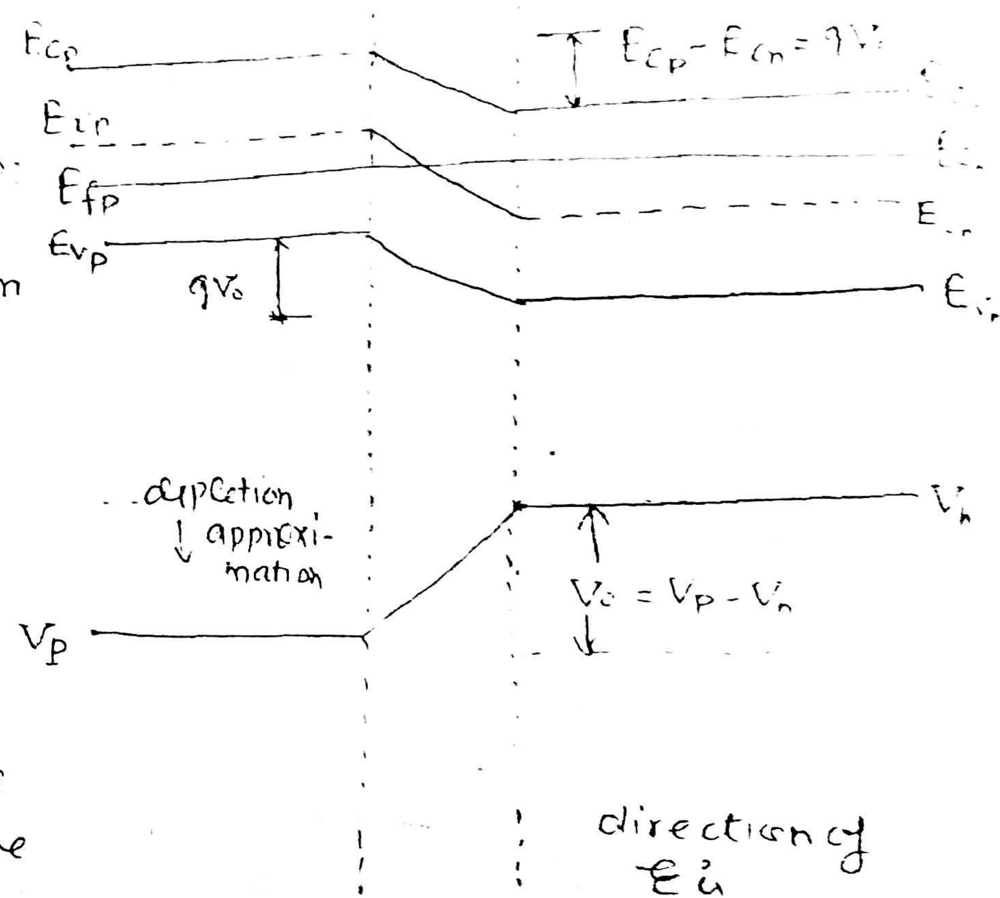


Na - Nd varies across the junction.

P-n. Junction:- [illegible] joined n type and p type then junction formed at Equilibrium. Equilibrium means no [illegible] at Equilibrium Fermi level at same energy level through the device.

As junction is formed diffusion of charge carriers starts in opposite region. Due to diffusion, depletion region or transition region is developed. Due to development of transition region an field $\mathcal{E}$ acting at junction. The direction of field is +ve to −ve side.





The pottential curve shows gradient in the Intrinsic level,

direction of $\mathcal{E}$ is Opposite to diffusion.

V_p = Occure due to diffused Acceptor.

V_n = Occure due to diffused donor.

&

$$\boxed{V_o = V_p - V_n}$$

V_o = Called Contact pottential

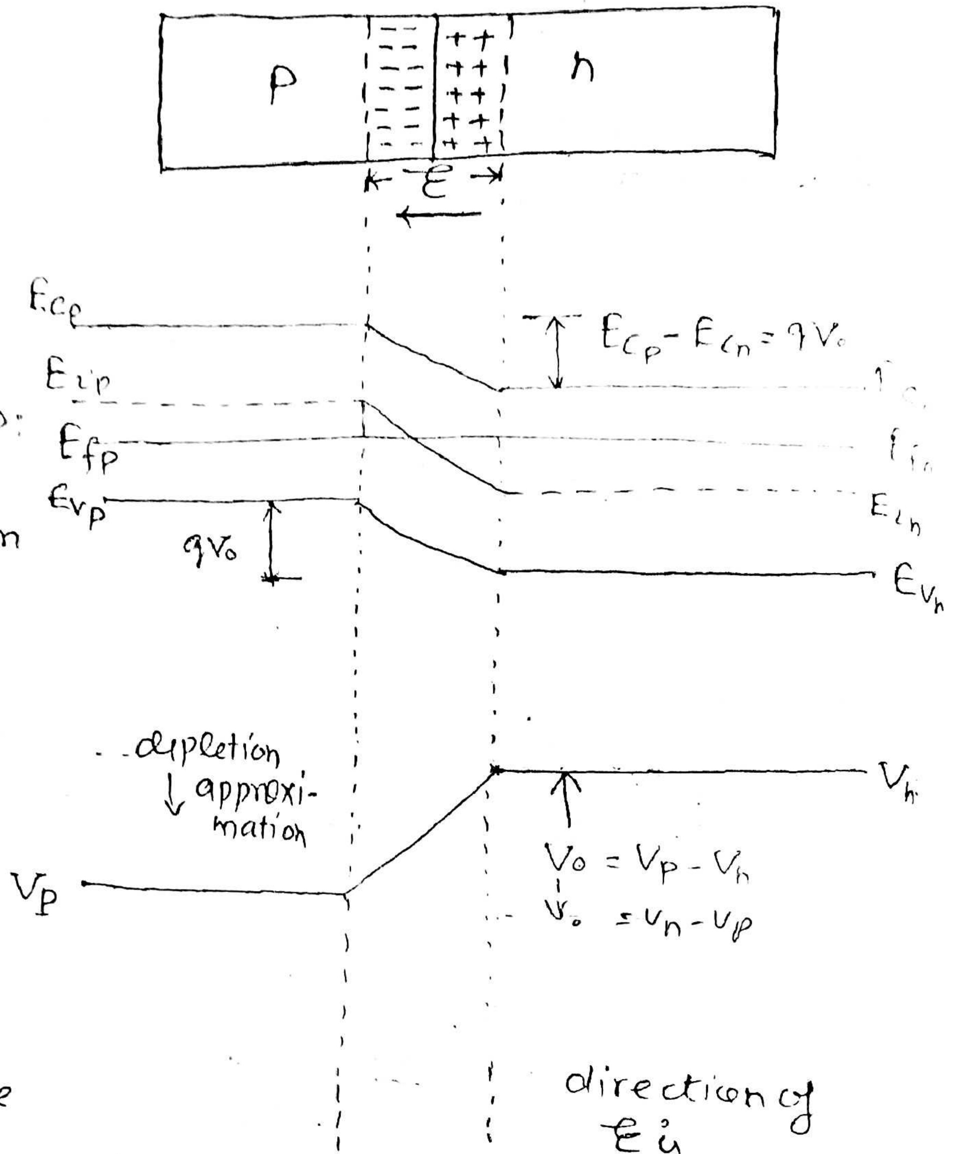
Following four terms are occure at Equilibrium —

→ 1. Hole diffusion.

→ 2. Hole drift

P-n. Junction:- Let us consider junction is step type. when joined p type and n-type then junction formed at Equilibrium. Equilibrium means no biasing. At Equilibrium Fermilevel at same energy level through the device.

As junction is formed diffusion of charge carriers starts in opposite region. Due to diffusion. Depletion region or transition region is developed. Due to development of transition region an field ε acting at junction. The direction of field is +ve to -ve side.



The pattential curve shows gradient in the Intrinsic level,

direction of ε is opposite to diffusion.

V_p = Occure due to diffused Acceptor.

V_n = Occure due to diffused donor.

&

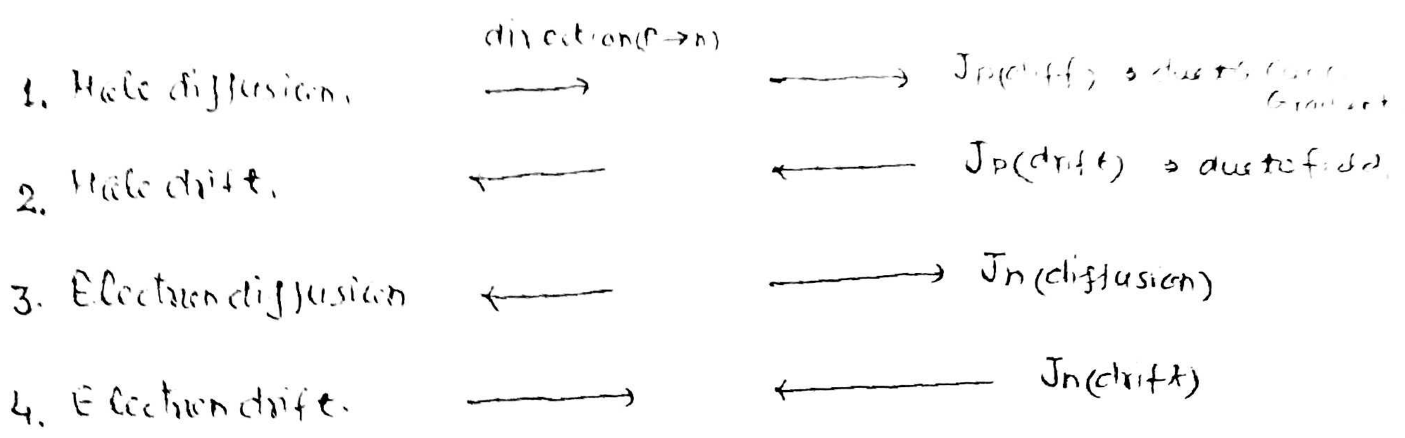
$$V_0 = V_p - V_n$$

V_0 = Called Contact pattential

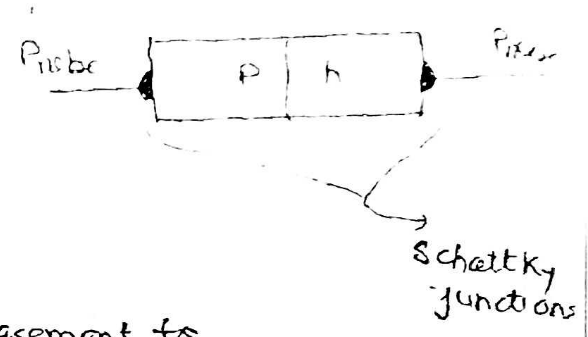
Fallowing four terms are occure at Equilibrium —

→ 1. Hole diffusion.

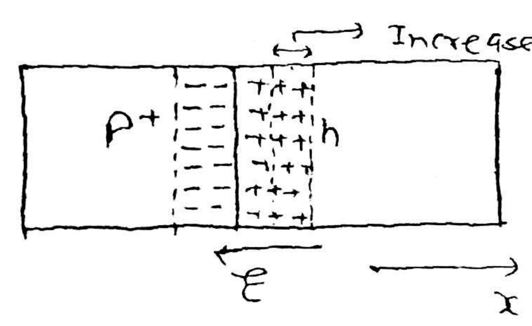
$J_{p(drift)} + J_{p(diffusion)} = 0$
$J_{n(diffusion)} + J_{n(drift)} = 0$
} at Equilibrium



Note:-1 The contact potential V_0 can not be measured because when we connected probs then schottky junctions are formed at the ends.



Note:-2:-



Now-

$$\mathcal{E} = -\frac{dV(x)}{dx}$$

field is opposite to direction of x.

→ Now we consider Hole current density at equilibrium-

$$J_{p(x)} = q\left[\mu_p P_{(x)} \mathcal{E}_{(x)} - D_p \frac{dP(x)}{dx}\right] = 0$$

(drift) (Diffusion.)

or. $\mu_p P_{(x)} \mathcal{E}_{(x)} = D_p \frac{dP_{(x)}}{dx}$

$$\frac{\mu_p}{D_p} * \mathcal{E}_{(x)} = \frac{1}{P_{(x)}} \cdot \frac{dP_{(x)}}{dx}$$

$\mathcal{E}_{(x)} = -\frac{d}{dx}V_{(x)}$

$\frac{\mu_p}{D_p} \cdot \frac{q}{KT} \cdot -\frac{d}{dx}V_{(x)} = \frac{1}{P_{(x)}}\frac{d}{dx}P_{(x)}$

$-\frac{q}{KT}\int_{V_p}^{V_n} dV = \int_{P_p}^{P_n} \frac{1}{P} dP$

Hence equation (i) becomes-

$$\frac{q}{kT} = -\frac{dV(x)}{dx} = \frac{1}{P(x)}\frac{dP(x)}{dx} \quad \text{--- (ii)}$$

Now integrating equation (ii) under the limits

$$-\frac{q}{kT}\int_{V_p}^{V_n} dV(x) = \int_{P_p}^{P_n} \frac{1}{P}\, dP$$

where, P_p = concentration in P region.

P_n = concentration in n region.

$$-\frac{q}{kT}(V_n - V_p) = \log P_n - \log P_p$$

$$= \log\frac{P_n}{P_p}$$

$$\therefore -\frac{q}{kT}(V_n - V_p) = \log\frac{P_n}{P_p}$$

$$\frac{q}{kT}(V_n - V_p) = \log\frac{P_p}{P_n}.$$

$$\frac{q}{kT}V_0 = \log\frac{P_p}{P_n}$$

$$\therefore \boxed{V_0 = \frac{KT}{q}\log\frac{P_p}{P_n}} \quad \text{--- (iii)}$$

P_p = Concentration in P region = N_a

P_n = n_i^2/N_d = Concentration in n-region.

$$\Rightarrow V_0 = \frac{kT}{q}\log\frac{N_a}{n_i^2/N_d}$$

$$= \frac{kT}{q}\log\frac{N_a N_d}{n_i^2}$$

$$\Rightarrow \boxed{V_0 = \frac{kT}{q}\log\frac{N_a N_d}{n_i^2}} \quad \text{--- (iv)}$$