A] PN Junction under Zero applied bias:

Conditions: Thermal equilibrium
(no currents exists, and
no external excitation is applied)

Aim: To find space-charge region width, electric field and potential through the depletion region and builtin voltage.

- Energy band diagram of a pn Junction in thermal equilibrium

(homo-junction)

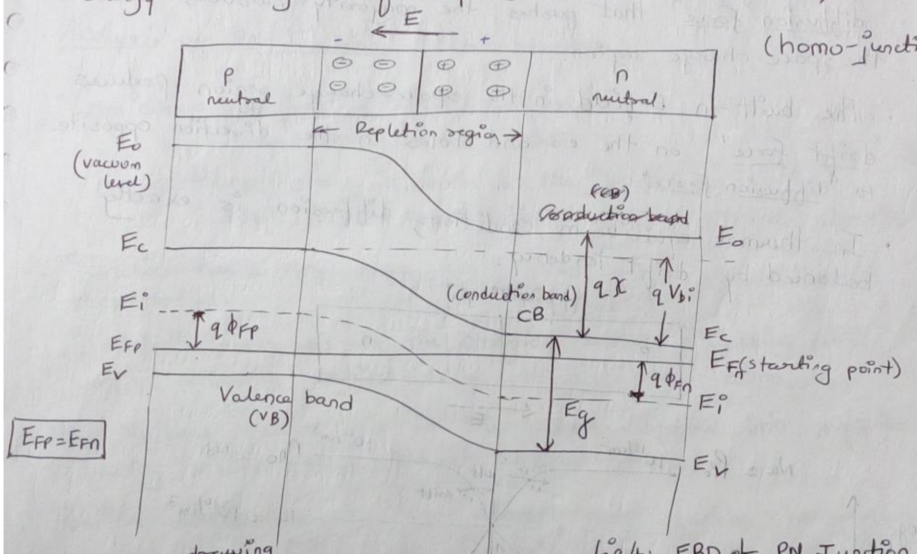


fig 4: EBD of PN Junction in thermal equilibrium

Steps for drawing EBD:

1) A constant E_F as a $f^n(x)$. (throughout the device).
2) Draw E_c and E_v, E_i for neutral n & p regions
3) E_c & E_v should have continuous variation in depletion layer.

E_c and E_v should be continuous, becoz energy gap is same in (homo-junctions.) ⟶ (both p and n are made of same material)

Explanation for fig(4) → [PN Junction under zero applied bias]

- Under no applied ap. voltage ~~a~~ across the pn junction, then pn junction is in thermal equilibrium.

  ⇒ Fermi energy level (E_F) is constant throughout the entire system.

- The CB and V.B energies must <u>bend</u> as we go through the space charge region, since the relative position of CB and V.B w.r.t Fermi energy (E_F) changes between p and n regions.

- → Electrons in the CB of n region see a <u>potential barrier</u> in trying to move into the CB of p region. This potential barrier is called 'build-in potential' (V_{bi}).

- V_{bi} is responsible for maintaining equilibrium betn majority carriers és in n-region and minority carrier és in p region, and also betn majority carrier holes in p region and minority carriers holes in the n regions.

- Note: The potential V_{bi} maintains equilibrium, so no current flows through the pn junction.

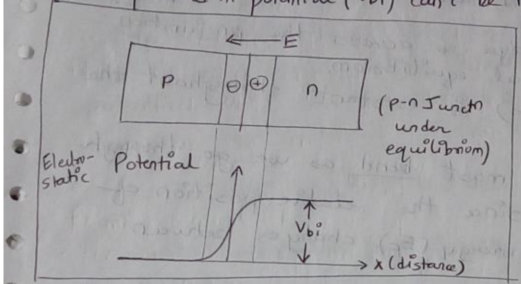
(V_{bi} ie built-in voltage of a p-n junction cannot be measured by with a voltmeter) → (becoz new potential barriers will be formed between probes and the Semiconductor that will cancel V_{bi})

Any content in brackets ( ) in given text is just for understanding.

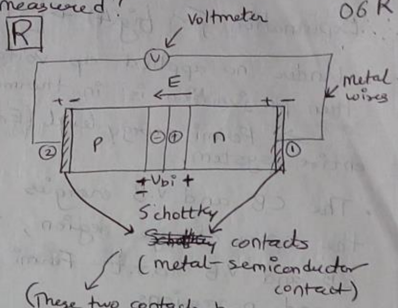
Next: Derivation for V_{bi}

--- Contd in Page (07)

Q. Why build-in potential (V_{bi}) can't be measured? 06 R



R

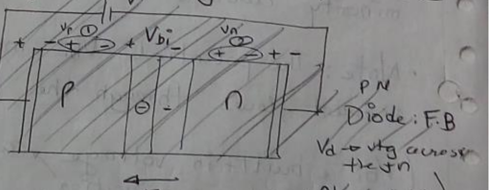


(These two contacts have build in voltages which will together oppose, V_{bi}, thus u get zero current)

. What happens to V_{bi}, will it come across Ⓥ ? → It does not becoz:-

. Moment you want to connect Ⓥ to PN Junction, we are using metal wires here,

Now, what is going to happen is that there is going to be build-in potential between ① & n type and ② metal wire and p type SC. Now, these built-in voltages which are coming across these two metal-SC junctn, which cancel the V_{bi} across PN Junction and overall in the device, u will get zero voltage. Thus, across Ⓥ no voltage will appear.



. Misconcept: (or over-exaggerated statement)

(Whenever applied voltage across the pn junction diode is more than built-in voltage (V_{bi}), then current starts flowing? (Absolutely wrong))

Becoz, if you go on ↑sing applied voltage (V), please note that V_d will always remain less than V_{bi} ($V_d < V_{bi}$).

If V goes on ↑sing, extra voltage beyond V_{bi}, is going to drop (V_p ① & V_n ②) here. in diagm above.

So, built-in voltage can never be washed out by externally applied voltage.

Derivation for built-in potential of a pn junction:

- The intrinsic Fermi level (E_i), is equidistant from the CB edge through the junction, → thus the built-in potential (V_{bi}) can be determined as the difference between the intrinsic Fermi levels in the p and n regions — ① (Refer fig 4)

$$\therefore \quad V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|$$

- The electron concentration (n_o) in the CB for the n-region is given by,

$$n_o = N_C \exp\left[-\frac{(E_C - E_F)}{KT}\right]$$

$$\text{Also, } n_o = n_i \exp\left[\frac{E_F - E_i}{KT}\right] \quad — ②$$

where, n_i and E_i are intrinsic carrier concentration & the intrinsic Fermi energy.

In n-region, the potential ϕ_{Fn} → (Fermi-potential) is

$$q\phi_{Fn} = E_{in} - E_F \quad — ③$$

Equation ② can be written as (using ③ in ②)

$$n_o = n_i \exp\left[\frac{-q\phi_{Fn}}{KT}\right] \quad — ④$$

$$\text{ie} \quad \phi_{Fn} = -\frac{KT}{q} \ln\left[\frac{n_o}{n_i}\right] \quad — ⑤$$

→ (By taking natural log on both sides of eqn ④)

Putting $n_o \simeq N_d$ (donor concentration) in n-region,

$$\boxed{\phi_{Fn} = -\frac{KT}{q} \ln\left[\frac{N_d}{n_i}\right]} \quad — ⑥$$

Similarly, in the p region, hole concentration (p_o) in the V.B is given by, ($p_o \approx N_a$)

$$p_o \approx N_a = n_i \exp\left[\frac{E_i - E_F}{KT}\right] \quad — ⑦$$

N_a → acceptor impurity concentration,

Fermi potential (ϕ_{FP}) in p-region is defined as,

$$q\phi_{FP} = E_{i_p} - E_F \quad — ⑧$$

Combining ⑦ and ⑧, we get

$$N_a = n_i \exp\left[\frac{q\phi_{FP}}{KT}\right]$$

$$\Rightarrow \boxed{\phi_{FP} = \frac{KT}{q} \ln\left[\frac{N_a}{n_i}\right]} \quad — ⑨$$

Now, since $V_{bi} = |\phi_{Fn}| + |\phi_{FP}|$ (From ⑥ and ⑨), we get.

$$V_{bi} = \frac{KT}{q} \ln\left[\frac{N_d}{n_i}\right] + \frac{KT}{q} \ln\left[\frac{N_a}{n_i}\right]$$

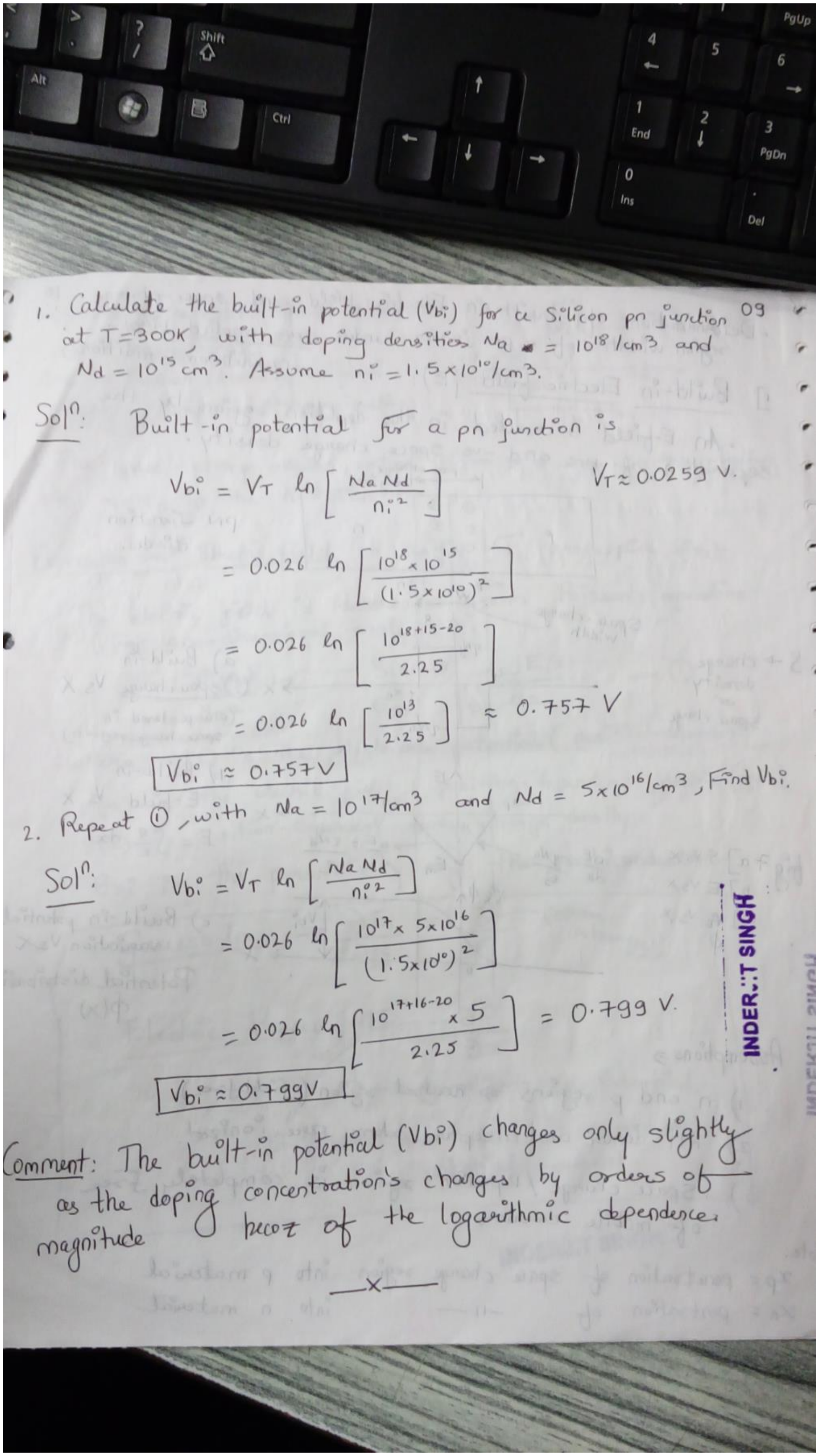
$$= \frac{KT}{q} \ln\left[\frac{N_a N_d}{n_i^2}\right]$$

$$\boxed{V_{bi} = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right]}$$ → Expression for built-in potential (V_{bi}) for an abrupt pn junction.

where, $V_T = \frac{KT}{q}$ → Thermal voltage

$V_T = 0.026 \approx 26\,mV$ at $T = 300K$ (Room temperature)

∴ N_a and N_d denote the net acceptor and donor concentration in the p and n regions.



1. Calculate the built-in potential (V_{bi}) for a Silicon pn junction at $T=300K$, with doping densities $N_a = 10^{18}/cm^3$ and $N_d = 10^{15} cm^3$. Assume $n_i = 1.5\times10^{10}/cm^3$. 09

Sol^n: Built-in potential for a pn junction is

$$V_{bi} = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right] \qquad V_T \approx 0.0259 \text{ V.}$$

$$= 0.026 \ln\left[\frac{10^{18}\times10^{15}}{(1.5\times10^{10})^2}\right]$$

$$= 0.026 \ln\left[\frac{10^{18+15-20}}{2.25}\right]$$

$$= 0.026 \ln\left[\frac{10^{13}}{2.25}\right] \approx 0.757 \text{ V}$$

$$\boxed{V_{bi} \approx 0.757V}$$

2. Repeat ①, with $N_a = 10^{17}/cm^3$ and $N_d = 5\times10^{16}/cm^3$, Find V_{bi}.

Sol^n:

$$V_{bi} = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right]$$

$$= 0.026 \ln\left[\frac{10^{17}\times 5\times10^{16}}{(1.5\times10^{10})^2}\right]$$

$$= 0.026 \ln\left[\frac{10^{17+16-20}\times 5}{2.25}\right] = 0.799 \text{ V.}$$

$$\boxed{V_{bi} \approx 0.799V}$$

Comment: The built-in potential (V_{bi}) changes only slightly as the doping concentration's changes by orders of magnitude becoz of the logarithmic dependence.

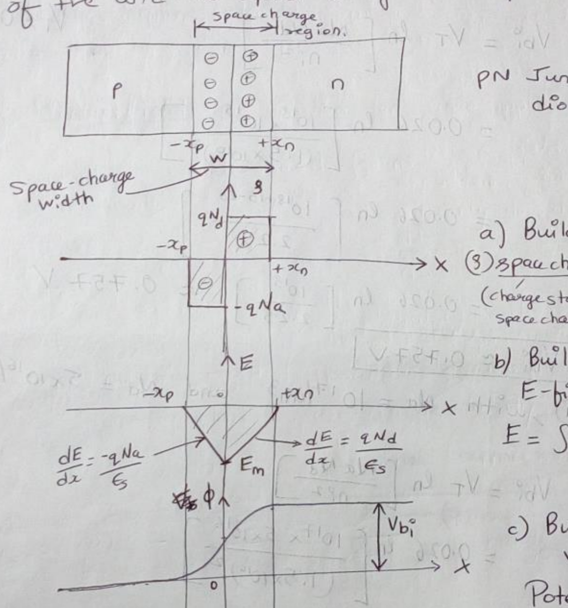
—x—

- Determination of built-in Electric field and space-charge region width of a pn junction under <u>zero applied bias</u>:- (equilibrium conditions)

1] Build-in Electric field: (E):

- An E-field is created in the depletion region by the separation of +ve and -ve space charge density.

ρ → charge density or space-charge.



PN Junction diode.

a) Build-in (ρ) space charge Vs X (charge stored in space charge region)

b) Build-in E-field Vs X

$E = \int \frac{\rho}{\epsilon} dx$

c) Build-in potential variation Vs X. Potential distribution $\phi(x)$

fig 7 a] ρ Vs X
b] E Vs X
c] ϕ Vs X

Assumptions ⇒

1) n and p regions ⇒ neutral region (field free)
2) All donor and acceptor atoms are ionized.
3) Space charge / Depletion region is completely free of mobile carriers.

Note:
x_p = penetration of space charge region into p material.
x_n = pentration of —"— into n material.