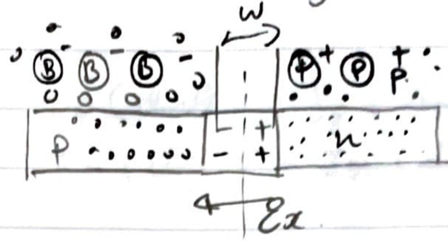
① Chapter 5 - Junctions

- Let consider: separate p & n type semiconductors brought together to form a junction.



<u>Note</u>: * diffusion only happens very close to the junction.
∴ Electron (from n-type) recombine with holes in the p-type.

- Before joining the n-material has a large number of electron concentration & few holes
(p-type vice versa).

* Upon joining we expect diffusion to occur due to the difference in gradient
∴ holes diffuse from the p side into the n-side.
& electrons diffuse from n- to p.

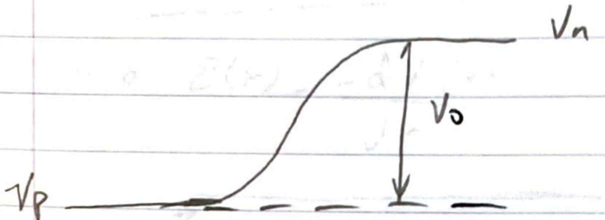
* The resulting diffusion current cannot be built up indefinetly however,
because an opposing electric field is created at the junction.
* <u>Note</u>: Not similar to gases diffusion, because of the development of space charges & the electric field $\mathcal{E}$

*? - Consider that electron diffusion from n → p leave behind uncompensated donor ions (N_d^+) in the n-material
& holes leaving behind uncompensated acceptors (N_a^-)
∴ development of positive space charge near the n-side of junction & negative space charge near the p-side of junction.
∴ Electric field from n-to-p. ∴ direction opposite of diffusion current for each type of carrier.

Since we know no net current can flow accross the junction at equillibrium, the current due to the drift of carriers in the $\mathcal{E}$ field must exactly cancell the diffusion current

$$\therefore J_p(\text{drift}) + J_p(\text{diff.}) = 0$$
$$J_n(\text{drift}) + J_n(\text{diff}) = 0$$

- At region W an electric field appears & there is an equillibrium potential difference accross V_0 accross W



Electrostatic potential.

=> there is gradient in potential in the direction opposite to $\mathcal{E}$. in accordance to fundamental relation ($\mathcal{E}(x)$)

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

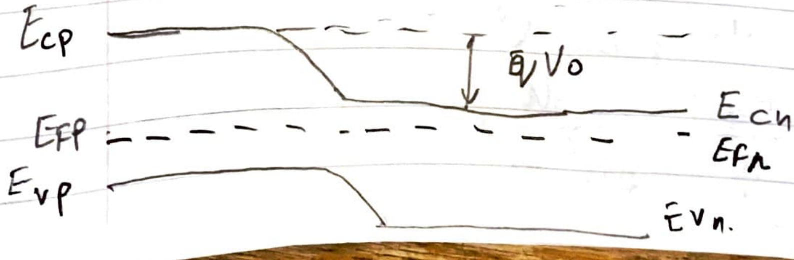
(*) Assume electric field is ϕ outside W.

$\therefore$ - Constant potential V_n in neutral n-material
- Constant potential V_p in neutral p-material.

(=) Potential difference => $\boxed{V_0 = V_n - V_p}$

- region W is called transition region
- potential difference V_0 is called contact potential
(*) ↳ Built in potential barrier → necessary to maintain equillibrium conditions ; Does NOT imply external potential.
↳ cannot be measured with voltmeter. because new contact potentials are formed at each probe → cancelling V_0.

(*)



- To obtain a relationship between V_0 & the doping concentration on each side of the junction:

- At equillibrium: (diffusion &

$$J_p(x) = q\left[\mu_p\, p(x)\, \mathcal{E}(x) - D_p \frac{dp(x)}{dx}\right] = 0$$

Rearrange:

$$\boxed{\frac{\mu_p}{D_p}}\ \mathcal{E}(x) = \frac{1}{p(x)} \frac{dp(x)}{dx}$$ where x-direction is from $p \to n$.

→ Einstein's relationship.

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

$$\Rightarrow \boxed{\frac{-q}{kT}} \frac{dV(x)}{dx} = \frac{1}{p(x)} \frac{dp(x)}{dx}$$

→ This equation can be solved by integration over the appropriate limits

$$\therefore \frac{-q}{kT} \int_{V_p}^{V_n} dV = \int_{P_p}^{P_n} \frac{1}{P}\, dp$$

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

$$\therefore \frac{-q}{kT}(V_0) = \ln \frac{P_n}{P_p} \Rightarrow V_0 = \frac{kT}{q} \ln \frac{P_p}{P_n}.$$

If we consider the step junction be made up of material with N_a (acceptors/cm³) on p-side & N_d donors on n-side

$$V_0 = \frac{kT}{q} \ln \frac{N_a}{n_i^2/N_d} = \boxed{\frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}}$$

Another useful equation is

$$\frac{P_p}{P_n} = e^{qV_0/kT}$$

By considering equilibrium conditions $P_p n_p = n_i^2 = P_n n_n$

$$\frac{P_p}{P_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$$ → valuable in the calculation of I-V characteristics.

Example

Si p-n junction has $N_a = 10^{18}\ cm^{-3}$ on one side & $N_d = 5 \times 10^{15}\ cm^{-3}$

a) Fermi level at 300K

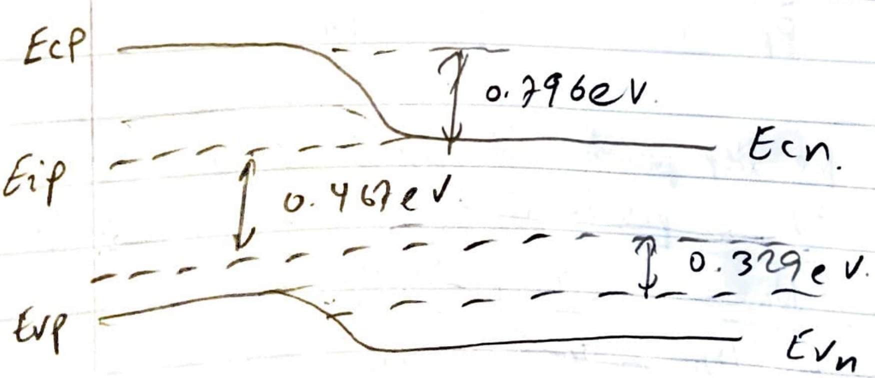
$$E_{ip} - E_F = kT \ln \frac{P_p}{n_i} = 0.0259 \ln \left(\frac{10^{18}}{1.5 \times 10^{10}}\right) = 0.467\ eV$$

$$E_F - E_{in} = kT \ln \frac{n_n}{n_i} = 0.0259 \ln \left(\frac{5 \times 10^{15}}{1.5 \times 10^{10}}\right) = 0.329\ eV$$

b) Band diagram & V_0

$$qV_0 = 0.467 + 0.329 = 0.796\ eV.$$

(c) $$qV_0 = kT \ln \frac{N_a N_d}{n_i^2} = 0.0259 \ln \left(\frac{5 \times 10^{33}}{2.25 \times 10^{20}}\right) = 0.796\ eV$$



- Equillibrium Fermi-levels

- Fermi levels must be constant throughout the device at equillibrium

$$\therefore \frac{p_p}{p_n} = e^{qV_0/kT} = \frac{N_v e^{-(E_{Fp} - E_{vp})/kT}}{N_v e^{-(E_{Fn} - E_{vn})/kT}}$$

$$e^{qV_0/kT} = e^{(E_{Fn} - E_{Fp})/kT} e^{(E_{vp} - E_{vn})/kT}$$

$$qV_0 = E_{vp} - E_{vn}.$$

- Fermi levels & valence bands energies are written with subscripts to indicate p-side & n-side of the junction

⇒ When biased is applied to the junction, the potential barrier is raised or lowered from the value of the contact potential & Fermi levels are shifted with respect to each other by an energy in (eV) equal to applied voltage in (V.)

Space Charge at a Junction

- Some electrons diffuse from $n \to p$
- Some are swept by the electric field from $p \to n$.
  ↳ however, very few carriers within the transition region at any given time.
  Forming depletion region

Since the dipole about the junction must have an equal number of charges on either side. ($Q+ = |Q-|$.)

- For a sample of cross sectional area A, the total uncompensated charge on either side of junction is:

$$qAx_{po}N_a = qAx_{no}N_d$$

where $x_{po} \to$ penetration of the space charge region into the p-material.
& $x_{no} \to$ penetration into n

Total width of the transition region (W) is the sum.

Poisson's equation

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon}\left(p - n + N_d^+ - N_a^-\right)$$ Relates the gradient of electric field to the local charge.

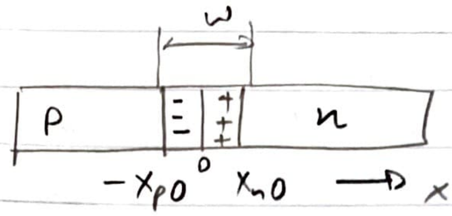
i.e.

$$\frac{d\mathcal{E}(x)}{dx} = \frac{q}{\epsilon}N_d \qquad 0 < x < x_{no}$$

$$\frac{d\mathcal{E}}{dx} = \frac{q}{\epsilon}N_a \qquad 0 < x < x_{po}.$$

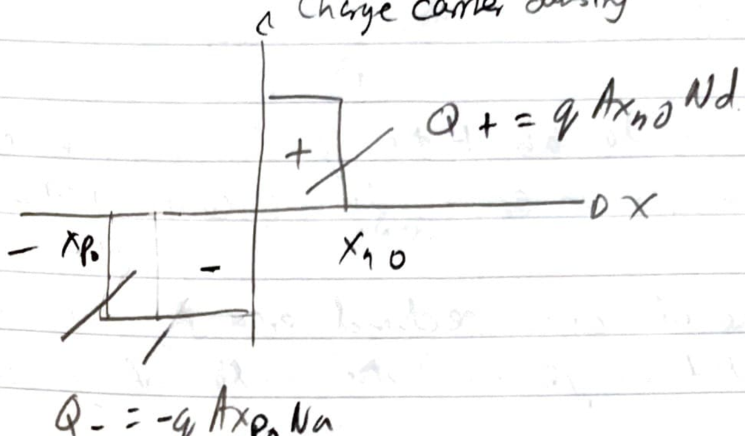
Assuming complete ionisation $(N_d^+ = N_d \ \& \ N_a^- = N_a)$

a)

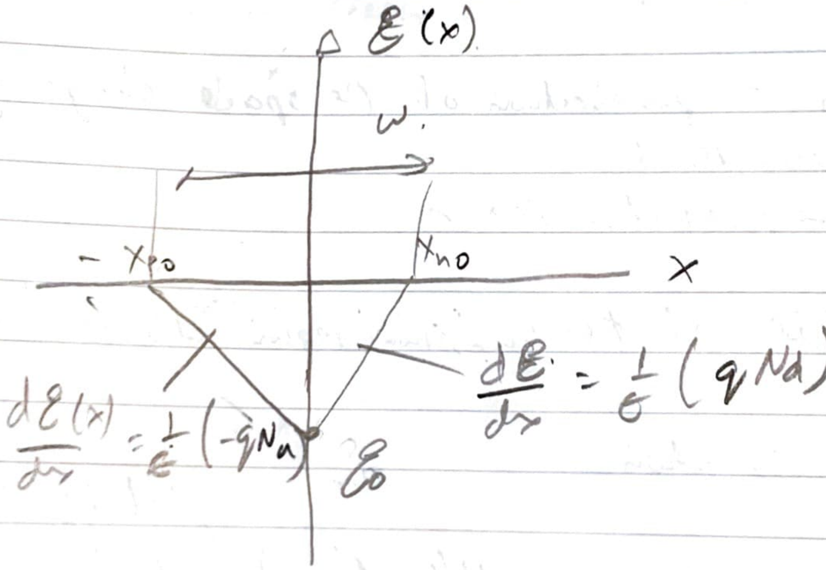


; $N_d > N_a$

(b)



(c)



- Value of $\mathcal{E}_0$ can be found by integrating:

$$\int_{\mathcal{E}_0}^{0} d\mathcal{E} = \frac{q}{\epsilon} N_d \int_{0}^{x_{n0}} dx \qquad 0 < x < x_{n0}$$

$$\int_{0}^{\mathcal{E}_0} d\mathcal{E} = \frac{-q}{\epsilon} N_a \int_{-x_{p0}}^{0} dx \qquad -x_{p0} < x < 0$$

- The maximum value of the electric field

$$\mathcal{E}_0 = \frac{-q}{\epsilon} N_d x_{n0} = \frac{-q}{\epsilon} N_a x_{p0}$$

- Relationship between electric field $\mathcal{E}$ contact V_0 since the $\mathcal{E}$ field at any x is the negative of the potential gradient at that point

$$\mathcal{E}(x) = -\frac{dV(x)}{dx} \quad \text{or} \quad V_0 = \int_{-x_{p0}}^{x_{n0}} \mathcal{E}(x)\, dx$$

Thus the negative of the contact potential is simply the area under the $\mathcal{E}(x)$ vs x. triangle.

$$V_0 = -\frac{1}{2} \mathcal{E}_0 W = \frac{1}{2} \frac{q}{\epsilon} N_d x_{n0} W$$

Since the balance of charge is $x_{n0} N_d = x_{p0} N_a$.
we can write $x_{n0} = W N_a / (N_a + N_d)$

$$V_0 = \frac{1}{2} \frac{q}{\epsilon} \frac{N_a N_d}{N_a + N_d} W^2$$

· By solving for W.

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

w/in terms of doping concentrations.

$$W = \left[\frac{2\epsilon kT}{q^2}\left(\ln \frac{N_a N_d}{n_i^2}\right)\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

penetration of the transition region into the n & p material.

$$x_{p0} = \frac{W N_d}{N_a + N_d} = \frac{W}{1 + N_a/N_d} = \left\{\frac{2\epsilon V_0}{q}\left[\frac{N_d}{N_a(N_a + N_d)}\right]\right\}^{1/2}$$

$$x_{n0} = \frac{W N_a}{N_a + N_d} = \frac{W}{1 + N_d/N_a} = \left\{\frac{2\epsilon V_0}{q}\left[\frac{N_a}{N_d(N_a + N_d)}\right]\right\}^{1/2}$$

As expected transition region extends further into the side with the lighter doping.

(+) pg 169 Example 5-2 (X)

• The electric field can be deduced from the potential barrier.

- Forward Bias → electric field decreases ; opposes the built-in-field.
- Reverse Bias → electric field increases ; same direction as the equilibrium field

• ΔE → change in the transition region width (W)

• Seperation of the energy bands is a direct function of the electrostatic potential barrier junction.

• For forward bias → barrier is lowered to ($V_0 - V_f$) ∴ more electrons can diffused ∴ Diffusion current ↑↑.

• For reverse bias → Barrier ↑↑ ($V_0 + V_r$) ∴ virtually no electrons can diffuse ∴ → diffusion current is negligible.

• Drift current is insensitive to the height of the potential barrier.

↳ Drift current is limited not by how fast carriers are swept down the barrier, but rather how often

Minority charge carriers will be swept down the barrier by E field.

eg: ↳ Every electron will be swept regardless of the height.

• Supply of minority charge carriers on each side of the junction required to participate in the drift components are generated by thermal excitation of EHP

↳

• Generation current → Resulting current of Electrons being swept down the barrier ; since magnitude is dependend on the rate of generation of EHP

Forward & Reverse Biased junctions at steady state

- Current flows easily from p to n when p is connected to a positive external voltage bias relative to n. → forward bias (forward current)
- No current flows when p is made negative relative to n → reverse bias. (reverse current)

↳ This assymetry of current flow → useful as rectifier

- Description of Current Flow at a Junction

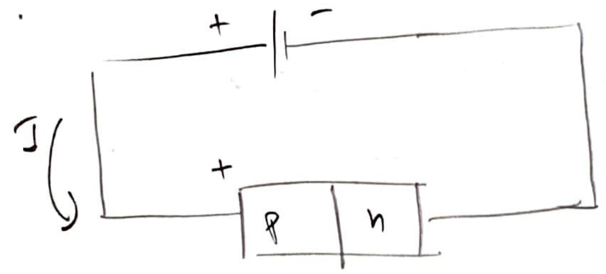
- Since an applied voltage changes the electrostatic potential barrier and therefore the electric field within the transition region.
  - Seperation of the energy bands } are also affected
  - Width of depletion region

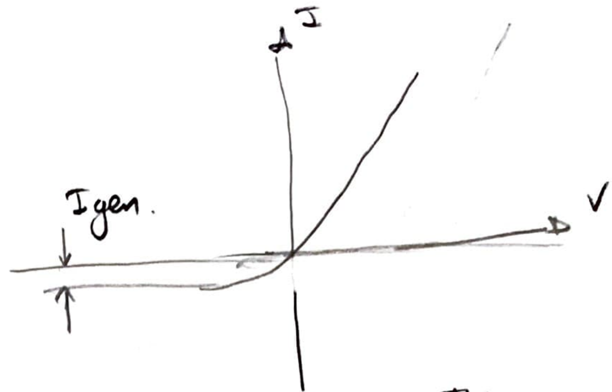
- The electrostatic potential barrier at the junction is lowered by forward bias V_f from equillibrium contact potential V_0 → $(V_0 - V_f)$
  ↳ This is because a forward bias raises the electrostatic potential on the p-side relative to the n-side.
  - For reverse bias $(V = -V_r)$ the opposite occurs.
  ↳ Electrostatic potential of the p-side is depressed relative to the n-side
  ∴ potential barrier at junction becomes larger $(V_0 + V_r)$

· Total current = Diff current + Drift current.

↳ Reverse bias : Diffusion current is small. because of large barrier at the junction, only current generated is small. from $n \to p$.

(A).





· Small current (I gen) due to carriers generated in the transistion region or minority carries which diffuse to the junction and are collected.

Current At V=0 is ϕ since generation & diffusion current cancell out.

$$I = I(\text{diff}) - |(I_{gen})| = 0 \quad \text{for } V=0$$

• For forward bias.

↳ increases the probability that a carriers can diffuse accross the junction by a factor of (qV_f/kT).

• Since equilibrium diffusion current = |Igen|

∴ Total current = Diffusion current − absolute value of Igen. (Io)

$$\Rightarrow \boxed{I = I_o\left(e^{qV/kT} - 1\right)}$$

→ When kT/q is positive & greater. → I increases exponentially.

→ When V is negative (reverse bias). → exponential approaches ∅

& $(-I_o)$ which is the n to p direction.

↳ negative generation current is also called reverse-saturation current

Doping In Semiconductors