Semiconductor:

Carrier: e^-: electrons and h: holes.

$$n_p \cdot n_e = n_i^2$$

Diffusion current:

Current from high density to low density

Drift current:

Current because of a electric field.

p-type Semiconductor:

Doping Si ~~with~~ with group 13 elements

Majority carrier: hole.

Minority carrier: electron

Doping strength: N_A.

$$n_p \approx N_A \cdot \quad n_e = \frac{n_i^2}{N_A}.$$

n-type Semiconductor:

Doping Si with group 15 elements

Majority carrier: electron

Minority carrier: hole

Doping strength: N_D

$$n_e \approx N_D, \quad n_p = \frac{n_i^2}{N_D}$$

Drift current in a semiconductor:

For a field 'E' present in a semiconductor

$$v_{drift} = \mu \cdot E \qquad (\mu: \text{mobility})$$

$$I = A \cdot q \cdot [p \cdot v_{d,p} + n \cdot v_{d,n}]$$

(p, n: conc of holes and e^- respectively)

$$I = A \cdot qE \, [\mu_p \cdot p + \mu_n \cdot n]$$

$\Rightarrow$ $I = A \cdot \sigma \cdot E.$

$\Rightarrow$ Conductivity (σ): $q(p \cdot \mu_p + n \cdot \mu_n)$.

Resistivity (ρ): $\dfrac{1}{q(p \cdot \mu_p + n \cdot \mu_n)} = \dfrac{E}{J}$

Diffusion Current:

$$J_p = q D_p \frac{dp(x)}{d(x)} \qquad \text{(for holes)}.$$

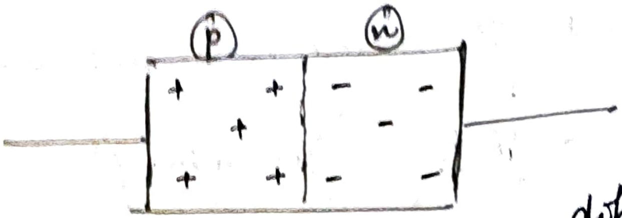
D_p: diffusion constant.

$$I_p = A q D_p \frac{d}{dx} p(x).$$

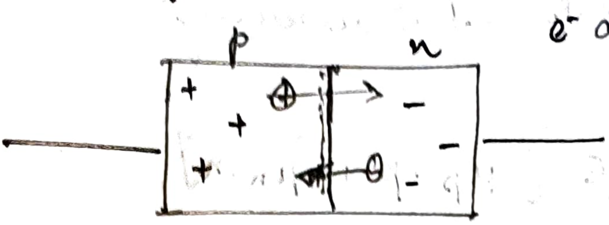
$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T \qquad \text{(Thermal voltage)}$$

$$\left[V_T = \frac{kT}{q} \right]$$

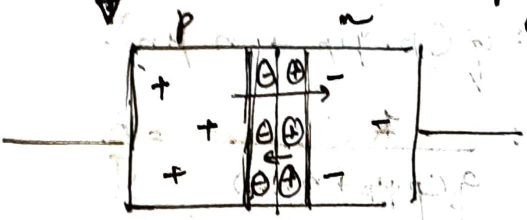
p-n Junction:



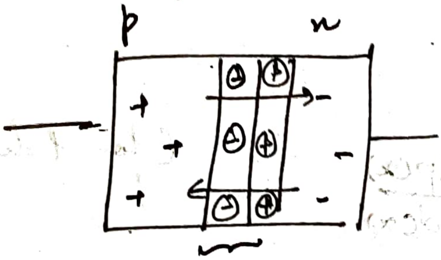
diffusion current.
holes diffuse from
p → n
e^- diffuse from n → p



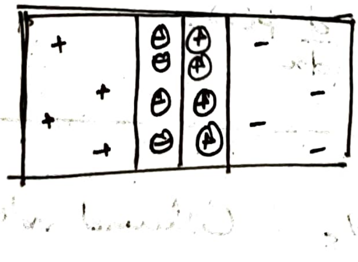
minority carriers merge and form an electric field, causing drift current.

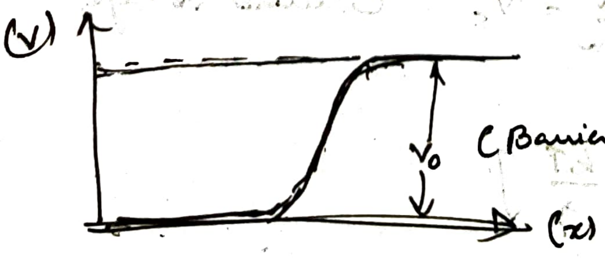


An equilibrium between drift and diffusion current is achieved.



depletion region.





(Barrier voltage)

Barrier Voltage:

$$V_0 = V_T \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$

$\Rightarrow$ V_0 depends on both temperature and doping concentration

Width of ~~charge in~~ depletion layer:

$$x_p \cdot N_A = x_n \cdot N_D.$$

$$\Rightarrow \quad \frac{x_p}{x_n} = \frac{N_D}{N_A} = \frac{p_n}{n_p}.$$

Current Voltage relationship of junction:

$$p_n(x_n) = p_{no} \cdot e^{V/V_T}$$

(where p_{no} = value when $V=0$)

$\Rightarrow$ Excess concentration = $p_{no}(e^{V/V_T} - 1)$

$\Rightarrow$ Total Concentration:

$$p_{no}\left[1 + (e^{V/V_T} - 1)\, e^{-\frac{(x-x_n)}{L_p}}\right]$$

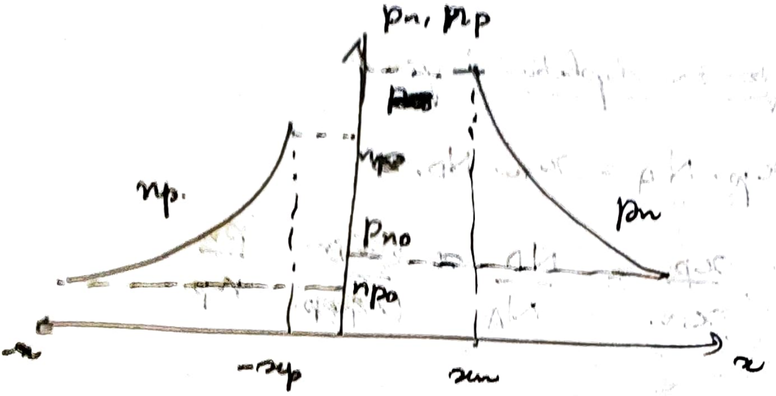
L_p: diffusion length

[This is specific for hole conc. in n-type.
We can get similar result for e^- in p-type]

We know diffusion current density,

$$J_p(x) = -q D_p \frac{d}{dx} p_n(x).$$

$$= q \frac{D_p}{L_p} p_{no} [e^{V/V_T} - 1] (e^{-\frac{(x - x_n)}{L_p}})$$



$$I = A(J_p + J_n)$$

$$= A \cdot q \cdot (e^{V/V_T} - 1) \left[\frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po} \right]$$

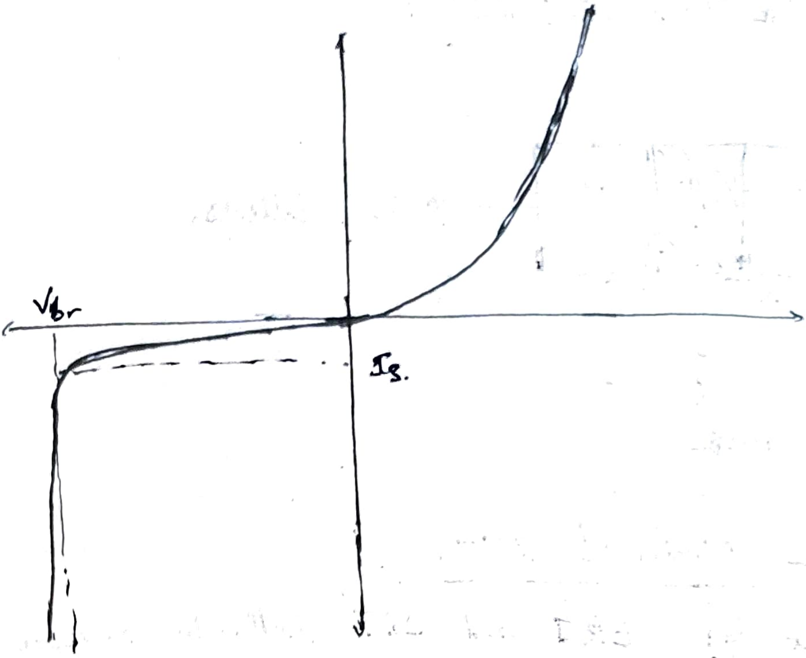
$$= A q n_i^2 (e^{V/V_T} - 1) \left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right].$$

$$\downarrow$$

$$I = I_S (e^{V/V_T} - 1)$$

where $I_S = A q n_i^2 \left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right)$

is called saturation current.



Junction capacitance:

$$Q_J = \alpha \sqrt{V_0 + V_R} \quad [\alpha: \text{Proportionality constt.}]$$

(V_R : Reverse bias Volt).

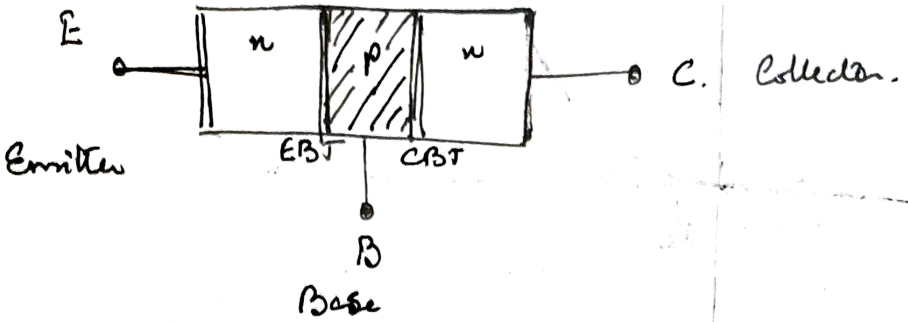
$$C_J = \frac{dQ_J}{dV_R}$$

$$= \frac{\alpha}{2\sqrt{V_0 + V_R}}$$

$$C_{J0} = \frac{\alpha}{2\sqrt{V_0}} \quad (V_R = 0).$$

$$\Rightarrow C_J = \frac{C_{J0}}{\sqrt{1 + (V_R/V_0)}}$$

Bipolar Junction Transistors (BJT):

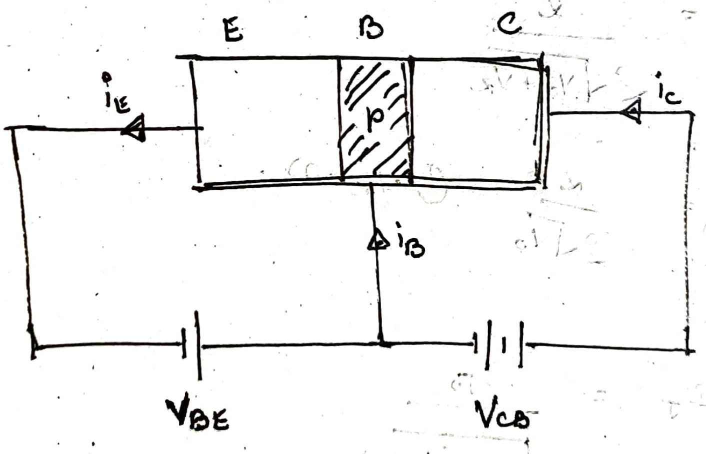


Operation Modes of BJT:

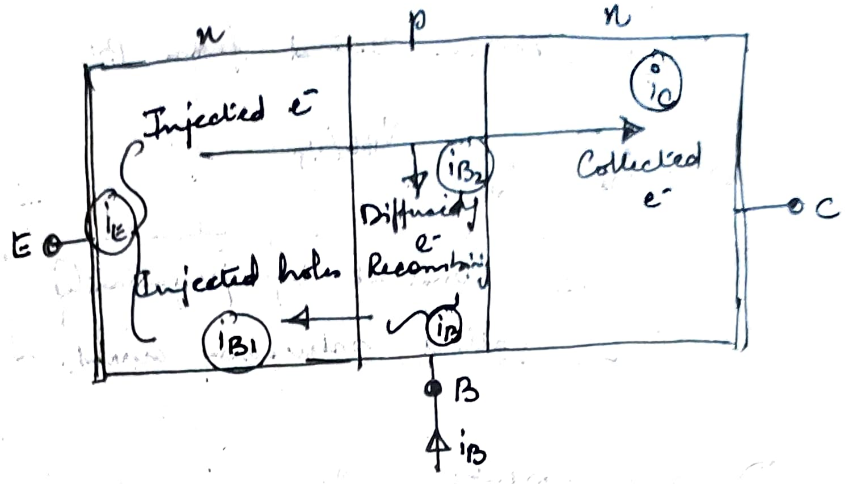
- Cut-off: EBJ and CBJ both in reverse bias
- Active: EBJ is forward bias, CBJ is reverse bias
- Saturation: Both are in forward bias.

Active Mode:

Circuit (Common Base Connection).



Current flow:



i_E: Combination of injected holes / e^-

i_B $\begin{cases} i_{B1}: \text{Injected holes from B.} \\ i_{B2}: \text{Electrons recombining with holes from } i_B \end{cases}$

i_C: Electrons collected from B.

$i_{B1} + i_{B2} = i_B$.

$\left[\, i_B + i_C = i_E \,\right]$ → Eqn is important.

$\frac{i_C}{i_B} = \beta$: Common-emitter current gain.

$\frac{i_C}{i_E} = \alpha$: Common-base current gain.

Putting in eqn 1, we get.

$$\frac{1}{\beta} + 1 = \frac{1}{\alpha} \Rightarrow \alpha = \frac{\beta}{\beta + 1}.$$

Currents:

(+) Collector current:

i_C: Electron carried from BE

→ $i_C = i_S \, e^{V_{BE}/V_T}$

[i_S: Constant of proportionality
Called saturation current.]

(+) Base current:

$$i_B = \frac{i_C}{\beta} = \left(\frac{i_S}{\beta}\right) e^{V_{BE}/V_T}$$

(+) Emitter current:

$$i_E = \frac{i_C}{\alpha} = \left(\frac{i_S}{\alpha}\right) e^{V_{BE}/V_T}$$

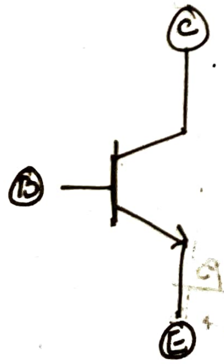
For a good BJT, we prefer a high value of 'β'.

→ Length of B is small

→ Doping strength of B is low. (light)

→ Doping strength of E is high (heavy).

Symbols:



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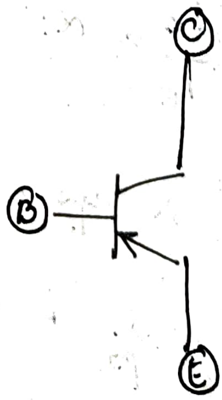

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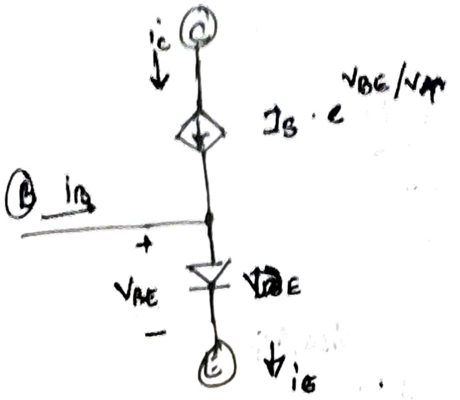
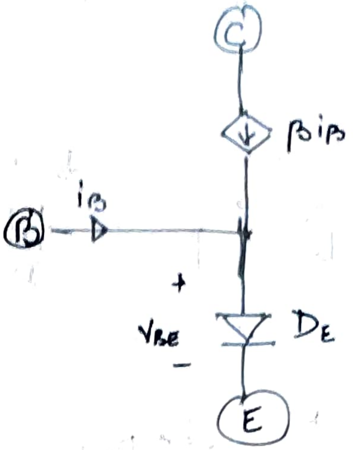
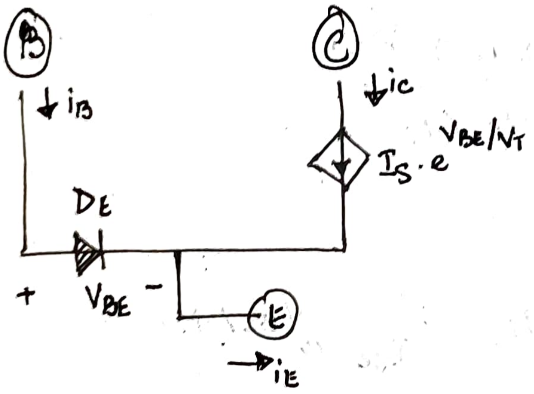
Equivalent models:

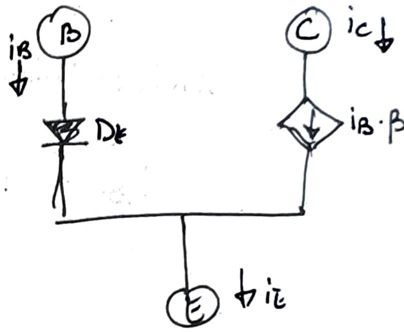
T - Models:





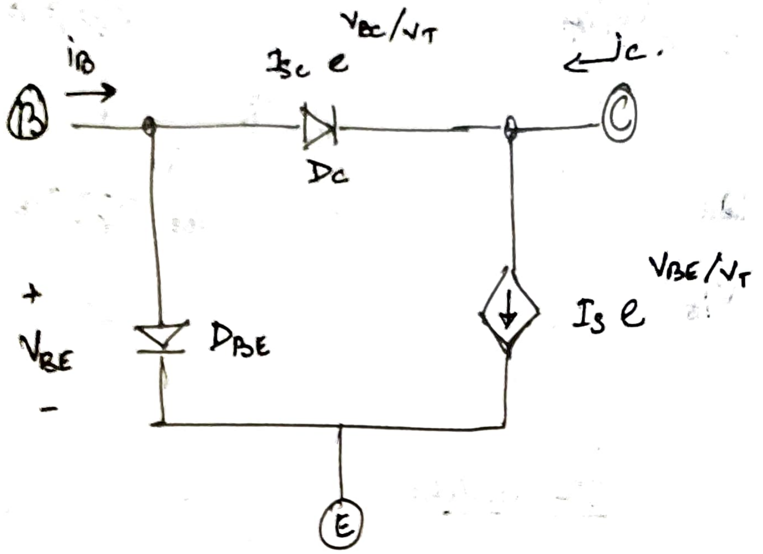
π - Models:





Saturation Mode:

(*): Both CBJ and EBJ are forward bi[as]

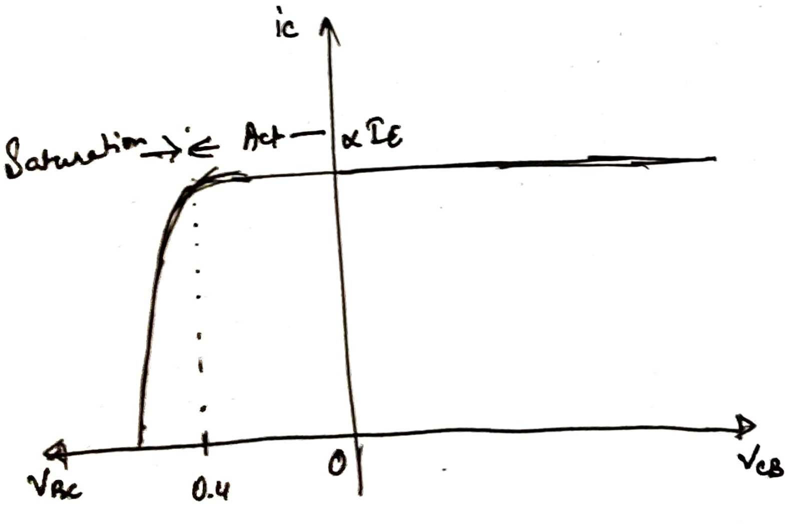


Current across Diode & D_C:

$$i_{BC} = (I_S)_c\, e^{V_{BC}/V_T}$$

$$\Rightarrow i_C = I_S\, e^{V_{BE}/V_T} - I_{SC}\, e^{V_{BC}/V_T}.$$

$$i_B = \left(\frac{I_S}{\beta}\right) e^{V_{BE}/V_T} + I_{SC}\, e^{V_{BC}/V_T}$$



As V_{BC} increases and crosses $0.4V$ (general BJT data), it reaches saturation and i_C eventually reaches 0.

By adjusting V_{BC}, we can change the value of $\frac{i_C}{i_B}$ (β) to a forced value.

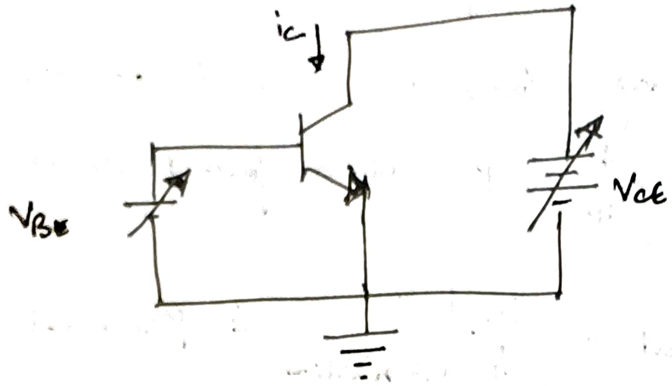
$$\beta_{forced} = \left.\frac{i_C}{i_B}\right|_{Saturation} \le \beta_{natural}$$

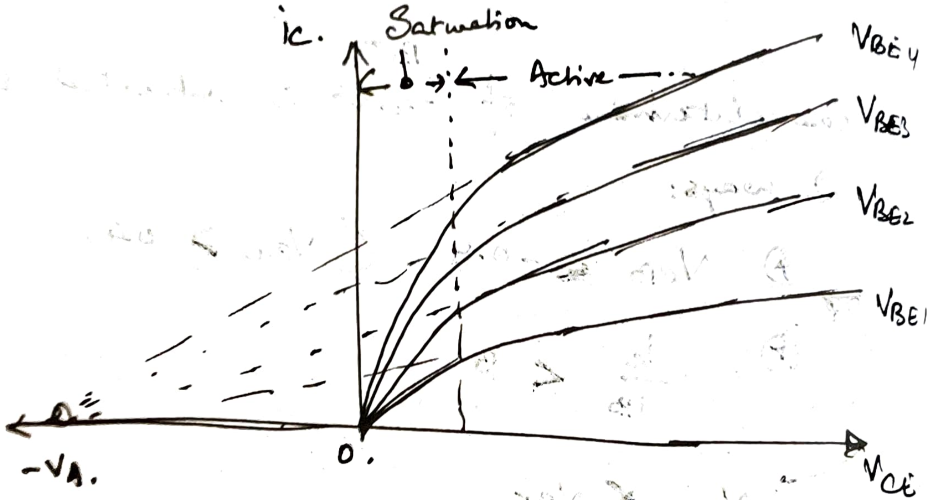
We can determine if BJT ~~circuit~~ is saturated by 2 ways:

- $V_{CB} \le -0.4$ ($V_{BC} \ge 0.4$)
- $\frac{i_C}{i_B} < \beta$

$V_{BC} < V_{BE}$

Dependance of i_c on Collector Voltage:





V_A : Early Voltage.

generally b/w 10V – 100V.

$$i_c = I_S \, e^{V_{BE}/V_T} \left[1 + \frac{V_{CE}}{V_A} \right]$$

This equation is for the linear part (active mode).

Output resistance (r_o)

$$r_o = \left[\frac{\partial i_C}{\partial v_{CE}} \bigg|_{V_{BE}} \right]^{-1}$$

$$\Rightarrow \frac{1}{r_o} = \frac{I_C}{V_A + V_{CE}} = \frac{I_S \cdot e^{V_{BE}/V_T}}{V_A}$$

$$\Rightarrow r_o = \frac{V_A + V_{CE}}{I_C}.$$