$\therefore$ Net hole current, $J_h = J_{hp} - J_{hn} = J_{hn}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$

$\therefore$ Net electron current, $J_e = J_{en} - J_{ep} = J_{ep}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$

Total diode current $J = J_h + J_e = J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$,

where $J_o = J_{hn} + J_{ep}$, also called the minority or saturation current density.

Metal / Semiconductor Junctions *(pg. 178 JA)*

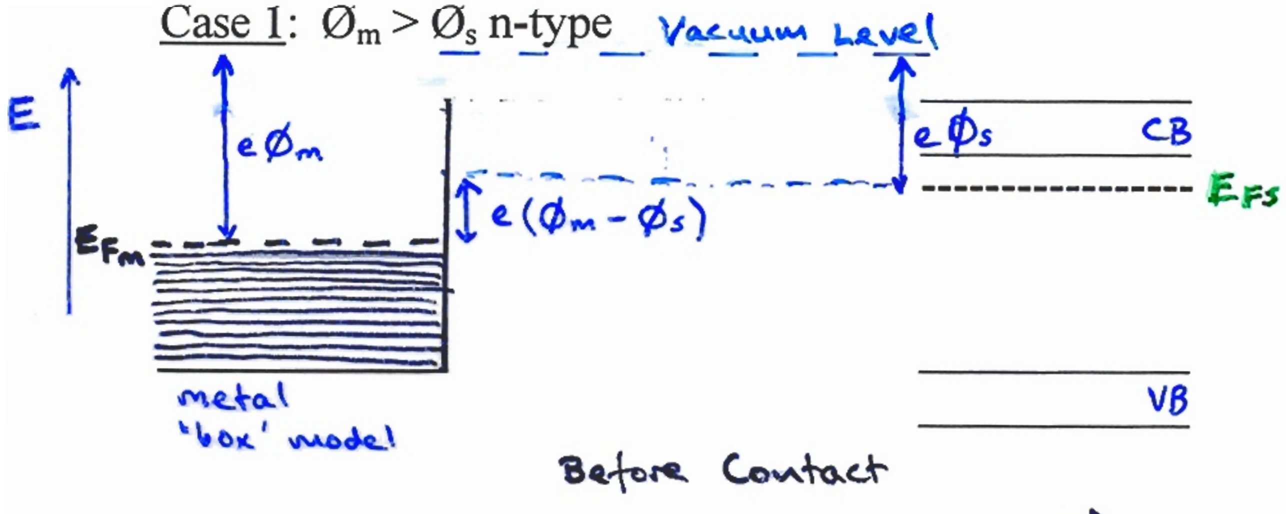
Two types

- Ohmic
- Rectifying

Depends on relative work functions (Ø) of metal and semiconductor

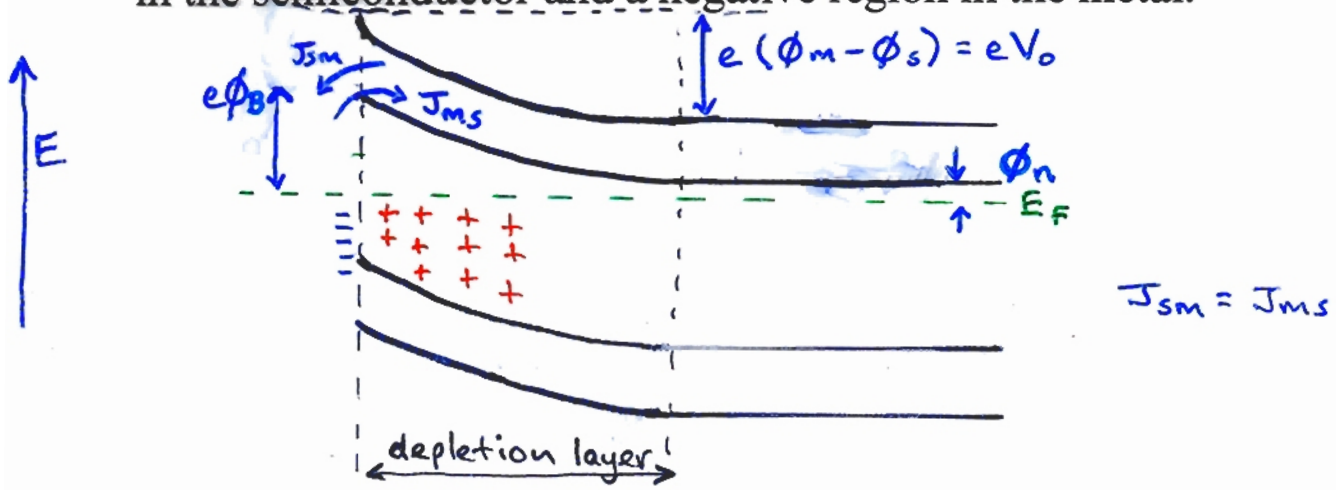
eg metal on n-type semiconductor

Case 1: $\text{Ø}_m > \text{Ø}_s$ n-type



$(\text{Ø}_m, \text{Ø}_s \equiv E_F$ to vacuum level$)$

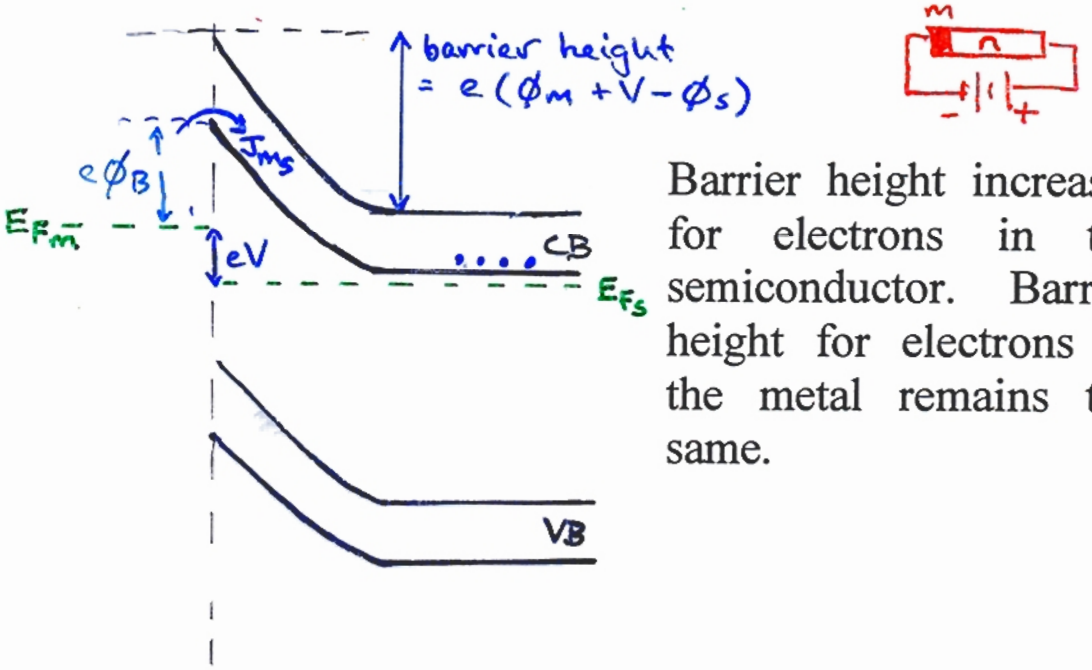
On contact, electrons spill over from the semiconductor to empty level in the metal , leaving a positive depletion layer in the semiconductor and a negative region in the metal.



In equilibrium, electron currents each way are equal (J_{sm} = J_{ms}). Band edges bend-up in semiconductor depletion layer to form a potential energy barrier and $eV_o = e\,(Ø_m – Ø_s)$

Reverse bias

All levels in n-type are lowered as +ive potential is applied.



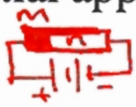
Barrier height increases for electrons in the semiconductor. Barrier height for electrons in the metal remains the same.

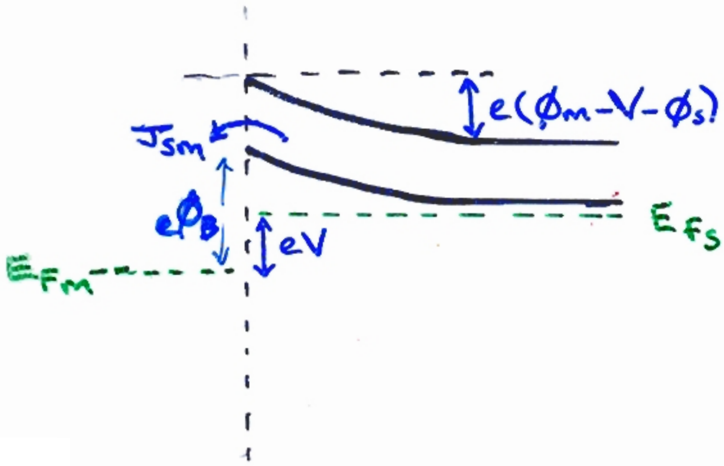
- J_{sm} reduced
- J_{ms} remains same.

V increase the barrier height and cuts off any electron flow from semiconductor to the metal. There remains a small saturation current independent of V due to thermal emissions across the barrier seen by electrons in the metal.

Forward bias

All levels in n-type are raised as –ive potential applied.





Barrier height decreases for electrons in the semiconductor. Barrier height for electrons in the metal remains the same.

i.e. J_{sm} increased while J_{ms} remains the same.

∴ i.e. Junction rectifies if $\varnothing_m > \varnothing_s$ for an n-type semiconductor.

I-V Characteristics

Electrons from metal → semiconductor need energy $e\phi_B$ to surmount barrier and move into semiconductor, so:

$$J_{ms} \propto P(e\Phi_B) \propto \frac{1}{1+\exp\left(\frac{e\Phi_B - E_F}{kT}\right)} \propto \exp-(e\Phi_B)$$

Barrier height to electron from semiconductor side is $e(V_o \pm V)$ where + is for reverse bias and –is for forward bias. Barrier for electrons in metal stays the same.

$$J_{sm} \propto \exp-\left(\frac{e(V_o \pm V) + e\Phi_n - E_F}{kT}\right) \propto \exp-(e\Phi_B \pm V)$$

✱ n.b.: no hole conduction

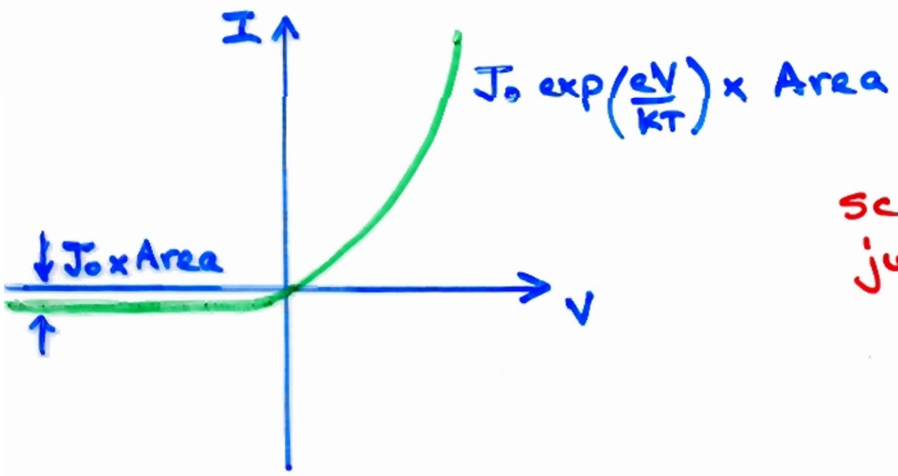
$\left.\begin{array}{l}\rightarrow J_{ms} \\ \leftarrow J_{sm}\end{array}\right\} e^-$ flow

→ conventional current flow, $J = J_{sm} - J_{ms}$

$$J \propto \exp\left[\frac{-(e\Phi_B)}{kT}\right]\left[\exp\left(\frac{eV}{kT}\right) - 1\right] = J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

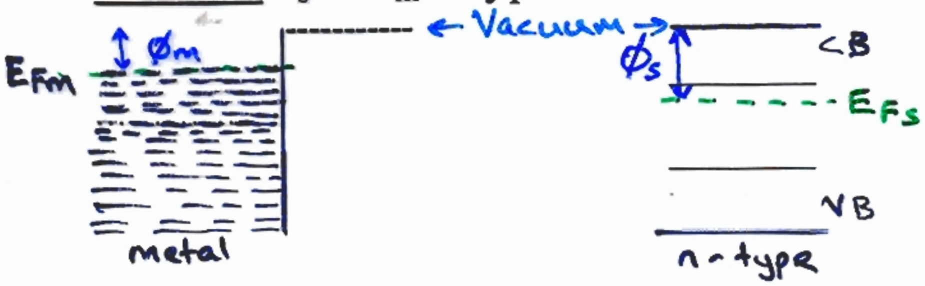
$(V_o + \phi_n = \phi_B)$

This is the usual rectifier equation – same form as p-n junction but J_o is different. – thermionic emission

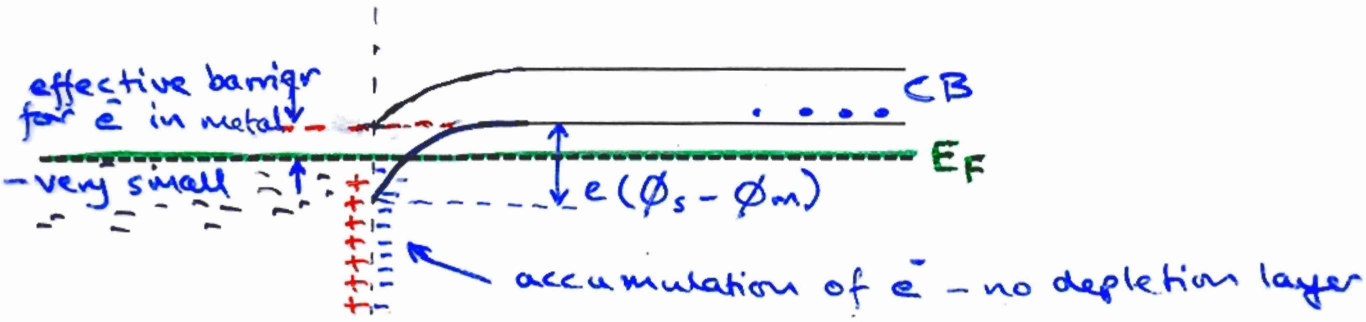


schottky junction/diode

CASE 2 $\emptyset_s > \emptyset_m$ n-type semiconductor

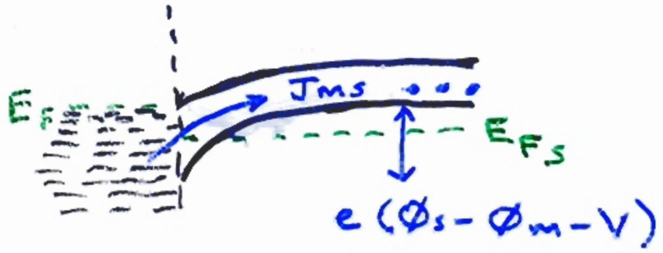


Before contact $\emptyset_s > \emptyset_m$ and $E_{FM} > E_{FS}$
On contact electrons flow from metal to semiconductor.

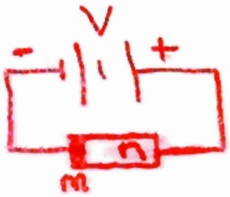


In equilibrium there is virtually no barrier to impede the flow of electrons in either direction.

e.g.



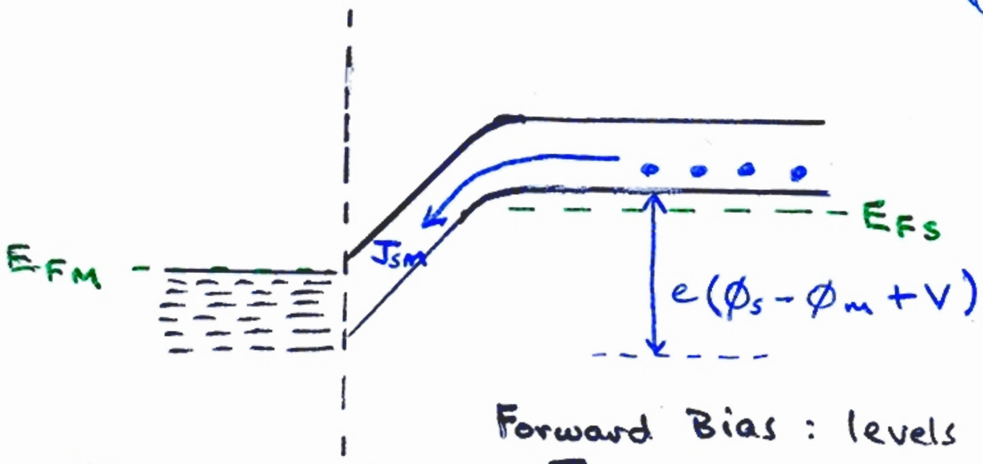
Reverse Bias: Levels in n-type ↓, J_{ms} flows



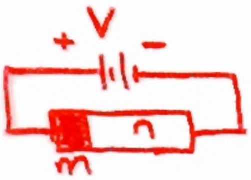
Similar arguments hold for metal/P-type semiconductor – just opposite.

N.B.: Metal-semiconductor junctions can be dominated by surface effects

Ohmic Contact



Forward Bias : levels in n-type ↑
J_{sm} flows



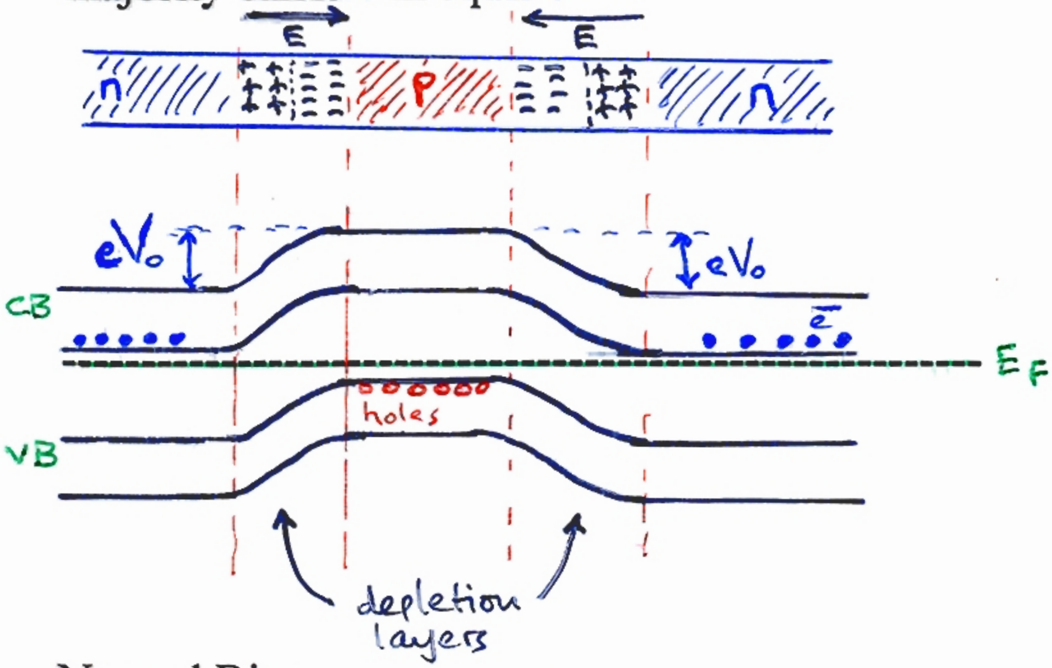
Advantages of Schottky Diode

- Smaller V_0 than p-n junction
- Faster operation – unipolar device

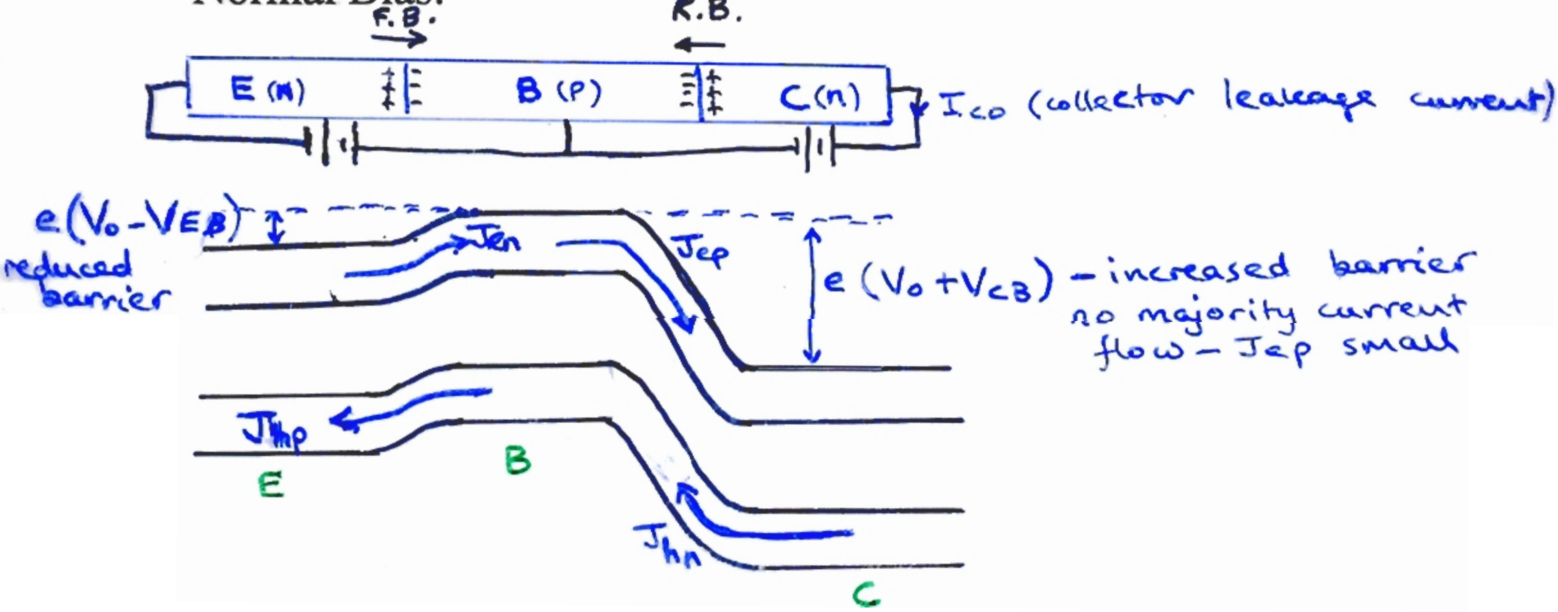
Band Picture of A Bipolar Junction Transistor *(pg. 203 JA)*

Consider symmertically doped n-p-n transisitor.

No Bias: Barrier eV_o established to prevent diffusion of majority carriers in equilibrium



Normal Bias:



Majority currents J_{en} and J_{np} flow at the EB junction.
Arrange for $J_{en} >> J_{hp}$ by doping the base to be less than that in the emitter .
i.e. N_d (E) >> N_a (B)$\Rightarrow$ $\sigma_E >> \sigma_B$ $\Rightarrow$high injection efficiency, so most of the junction current carried by electrons.

If the base is thin compared to the electron diffusion length, little recombination in the base, most electrons from the emitter will make it across to the collector. A small change in base current results in a large change in emitter (i.e. collector) current– hence gain and amplification of power.

E-B junction forward biased – low impedance $\frac{\Delta V_{EB}}{\Delta I_E (\approx I_C)}$ = small
C-B junction reverse biased – high impedance $\Delta V_{CB} / \Delta I_C$ = large
Transfer of power from low Z to high Z circuit – Transfer Resistor – TRANSISTOR

Common Emitter Gain $\alpha_E = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE} \text{ constant}}$

$$I_B + I_C + I_E = 0 \quad \text{(Kirchoff)}$$

$$\therefore \quad \Delta I_B = -(\Delta I_C + \Delta I_E)$$

By substitution, $\Delta I_B = \Delta I_C [1 - (1/\alpha_B)]$

[Remember $\alpha_B = -\left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB}}$ common base gain]

$$\frac{\Delta I_C}{\Delta I_B} = \alpha_E = \frac{\alpha_B}{1 - \alpha_B}$$

(see J. A. pg 206)

$\alpha_B = \eta_E \beta$

η_E = injection efficiency = ratio of electron current into base from emitter to total emitter-base junction current

β = base transport factor = ratio of electron current at collector junction to that at emitter junction

$$\eta_E = \frac{J_{en}}{J_{en} + J_{hp}}$$

$$J_{en} = \frac{e D_e n_p}{l_B}$$ where l_B (base length) $\ll L_e$ (minority carrier diffusion length)

$$\frac{J_{en}}{J_{hp}} \approx \frac{D_e n_p}{l_B} \Big/ \frac{D_h p_n}{l_E}$$ (l_E = emitter length)

$$\approx \frac{\sigma_E l_E}{\sigma_B l_B}$$

$$\eta_E \approx 1 - \frac{\sigma_B l_B}{\sigma_E l_E} \longrightarrow 100\% \text{ if } \sigma_E l_E \gg \sigma_B l_B$$

β tends to be $\sim 0.95 - 0.99$ in well designed transistor $\left(\beta \approx 1 - \frac{1}{2} (l_B / L_e)^2 \right)$

α_E can therefore be very large.