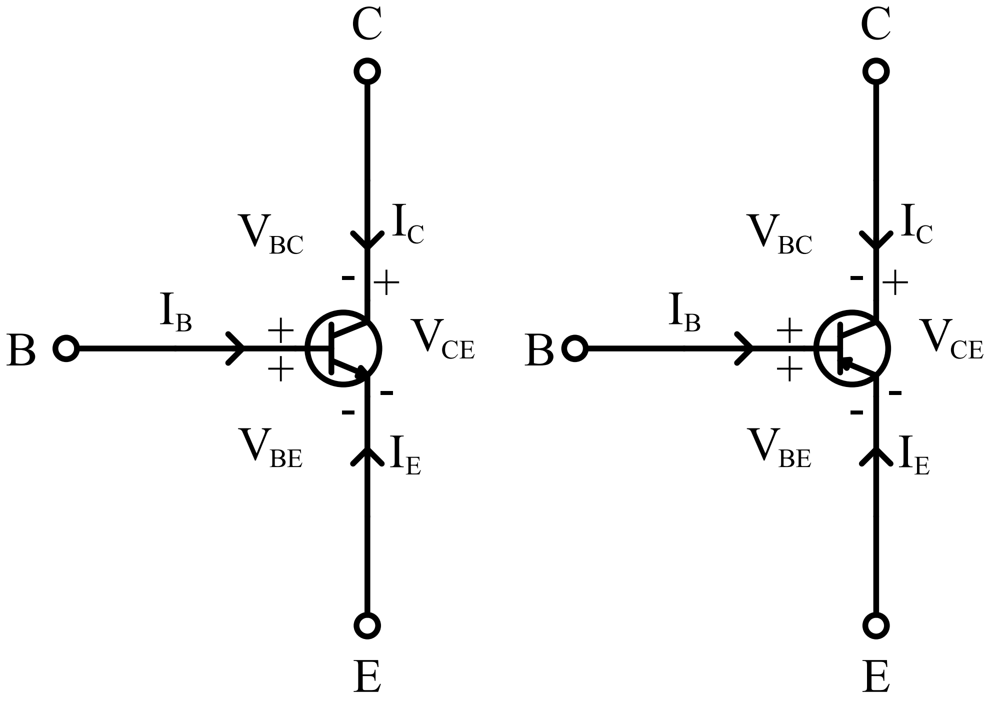
1.3 Large Signal Operation of BJT (pg. 8)

In this book, the current direction and voltage polarity for the npn and pnp are as shown below:

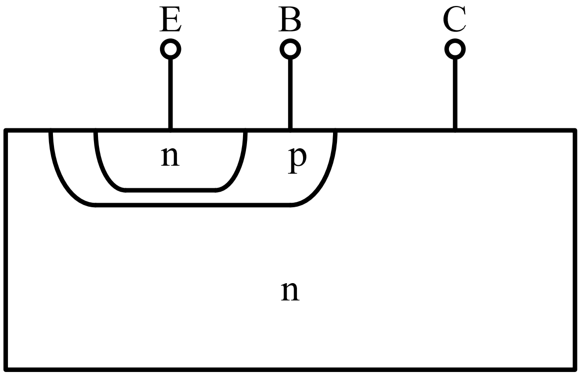


Biasing current entering the device is considered positive for both npn and pnp.

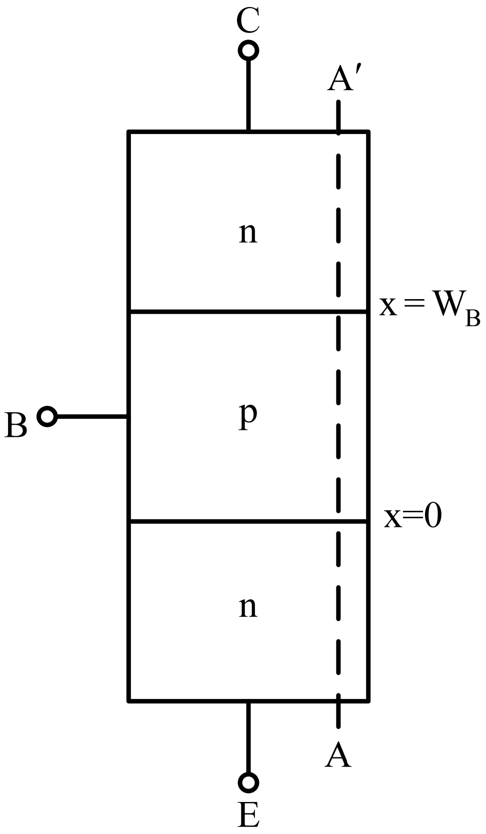
Symbol convention

Condition	Examples
Bias or DC quantities are represented by uppercase symbols with uppercase subscripts.	I_B and V_{BE}
Small-signal quantities are represented by lowercase symbols with lowercase subscripts.	i_b and v_{be}
Elements in small-signal circuit are represented by lowercase symbols with lowercase subscripts.	g_m and c_{gs}
Total quantities, i.e. sum of bias and signal, are represented by uppercase symbols and lowercase subsripts.	I_b and V_{be}

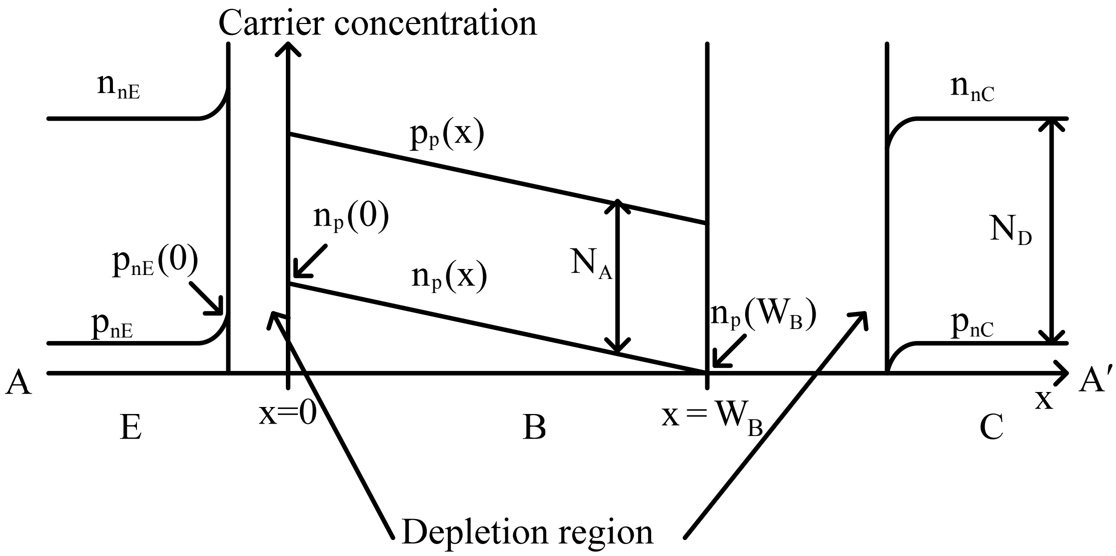
1.3.1. Large-signal model in the forward active region (pg. 9)

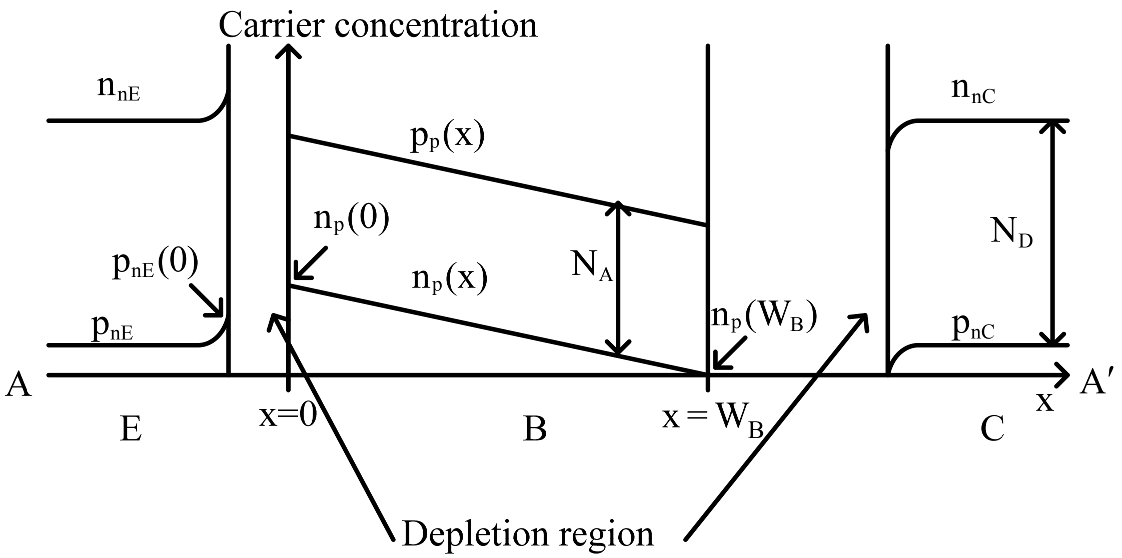


Cross-section



Idealized structure





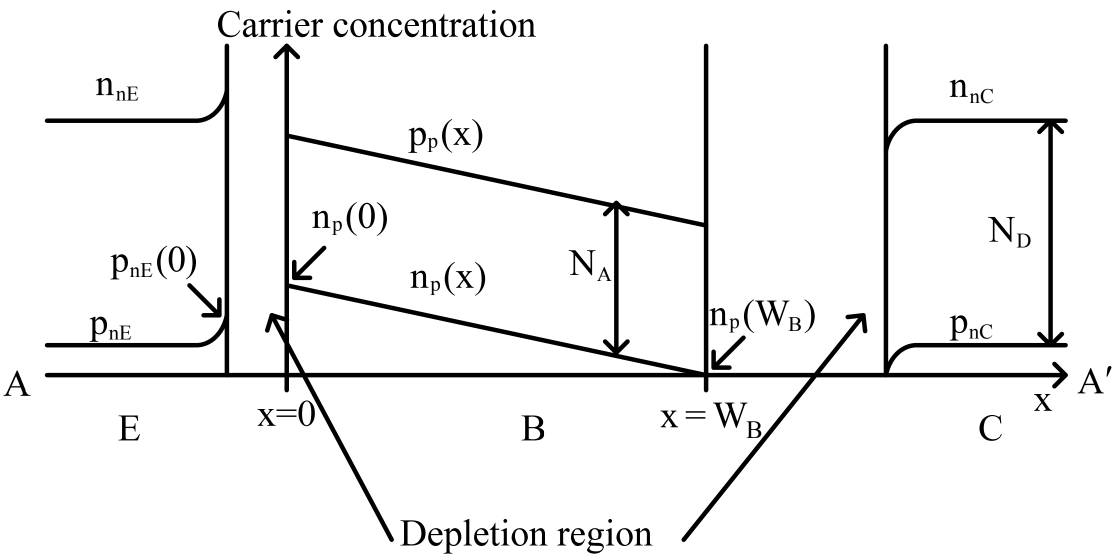
Carrier concentration along the cross-section AA'.

Uniform doping densities are assumed. Under this condition, the transistor is called uniform-base transistor.

n_n and n_p = electron concentration in the n-type and p-type region, respectively

p_p and p_n = hole concentration in the p-type and n-type region, respectively

In the forward active region, BE junction is fb and BC junction is rb.



Minority-carrier concentrations in the B:

at x = 0; $n_p(0) = n_{p0} \exp(V_{BE} / V_T)$ (1.27)

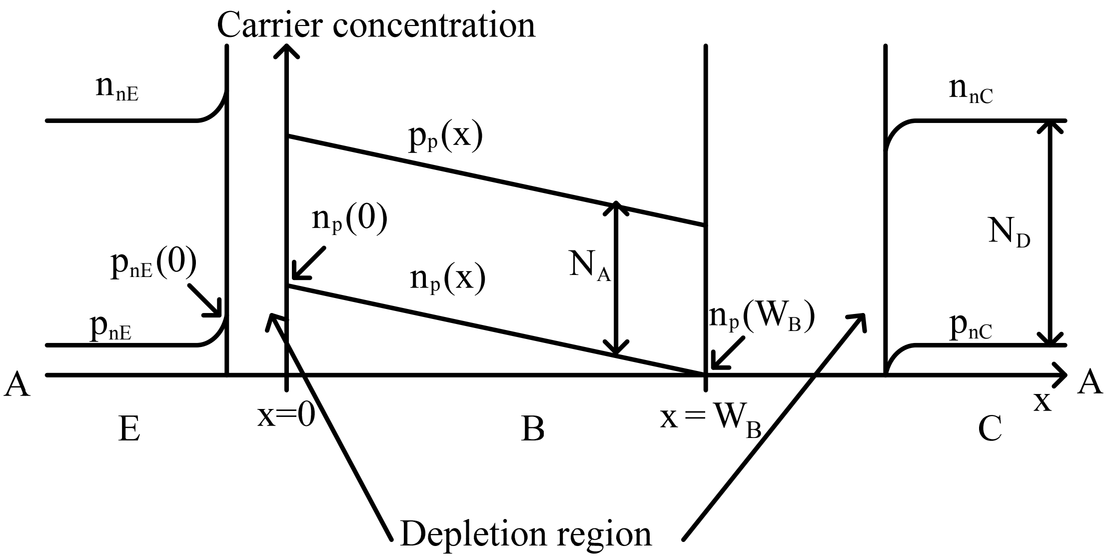
at x = W_B ; $n_p(W_B) = n_{p0} \exp(V_{BC} / V_T) \approx 0$ (1.28)

n_{p0} = equilibrium concentration of electrons in the B.

V_T = thermal voltage = kT / e
= 26 mV at 300 K.

k = Boltzmann constant = 1.38×10^{-23} J/K
T = temperature in Kelvin (K)
e = electronic charge = 1.6×10^{-9} Coulomb (C)

Since BC is rb, V_{BC} is negative. In most cases, $V_{BC} >> V_T$. This is the reason why $n_p(W_B) \approx 0$. Equations (1.27) and (1.28) are for low-level injection condition whereby minority-carrier concentrations are always assumed to be << majority-carrier concentrations.



If recombination of holes and electrons in B is small, minority-carrier concentration in B, $n_p(x)$, varies linearly with distance.

For charge neutrality in B,

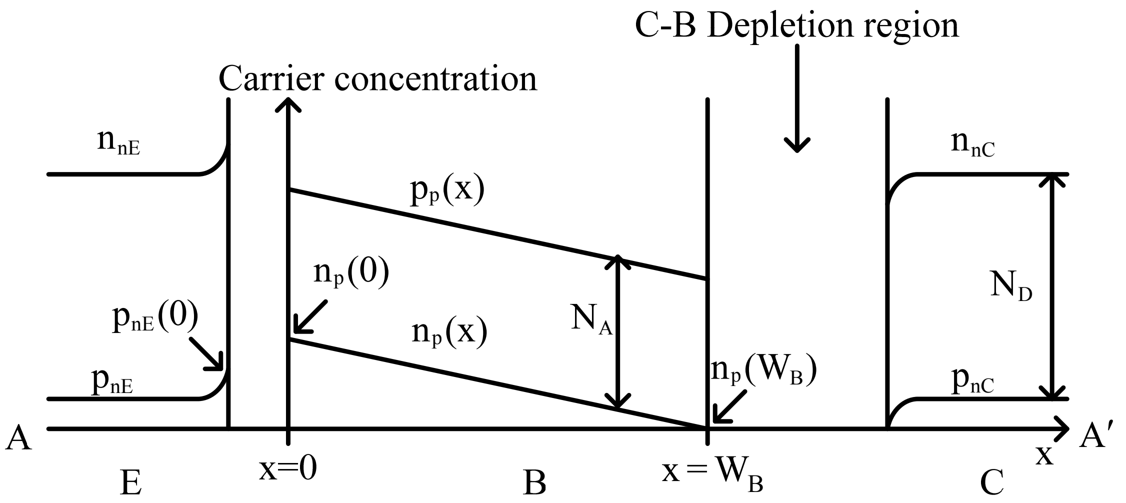
$$N_A + n_p(x) = p_p(x)$$

$$p_p(x) - n_p(x) = N_A \tag{1.30}$$

$p_p(x)$ = hole concentration in B

N_A = B doping density that is assumed constant

(1.30) shows that the hole and electron concentrations are separated by a constant. Hence, if $n_p(x)$ varies linearly with distance, $p_p(x)$ will also behave the same way.



Collector current is produced by minority-carriers (electrons) in B diffusing in the direction of the concentration gradient and being swept across the CB depletion region by the field existing there.

Diffusion current density due to electrons in B:

$J_n = q\, D_n\, [dn_p(x) / dx\,]$

D_n = diffusion constant for electrons

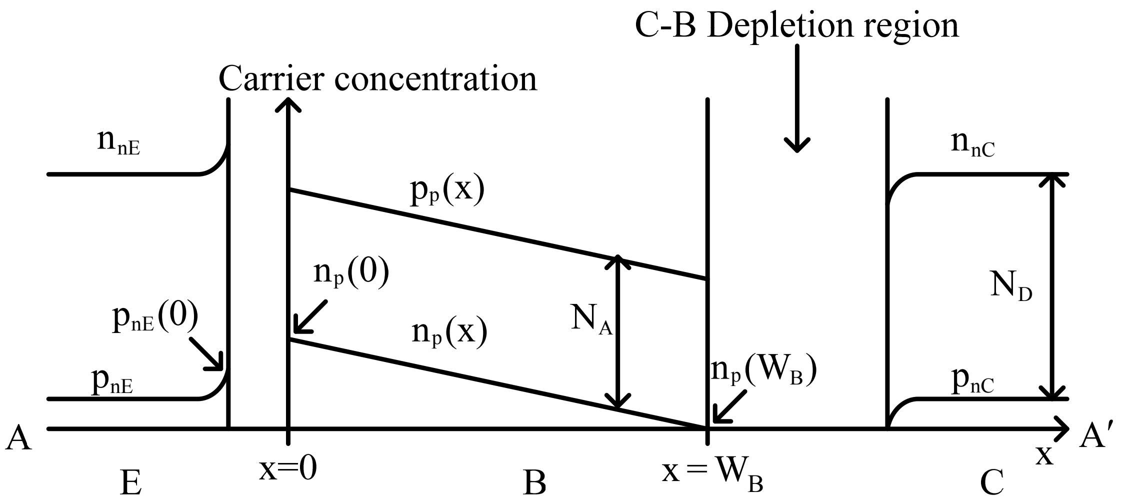
$J_n = q\, D_n\ \ [n_p(W_B) -\ n_p(0)] / [W_B - 0]$

$J_n = -\, q\, D_n\, n_p(0) / W_B$ as $n_p(W_B) \approx 0$

Since $J_n = I_C / A$ where A = area, then

$I_C = q\, A\, D_n\, n_p(0) / W_B$

I_C is positive as the collector current flows into the collector.



From equation (1.27),

$n_p(0) = n_{p0} \exp (V_{BE} / V_T)$

$I_C = q A D_n n_p(0) / W_B$

$I_C = q A D_n n_{p0} \exp (V_{BE} / V_T) / W_B$

$I_C = I_S \exp (V_{BE} / V_T)$

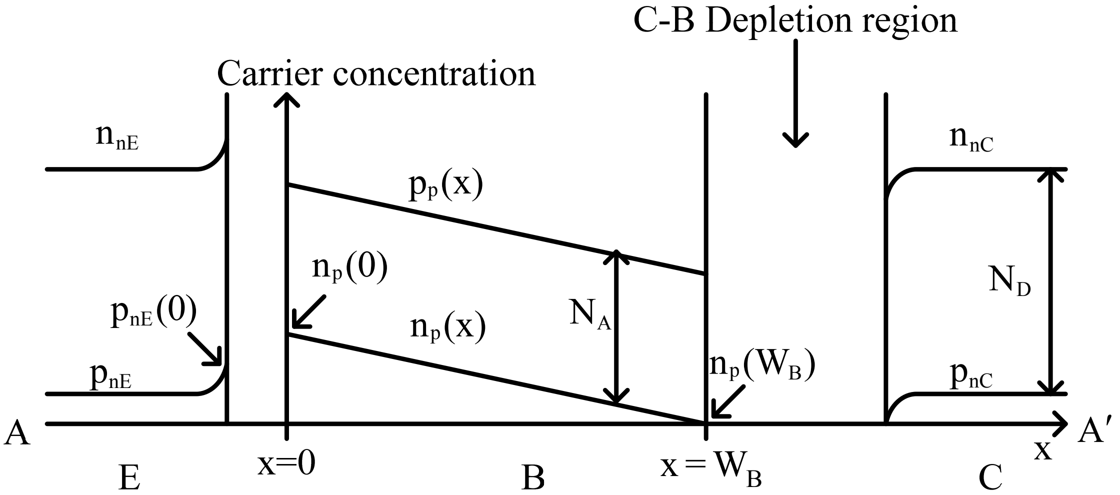
$I_S = q A D_n n_{p0} / W_B$

I_S is a constant used to describe the transfer characteristic of the transistor in the forward active region.

$n_{p0} = n_i^2 / N_A$

n_i = carrier concentration in intrinsic Si
$\approx 1.5 \times 10^{16}$ carriers / m^3

$I_S = q A D_n n_i^2 / (N_A W_B)$ typically 10^{-14} to 10^{-16} A.



Base current, I_B, consists of two major components, I_{B1} and I_{B2}.

I_{B1} = recombination of holes and electrons in B.

$I_{B1} \propto$ minority-carrier charge, Q_e , in B.

$Q_e = (1/2)n_p(0)W_BqA$

$I_{B1} = Q_e / \tau_b = (1/2)n_p(0)W_BqA / \tau_b$

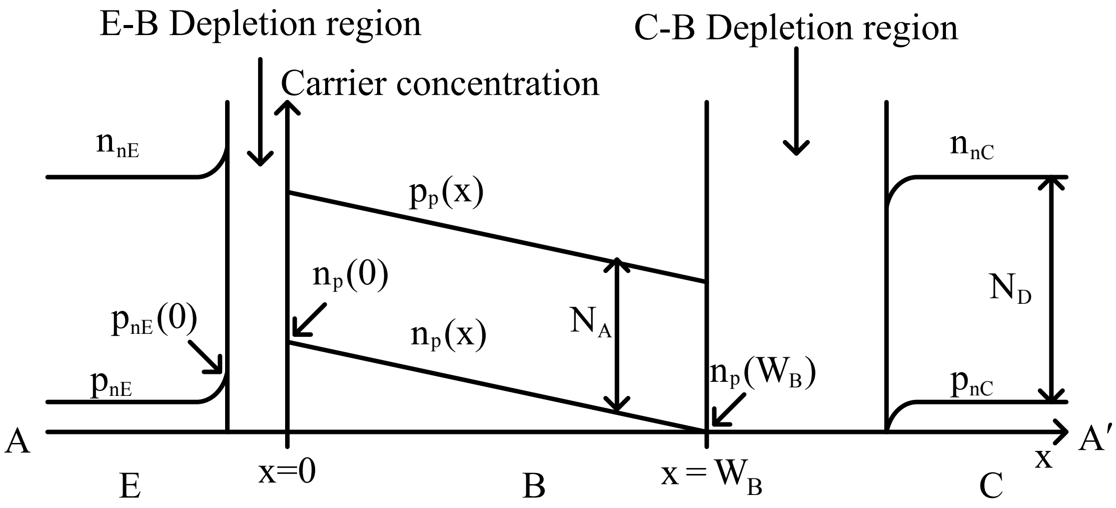
τ_b = minority-carrier lifetime in B

I_{B1} represents a flow of majority holes from the B lead into the B region.

Since $n_p(0) = n_{p0} \exp (V_{BE} / V_T)$,

then $I_{B1} = \frac{1}{2}\frac{W_BqAn_{p0}}{\tau_b}\exp\frac{V_{BE}}{V_T}$.

The dominant current component of I_B is I_{B2}. I_{B2} is due to the injection of holes from B into E. I_{B2} depends on the gradient of minority-carrier holes in E.



$I_{B2} = qAD_p p_{nE}(0) / L_p$

D_p = diffusion constant for holes

L_p = diffusion length (assumed small) for holes in the E

$p_{nE}(0)$ = concentration of holes in the E at the edge of the BE depletion region.

$p_{nE}(0) = p_{nE0} \exp (V_{BE} / V_T)$

$p_{nE0} = n_i^2 / N_D$

N_D = donor atom concentration in E.

E is deliberately doped much more heavily than the B, making N_D large and p_{nE0} small, so that I_{B2} is minimized.

$$I_{B2} = (qAD_p / L_p)\,(n_i^2 / N_D)\,\exp\,(V_{BE} / V_T)$$

Total B current:

$$I_B = I_{B1} + I_{B2} = \frac{1}{2}\frac{W_B qA n_{p0}}{\tau_b}\exp\frac{V_{BE}}{V_T} + \frac{qAD_p}{L_p}\frac{n_i^2}{N_D}\exp\frac{V_{BE}}{V_T}$$

$$I_B = \left(\frac{1}{2}\frac{W_B qA n_{p0}}{\tau_b} + \frac{qAD_p}{L_p}\frac{n_i^2}{N_D}\right)\exp\frac{V_{BE}}{V_T}$$

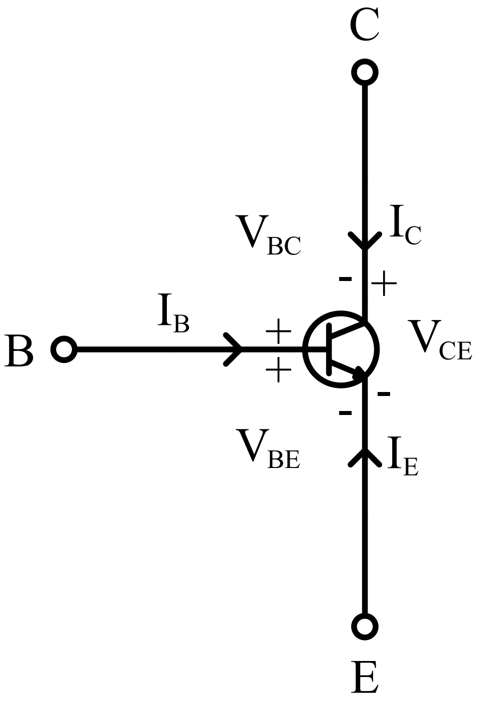
Forward current gain:

$$\beta_F = \frac{I_C}{I_B} = \frac{\dfrac{qAD_n n_{p0}}{W_B}}{\left(\dfrac{1}{2}\dfrac{W_B qA n_{p0}}{\tau_b} + \dfrac{qAD_p}{L_p}\dfrac{n_i^2}{N_D}\right)}$$

$$= \frac{1}{\left(\dfrac{W_B^2}{2\tau_b D_n} + \dfrac{D_p}{D_n}\dfrac{W_B}{L_p}\dfrac{N_A}{N_D}\right)}$$

β_F is maximized by minimizing base width W_B and maximizing the ratio of E to B doping densities, N_D/N_A i.e. $N_D >> N_A$.

Typical β_F is 50 to 500 for npn and for pnp is 10 to 100.



$I_B + I_C + I_E = 0$

$I_E = - (I_B + I_C)$

$I_B = I_C / \beta_F$

$I_E = - [(I_C / \beta_F)+ I_C] = - I_C [1 + (1/\beta_F)] = - I_C [(1 + \beta_F)/ \beta_F]$

$\alpha_F = \beta_F /(1 +\beta_F)$

$I_E = - I_C / \alpha_F$

$\alpha_F = \beta_F /(1 + \beta_F) = 1 / [1 + (1 / \beta_F)]$

$$\beta_F = \frac{1}{\left(\frac{W_B{}^2}{2\tau_b D_n} + \frac{D_p}{D_n}\frac{W_B}{L_p}\frac{N_A}{N_D}\right)}$$

$$\alpha_F = \frac{1}{1+\left(\frac{W_B{}^2}{2\tau_b D_n} + \frac{D_p}{D_n}\frac{W_B}{L_p}\frac{N_A}{N_D}\right)} \approx \alpha_T \gamma \qquad (1.51)$$

where,

$$\alpha_T = \text{base transport factor} = \frac{1}{1+\frac{W_B{}^2}{2\tau_b D_n}}$$

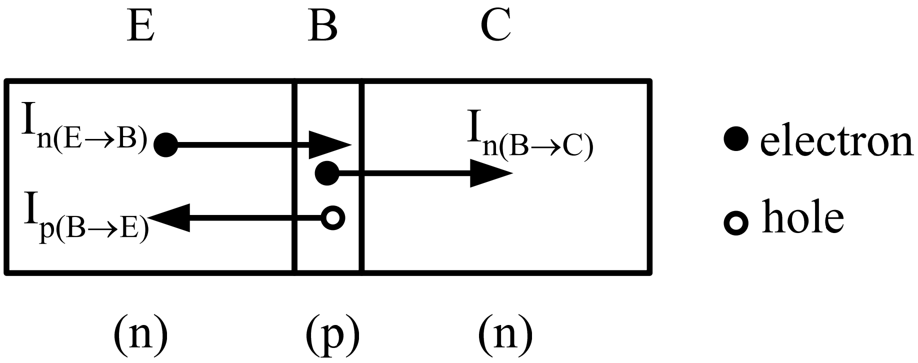
$$\gamma = \text{emitter injection efficiency} = \frac{1}{1+\frac{D_p}{D_n}\frac{W_B}{L_p}\frac{N_A}{N_D}}$$

(1.51) is valid if $\frac{W_B{}^2}{2\tau_b D_n} << 1$ and $\frac{D_p}{D_n}\frac{W_B}{L_p}\frac{N_A}{N_D} << 1$. These conditions happen when β_F is large.

$$\alpha_F = \frac{1}{\frac{1}{\alpha_T}+\frac{1}{\gamma}-1} = \frac{\gamma\alpha_T}{\gamma+\alpha_T-\gamma\alpha_T}$$

$$\alpha_F = \frac{1}{\frac{1}{\alpha_T}+\frac{1}{\gamma}-1} = \frac{\gamma\alpha_T}{\gamma+\alpha_T-\gamma\alpha_T}$$

If $\gamma \to 1$ and $\alpha_T \to 1$, $\alpha_F = \alpha_T \gamma$



$$\gamma = \frac{I_{n(E\to B)}}{I_{n(E\to B)}+I_{p(B\to E)}}$$

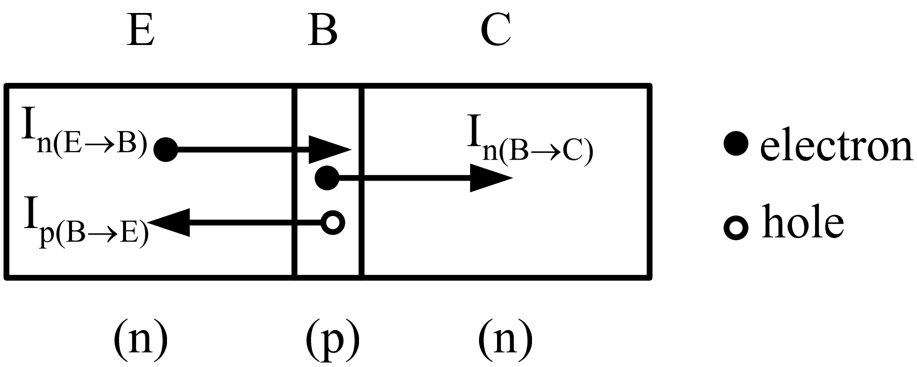
$I_{n(E\to B)}$ = current contributed by the flow of electrons from E to B.

$I_{p(B\to E)}$ = current contributed by the flow of holes from B to E.

Ideally, $\gamma \approx 1$. From the expression above, this condition is achieved when $I_{p(B\to E)} << I_{n(E\to B)}$.

As $\gamma = \frac{1}{1+\frac{D_p}{D_n}\frac{W_B}{L_p}\frac{N_A}{N_D}}$, $\gamma \approx 1$ can also be achieved by making

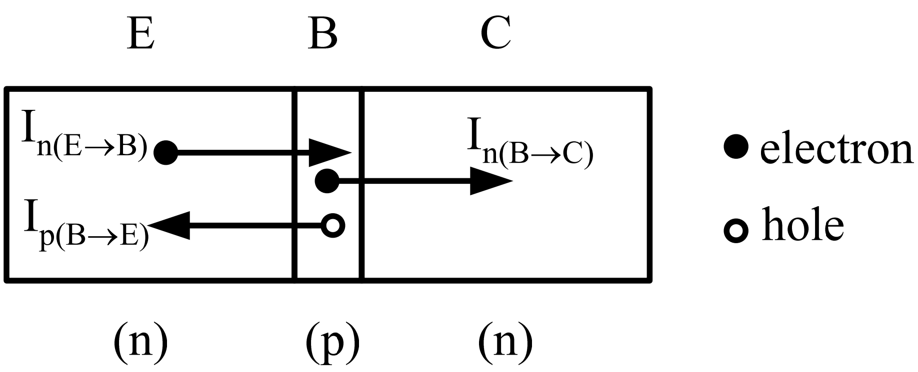
$N_A/N_D \ll 1$ (or $N_D \gg N_A$) and W_B small.



α_T represents the fraction of carriers injected into B from E that reaches C.

$$\alpha_T = \frac{I_{n(B\to C)}}{I_{n(E\to B)}}$$

where $I_{n(B\to C)}$ is the current contributed by the amout of electrons swept from B to C.

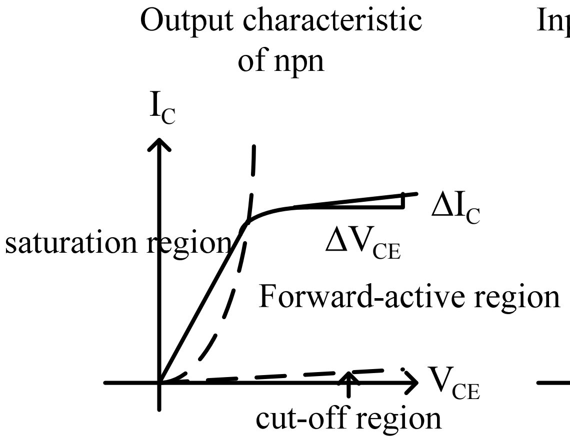


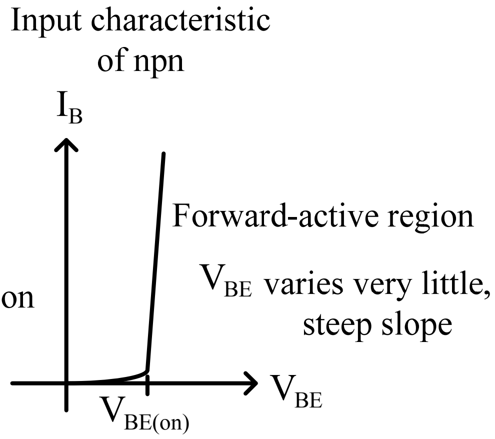
$$\alpha_T = \frac{I_{n(B\to C)}}{I_{n(E\to B)}}$$

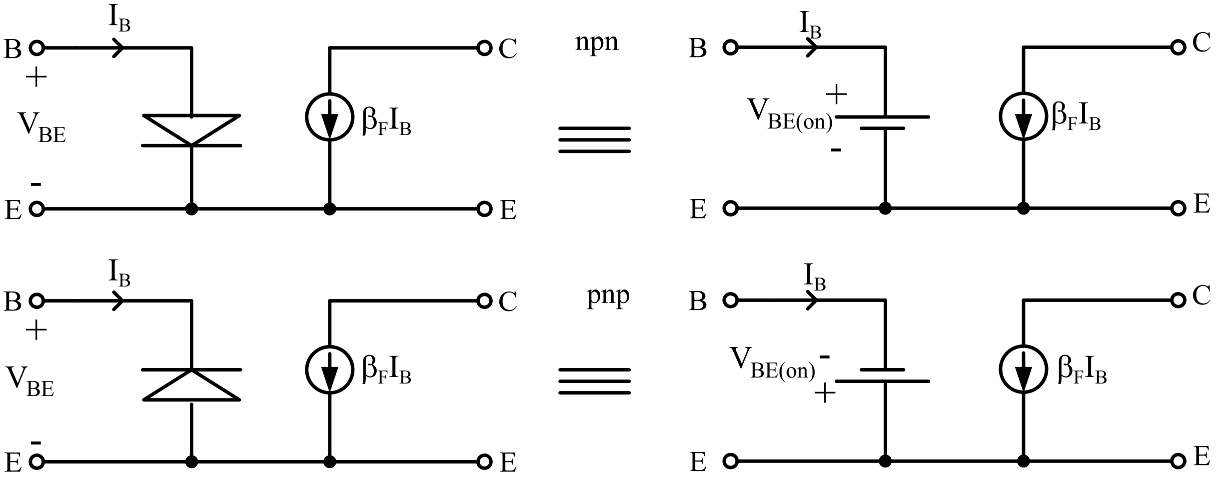
Ideally, $\alpha_T \approx 1$ and this happens when $I_{n(B\to C)} \approx I_{n(E\to B)}$. This can happen when W_B is small as can be seen from

$$\alpha_T = \frac{1}{1 + \frac{W_B^2}{2\tau_b D_n}}.$$

Large-signal models of npn transistors for use in bias calculations.







Collector voltage ideally has no influence on the collector current and the collector node acts as a high impedance current source.

In the forward-active region, V_{BE} varies very little because of the steep slope of the exponential characteristic.

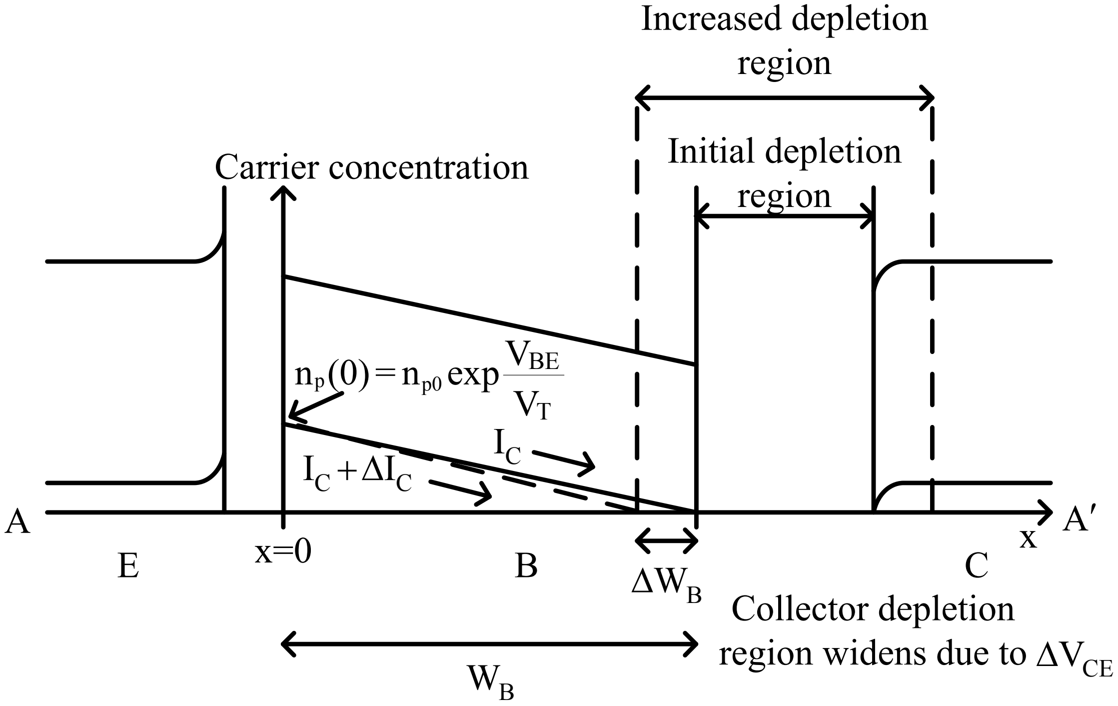
1.3.2 Effects of the collector voltage on large-signal characteristics in the forward active region.

The rb CB junction has ideally no effect on the collector current. This approximation is useful for 1st order calculation, but not true in practice. There are occasions when the influence of the collector voltage on the collector current is important.

Collector voltage has dramatic effect on the collector current in 2 regions of device operation:

1. saturation region ($V_{CE} \rightarrow 0$)
2. breakdown region (V_{CE} very large)

Between these two extremes, I_C increases slowly with the increase of V_{CE}.



If V_{BE} is constant, the change in V_{CB} equals the change in V_{CE} . This causes an increase in the CB depletion layer width.

The change in the B width = ΔW_B = change in depletion layer width.

The change in width causes the change in the collector current as much as ΔI_C.

$$I_C = \frac{qAD_n n_{p0}}{W_B} \exp \frac{V_{BE}}{V_T}$$

From this equation, I_C will increase when W_B decreases at a fixed V_{BE}.

$$\begin{aligned} I_C &= \frac{qAD_n n_{p0}}{W_B} \exp \frac{V_{BE}}{V_T} \\ &= \frac{qAD_n}{W_B} \frac{n_i^2}{N_A} \exp \frac{V_{BE}}{V_T} \\ &= \frac{qAD_n n_i^2}{Q_B} \exp \frac{V_{BE}}{V_T} \end{aligned}$$

where $Q_B = W_B N_A =$ no of doping atoms in B per unit area of E

$$\frac{\partial I_C}{\partial Q_B} = -\frac{qAD_n n_i^2}{Q_B^2} \exp \frac{V_{BE}}{V_T}$$

$$\frac{\partial I_C}{\partial V_{CE}}\frac{dV_{CE}}{dQ_B} = -\frac{qAD_n n_i^2}{Q_B^2}\exp\frac{V_{BE}}{V_T}$$

$$\frac{\partial I_C}{\partial V_{CE}} = -\frac{I_C}{Q_B}\frac{dQ_B}{dV_{CE}}$$

$$\frac{\partial I_C}{\partial V_{CE}} = -\frac{I_C}{W_B N_A}\frac{dW_B N_A}{dV_{CE}}$$

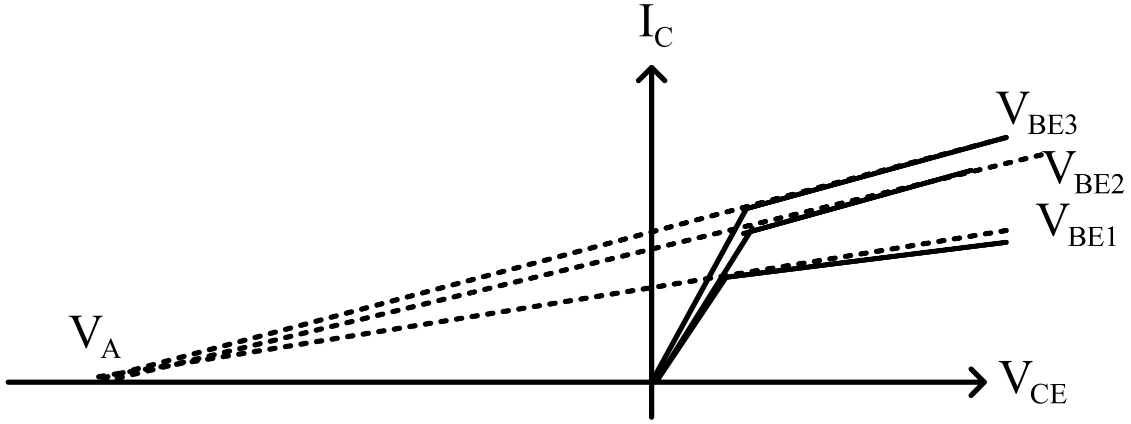
$$= -\frac{I_C}{W_B}\frac{dW_B}{dV_{CE}} \qquad (1.55)$$

Since W_B decreases when V_{CE} increases, then $\frac{dW_B}{dV_{CE}}$ is negative. Hence, $\frac{\partial I_C}{\partial V_{CE}}$ is positive, i.e. when V_{CE} increases I_C will also increase.

$$\frac{\partial I_C}{\partial V_{CE}} = -\frac{I_C}{W_B}\frac{dW_B}{dV_{CE}}$$

$$\frac{\partial I_C}{\partial V_{CE}} \propto I_C \text{ or } \frac{\partial I_C}{\partial V_{CE}} \propto I_C$$

Narrow-base transistors show a greater dependence of I_C on V_{CE} in the forward-active region.



Early voltage,

$$V_A = \frac{I_C}{\frac{\partial I_C}{\partial V_{CE}}} = -W_B \frac{dV_{CE}}{dW_B} \; . \tag{1.57}$$

Hence, V_A independent of I_C.

Variation of I_C with V_{CE} is called the Early effect. V_A is typically 15 to 100 V.

The influence of the Early effect on the transistor large-signal characteristics in the forward-active region is shown by the following equation:

$I_C = I_S (1 + V_{CE} / V_A) \exp (V_{BE} / V_T)$

When no Early effect considered:

$I_C = I_S \exp (V_{BE} / V_T)$