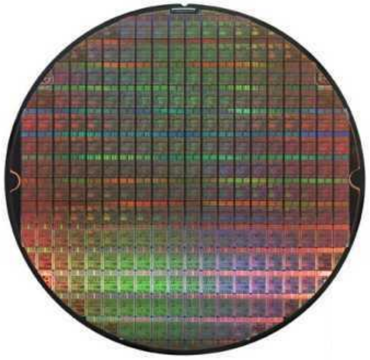
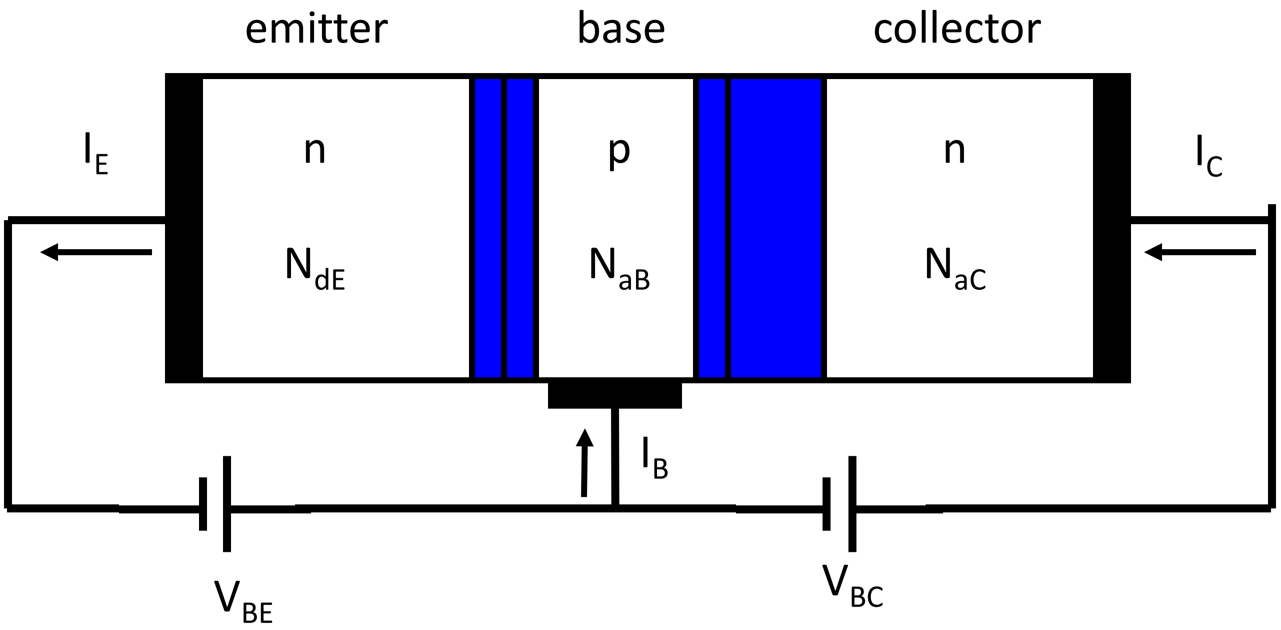


Physics of Semiconductor Devices
Module – II.5

Bipolar Junction Transistor

BJT Model



- Two back to back p-n junctions
- Base region is thin enough to enable minority carriers to diffuse through base region.
- Junction are far apart so that their depletion layers do not overlap.

Bipolar Junction Transistor

- Bipolar junction transistor or BJT was invented in 1948 at Bell Lab., USA.

- They are useful in some high-frequency and analog applications because of their high speed, low noise, and high output power, is capable of current gain, voltage gain, and signal-power gain.

- Transistor is the active device whereas the diode is passive.

- Three basic transistor are:- bipolar junction transistor(BJT) , metal-oxide semiconductor field-effect transistor (MOSFET), and junction field-effect transistor (JFET).

- The bipolar transistor has three separately doped regions and two pn junctions, Since the flows of both electrons and holes are involved in this device, it is called a bipolar transistor.

- As with the pn junction diode, minority carrier distributions in the bipolar transistor are an important part of the physics of the device; minority carrier gradients produce diffusion currents.

CONSTRUCTION

- The three terminals of BJT are :- the emitter, base, and collector. The width of the base region is small compared to the minority carrier diffusion length.

- If the emitter is N-type, base P-type , and collector is N-type, the device is an NPN BJT.

- NPN transistors exhibit higher performance and speed than PNP transistors because the electron mobility is larger than the hole mobility.

- The emitter region has the largest doping concentration (N^+) and the collector region has the smallest.

- Typical impurity doping concentrations in the emitter, base, and collector may be on the order of 10^{19} 10^{17}. and $10^{15}cm^{-3}$, respectively.

- As the impurity doping conc. in the emitter and collector are different and the geometry is also different(not symmetrical).

PRINCIPLE OF OPERATION

- The base-emitter (B-E) pn junction is forward-biased (V_{BE}), and the base-collector (B-C) pn junction is reverse-biased (V_{BC}) which is called **FORWARD-ACTIVE** operating mode.

- Electrons from the emitter are injected across the B-E junction into the base due to forward biasing.

- Injected electrons create an excess concentration of minority carriers in the base.
- As B-C junction is reverse biased, minority carrier electron concentration at the edge of the B-C junction is ideally zero.

- They diffuse across the base to the reverse-biased B-C junction and get swept into the collector. This produces a **collector current, I_C.**

- Since, as many electrons as possible should reach the collector without recombining with any majority carrier holes in the base, the width of the base needs to be small compared with the minority carrier diffusion length.

Cut-off, Saturation and Inverse active mode

- [1] If the B-E voltage is zero or reverse biased ($V_{BE} \leq 0$), then majority carrier electrons from the emitter will not be injected into the base. The B-C junction is also reverse biased; so emitter and collector currents will be zero for this case. This condition is referred to as **cutoff**-all currents in the transistor are zero.

[2]voltage equation around the C-E loop

$$V_{CE} = V_{CC} - I_C R_C$$

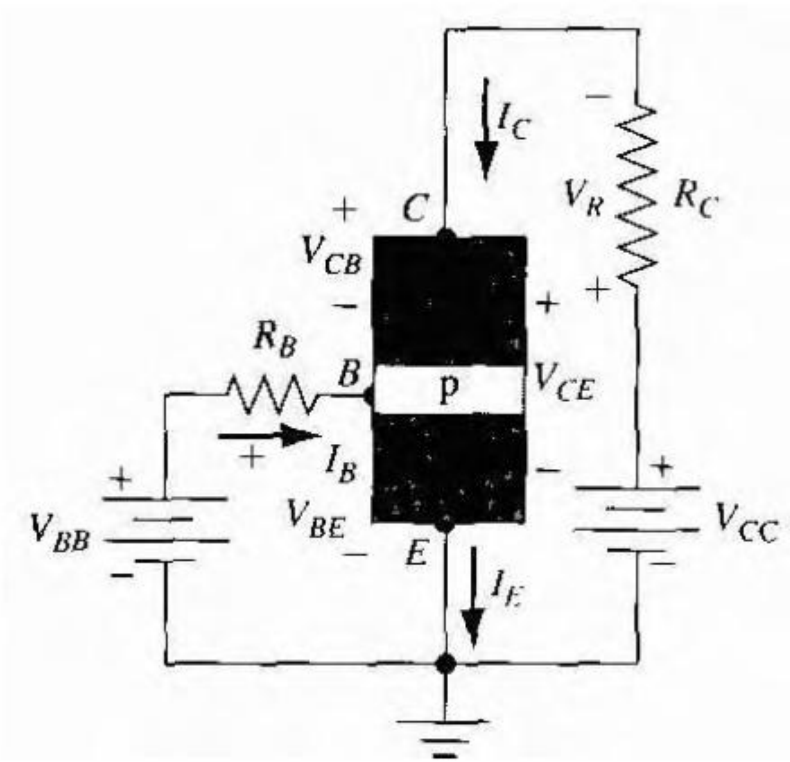
linear relation between collector current and collector emitter voltage is called a **load line.**

[3]when the B-E junction is reverse biased and the B-C junction **is** forward biased, the transistor operates "upside down," and the roles of the emitter and collector are reversed;- is called **Inverse Active mode**.

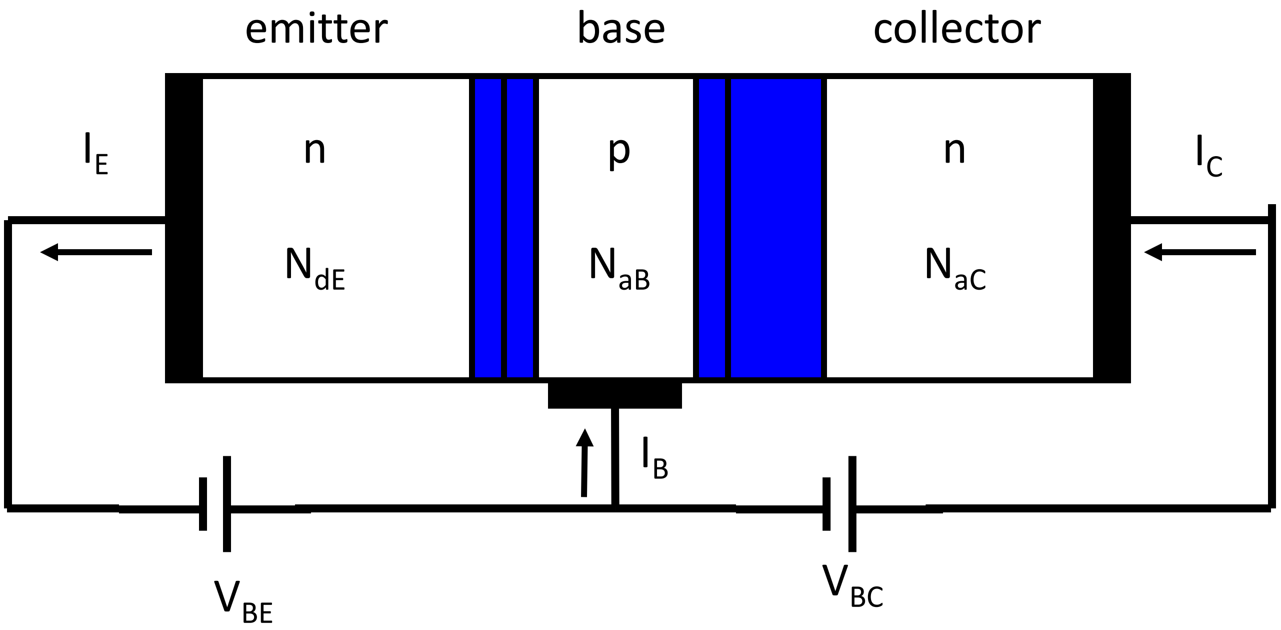
[4] As the forward-biased B-E voltage increases, the collector current and hence VR will also increase & so the reverse-biased C-B voltage decreases, The collector current may become large enough that the combination of VR and Vcc produces zero voltage across the B-C junction. A slight increase in Ic beyond this point will cause a slight increase in VR and the B-C junction will become forward biased (VCB < **0).** This condition is called **saturation**. In the saturation mode of operation, both B-E and B-C junctions are forward biased and the collector current is no longer controlled

equations around the collector-emitter loop

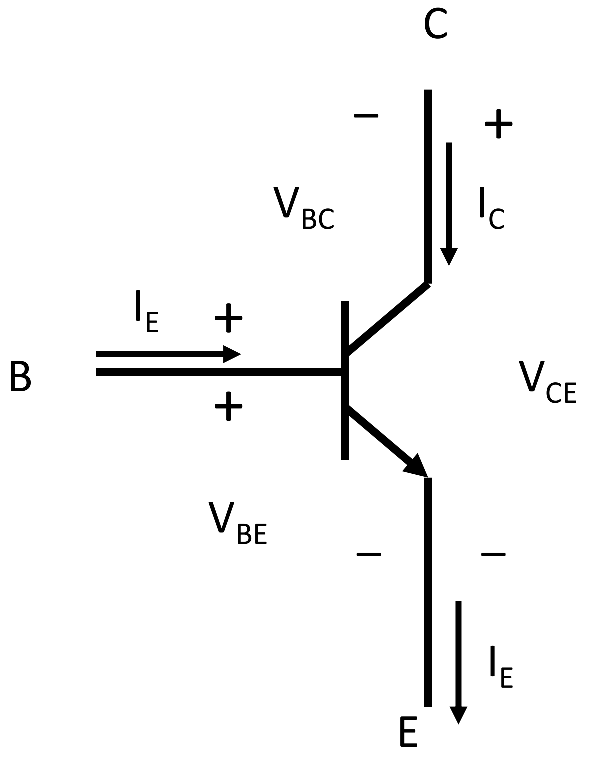
$$V_{CC} = I_C R_C + V_{CB} + V_{BE} = V_R + V_{CE}$$



BJT Model

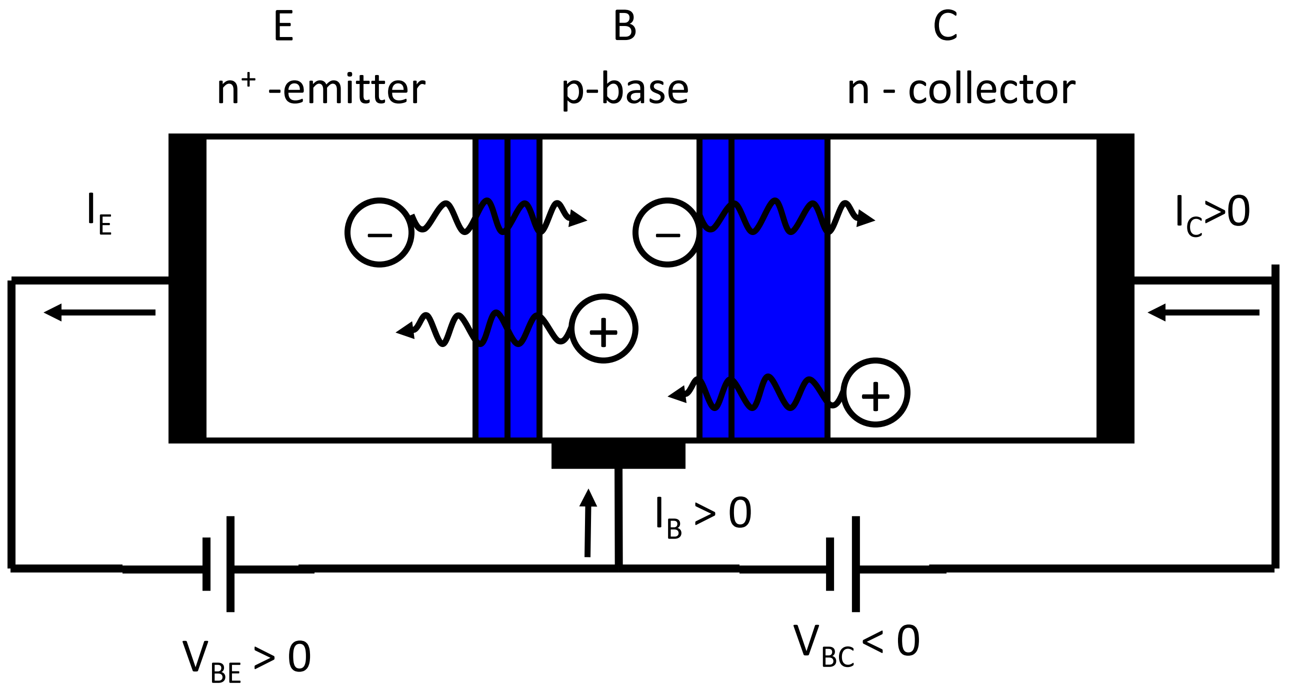


- Two back to back p-n junctions
- Base region is thin enough to enable minority carriers to diffuse through base region.
- Junction are far apart so that their depletion layers do not overlap.



n-p-n transistor

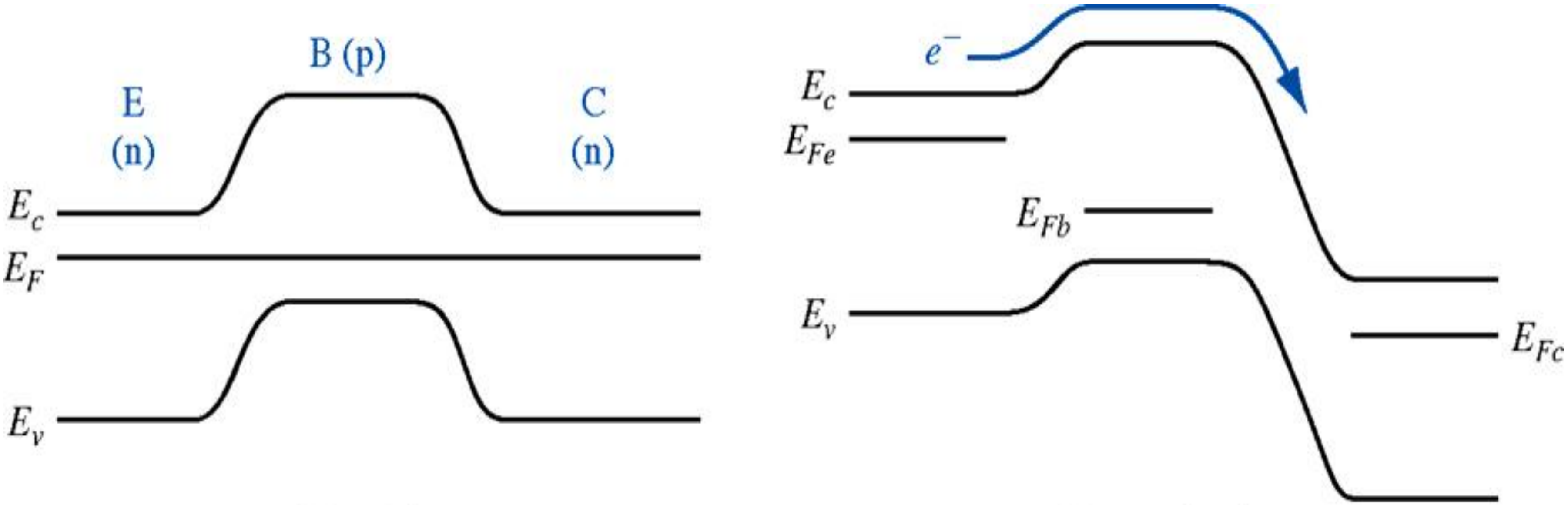
Forward Active Mode



$V_{BE} > 0$ & $V_{BC} < 0$

$V_{BE} > 0 \Rightarrow$ injection of electrons from E to B
injection of holes from B to E
$V_{BC} < 0 \Rightarrow$ extraction of electrons from B to C
extraction of holes from C to B

Electron injected into B is extracted by C due to reverse bias.

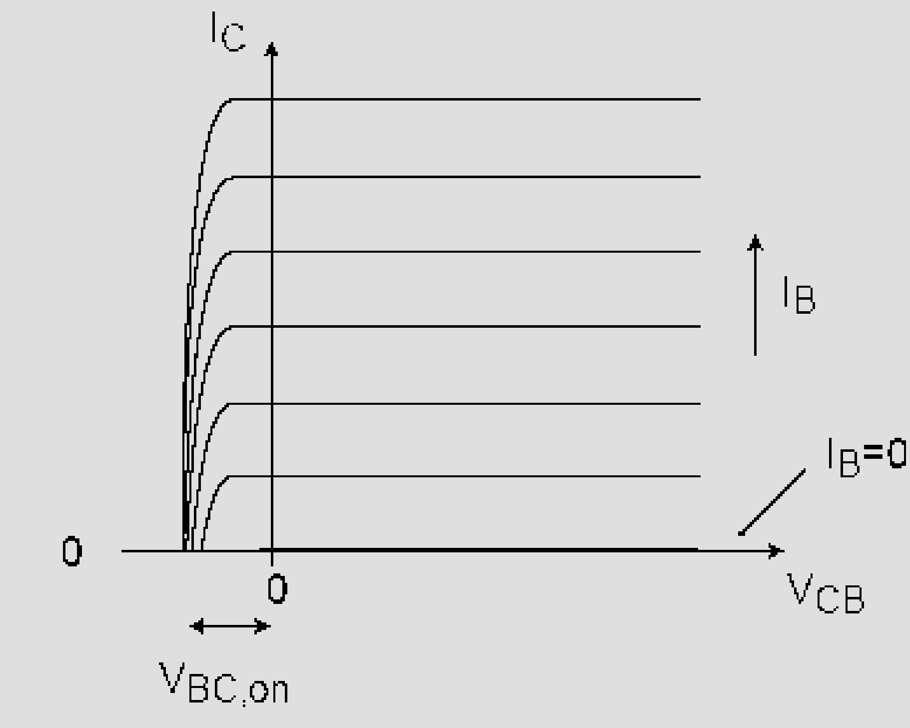


Zero bias

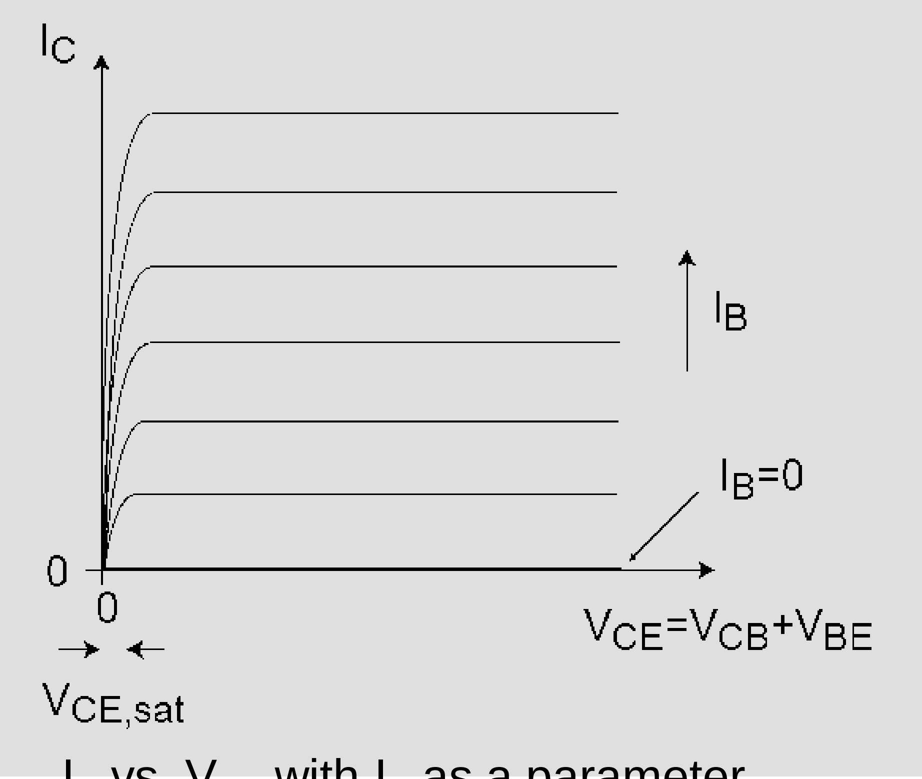
Forward active

(c)

I-V Characteristics

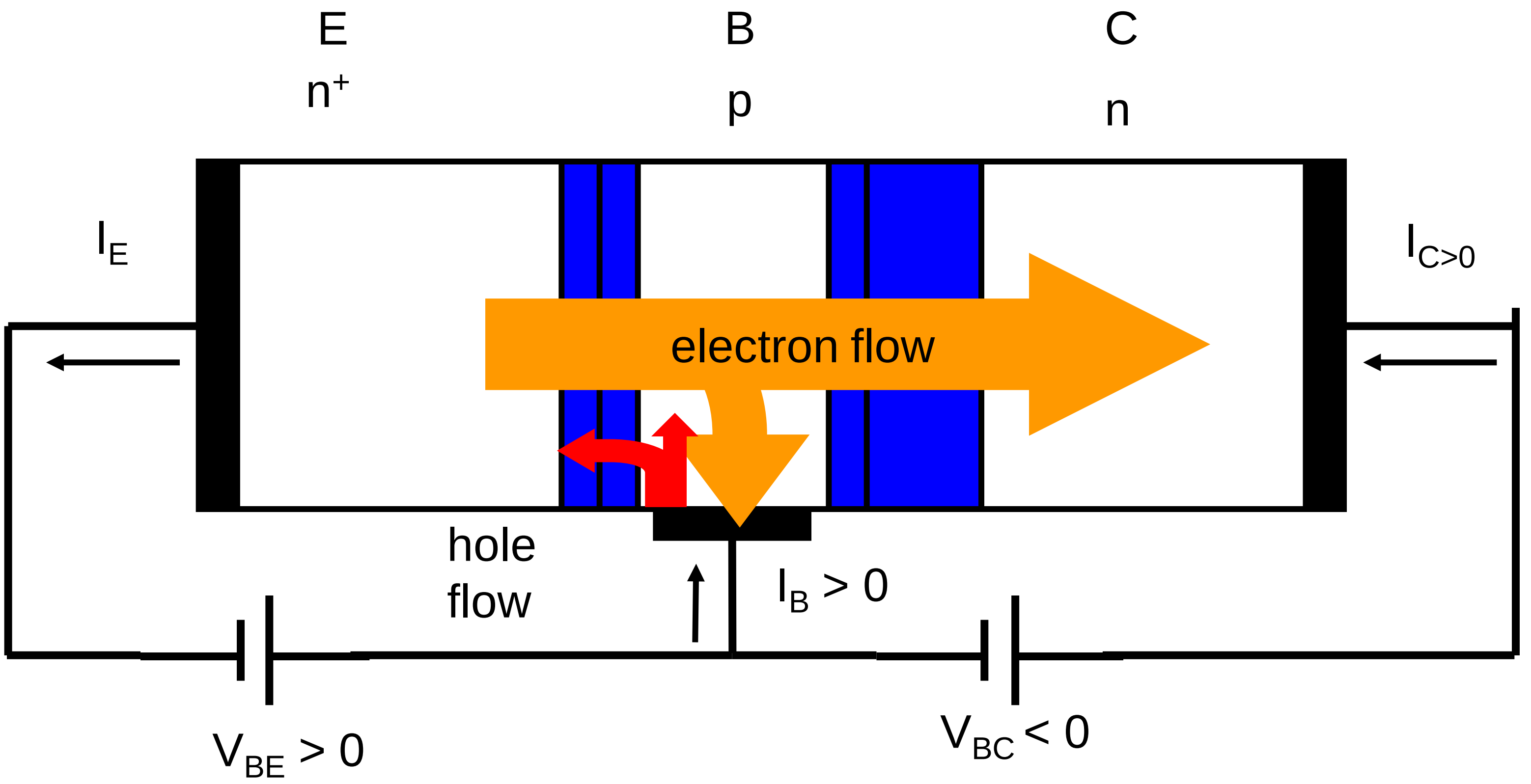


I_C vs. V_{CB} with I_B as a parameter



I_C vs. V_{CE} with I_B as a parameter

Current flow in Forward Active mode



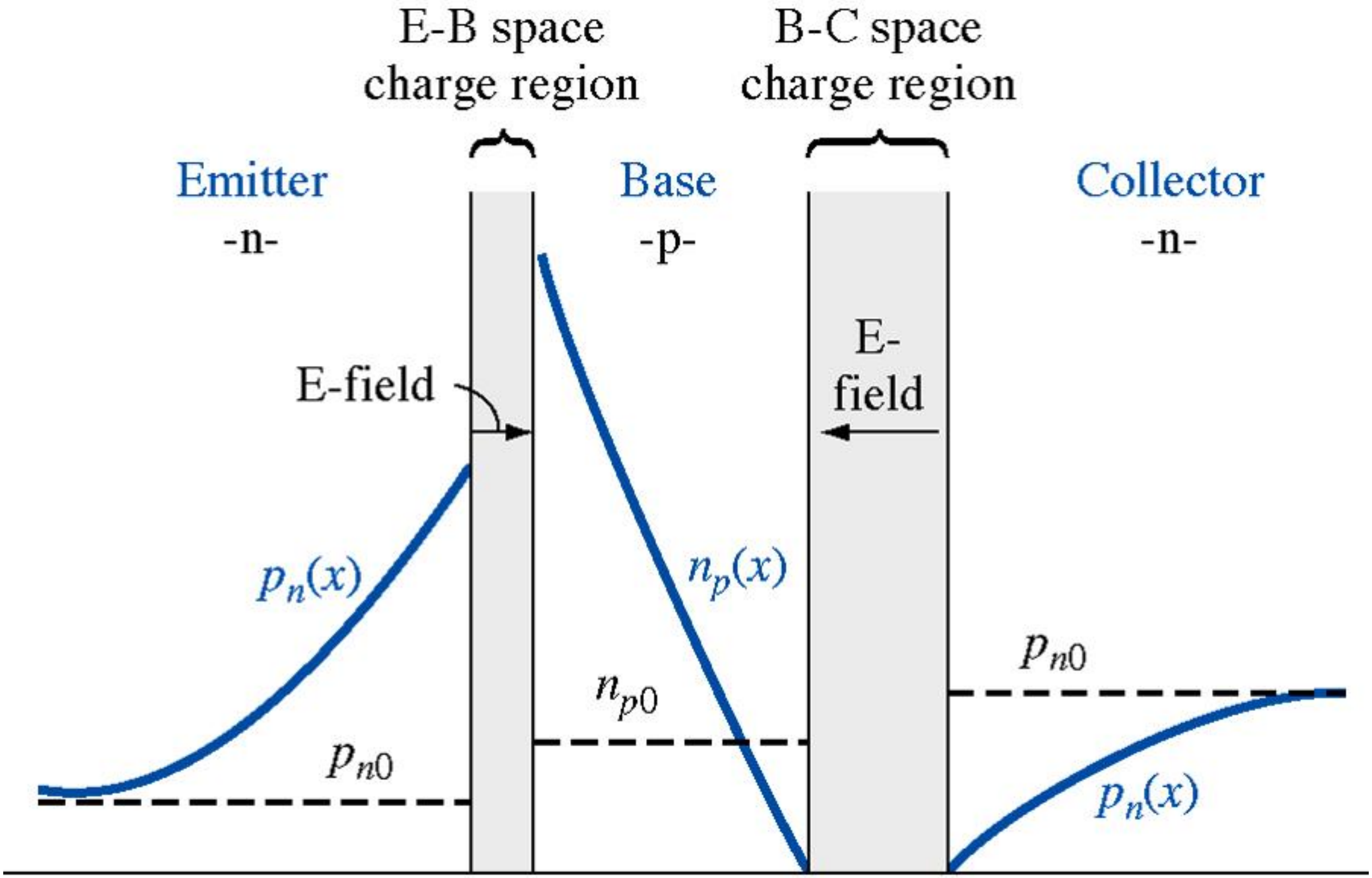
- **I_C is** independent of V_{CB} as long as V_{CB} is a reverse bias.

- I_C is determined by the rate of electron injection from the emitter into the base, is determined by V_{BE}.

- The rate of injection is proportional to $e^{qV_{BE}/kT}$

- Emitter:- source, collector:- Drain & Base:- gate

- Because of IR drops, it is difficult to accurately ascertain the true base–emitter junction voltage, so , the easily measurable base current, I_B, is commonly used as the variable parameter in lieu of V_{BE} .


E-B space charge region
B-C space charge region
Emitter
-n-
Base
-p-
Collector
-n-
E-field
E-field
$p_n(x)$
$n_p(x)$
$p_n(x)$
p_{n0}
n_{p0}
p_{n0}

(b)

Other operating Modes

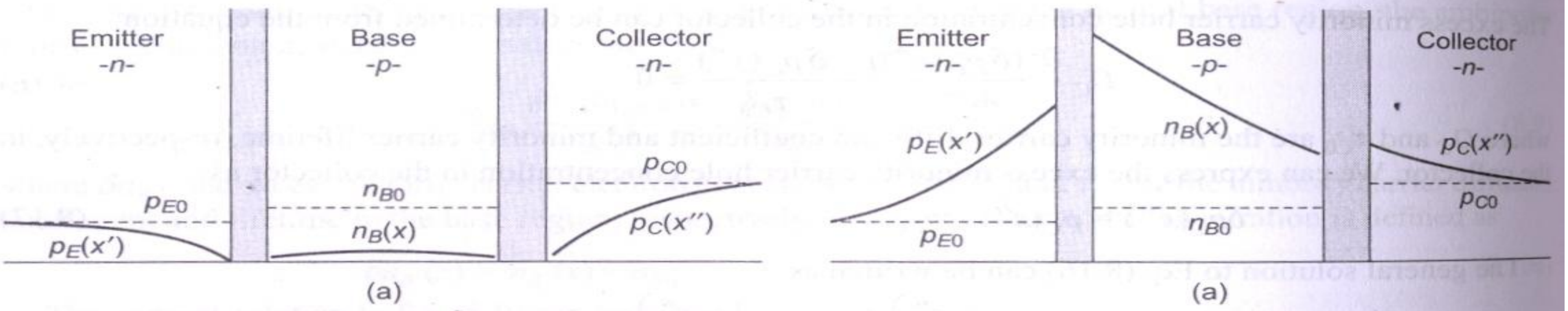


Fig. 8.15 *Minority carrier distribution in an npn bipolar transistor operating in (a) cutoff, and (b) saturation*

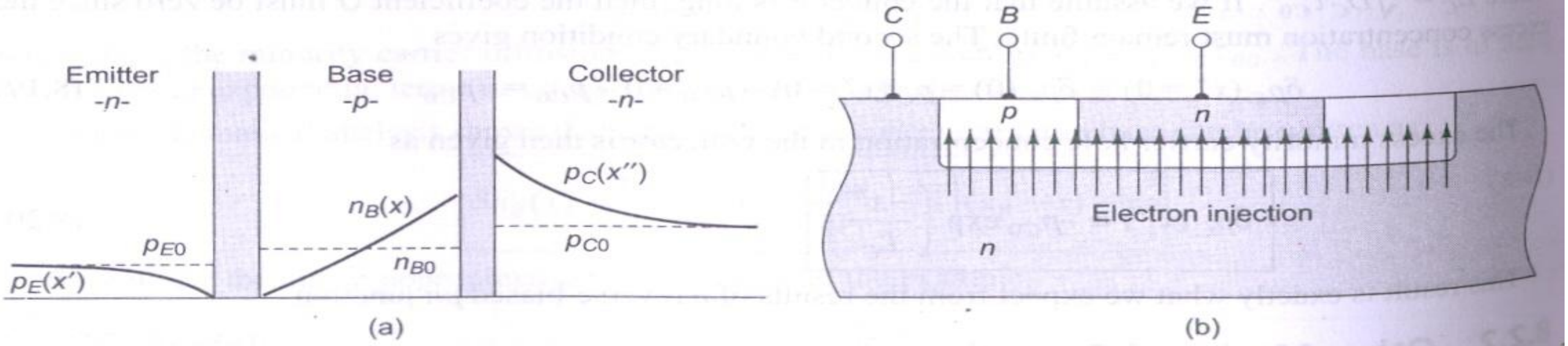


Fig. 8.16 *(a) Minority carrier distribution in an npn bipolar transistor operating in the inverse-active mode (b) Cross section of an npn bipolar transistor showing the injection and collection of electrons in the inverse-active mode*

cutoff

Both the junctions
reverse biased

saturation

Both the junctions
forward biased

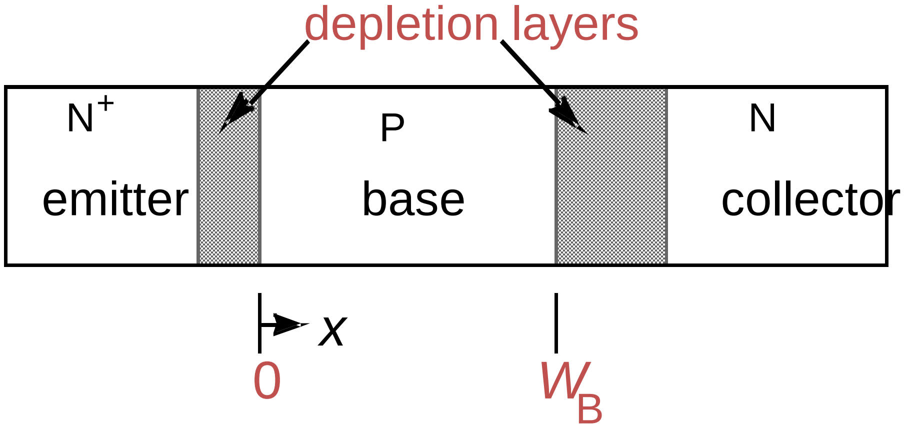
inverse-active mode.

B-E reverse biased
& B-C forward biased

Collector Current

Applying the ambipolar transport equation for excess minority carrier electrons in the base region

$$\frac{d^2(\delta n_B(x))}{dx^2} = \frac{\delta n_B(x)}{L_B^2}$$



$$L_B \equiv \sqrt{\tau_B D_B}$$

τ_B : base recombination lifetime
D_B : base minority carrier (electron) diffusion constant

Boundary conditions

$$\delta n_B(0) = n_{B0}(e^{eV_{BE}/kT} - 1)$$

$$\delta n_B(W_B) = n_{B0}(e^{eV_{BC}/kT} - 1) \approx -n_{B0} \approx 0$$

$$\delta n_B(x) = n_{B0}(e^{eV_{BE}/kT}-1)\frac{\sinh\left(\frac{W_B - x}{L_B}\right)}{\sinh(W_B/L_B)}$$

$$\delta n_B(x) = \delta n_B(0)(1 - x/W_B)$$

$$= \frac{n_{iB}^2}{N_B}(e^{eV_{BE}/kT}-1)(1 - x/W_B)$$

$$I_C = \left| A_E e D_B \frac{dn}{dx} \right|$$

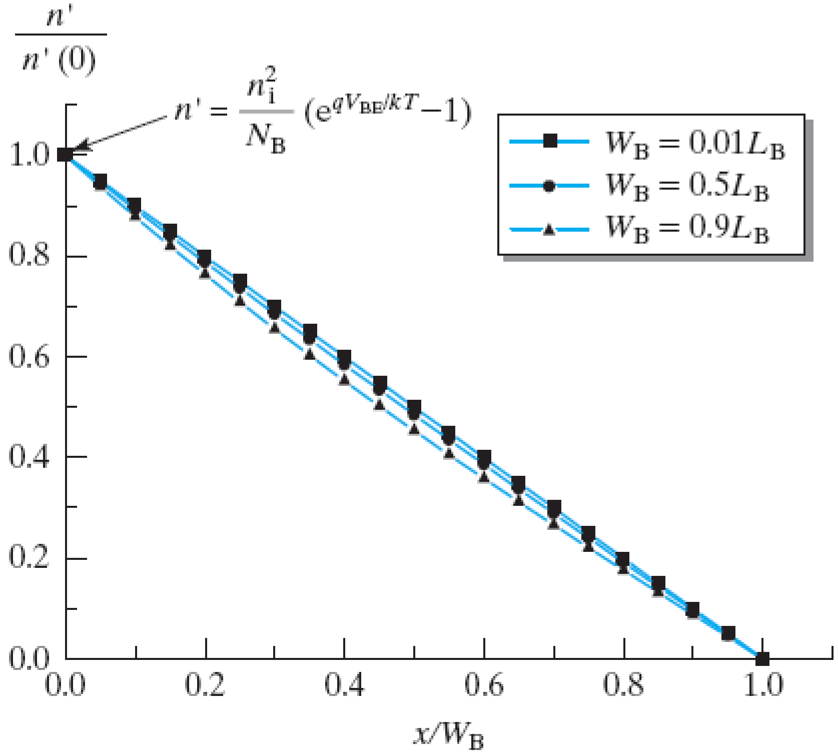
$$= A_E e \frac{D_B}{W_B}\frac{n_{iB}^2}{N_B}(e^{eV_{BE}/kT}-1)$$

$$I_C = A_E \frac{e n_i^2}{G_B}(e^{eV_{BE}/kT}-1)$$

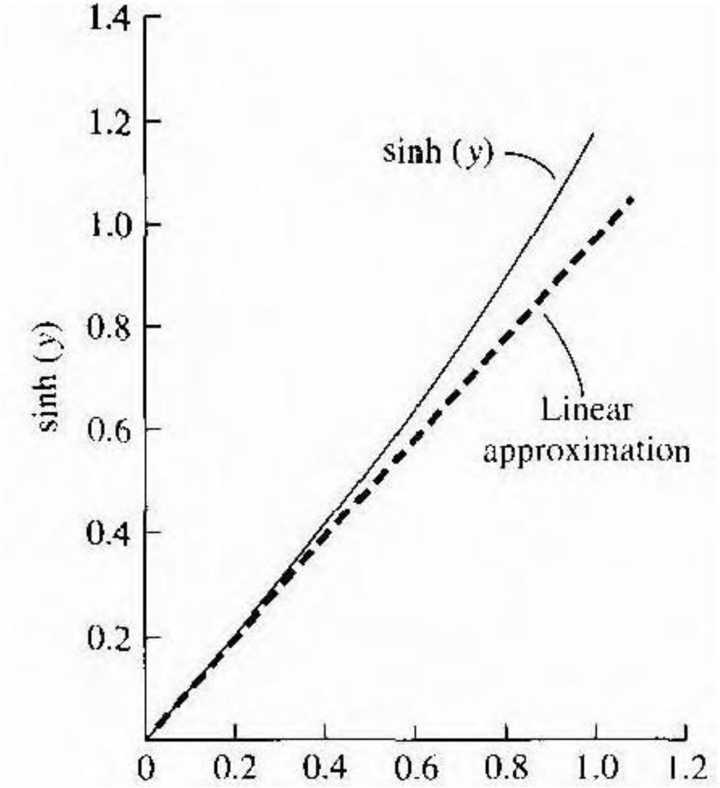
$$G_B \equiv \int_0^{W_B} \frac{n_i^2}{n_{iB}^2}\frac{p}{D_B}\,dx$$

$$I_C = I_S(e^{eV_{BE}/kT}-1)$$

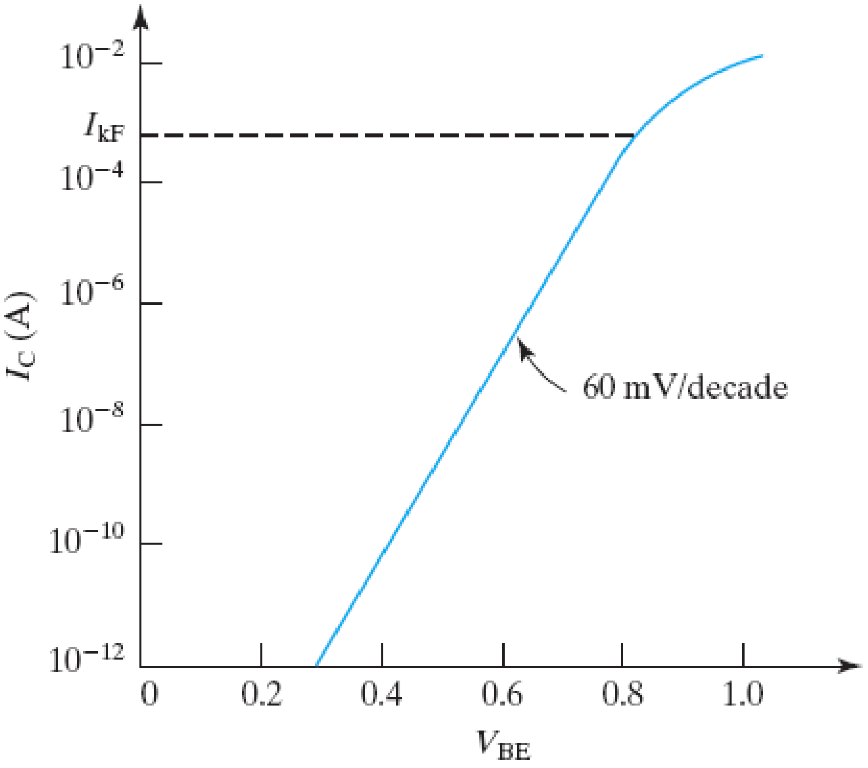
G_B (s·cm^4) is the ***base Gummel number***



When $W_B \ll L_B$, the excess minority carrier concentration in the base is approximately a linear function of x.



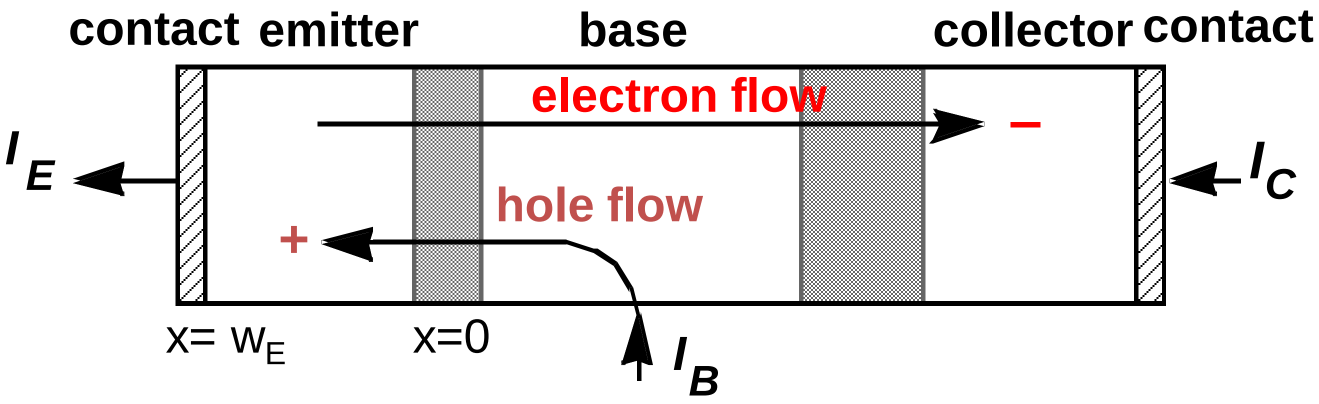
Hyperbolic sine function
and its linear approximation.



I_C is an exponential function of V_{BE}.

Base Current

Some holes are injected from the P-type base into the N^+ emitter. The holes are provided by the base current, I_B.

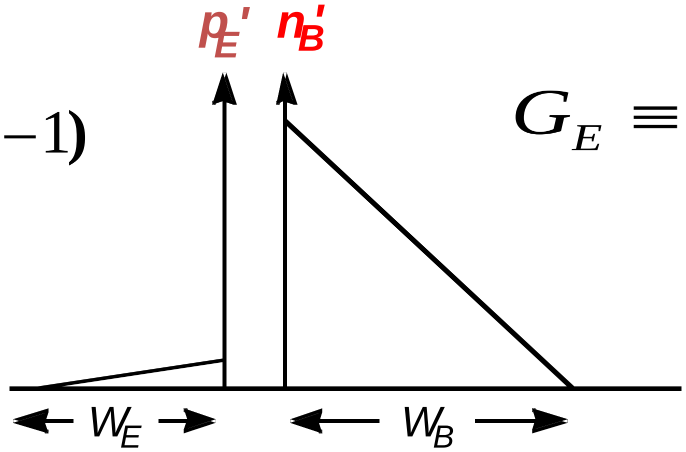


$$I_B = A_E \frac{e n_i^2}{G_E}\left(e^{eV_{BE}/kT} - 1\right)$$

$$G_E \equiv \int_0^{W_E} \frac{n_i^2}{n_{iE}^2}\frac{n}{D_E}\,dx$$

For a uniform emitter,

$$I_B = A_E e \frac{D_E n_{iE}^2}{W_E N_E}\left(e^{eV_{BE}/kT} - 1\right)$$



CURRENT GAIN

the most important DC parameter of a BJT is its **common-emitter current gain, β_F.**

Common-emitter current gain, β_F :

$$\boxed{\beta_F \equiv \frac{I_C}{I_B}}$$

Common-base current gain:

$$I_C = \alpha_F I_E$$

$$\alpha_F \equiv \frac{I_C}{I_E} = \frac{I_C}{I_B + I_C} = \frac{I_C / I_B}{1 + I_C / I_B} = \frac{\beta_F}{1 + \beta_F}$$

$$\boxed{\beta_F = \frac{\alpha_F}{1 - \alpha_F}}$$

$$\beta_F = \frac{G_E}{G_B} = \frac{D_B W_E N_E n_{iB}^2}{D_E W_B N_B n_{iE}^2}$$

β_F can be maximized by maximizing N_E

Or minimizing N_B A typical good β_F is 100

Amplification

***$Ic = \beta I_B$*.** then a relatively large sinusoidal collector current is superimposed on a dc value of collector current. The time-varying collector current induces a time varying voltage across the Rc- resistor which, by Kirchhoff's voltage law, means that a sinusoidal voltage, superimposed on a dc value, exists between the collector and emitter of the bipolar transistor. The sinusoidal voltages in the collector-emitter portion of the circuit are larger than the signal input voltage vi , so that the circuit has produced a voltage gain in the time-varying signals. Hence, the circuit is known as a voltage amplifier.

An emitter is said to be efficient if the emitter current is mostly the useful electron current injected into the base with little useless hole current (the base current). The **emitter efficiency is defined as**

$$\gamma_E = \frac{I_E - I_B}{I_E} = \frac{I_C}{I_C + I_B} = \frac{1}{1 + G_B/G_E}$$

Emitter Bandgap Narrowing

$$\boxed{\beta \propto \frac{N_E}{N_B}\frac{n_{iB}^2}{n_{iE}^2}}$$

To raise β_F, N_E is typically very large, but large N_E makes, $n_{iE}^2 > n_i^2$ which is called the **heavy doping effect.**

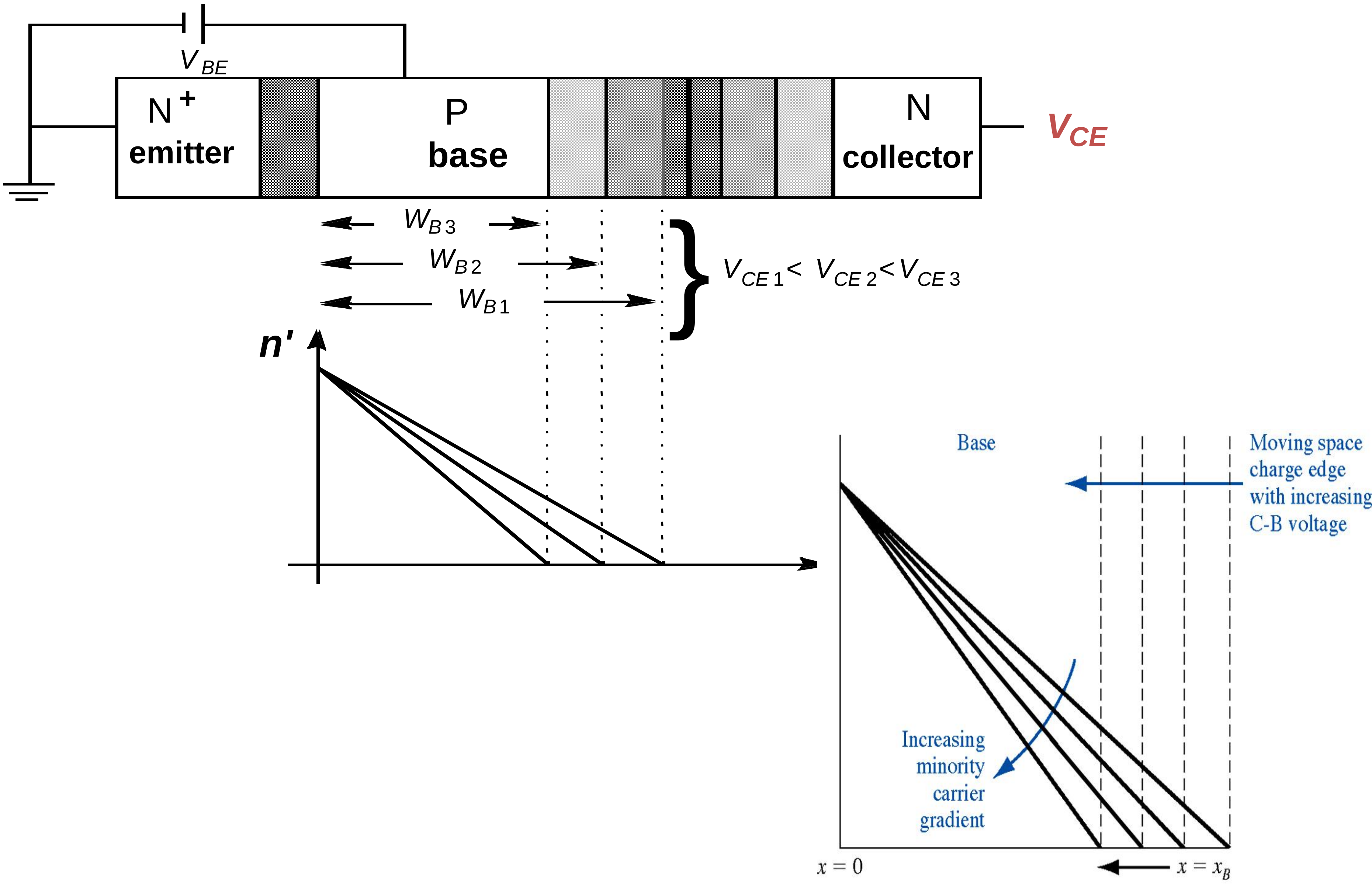
$$\boxed{n_i^2 = N_C N_V e^{-E_g/kT}}$$

Since n_i is related to E_g, this effect is also known as band-gap narrowing.

$$n_{iE}^2 = n_i^2 e^{\Delta E_{gE}/kT}$$

ΔE_g is called band gap narrowing factor.
Emitter bandgap narrowing makes it difficult to raise b_F by doping the emitter very heavily.

BASE-WIDTH MODULATION



- Base width is a function of the **B-C voltage, width of the space** charge region extending into the base region varies with B-C voltage.

- As the **B-C** reverse-bias voltage increases, the B-C space charge region width increases & W_B **reduces.**

- reduction in base width causes the minority carrier concentration gradient to increase, so an increase in the diffusion current.

- This effect (rise in output current due to band width modulation) is known as ***base width modulation or Early effect.***

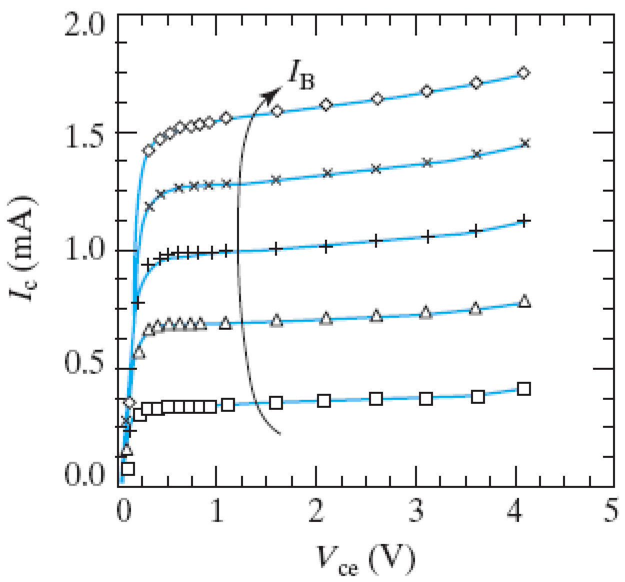
- Ideally the collector current is independent of the **output voltage so that the slope** of the curves would be zero:- so the output conductance is zero.
- But base width modulation (Early effect) , produces a nonzero slope and gives rise to a finite output conductance.

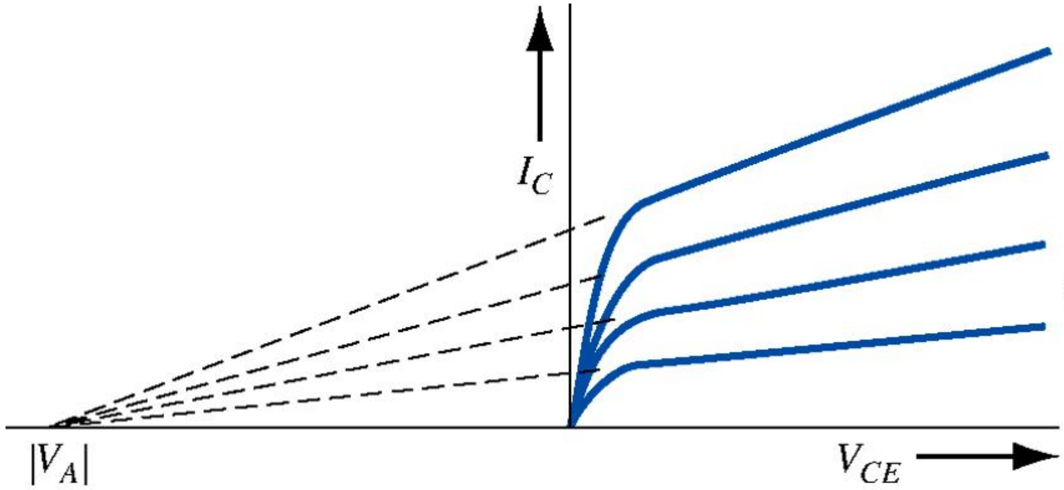
- If the collector current characteristics are extrapolated to zero collector current, the curves intersect the voltage axis at a point that is defined as the Early voltage.

- The Early voltage is considered to be a positive value, typical values of Early voltage are in the 100- to 300-volt range.

BASE-WIDTH MODULATION BY COLLECTOR VOLTAGE

V_A is a parameter that describes the flatness of the I_C curves.





V_A increases with:

(a) increase the base width

(b) increase the base doping concentration, N_B, *or*

(c) decrease the collector doping concentration, N_C.

$$\frac{dI_C}{dV_{CE}} \cong g_0 = \frac{I_C}{V_{CE} + V_A}$$

$$I_C = g_0(V_{CE} + V_A)$$

Shows the collector current is a function of the C-E voltage or the C-B voltage.

Breakdown Voltage

Two breakdown mechanisms in a bipolar transistor

(i) Punch-through
(ii) Avalanche breakdown

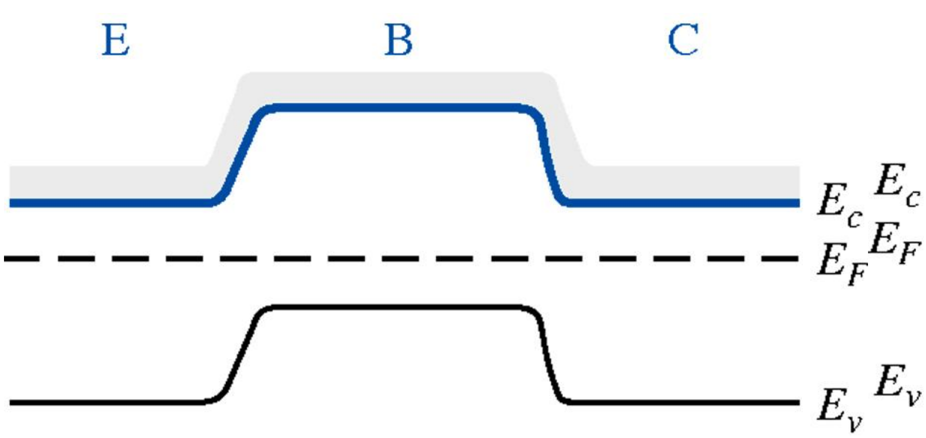
(i) Punch Through

When reverse-bias B-C voltage increases, the B-C space charge region widens and extends farther into the neutral base.

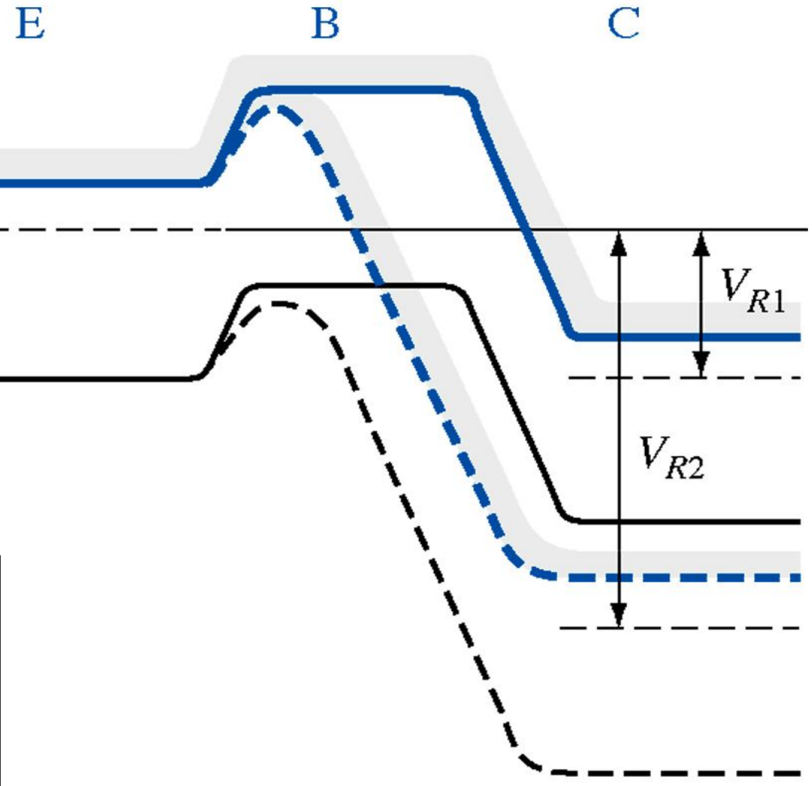
It is possible for the B-C depletion region to penetrate completely through the base and reach the B-E space charge region, the effect called punch-through

For small C-B voltage applied, the B-E potential barrier is not affected
When a large reverse-bias voltage is applied, the depletion region extends through the base region and the potential barrier is lowered because of the C-B voltage.

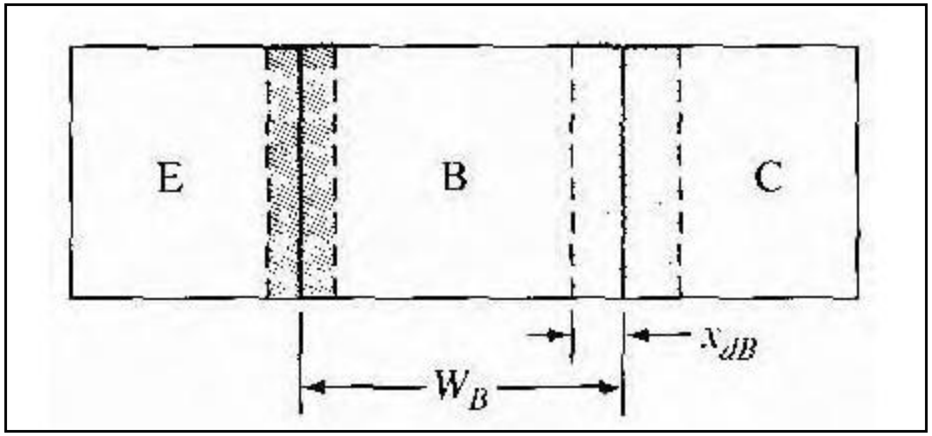
The lowering of the potential barrier at the B-E junction produces a large increase in current with very small increase in C-B voltage. This effect is the **punch-through breakdown** phenomenon.



(a)



(b)



$$x_{dB} = W_B = \left\{ \frac{2\epsilon_s(V_{bi}+V_{pt})}{e} \cdot \frac{N_C}{N_B} \cdot \frac{1}{N_C+N_B} \right\}^{1/2}$$

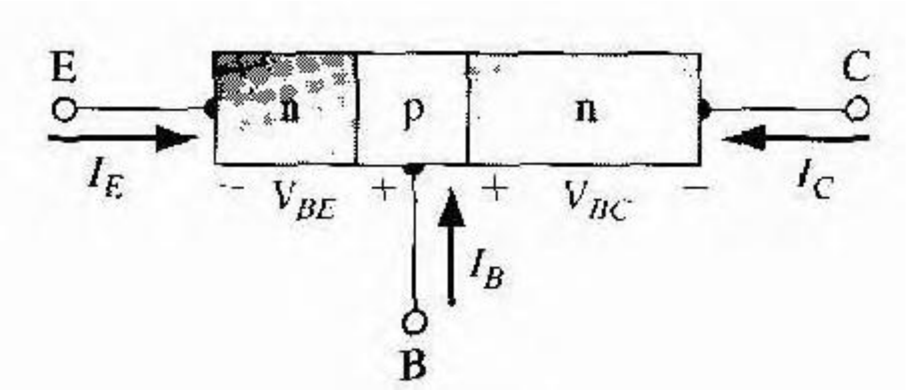
$$\boxed{V_{pt} = \frac{eW_B^2}{2\epsilon_s} \cdot \frac{N_B(N_C+N_B)}{N_C}}$$

Ebers-Moll Model

A mathematical model, or equivalent circuit, of the transistor is required to analyze a transistor circuit. Computer analysis of electronic circuits is more commonly used than hand calculations.

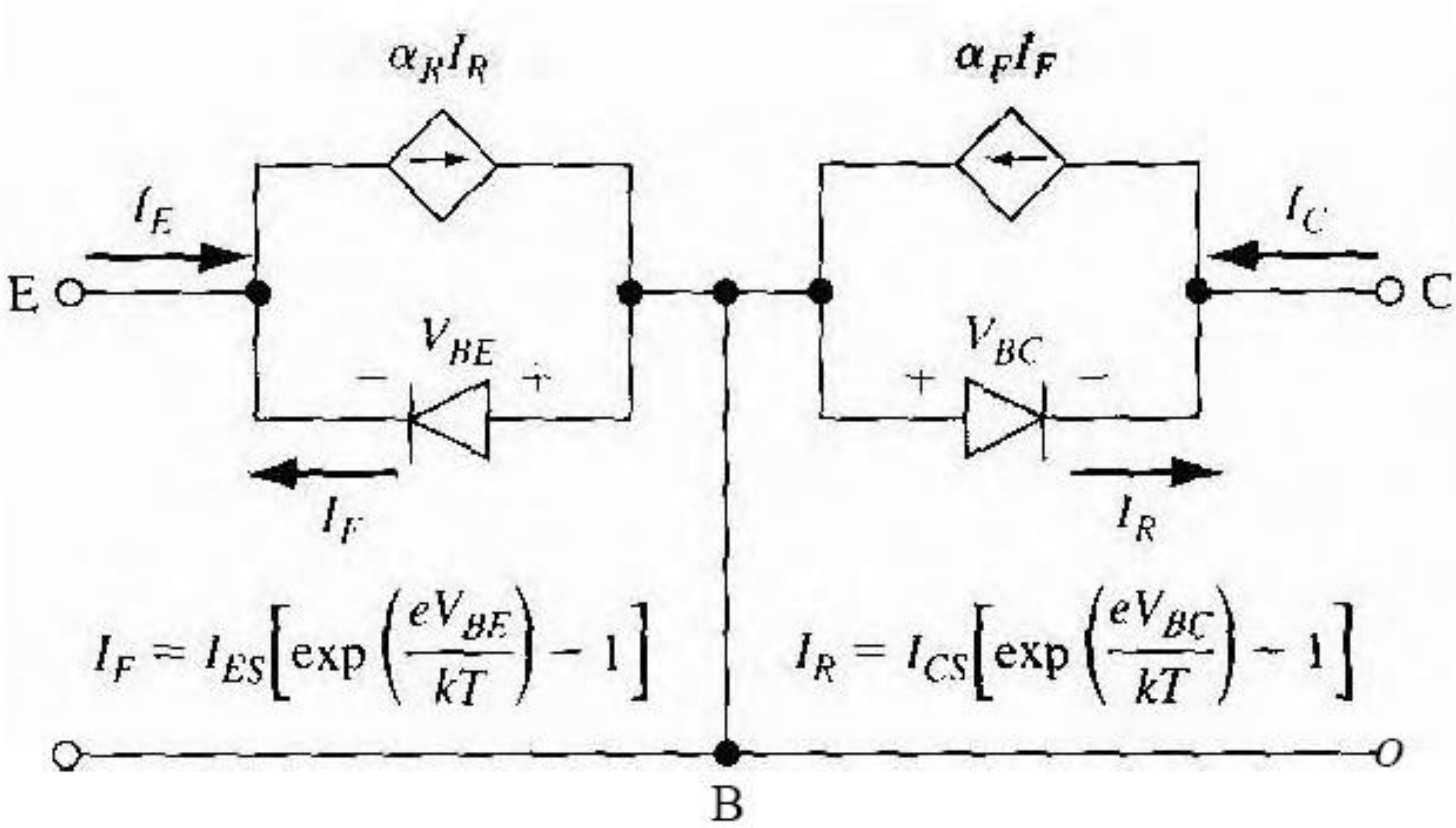
Bipolar transistors are used in switching:- usually involves turning a transistor from its "off" state, or cutoff, to its "on" state, either forward active or saturation, and then back to its "off" state.

The Ebers-Moll model is used in switching applications; model is based on the interacting diode junctions and **applicable in any of the transistor operating modes.**



The currents are defined as all entering the terminals so that

$$I_E + I_B + I_C = 0$$



Equivalent circuit corresponding to Ebers-Moll equations

The collector current can be written in general as

$$I_C = \alpha_F I_F - I_R$$

α_F is the common base current gain in the forward-active mode.

$$I_F = I_{ES}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]$$

If the B-C junction becomes forward biased, such as in saturation, then

$$I_R = I_{CS}\left[\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right]$$

The collector current

$$I_C = \alpha_F I_{ES}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] - I_{CS}\left[\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right]$$

the emitter current as

$$I_E = \alpha_R I_R - I_F$$

or

$$I_E = \alpha_R I_{CS}\left[\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right] - I_{ES}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right]$$

I_{ES} is the reverse-bias B-E junction current and α_R is the common base current gain for the inverse-active mode. Equations for I_c and I_E are the classic Ebers-Moll equations.