NANYANG TECHNOLOGICAL UNIVERSITY

Course: EE3013/ Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Week 11 – Bipolar Junction Transistors (BJT)

Learning Objectives

At the end of this lesson, you will be able to:

- Explain the physical structures of the BJT (PNP and NPN) and their corresponding energy band diagrams
- Explain the basic principle of operation of BJT under different modes of operation namely active, saturation, cutoff, and inverted modes
- Explain the minority carrier concentration distribution profiles in the emitter, base, and collector regions under various operating modes
- Derive the various current components in the BJT
- Explain the common base and common emitter configurations and their corresponding current gains
- Explain the two non-ideal effects in BJT namely base width modulation and punch through
- Explain the various types of cutoff frequencies in BJTs
- Explain how a BJT can perform as an amplifying device

- The word 'transistor' comes from a contraction of the phrase 'transfer resistor'.
- Bipolar devices are semiconductor devices in which both electrons and holes participate in the conduction process. This is in contrast to the "unipolar devices", in which only one kind of carrier predominantly participates.
- Currently, bipolar transistor or bipolar junction transistors (BJT) are used extensively in high speed circuits, analog circuits and power applications.

Image 2.1. The Fairchild's 1st commercial planar transistor (2N1613)

Image 2.2. Types of BJT products

The 1st Transistor

- On 16 December 1947, William Shockley, John Bardeen and Walter Brattain succeeded in building the first practical **point-contact** transistor at Bell Labs, followed by a demonstration to several of their colleagues and managers at Bell Labs on the afternoon of 23 December 1947.

Image 2.3. Bell Labs Scientists

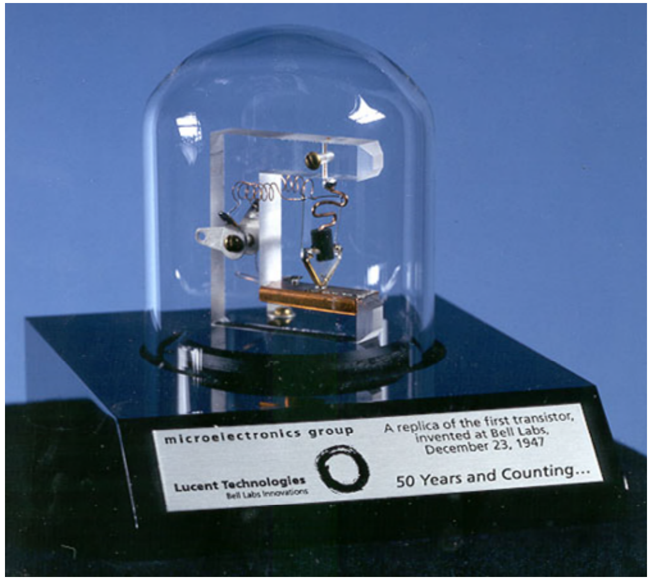


Image 2.4. Replica of the first working transistor

Image 2.5. Vacuum Tube

The 1st Transistor (Cont'd.)

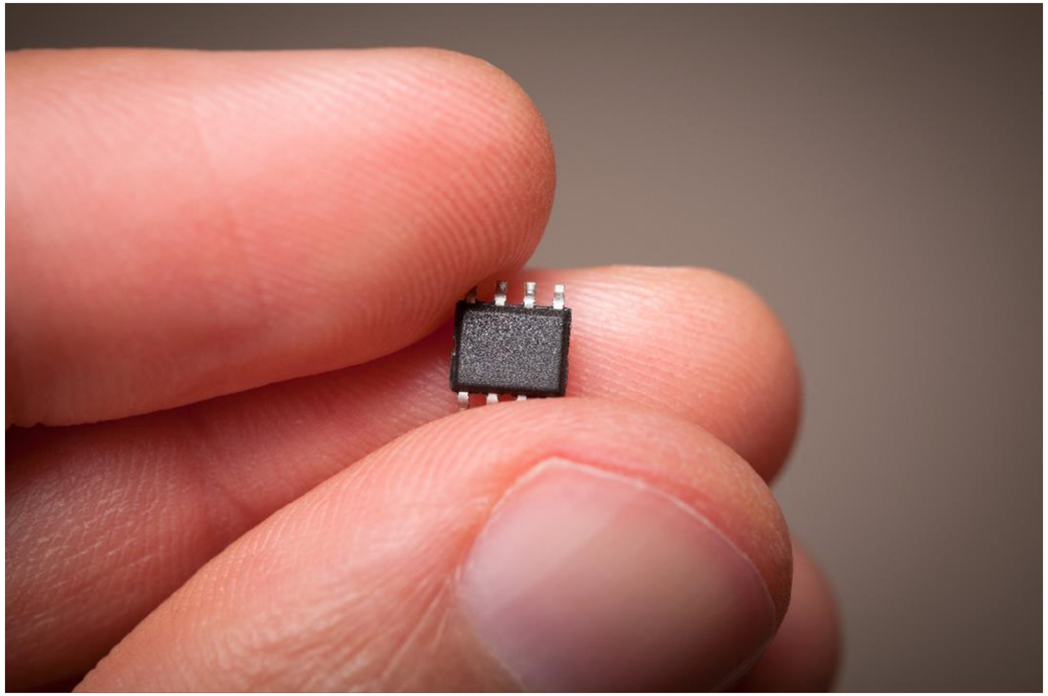


Image 2.6
World's first commercially produced transistor radio used Texas Instruments' NPN bipolar junction transistors.

- The invention of BJT lead to the Nobel Prize award in 1956.

The 1st Transistor (Cont'd.)

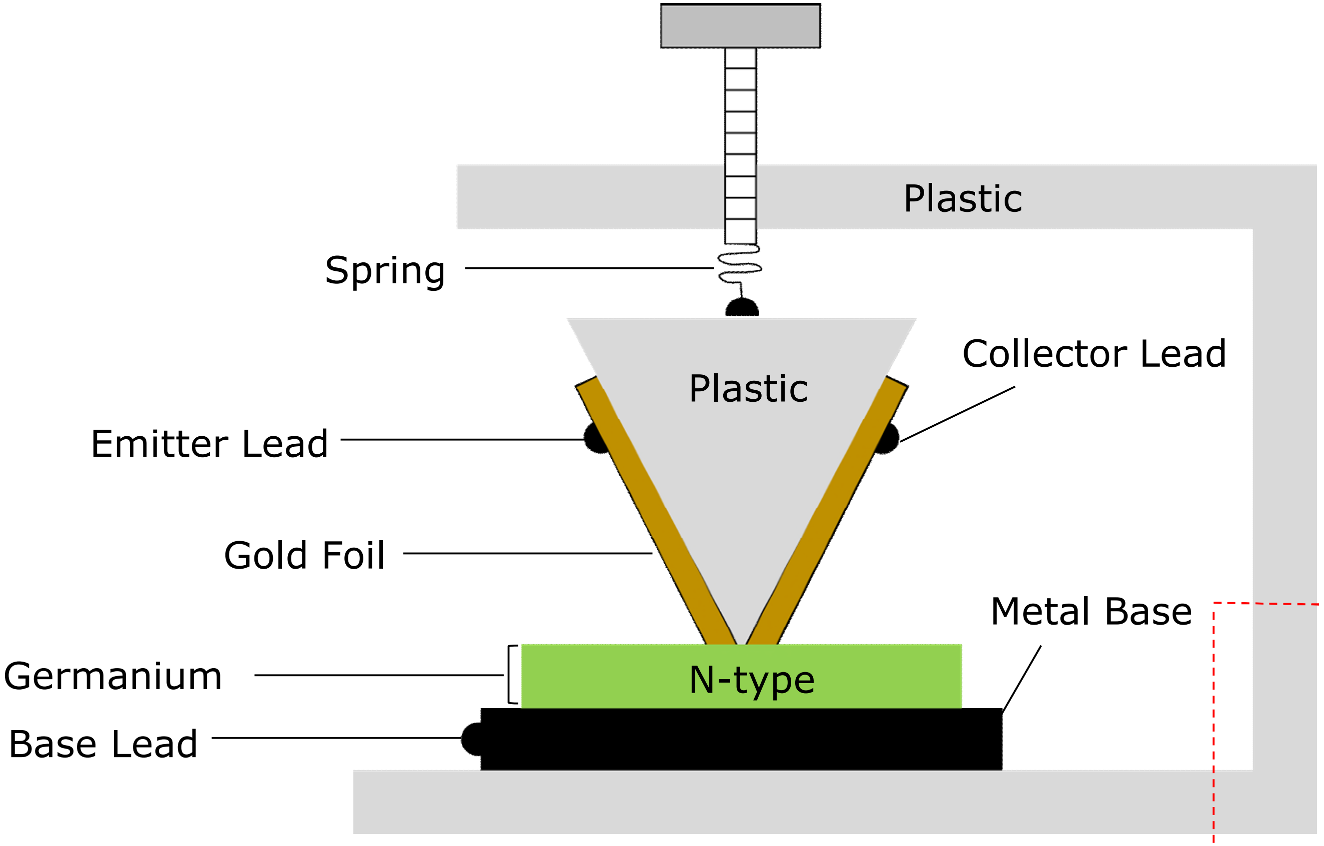


Figure 2.1. Schematic of BJT experimental setup

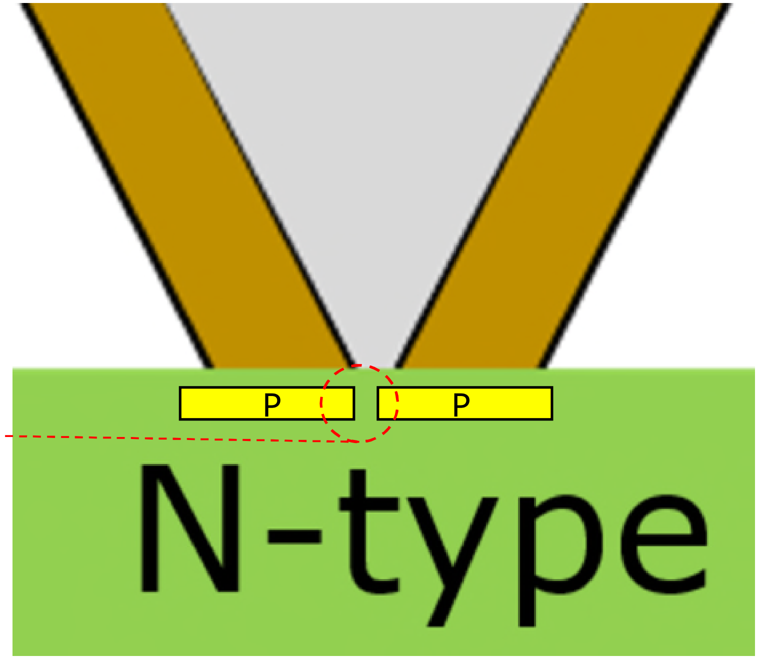


Figure 2.2. Zoomed in view

- The two point contact p-n junctions are **close** to (interact with) each other.
- The two coupled p-n junctions may result in transistor action.

Transistor Structure

- The perspective view of a silicon p-n-p bipolar transistor is shown in the image.
- The device structure consists of:
  - p-type substrate (C),
  - n-type region (B) formed by thermally diffusing P or As into the p-type substrate,
  - p^+-region (E) formed by diffusing B into the n-region, and
  - Metallic contacts made by evaporating metal to the p^+- and n-regions through the windows open in the oxide and to the bottom of the p-type wafer.

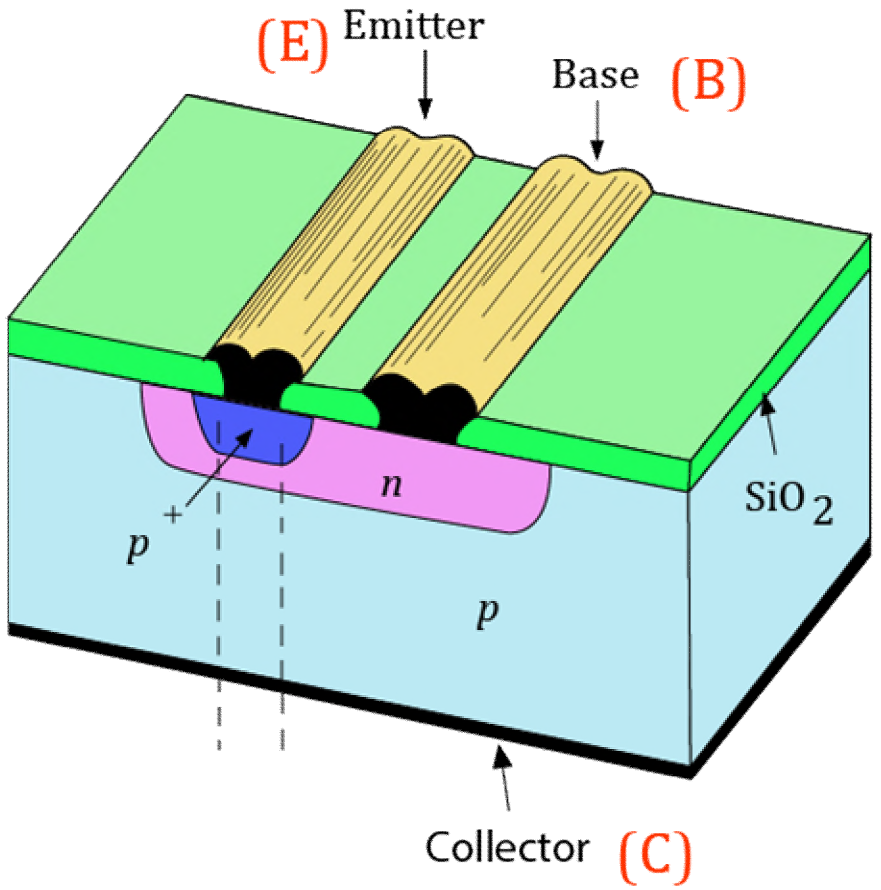
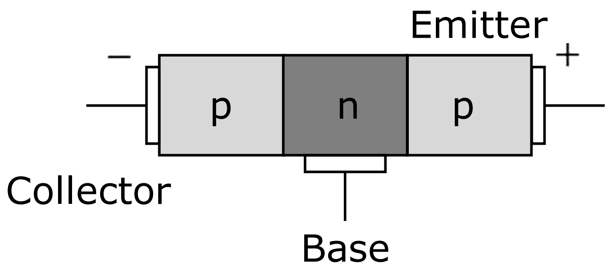
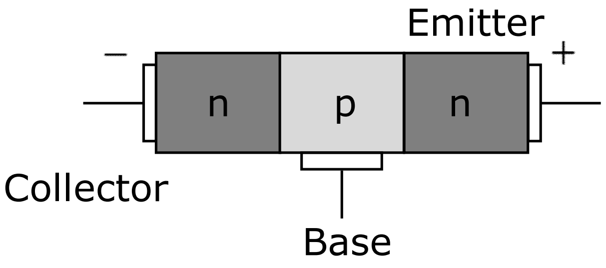
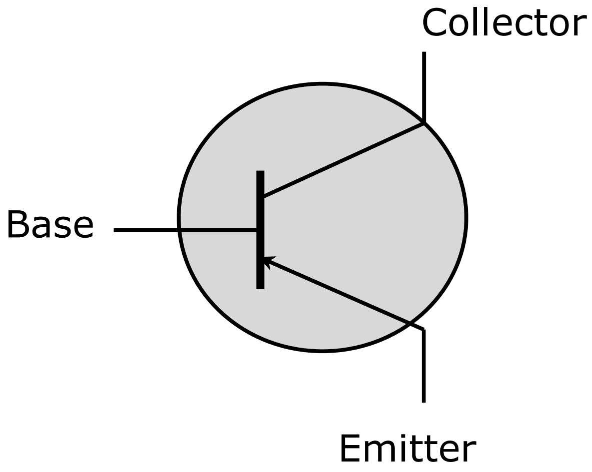
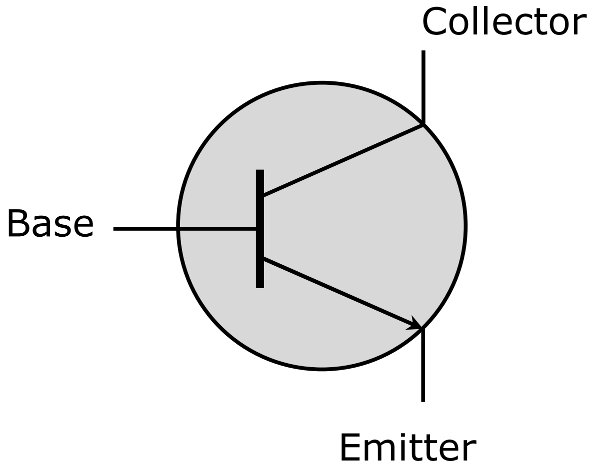


Figure 2.3. Transistor Structure

One-Dimensional Schematic

The schematic diagrams of bipolar transistors and circuit symbols are illustrated below.

PNP	**NPN**
 **Figure 2.4**	 **Figure 2.5**
 **Figure 2.6**	 **Figure 2.7**

- We shall take a p-n-p type BJT as an example because the direction of the minority-carriers (holes) flow is the same as current flow.
- So, it provides a more intuitive base for understanding the mechanism of charge transport.

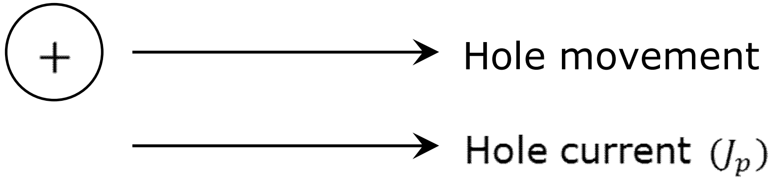


Figure 2.8

- For the n-p-n transistors, the principle and formulae derived for the p-n-p BJTs are also available but need to reverse the polarities and conduction types.

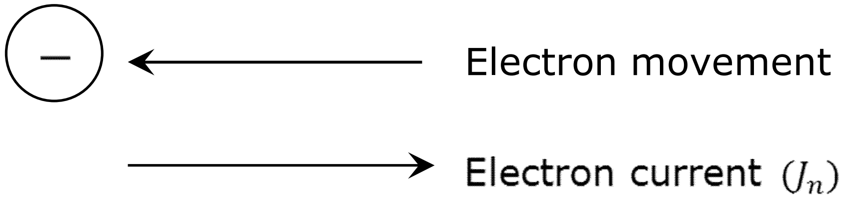


Figure 2.9

A p-n-p Transistor at Thermal Equilibrium

a. Consider a p-n-p transistor with no external voltage applied (**thermal equilibrium**). W_{eb} and W_{bc} are the depletion regions of the E-B and B-C junctions, respectively.

b. Doping profile of the transistor with abrupt impurity distributions in three regions.

N_{AE}**(emitter)**$>N_{DB}$**(base)**$>N_{AC}$**(collector)**

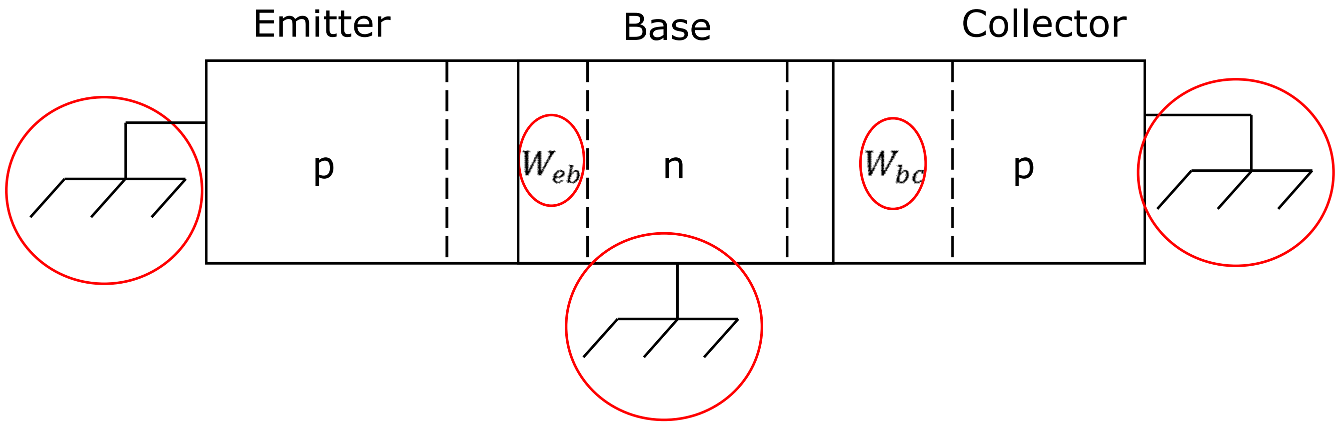


Figure 2.10a

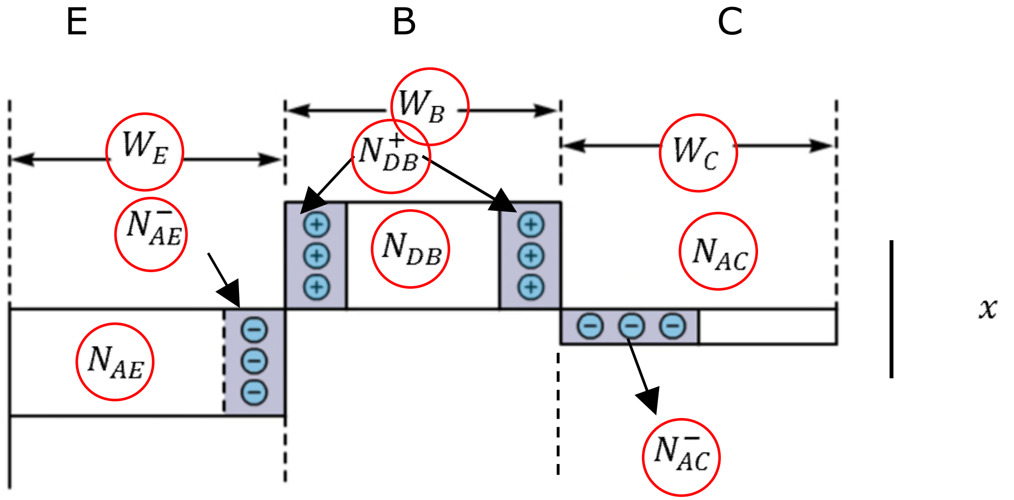


Figure 2.10b

A p-n-p Transistor at Thermal Equilibrium

c. Electric-field profile

d. Energy band diagram at thermal equilibrium ➔ E_F is constant throughout

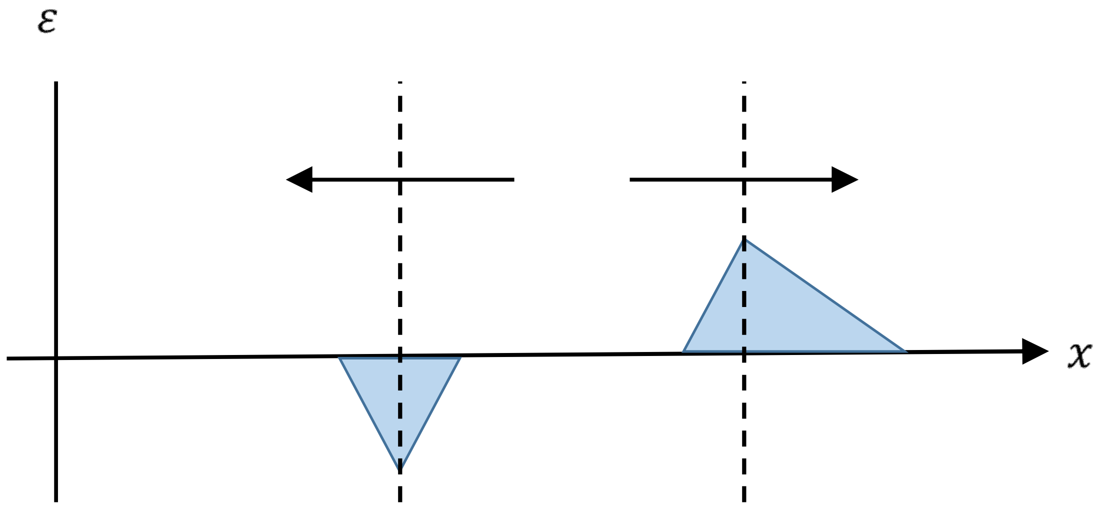
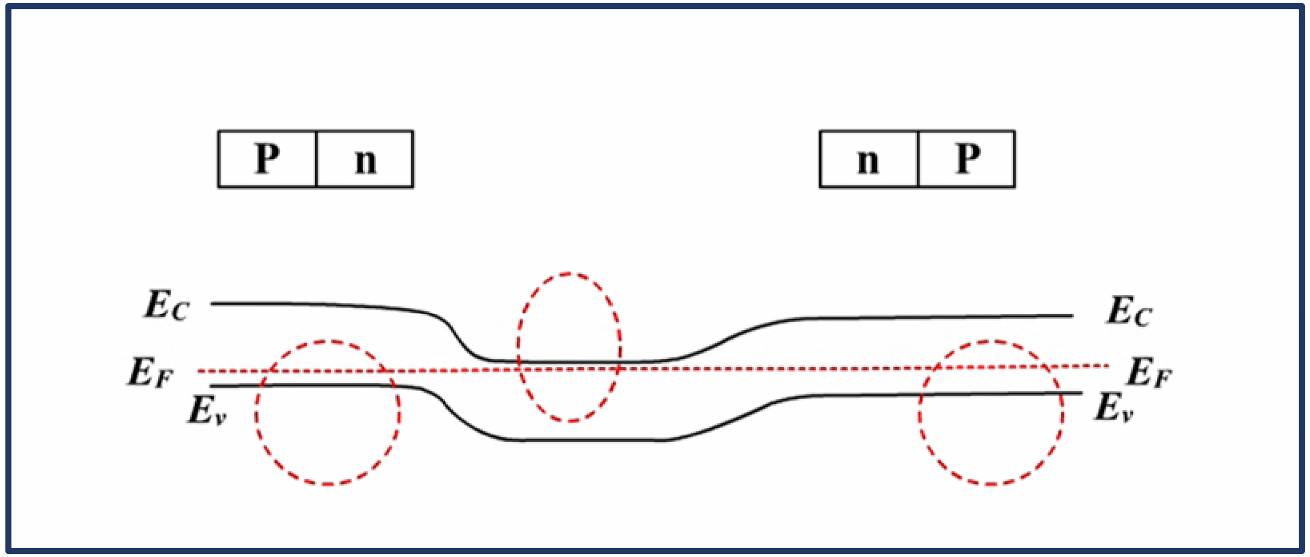


Figure 2.10c



Animation 2.1

Active mode:

a. Emitter-base junction is forward biased ➔ W_{eb} is decreased

Base-collector junction is reverse biased ➔ W_{bc} is increased

b. Less +ve and –ve charges in W_{eb} and more in W_{bc}

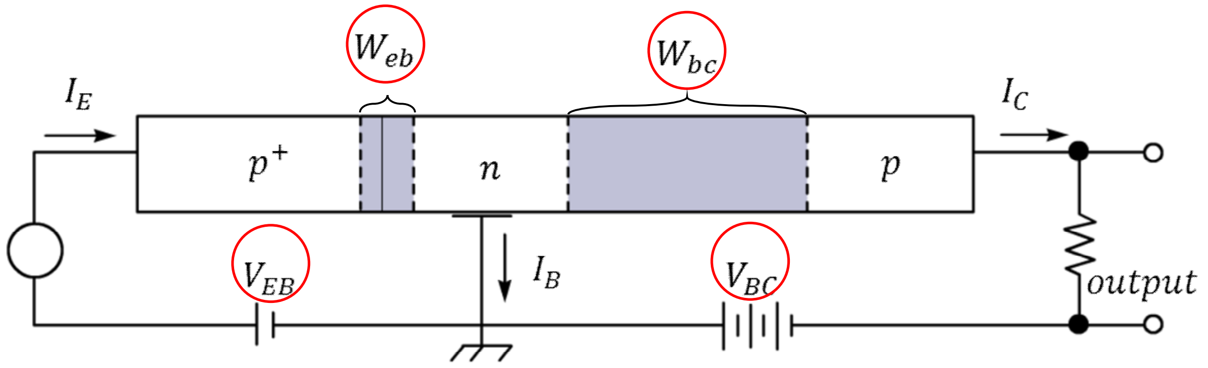


Figure 2.11a

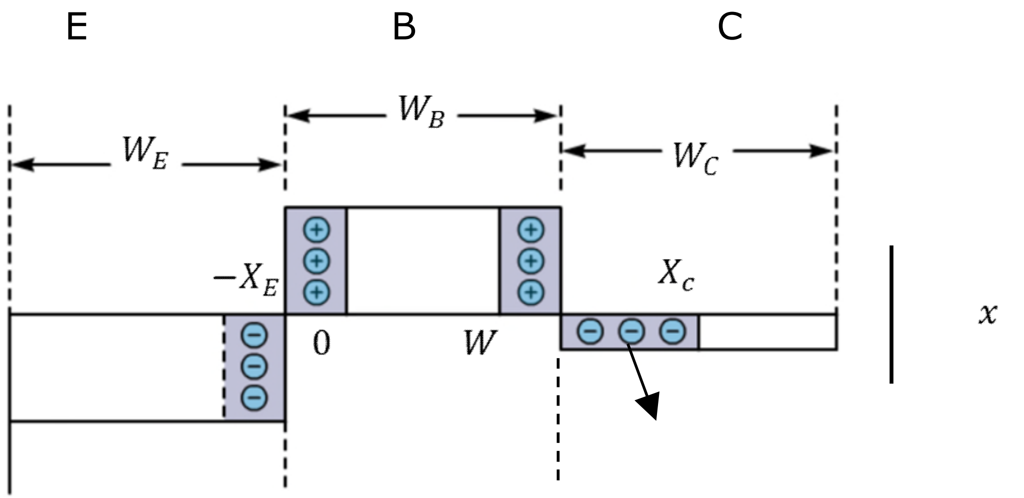


Figure 2.11b

A p-n-p Transistor Under Active Mode

c. **Electric-field:** Enhanced in B-C junction but decreased in E-B junction

d. Energy bands move up in collector and down in emitter
   - Holes easier to flow from E to B
   - Holes get swept from B to C due to the high positive electric field

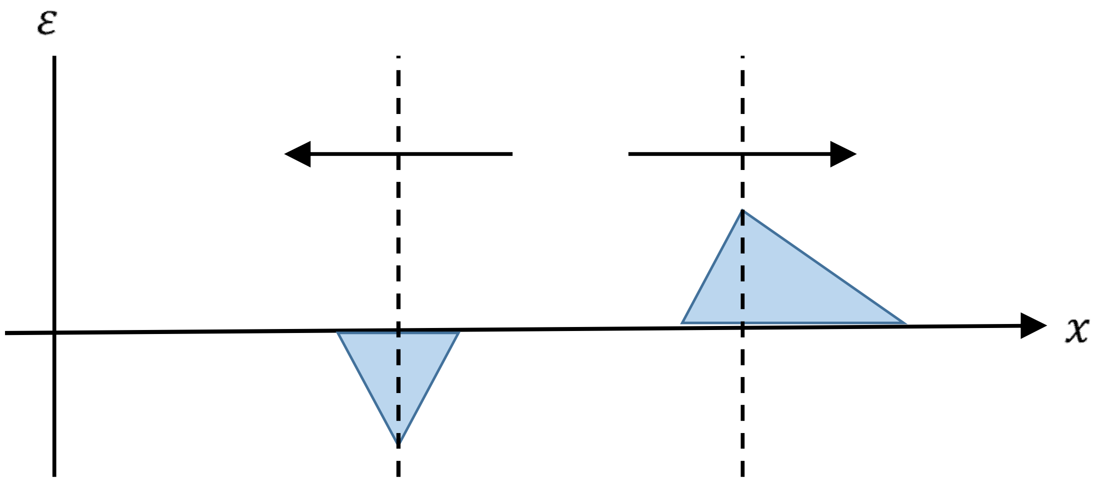


Figure 2.11c

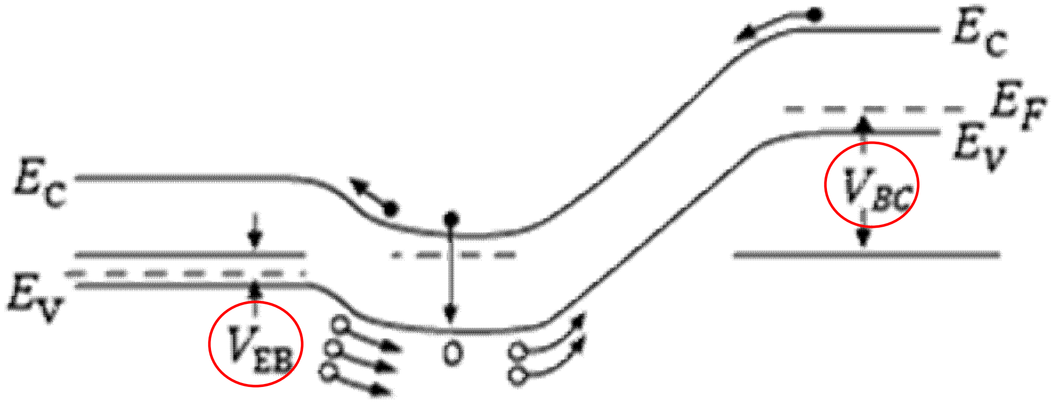


Figure 2.11d

Carriers Flow in a BJT

- In the BJT, there is a heavily doped region **called the emitter** where carriers (holes) are injected to the base in active mode.
- The emitted carriers (holes) to the base form **one of the two emitter current components**.
- The electrons will also be injected from the n-type base to the emitter **thus form the second component of the emitter current.**
- These two current components constitute the total emitter current.

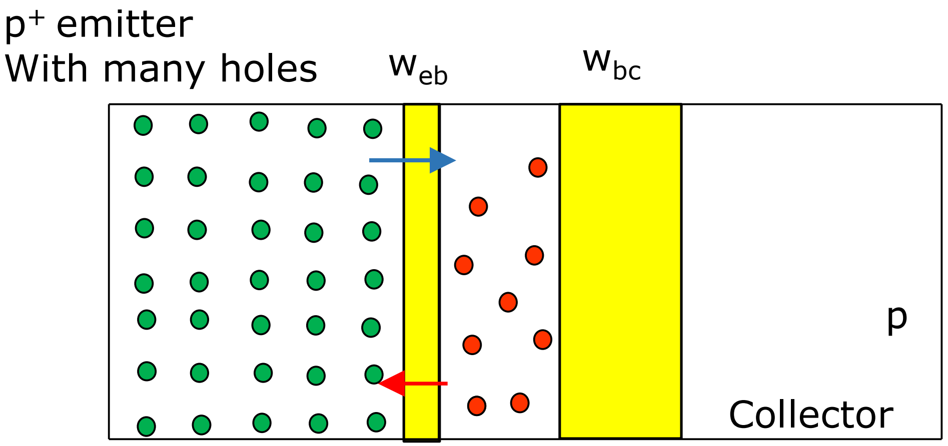


Figure 2.6

Carriers Flow in a BJT (Cont'd.)

- If the base width is sufficiently narrow, the holes injected from the emitter can diffuse through the base to reach the base-collector depletion edge and then float up into the collector due to the internal electrical field ξ of the B-C junction.

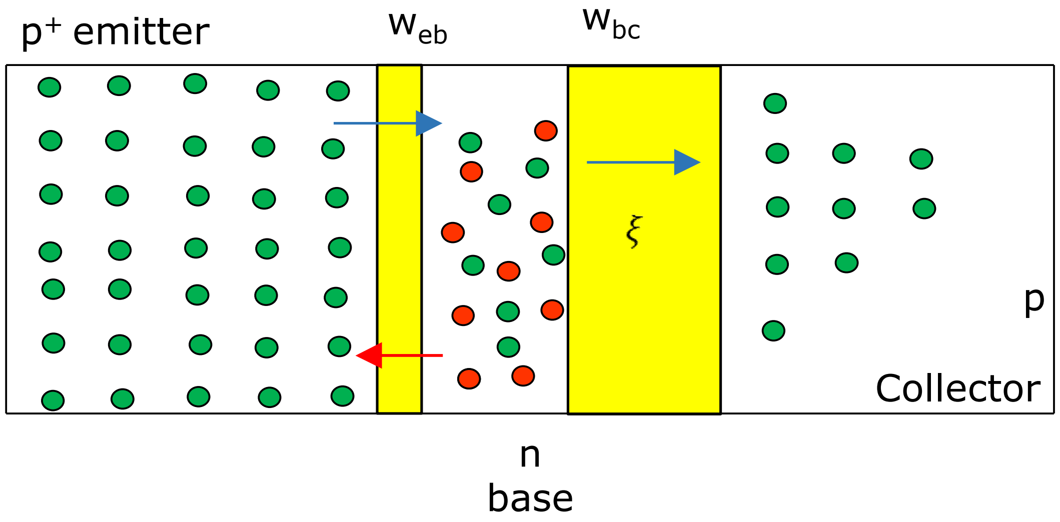


Figure 2.7

Transistor Action

- There will be a large current flow in the reverse-biased collector junction.
- This is the transistor action, and it can be realised only when the two junctions are physically close enough (i.e. the neutral base $W << L_p$).
- The two p-n junctions are called the interacting p-n junctions.

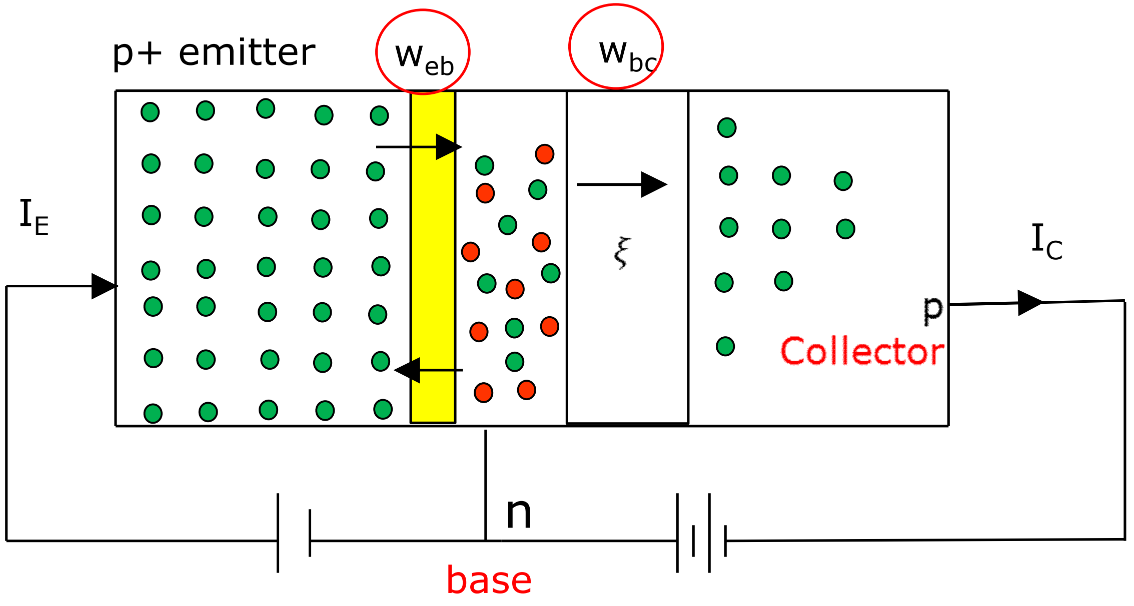


Figure 2.8

Current Components (PNP)

There are various current components in a p-n-p transistor under active mode of operation.

Hole current and hole flow

Electron current
Electron flow

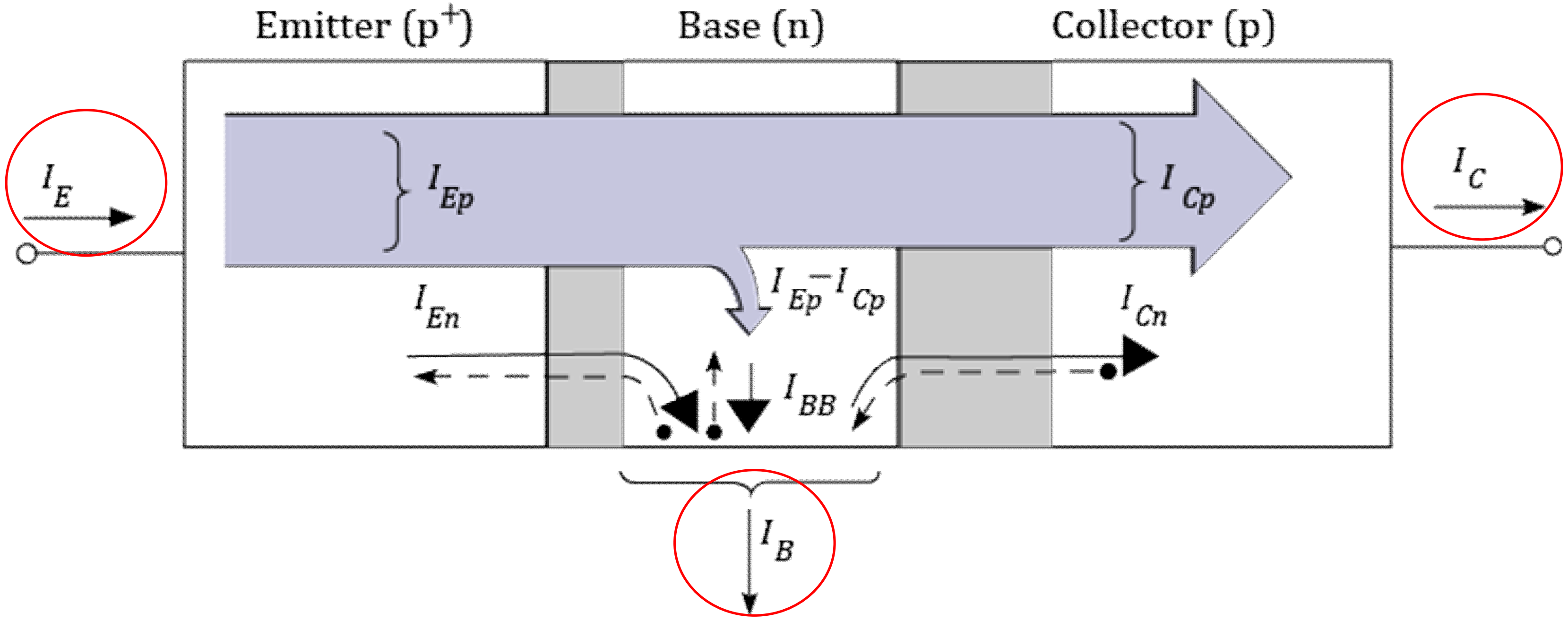


Figure 2.9

Recall:

- Holes flow in the same direction as the hole current.
- Electrons flow in the opposite direction as the electron current.

Transistor Current Relations (PNP)

Emitter:

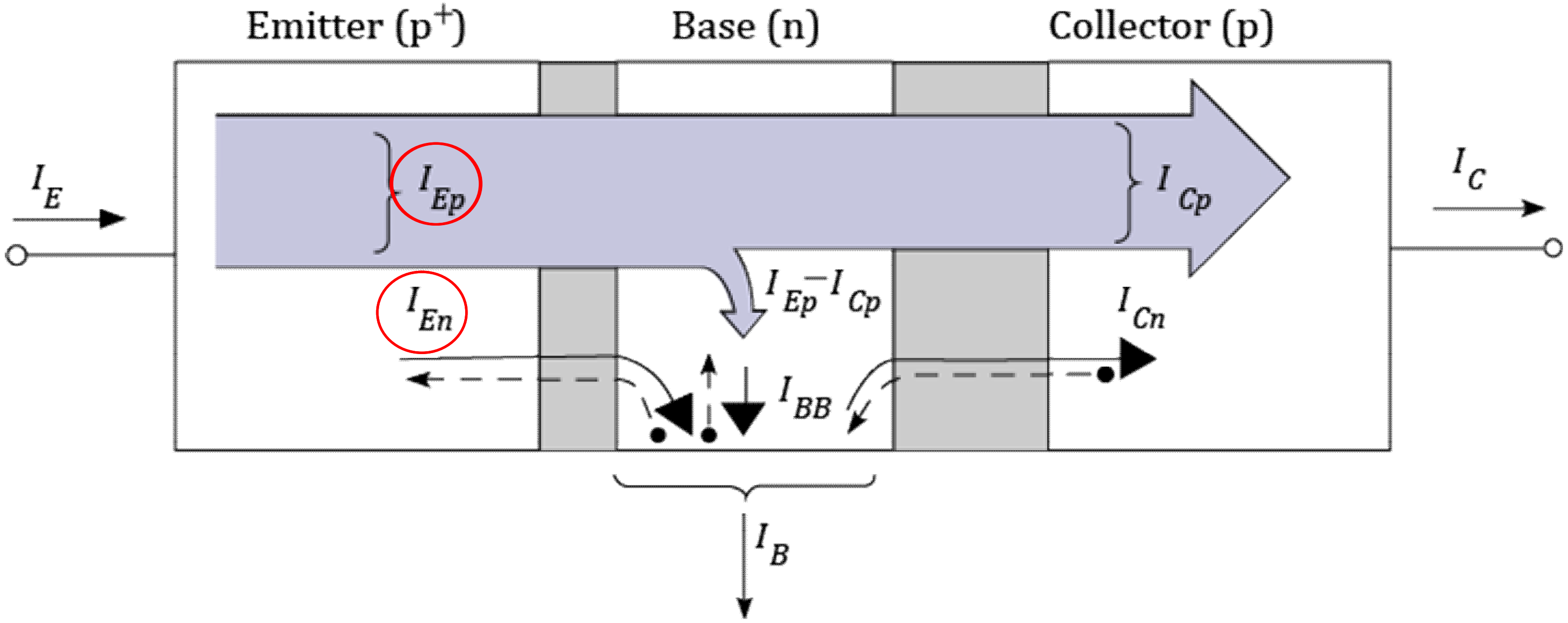


Figure 2.10

- I_{Ep}: The current of holes injected from the emitter, which is the largest current component.
- I_{En}: The current of electrons being injected from the base to the emitter.

Transistor Current Relations (PNP) (Cont'd.)

Collector:

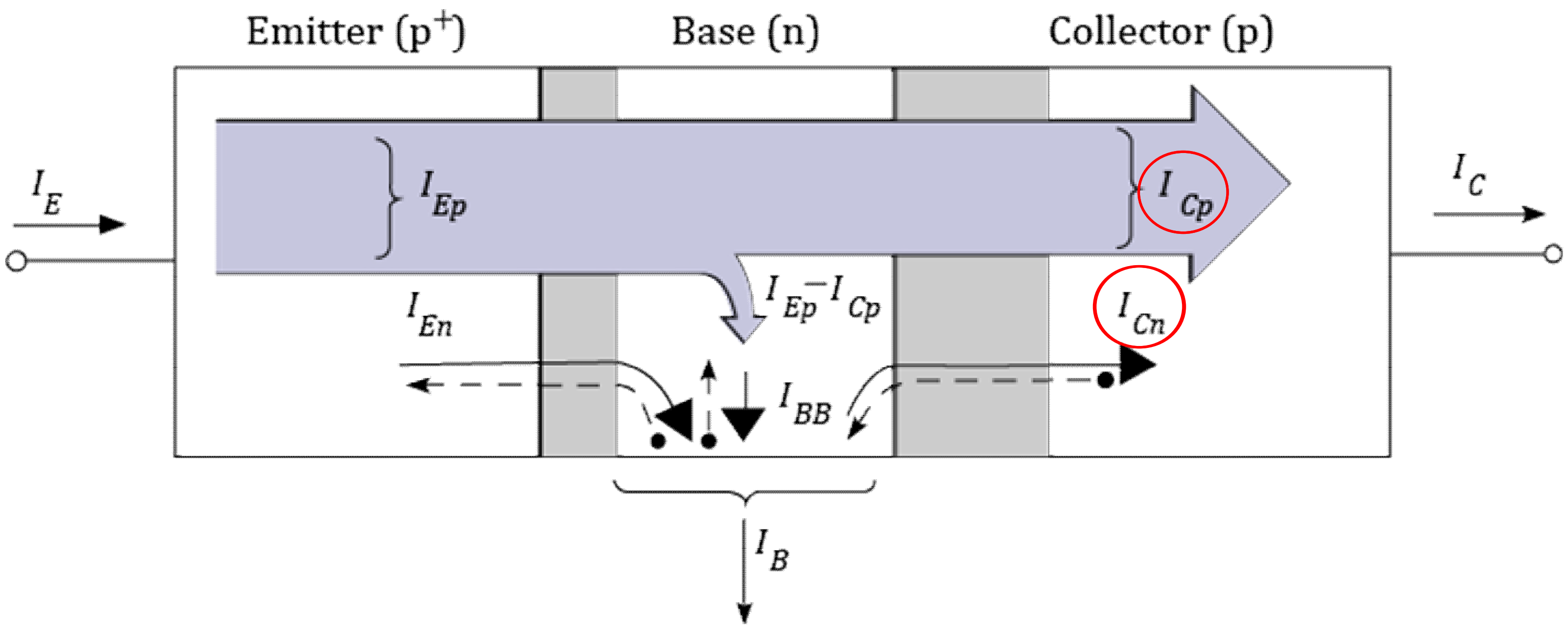


Figure 2.11

- I_{Cp}: The current of the injected holes which are collected by the collector.
- I_{Cn}: The current corresponding to thermally generated electrons that are near the B-C junction edge and are drifted from the collector to the base.

Transistor Current Relations (PNP) (Cont'd.)

Base:

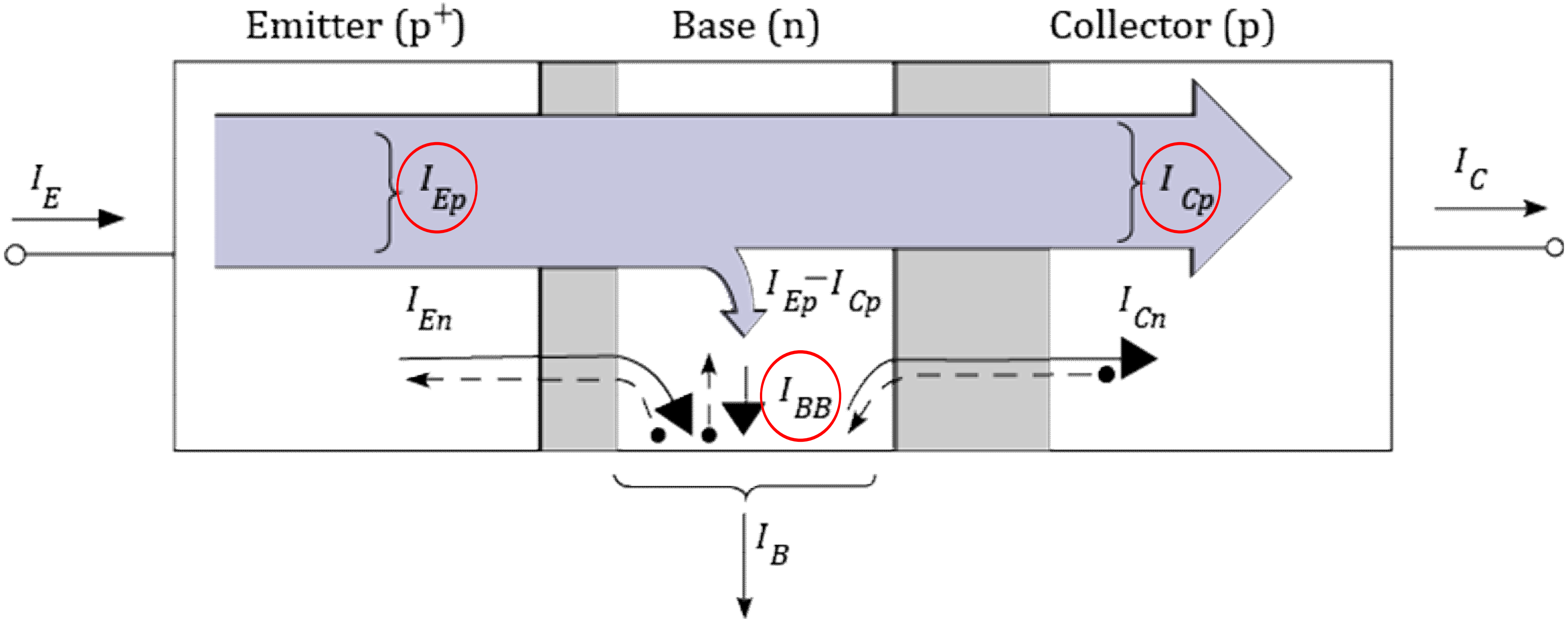


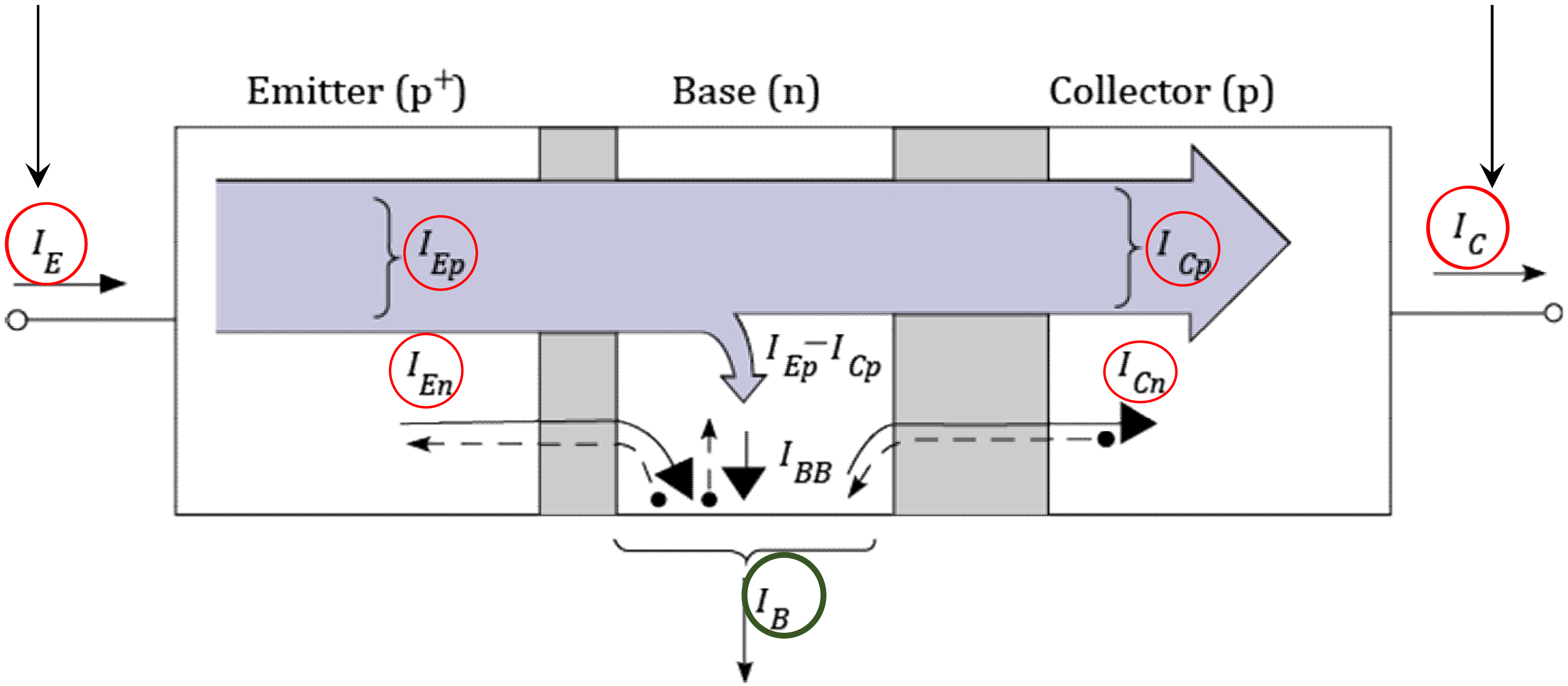
Figure 2.12

- I_{BB}: The current due to the electrons which recombine with some of the injected holes ($i.e., IBB = I_{Ep} - I_{Cp}$).

Terminal Currents of PNP transistor

$I_E = I_{Ep} + I_{En}$

$I_C = I_{Cp} + I_{Cn}$



$$\boxed{I_B = I_E - I_C = I_{En} + \underbrace{(I_{Ep} - I_{Cp})}_{= I_{BB}} - I_{Cn}}$$

Figure 2.13

Static Characteristics of Bipolar Transistors

To derive the current-voltage expressions for an ideal transistor, we assume the following:

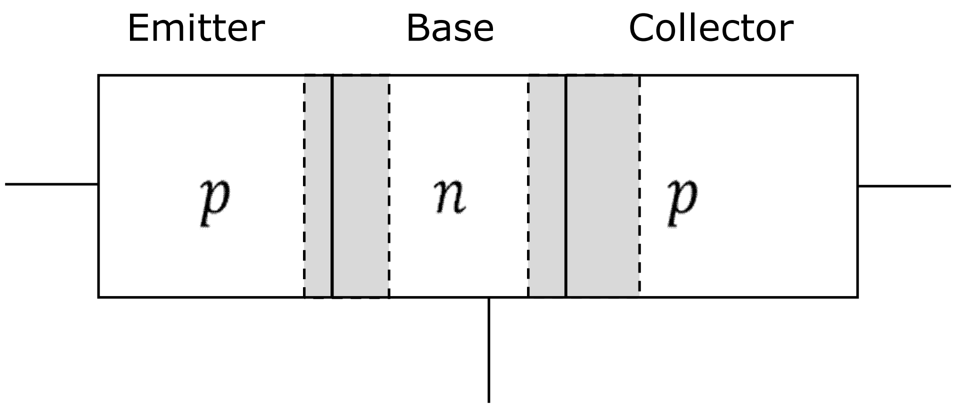


Figure 2.14

1. The device has **uniform doping** in each region.
2. The hole **drift current** in the base region as well as the collector saturation current **are negligible**.
3. There is **low-level injection** (Injected hole concentration $< N_{DB}$).
4. There are no generation-recombination currents in the **depletion regions**.
5. There are **no series resistances** in the device.

Calculate the Current Components in BJT

- **Recall:** hole and electron diffusion currents:

$$J_h(diff) = -qD_h \frac{dp}{dx} \qquad \textit{(Equation 2.4)}$$

$$J_e(diff) = qD_e \frac{dn}{dx} \qquad \textit{(Equation 2.5)}$$

- To determine the currents in a BJT, we just need to find out the carrier distributions.

Calculate the Current Components in BJT

- To determine the currents in a BJT, we just need to find out the carrier distributions.

- The currents are then calculated by:

$$J_{Ep} = A\left(-qD_p \frac{dp}{dx}\bigg|x=0\right) \qquad \textit{(Equation 2.6)}$$

$$J_{Cp} = A\left(-qD_p \frac{dp}{dx}\bigg|x=W\right) \qquad \textit{(Equation 2.7)}$$

$$J_{En} = A\left(qD_{En} \frac{dn_E}{dx}\bigg|x=-xE\right) \qquad \textit{(Equation 2.8)}$$

$$J_{Cn} = A\left(qD_{Cn} \frac{dn_C}{dx}\bigg|x=xC\right) \qquad \textit{(Equation 2.9)}$$

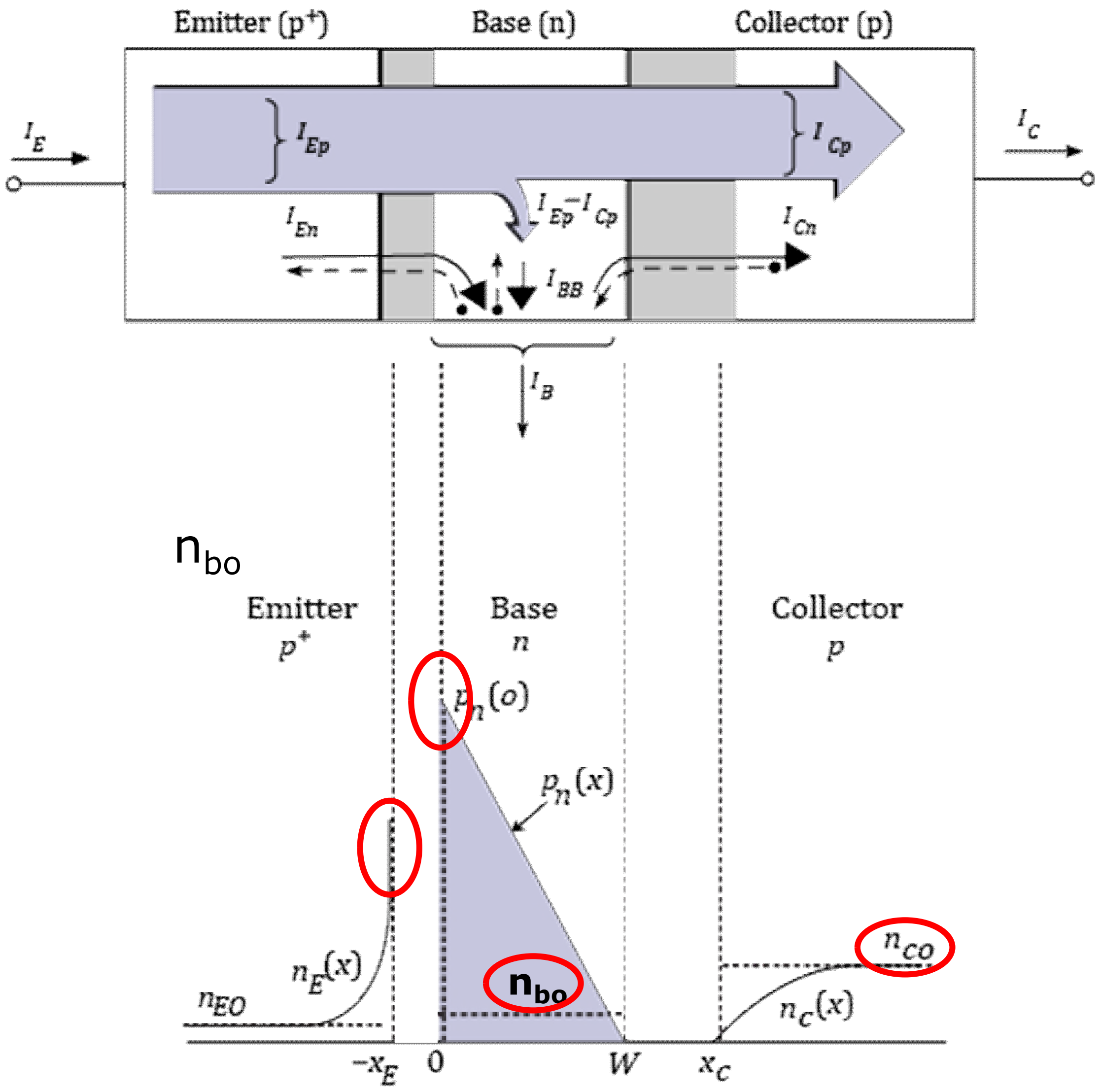
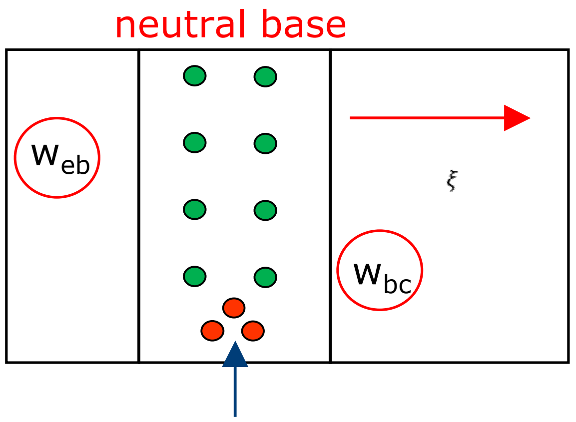


Figure 2.15

Minority Carrier Distribution in the Base Region

- To know the current-voltage expressions, we must know the minority carrier distribution first.
- When the E-B junction is forward biased, the holes are injected to the base region.
- The **minority carrier (hole) distribution** in the neutral base region can be described by the **field-free steady-state continuity equation***:



$$\boxed{D_p\left(\frac{d^2p_n}{dx^2}\right)-\frac{P_n-P_{no}}{\tau_p}=0 \quad \textit{(Equation 2.10)}}$$

where D_p and τ_p are the diffusion coefficient and lifetime of minority carriers, respectively, p_{no} is the equilibrium minority carrier concentration (Base is n type).

* Continuity equation describes the change of carrier concentrations in certain region of a sample as a function of space and time due to the external excitation such as optical excitation and the current flowing into and out of the region.

The general solution of the field free continuity equation is

$$p_n(x) - p_{no} = C_1 e^{x/L_p} + C_2 e^{-x/L_p} \quad \textit{(Equation 2.11)}$$

where $\boldsymbol{L_p}$ is the diffusion length of holes ($\boldsymbol{L_p} = \sqrt{\boldsymbol{D_p \tau_p}}$), and $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ are constants to be determined by the boundary conditions for the active mode:

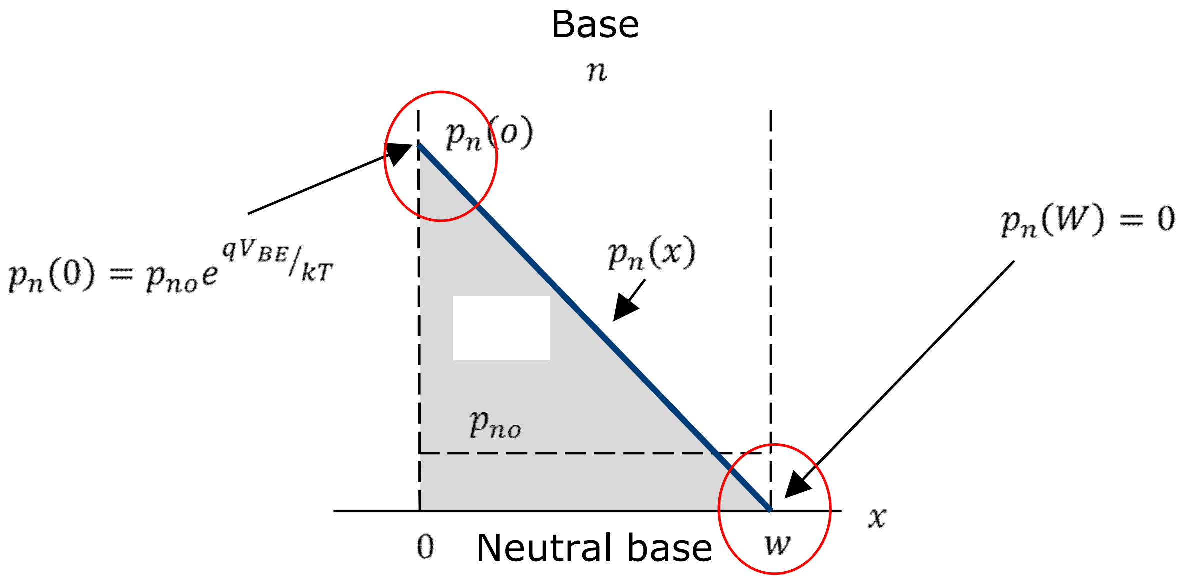


Figure 2.16

- The first boundary condition, $\boxed{p_n(0) = p_{no}e^{qV_{EB}/kT}}$ states that under forward bias, the minority hole concentration at the edge of the emitter-base depletion region $(x = 0)$ is increased above the equilibrium value by the exponential factor $\boxed{e^{qV_{BE}/kT}.}$
- The second boundary condition $p_n(W) = 0$ states that under reverse bias the minority hole concentration at the edge of the base-collector depletion region $(x = W)$ is zero.

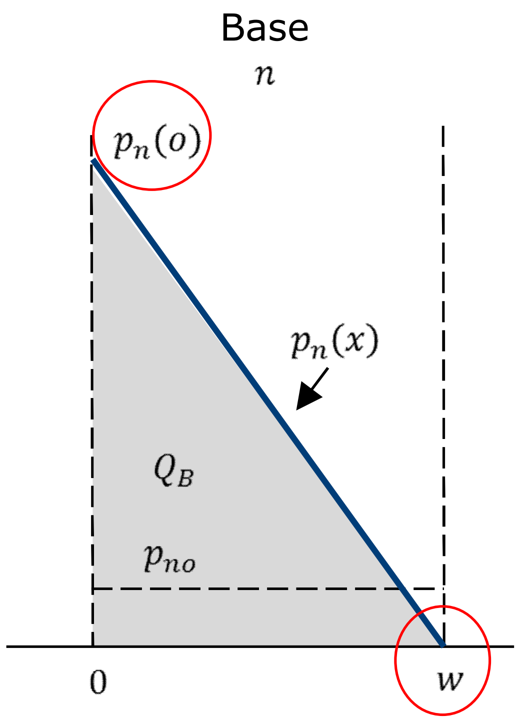


Figure 2.17

- Substituting the boundary conditions into the general solution and assume $W/L_p << 1$ (the neutral base width is much shorter than the diffusion length),

$$\boxed{p_n(x) = p_n(0)\left[1 - \frac{x}{W}\right] = p_{no}e^{qV_{EB}/kT}\left[1 - \frac{x}{W}\right] \qquad \textit{(Equation 2.12)}}$$

Minority Carriers in Emitter and Collector Regions

- The minority-carrier distributions in the emitter and collector can be obtained in a manner similar to the one used to obtain the distributions for the base region.
- The boundary conditions in the neutral emitter region are:

$$n_E(x = -x_E) = \boxed{n_{EO} e^{qV_{EB}/kT}} \qquad \textit{(Equation 2.13)}$$

where n_{EO} is the equilibrium electron concentrations in the emitter.

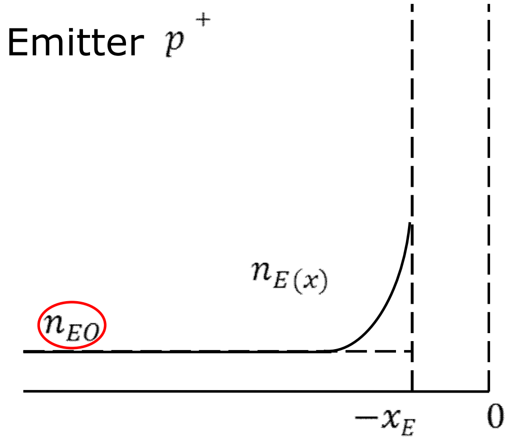


Figure 2.18

Minority Carriers in Emitter and Collector Regions

- We assume that the emitter depth is much larger than the corresponding diffusion length L_E. Substituting these boundary conditions to the general solution,

$$n_E(x) - n_{EO} = C_1 e^{x/L_n} + C_2 e^{-x/L_n} \quad \textit{(Equation 2.14)}$$

- We have

$$n_E(x) = n_{EO} + n_{EO}\left(e^{qV_{EB}/kT} - 1\right) exp\left(\frac{x+x_E}{L_E}\right) \text{ for } x \leq -x_E \quad \textit{(Equation 2.15)}$$

- Check: when $x = -x_E \rightarrow n_E(x) = n_E(-x_E) = n_{EO}\left(e^{qV_{EB}/kT}\right)$

  when $x = -\infty \rightarrow n_E(-\infty) = nE_0$

Minority Carriers in Emitter and Collector Regions

- Similarly, in the collector, the boundary conditions are:

$$n_C(x = x_C) = n_{co}e^{-q|V_{CB}|/kT} = 0 \text{ and } n_C(\infty) = n_{co} \qquad \textit{(Equation 2.16)}$$

- The minority carrier concentration is:

$$n_C(x) = n_{CO} - n_{CO}exp\left[-\frac{x-x_C}{L_C}\right] \text{ for } x \geq x_C \qquad \textit{(Equation 2.17)}$$

- Checks: when $x = 0 \rightarrow n_{c(0)} = 0$

  when $x = \infty \rightarrow n_c(\infty) = nc_0$

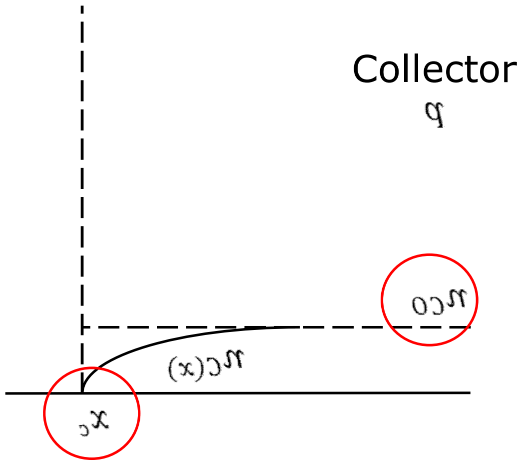


Figure 2.19

Summary: Minority Carrier Distributions in 3 Regions

$$n_E(x) = n_{EO} + n_{EO}\left[e^{qV_{EB}/kT} - 1\right]exp\left[\frac{x + x_E}{L_E}\right]$$

$$P_n(x) = P_n(0)\left[1 - \frac{x}{W}\right]$$

$$n_C(x) = n_{CO} - n_{CO}\,exp\left(-\frac{x - x_C}{L_C}\right)$$

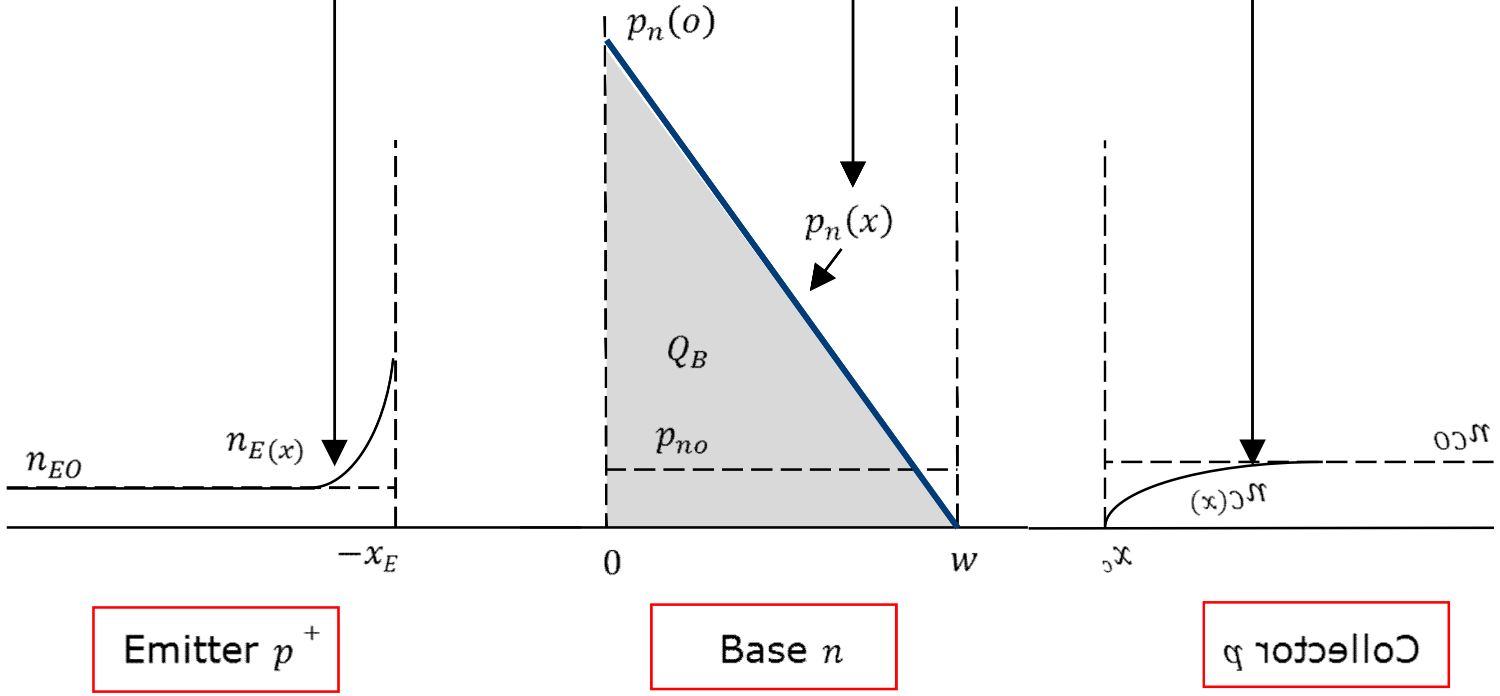


Figure 2.20

Ideal Transistor Currents for Active Mode Operation

- The hole current $\boldsymbol{I_{Ep}}$, injected from the emitter at $x = 0$, is proportional to the gradient of the minority carrier concentration and is expressed by:

$$I_{Ep} = \boxed{A\left(-qD_p \frac{dp_n}{dx}\bigg|x = 0\right)} \equiv \boxed{qA\frac{D_p P_{no}}{W} e^{qV_{EB}/kT} \quad \textit{(Equation 2.18)}}$$

- Similarly, the hole current collected by the collector at $x = W$ is:

$$\boxed{I_{Cp} = A\left(-qD_p \frac{dp_n}{dx}\bigg|x = W\right) \approx \frac{qAD_p P_{no}}{W} e^{qV_{EB}/kT} \quad \textit{(Equation 2.19)}}$$

- Note that I_{Cp} is (approximately) equal to I_{Ep} when $W/L_p << 1$.

Ideal Transistor Currents for Active Mode Operation

- The electron current I_{En}, due to the electron flow from base to emitter:

$$\boxed{I_{En} = A\left(qD_{En}\frac{dn_E}{dx}\bigg|x = -x_E\right)} = \boxed{\frac{qAD_{En}n_{EO}}{L_E}\left(e^{qV_{EB}/kT} - 1\right) \quad \text{(Equation 2.20)}}$$

- The collector current I_{Cn}, due to the electron flow from collector to base, are:

$$I_{Cn} = A\left(qD_{Cn}\frac{dn_C}{dx}\bigg|x = x_C\right) = \boxed{\frac{qAD_{Cn}n_{CO}}{L_C} \quad \text{(Equation 2.21)}}$$

where D_{En} and D_{Cn} are the diffusion coefficients of electron in the emitter and collector, respectively.

- The **base current** is the difference between the emitter current and collector current:

$$\boxed{I_B = I_E - I_C = I_{En} + \left(I_{Ep} - I_{Cp}\right) - I_{Cn} \quad \text{(Equation 2.22)}}$$

A bipolar transistor has four modes of operation, depending on the voltage polarities on the E-B junction and the B-C junction.

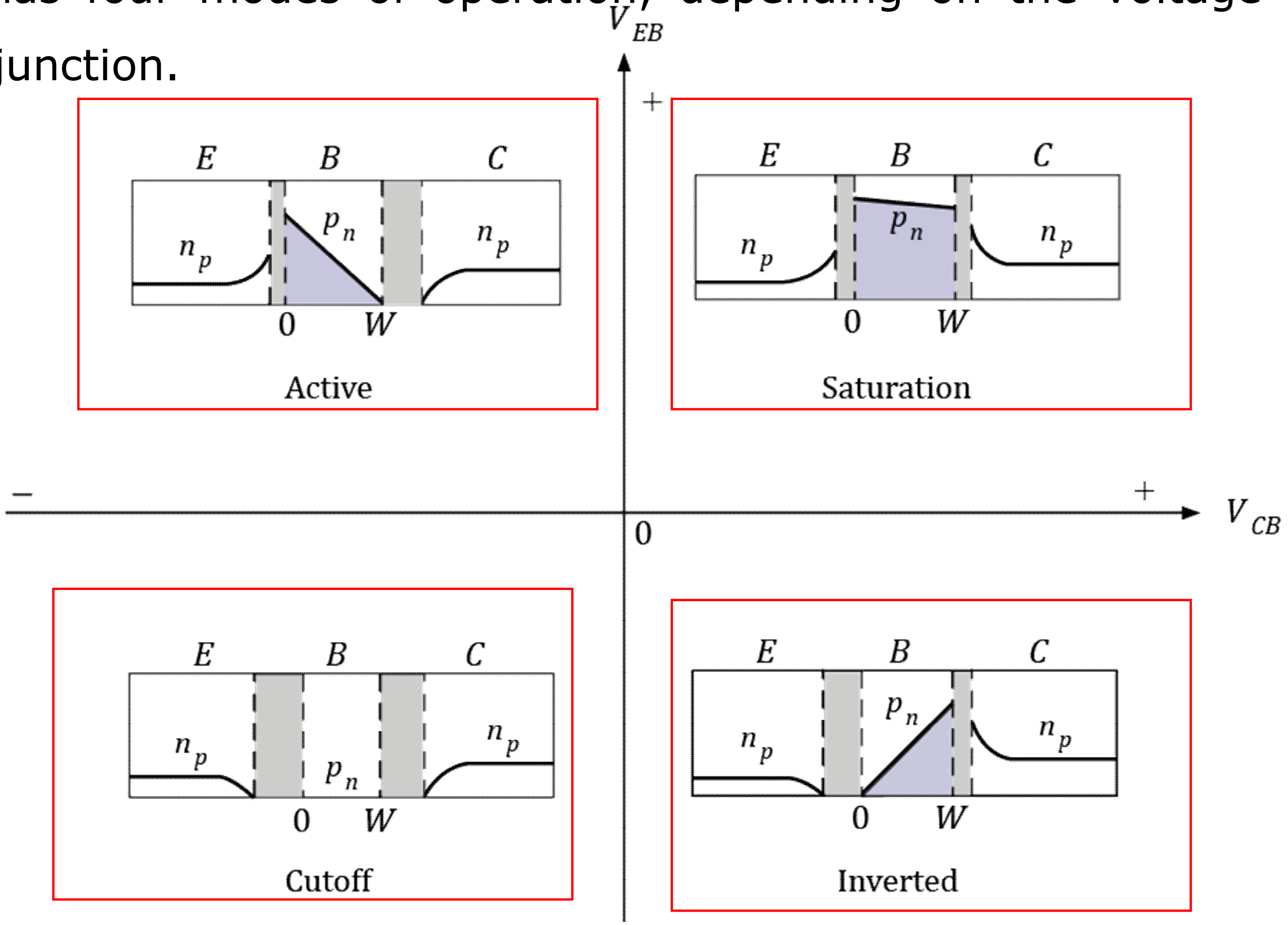


Figure 2.21

(1) Active Mode ($V_{EB} > 0$ and $V_{CB} < 0$)

The **E-B junction is forward-biased** and the **B-C junction is reverse-biased**. The minority carrier distributions are as shown below.

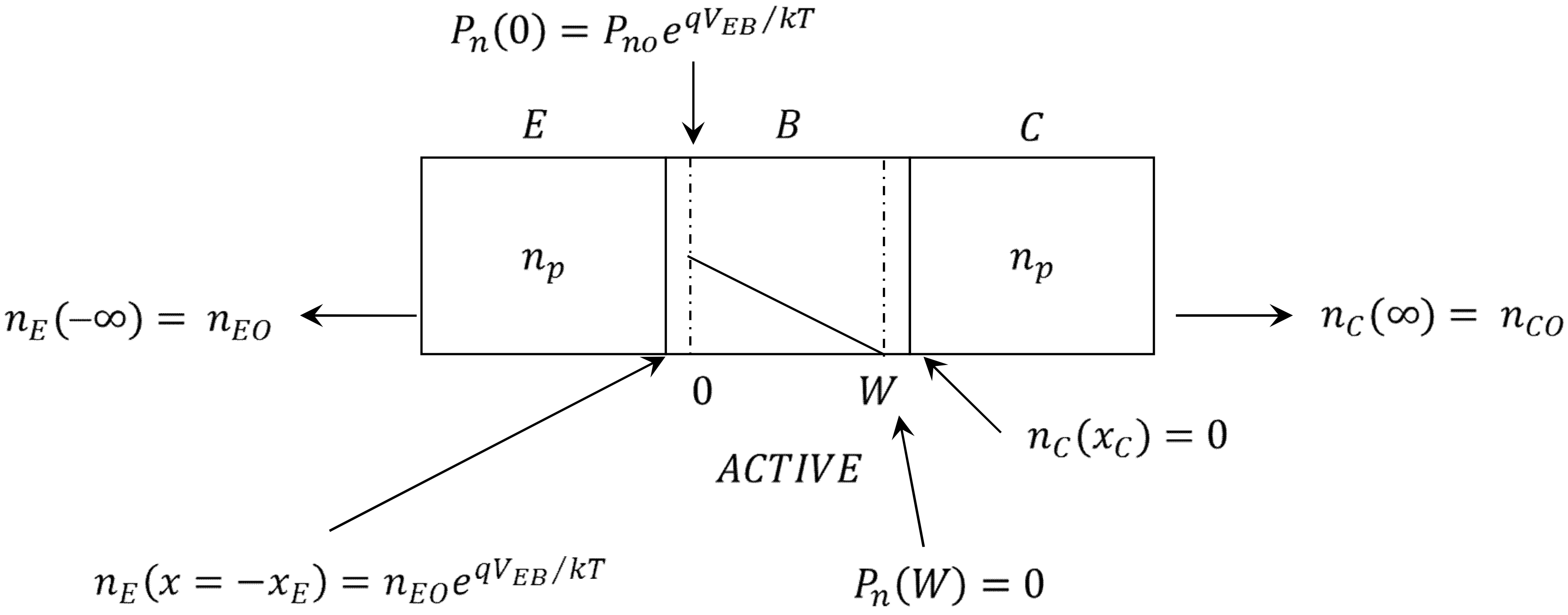


Figure 2.22

(2) Saturation Mode ($V_{EB} > 0$ *and* $V_{CB} > 0$)

Both junctions are forward-biased. The boundary condition at $x = W$ becomes instead of zero.

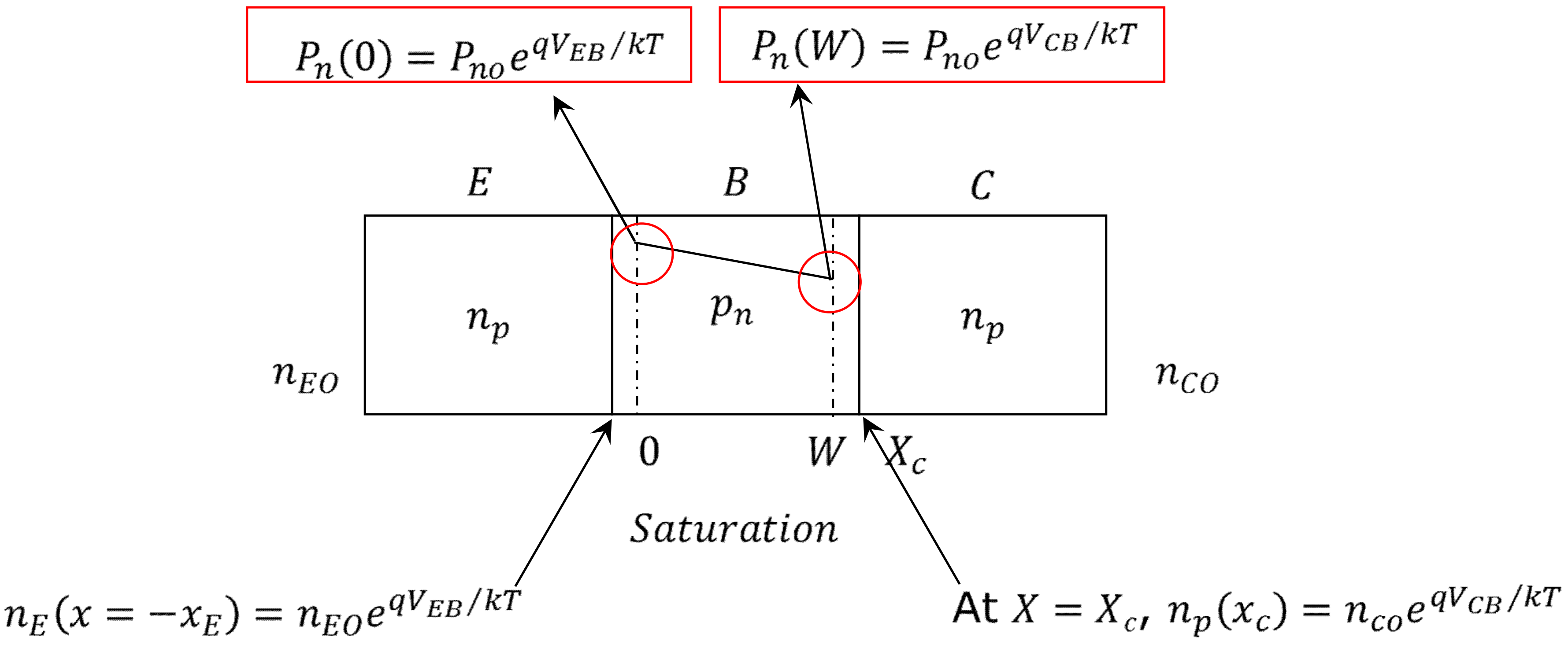
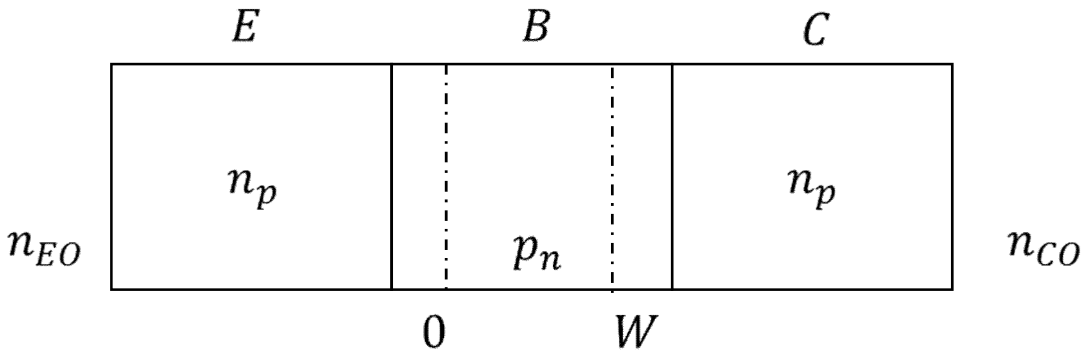


Figure 2.23

(3) Cutoff Mode ($V_{EB} < 0$ and $V_{CB} < 0$)

Both junctions are reverse-biased. The boundary conditions becomes $p_n(0) = p_n(W) = 0$. The cutoff mode corresponds to the open (or **off**) state of the transistor as a switch.



$Cutoff$

Figure 2.24

(4) Inverted Mode ($V_{EB} < 0$ and $V_{CB} > 0$)

- It is sometime called the inverted active mode.
- The **E-B junction is reverse-biased** and the **C-B junction is forward-biased**. It corresponds to the case where the collector acts like an emitter and the emitter acts like a collector.
- The current gain for the inverted mode is generally lower than that for the active mode because of **poor 'emitter efficiency'** resulting from low collector doping.

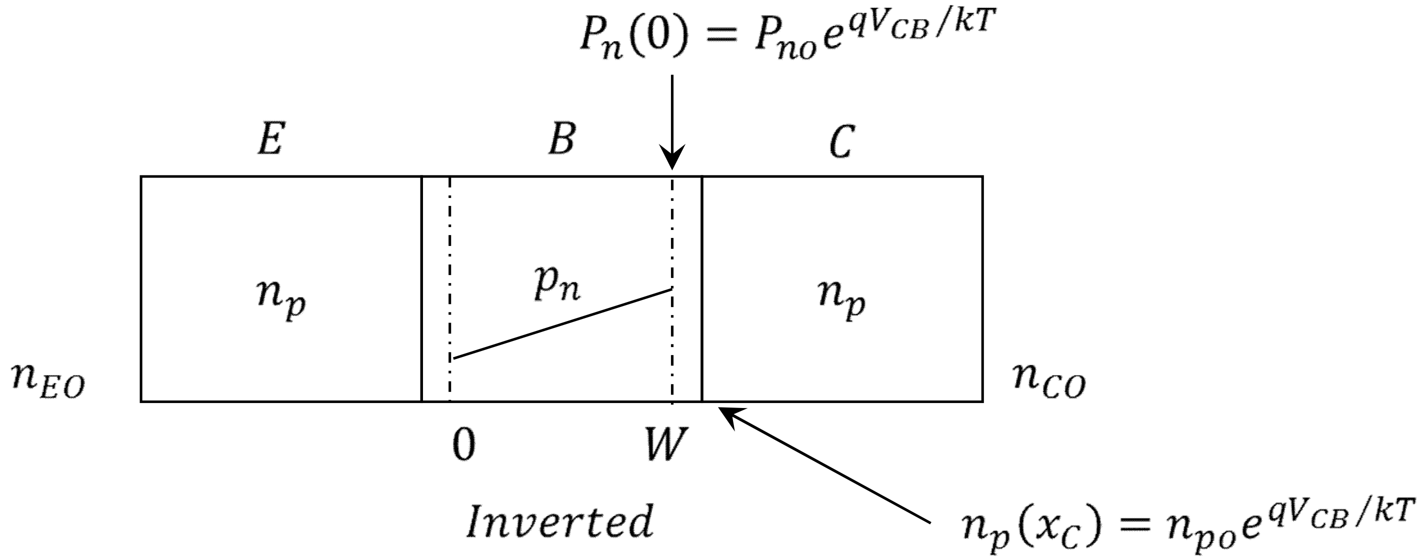


Figure 2.25

NANYANG TECHNOLOGICAL UNIVERSITY

(1) Common-base configuration

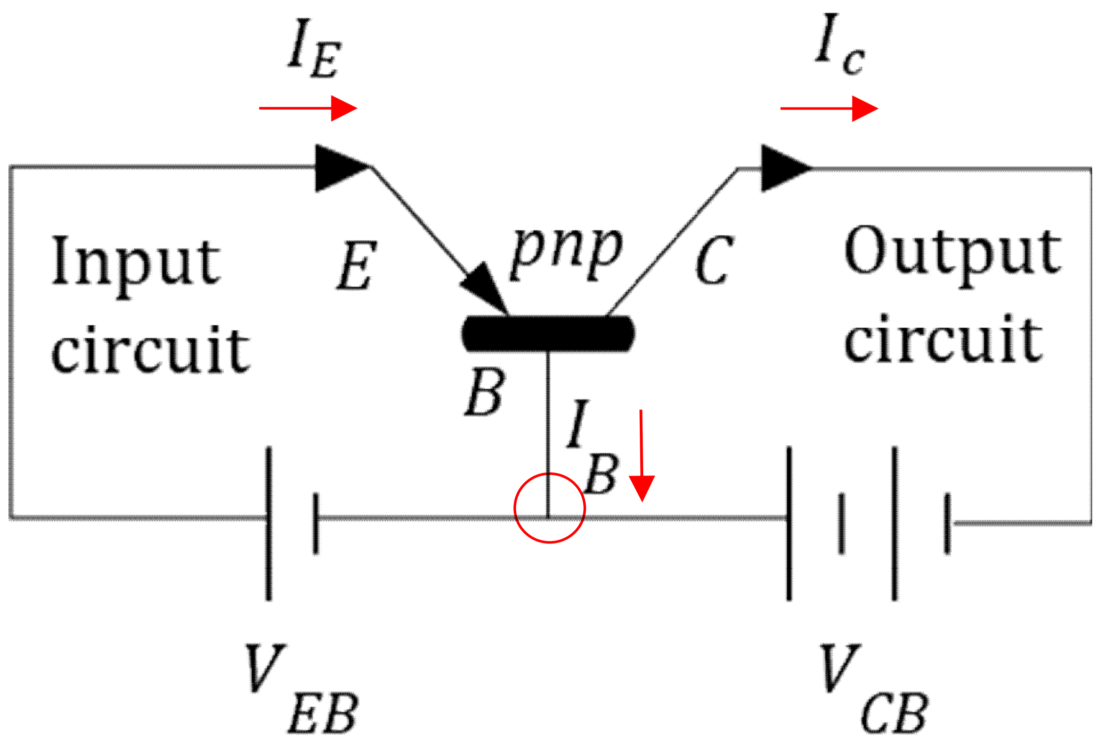


Figure 2.26

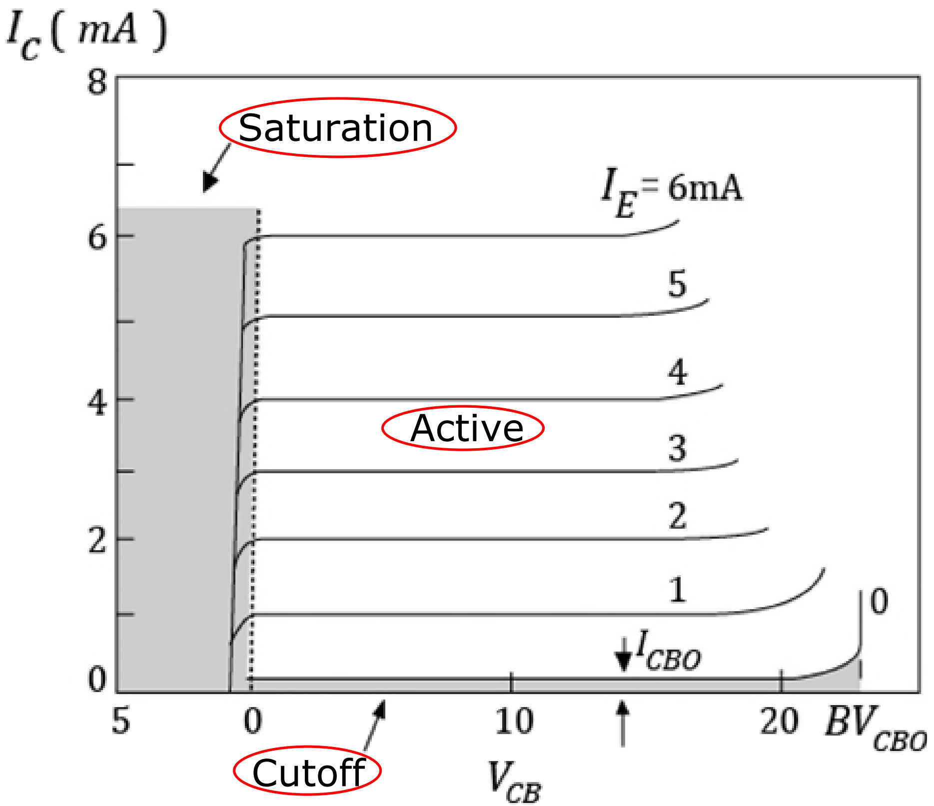


Figure 2.27

Common-Base Current Gain (α_0)

$$\alpha_0 \equiv \frac{I_{CP}}{I_E} = \boxed{\left[\frac{I_{Ep}}{I_{Ep} + I_{En}}\right]\left[\frac{I_{Cp}}{I_{Ep}}\right] \text{(Equation 2.23)}}$$

Emitter efficiency γ *Base transport factor* α_T,

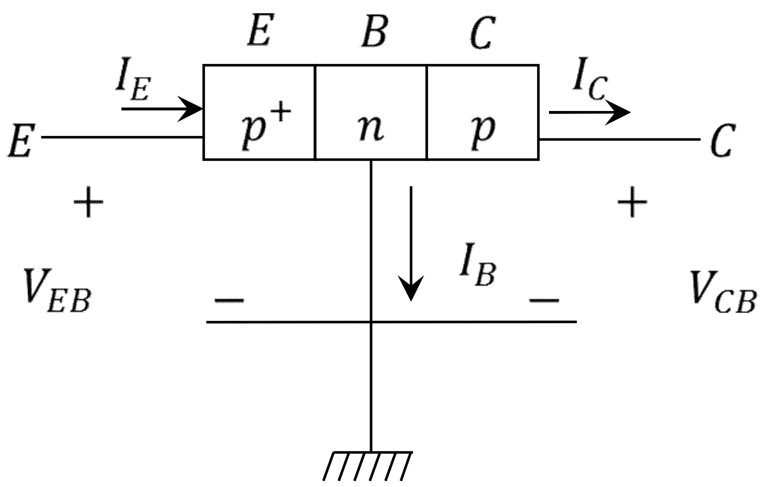


Figure 2.29

- The first term on the right hand side is called the **emitter efficiency** γ, which is a measure of the injected hole current compared to the total emitter current.
- The second term is called the **base transport factor** α_T, which is the ratio of the hole current reaching the collector to the hole current injected from the emitter. Thus: $\boxed{\alpha_0 = \gamma\alpha_T}$
- **For a well designed transistor, both γ and α_T approach unity, and α_0 is very close to 1.**

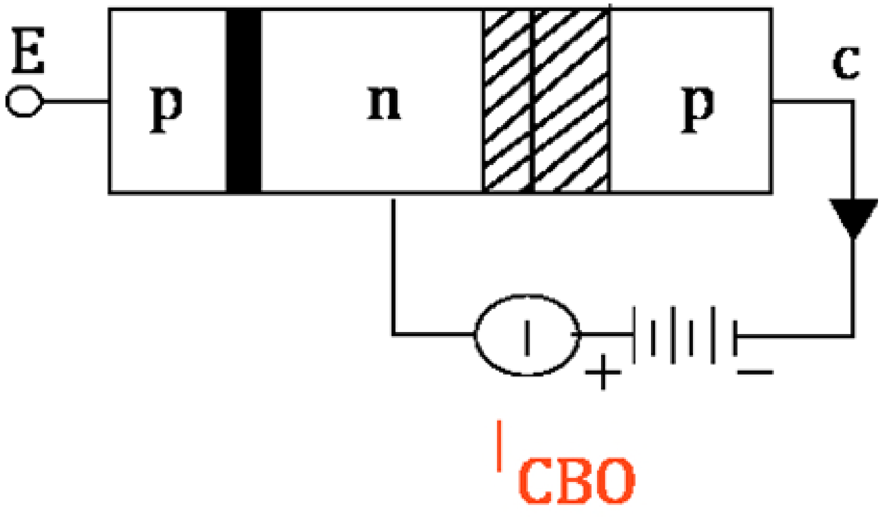
Collector Current in Terms of α_0

- $I_C = I_{Cp} + I_{Cn}$ *(Equation 2.24)*

$= \boxed{\alpha_T I_{Ep} + I_{Cn}} = \boxed{\gamma\alpha_T\left(\frac{I_{Ep}}{\gamma}\right) + I_{Cn} = \alpha_0 I_E + I_{Cn} \quad \textit{(Equation 2.25)}}$

where I_{Cn} corresponds to the collector-base current when the emitter is open-circuited $(IE = 0)$. We shall designate I_{Cn} as I_{CBO}

- The first two subscripts (CB) refer to the two terminals between which the current is measured. The third subscript (O) refers to the state of the third terminal.
- I_{CBO} designates the **leakage current between the collector and the base** with the emitter-base junction open.
- Therefore, $I_C = \alpha_0 I_E + I_{CBO}$ *(Equation 2.26)*



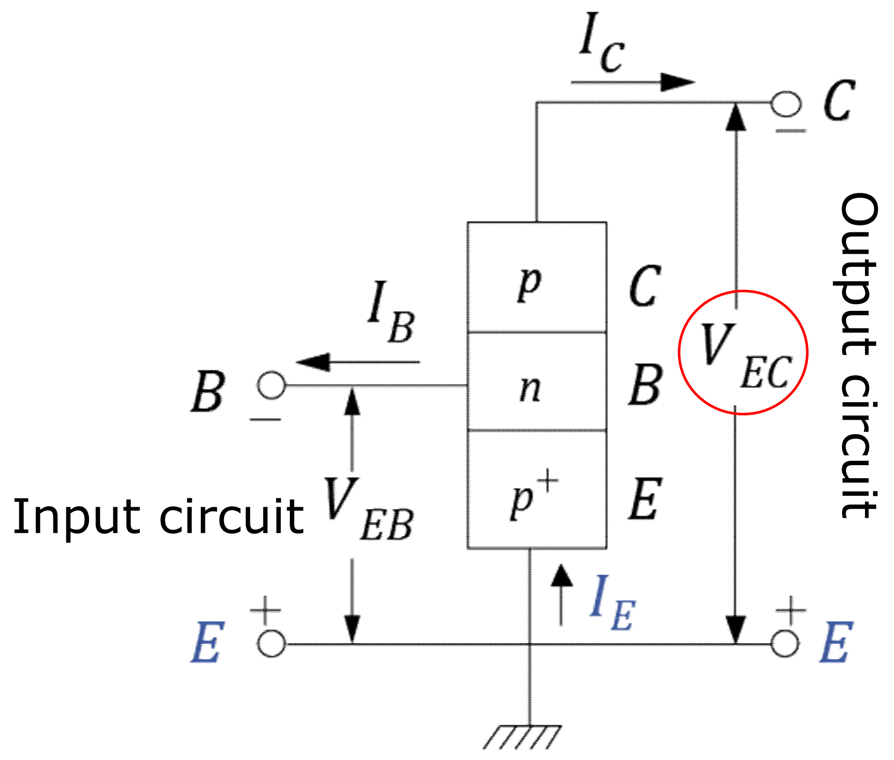


Figure 2.30

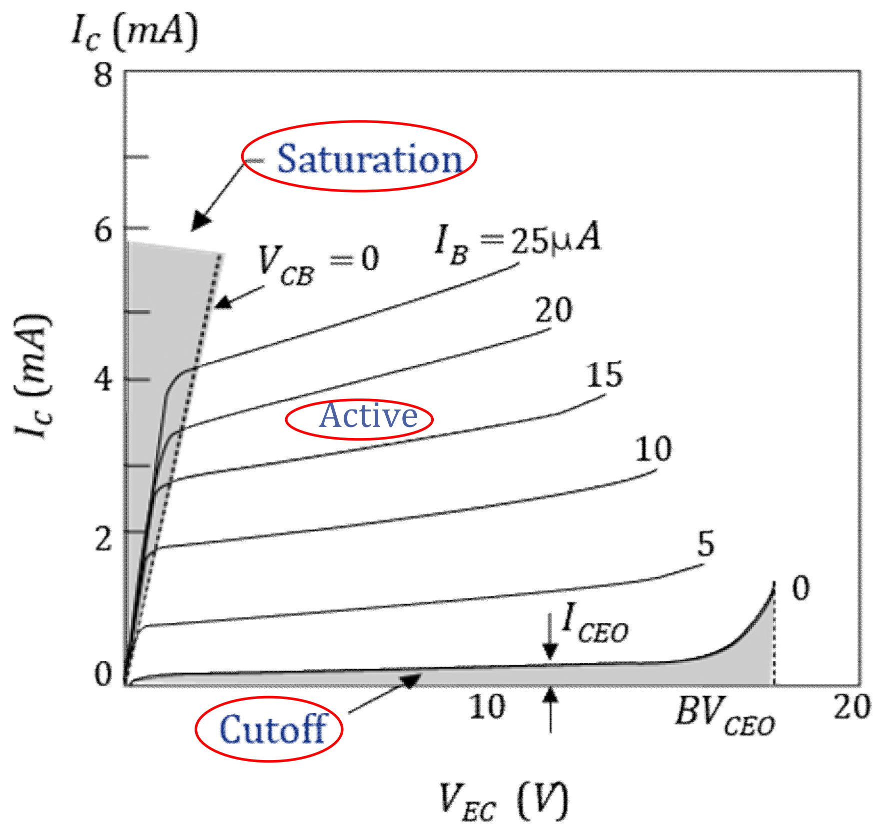


Figure 2.31

Common Emitter Current Gain β_0

- From $I_C = \alpha_0 I_E + I_{CBO} = \alpha_o(I_C + I_B) + I_{CBO}$ *(Equation 2.32)*
- Solving for I$_C$ we have $I_C = \frac{\alpha_o}{1-\alpha_o} I_B + \frac{I_{CBO}}{1-\alpha_o}$ *(Equation 2.33)*
- If we define β_0 as the common-emitter gain, which is the increment change of I_C with respect to an increment change of I_B, we have:

$$\beta_0 = \frac{\Delta I_C}{\Delta I_B} = \frac{\alpha_o}{1 - \alpha_o}$$ *(Equation 2.34)*

- And if we let $I_{CEO} = \frac{I_{CBO}}{1-\alpha_o}$
- Then, $I_C = \beta_0 I_B + I_{CEO}$ *(Equation 2.35)*

I_{CEO} and I_{CBO}

- I_{CEO} is the saturation/leakage current between emitter and collector when **base is open-circuited**.

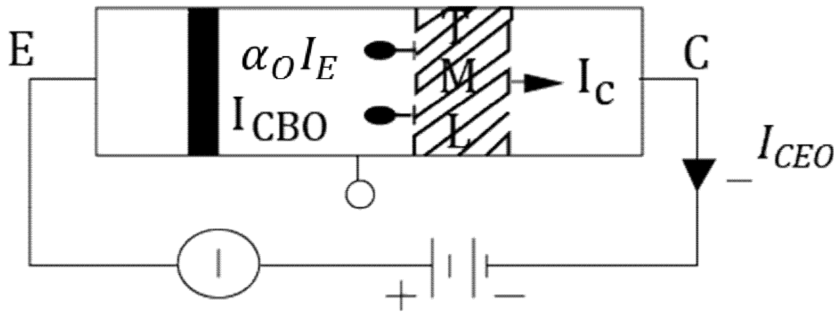


Figure 2.32

- For a given V_{EC}, the $E - B$ junction will be slightly forward-biased.
- Therefore I_{CEO} >> $ICBO$ ($I_{CEO} \approx \beta_0 ICBO$).

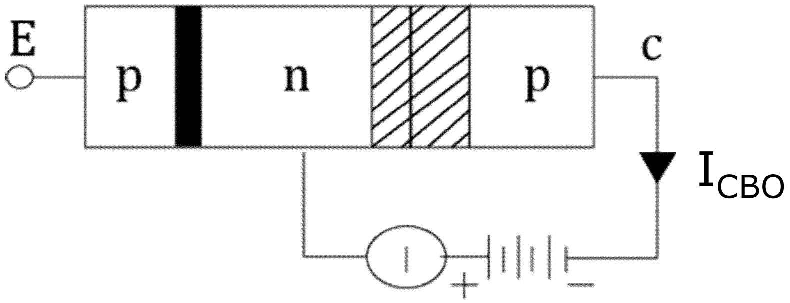


Figure 2.33

Base Width Modulation

- In the **ideal** transistors with common-emitter configuration, the $\boldsymbol{I_C}$ for a given $\boldsymbol{I_B}$ should be independent of $V_{EC}\, for\, VEC_{\,>\,0}$. This is true when we assume that the **neutral base width is a constant**.

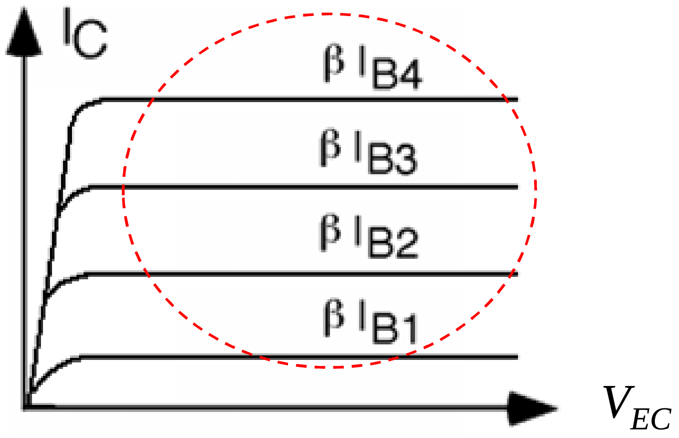


Figure 2.34 - I-V of ideal BJTs

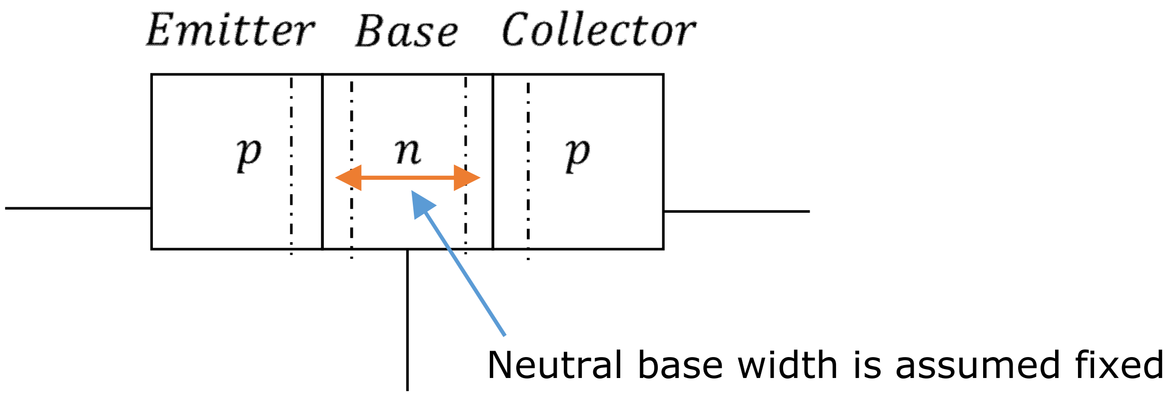


Figure 2.35

Base Width Modulation (Cont'd.)

- In practical BJTs, the width of space charge region extends into the base region varies with the base-collector voltage (V_{BC}) , the **neutral base width** is hence **a function of** V_{EC}. The collector current I_C is therefore dependent on V_{EC}.

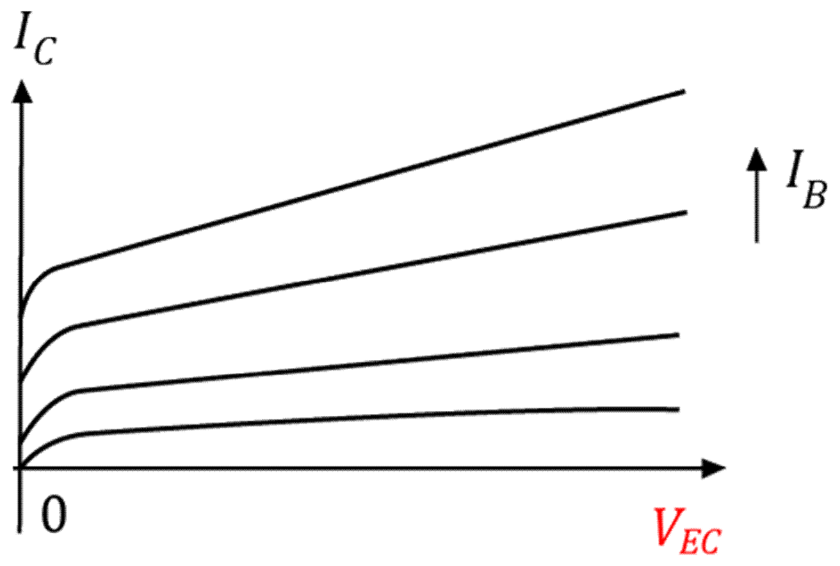


Figure 2.36 - I-V of practical BJTs

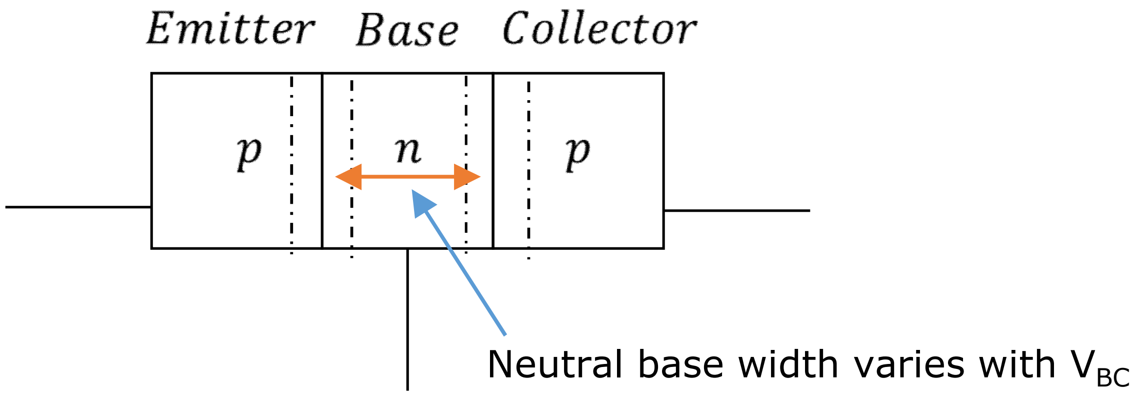


Figure 2.37

Base Width Modulation (Cont'd.)

- As the reverse bias to the C-B junction increases, the neutral base width decreases.
- The **reduced base width** will **cause the gradient** to **increase**.
- The **increased gradient** in the minority-carrier concentration **causes an increase in diffusion current I_c** and hence β.

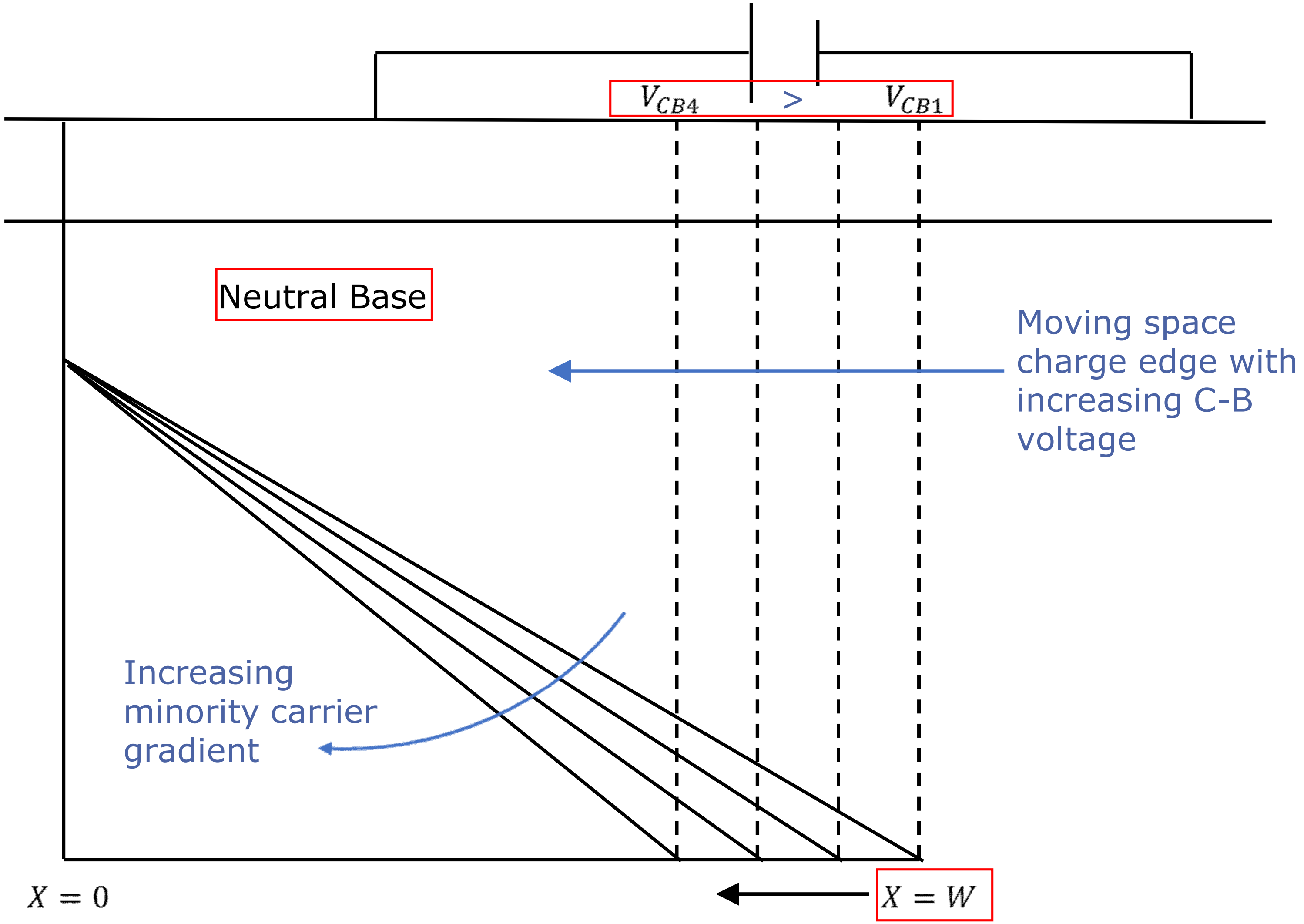


Figure 2.38

Early Voltage

By extrapolating the collector currents and intersecting the V_{EC} axis, one can obtain the voltage V_A, which is called the **Early voltage**.

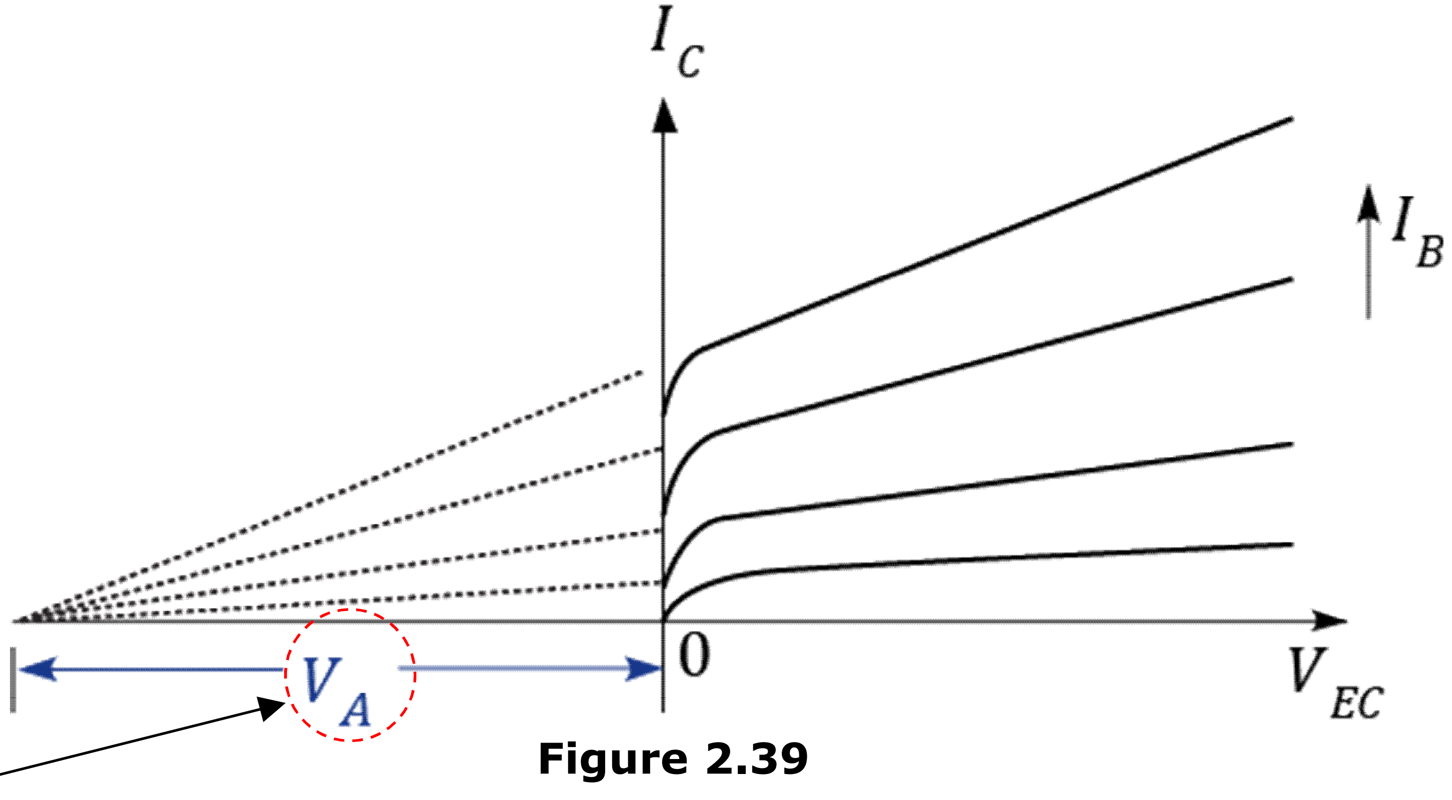


Figure 2.39

The extensions of collector currents for different base currents will meet at $-V_A$.

Early Voltage (Cont'd.)

- From the last figure 2.39, we can write that:

$$\frac{\Delta I_C}{\Delta V_{EC}} = \frac{I_C}{V_{EC} + V_A} = g_o \qquad \textit{(Equation 2.36)}$$

where g_o is defined as the output conductance.

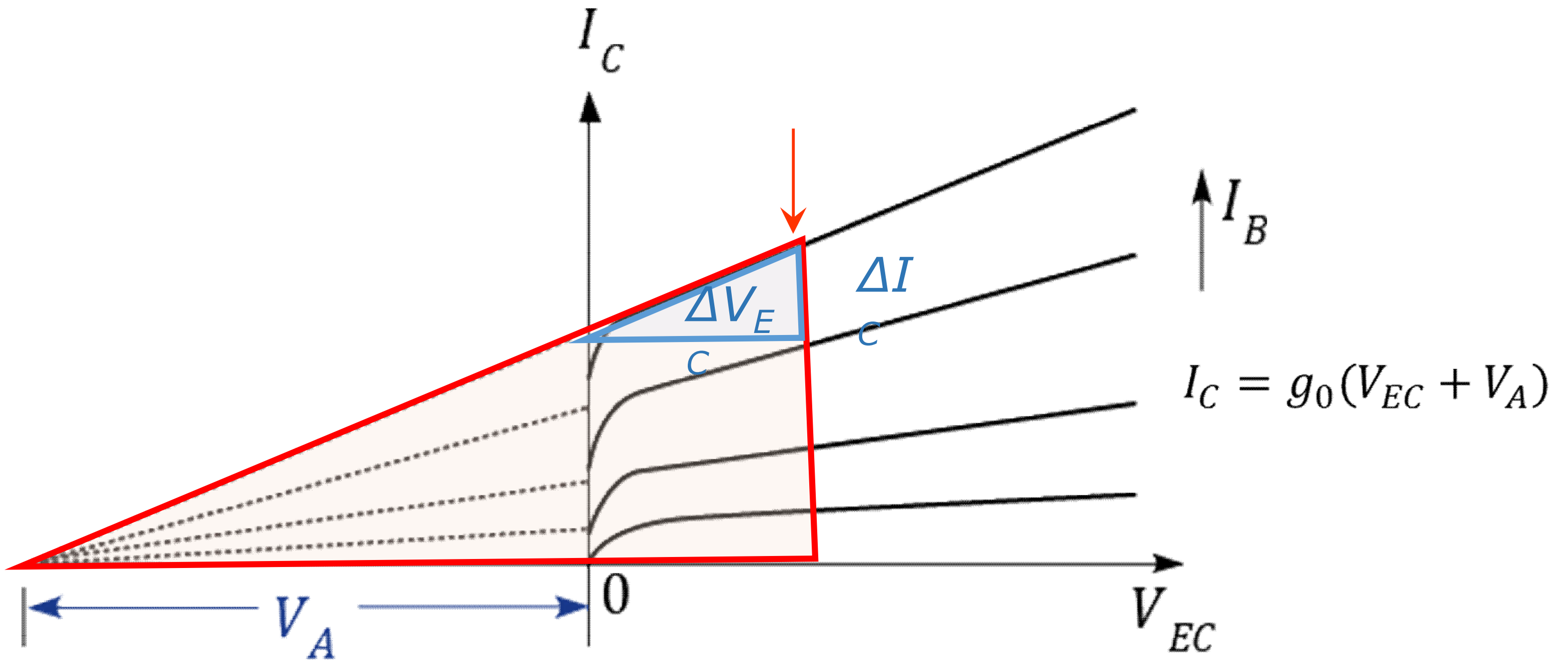
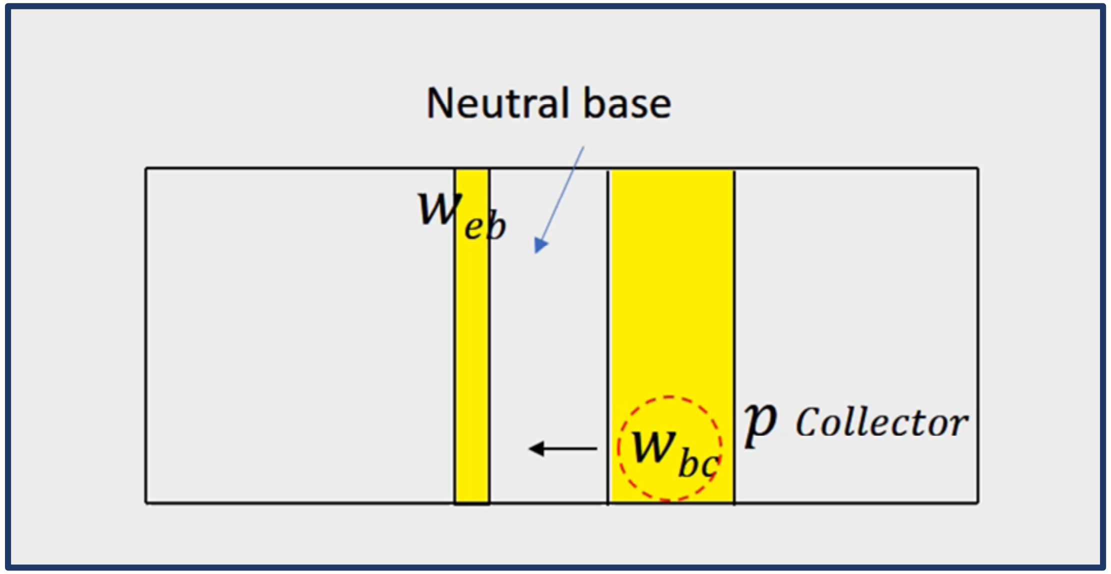


Figure 2.40

Punch Through Effect

- For a **very narrow base** or a **base with low doping**, the breakdown is caused by the punch-through effect; that is, the neutral base width is **reduced to zero** at a sufficient V_{BC} (reverse bias).
- As a result, the **collector depletion region comes in direct contact with the emitter depletion region**. Like a short circuit, a large current results. This is the main breakdown mechanism of BJTs.



Animation 2.2

Cutoff frequency of BJT

- Cutoff frequency is one of the key parameters which decide the operating frequency of the transistor.
- The current gain is a constant at low frequencies.
- However, it will decrease after a critical frequency is reached.
- There are 3 definitions of cutoff frequencies:
  - f_{α} : Common-base cutoff frequency.
  - f_{β} : Common-emitter cutoff frequency.
  - f_{T} : Unity current gain cutoff frequency.

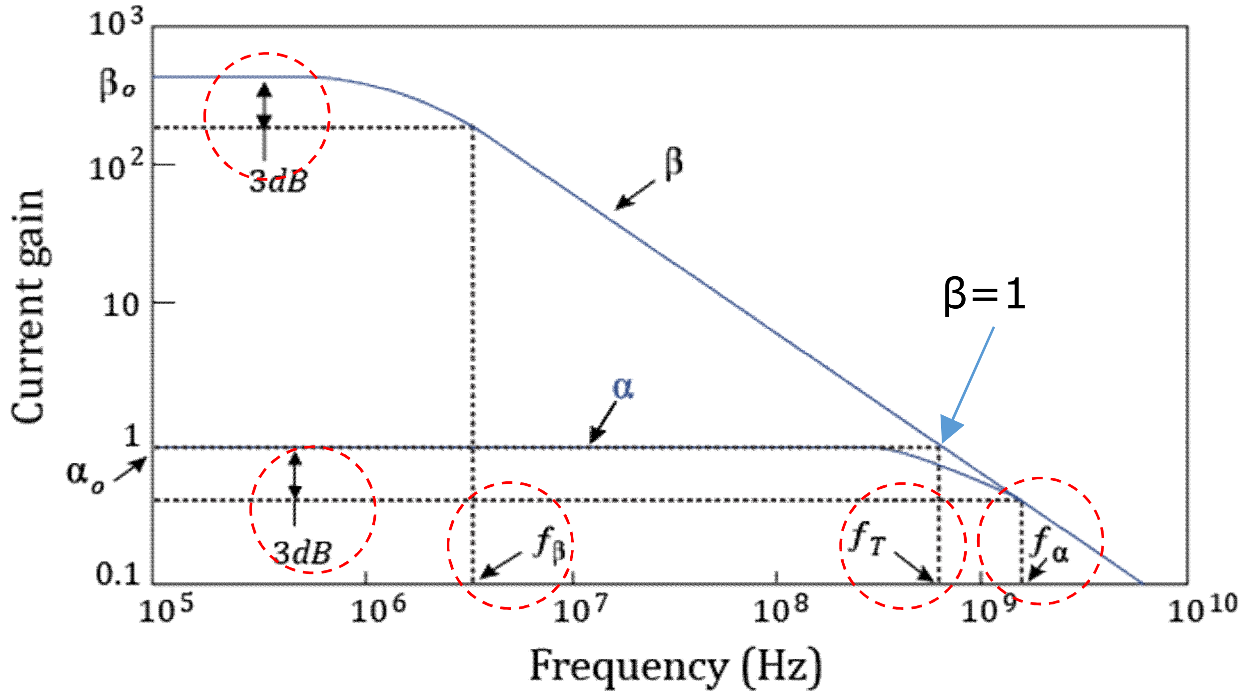


Figure 2.41

$f_T - \tau_B$ Relationship

- The cutoff frequency f_T can also be expressed as $\boxed{(2\pi\tau_T)^{-1}}$ where τ_T is the total time of the carrier transit from the emitter to the collector.
- τ_T includes the emitter delay time τ_E, the base transit time τ_B, and the collector transit time τ_C.
- The most important delay time is τ_B as it is much greater than the sum of others. For a p-n-p transistor:

$$\boxed{\tau_T \approx \tau_B = \frac{W^2}{2D_p}} \text{ and } \boxed{f_T \approx \frac{1}{2\pi\tau B} = \frac{D_P}{\pi W^2} \quad \textit{(Equation 2.37)}}$$

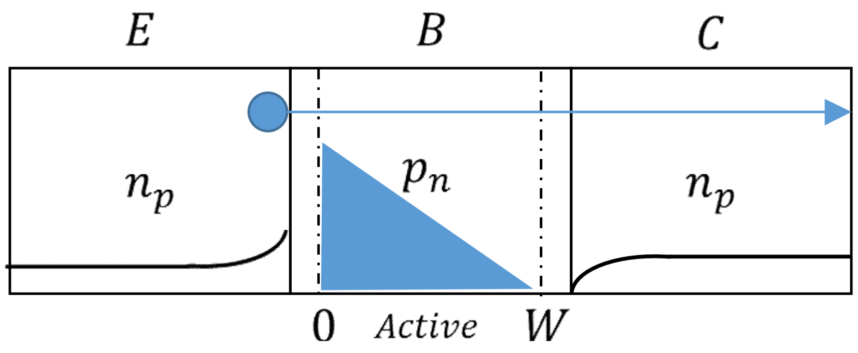


Figure 2.42

How does a BJT Amplify

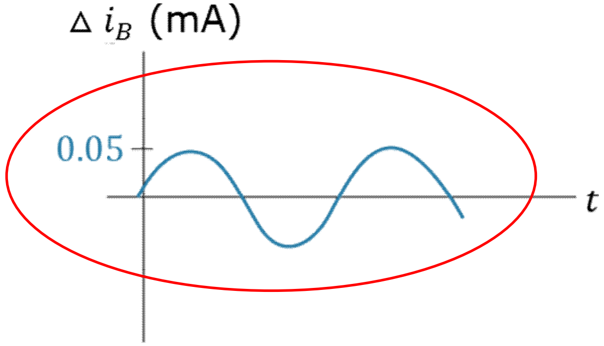


Figure 2.43 (b)

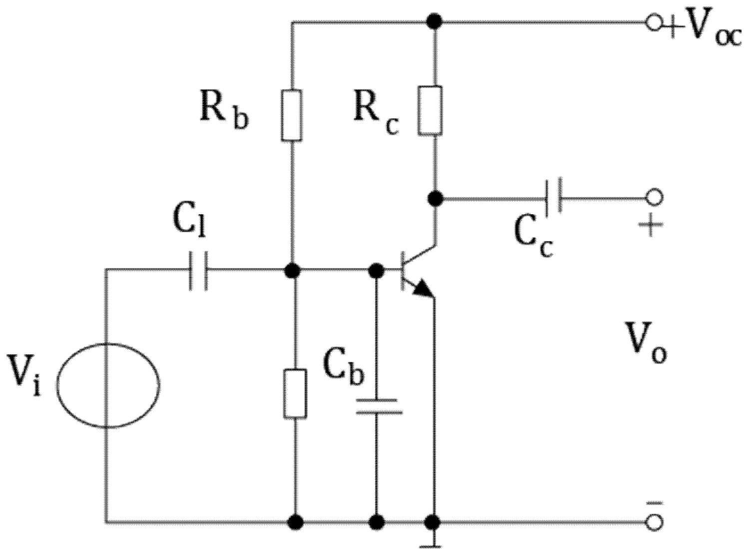


Figure 2.43 (a)

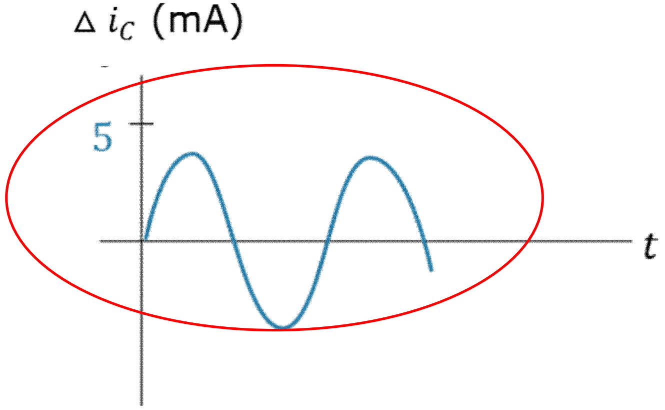


Figure 2.43 (c)

$$V_i \xrightarrow{\quad C_1 \quad} \Delta V_{BE} \longrightarrow \Delta i_B \longrightarrow \xrightarrow{\Delta i_C = \beta \Delta i_B} \Delta i_C \xrightarrow{\quad R_L \quad} \Delta V_{CE} \xrightarrow{\quad C_2 \quad} V_0$$

$$\beta = \frac{\Delta i_C}{\Delta i_B} \ and \ A_V = \frac{V_0}{V_i}$$

Lesson Summary

- A bipolar junction transistor consists of emitter, base and collector. It is essentially two back-to-back pn junctions in contact with a very narrow base thus resulting in transistor action.
- Under active mode for a PNP BJT, the emitter base is forward biased and the base collector is reversed biased. This will result in the injection of holes into the base and be collected at the collector. This is the main origin of the collector and emitter current in a BJT.
- Under active mode for a PNP BJT, the minority carrier concentrations in the emitter, base and collector are given by:

(1) $n_E(x) = n_{EO} + n_{EO}\left[e^{qV_{EB}/kT} - 1\right] exp\left[\frac{x+x_E}{L_E}\right]$ (2) $P_n(x) = P_n(0)\left[1 - \frac{x}{W}\right]$ (3) $n_C(x) = n_{CO} - n_{CO} exp\left(-\frac{x-x_C}{L_C}\right)$

Lesson Summary

- The corresponding current components can be obtained by taking the first derivative of the above carrier concentration distribution functions which give:

(1) $I_{Ep} = A\left(-qD_p \frac{dp_n}{dx}\middle|x=0\right) \equiv qA\frac{D_p P_{no}}{W} e^{qV_{EB}/kT}$ (2) $I_{Cp} = A\left(-qD_p \frac{dp_n}{dx}\middle|x=W\right) \approx \frac{qAD_P P_{no}}{W} e^{qV_{EB}/kT}$

(3) $I_{En} = A\left(qD_{En} \frac{dn_E}{dx}\middle|x=-x_E\right) = \frac{qAD_{En}n_{EO}}{L_E}\left(e^{qV_{EB}/kT}-1\right)$ (4) $I_{Cn} = A\left(qD_{Cn} \frac{dn_C}{dx}\middle|x=x_C\right) = \frac{qAD_{Cn}n_{CO}}{L_C}$

(5) $I_B = I_E - I_C = I_{En} + \left(I_{Ep} - I_{Cp}\right) - I_{Cn}$

- For a PNP BJT, there are four modes of operation:

(1) Active Mode ($V_{EB} > 0$ *and* $V_{CB} < 0$) (2) Saturation Mode ($V_{EB} > 0$ *and* $V_{CB} > 0$)

(3) cutoff Mode ($V_{EB} < 0$ *and* $V_{CB} < 0$) (4) Inverted Mode ($V_{EB} < 0$ *and* $V_{CB} > 0$)

- For common base configuration: $I_C = \alpha_0 I_E + I_{CBO}$, $\alpha_0 \equiv \frac{I_{CP}}{I_E} = \left[\frac{I_{Ep}}{I_{Ep}+I_{En}}\right]\left[\frac{I_{Cp}}{I_{Ep}}\right]$ and $\alpha_0 = \gamma\alpha_T$

Emitter efficiency γ *B*

Lesson Summary

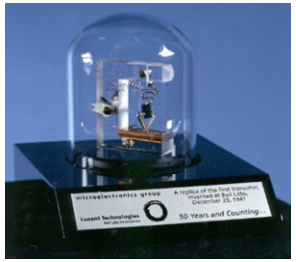
- For common emitter configuration: $I_C = \frac{\alpha_o}{1-\alpha_o} I_B + \frac{I_{CBO}}{1-\alpha_o}$ where $\beta_0 = \frac{\Delta I_C}{\Delta I_B} = \frac{\alpha_o}{1-\alpha_o}$ and $I_{CEO} = \frac{I_{CBO}}{1-\alpha_o}$
- For non-ideal BJT, when the reverse bias voltage V_{CB} increases, the neutral base width decreases. This in turns cause the minority carrier concentration gradient to increase thus the collector current to increase. This is so-called the base width modulation effect.
- One can express the collector current as a function of the Early voltage V_A as: $I_C = g_0(V_{EC} + V_A)$
- Punch through in a BJT will occur V_{CB} is large enough to cause the collector depletion region to come in direct contact with the emitter depletion region resulting in a current surge which cause the BJT to breakdown.

Lesson Summary

- The three different types of cutoff frequencies are:
  - f_α : Common-base cutoff frequency,
  - f_β : Common-emitter cutoff frequency, and
  - f_T : Unity current gain cutoff frequency.
- The cutoff frequency f_T is given by: $f_T \approx \frac{1}{2\pi\tau B} = \frac{D_P}{\pi W^2}$ where $\tau_T \approx \tau_B = \frac{W^2}{2D_p}$.

Reference

No.	Slide No.	Image	Reference
1.	3		Intel Free Press (2013, March 18). Early Fairchild Semiconductor Planar Transistor. Retrieved March 15, 2017, from https://www.flickr.com/photos/intelfreepress/8568453679/in/album-72157631636918757/
2.	3		By Benedikt.Seidl (Own work) Retrieved December 20, 2016 from [Public domain or Public domain], via Wikimedia Commons
3.	4		By AT&T; photographer: Jack St., Retrieved December 20, 2016 from Wikimedia Commons

No.	Slide No.	Image	Reference
4.	4		History of the transistor. (2017, February 19). Retrieved March 15, 2017, from https://en.wikipedia.org/wiki/History_of_the_transistor#/media/File:Replica-of-first-transistor.jpg
5.	4		By Mataresephotos (Own work) Retrieved March 15, 2017, from [CC BY 3.0 (http://creativecommons.org/licenses/by/3.0)], via Wikimedia Commons
6.	5		By Cmglee (Own work)) Retrieved March 15, 2017, from GFDL(http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons