NANYANG TECHNOLOGICAL UNIVERSITY

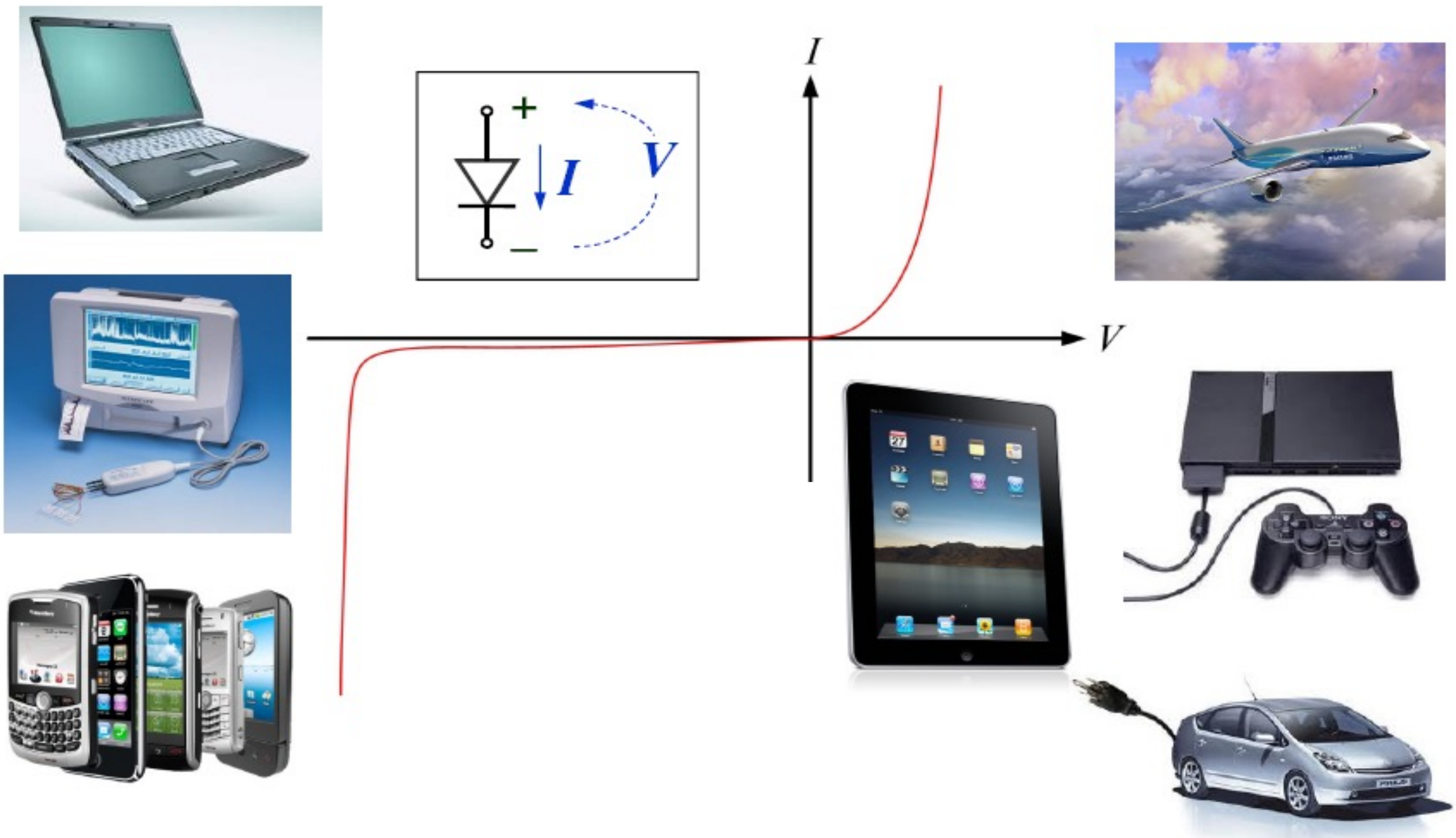
EE2003 Semiconductor Fundamentals (Part III)

Bipolar Junction Transistor (BJT)

BJT

(Lectures 1 - 3)

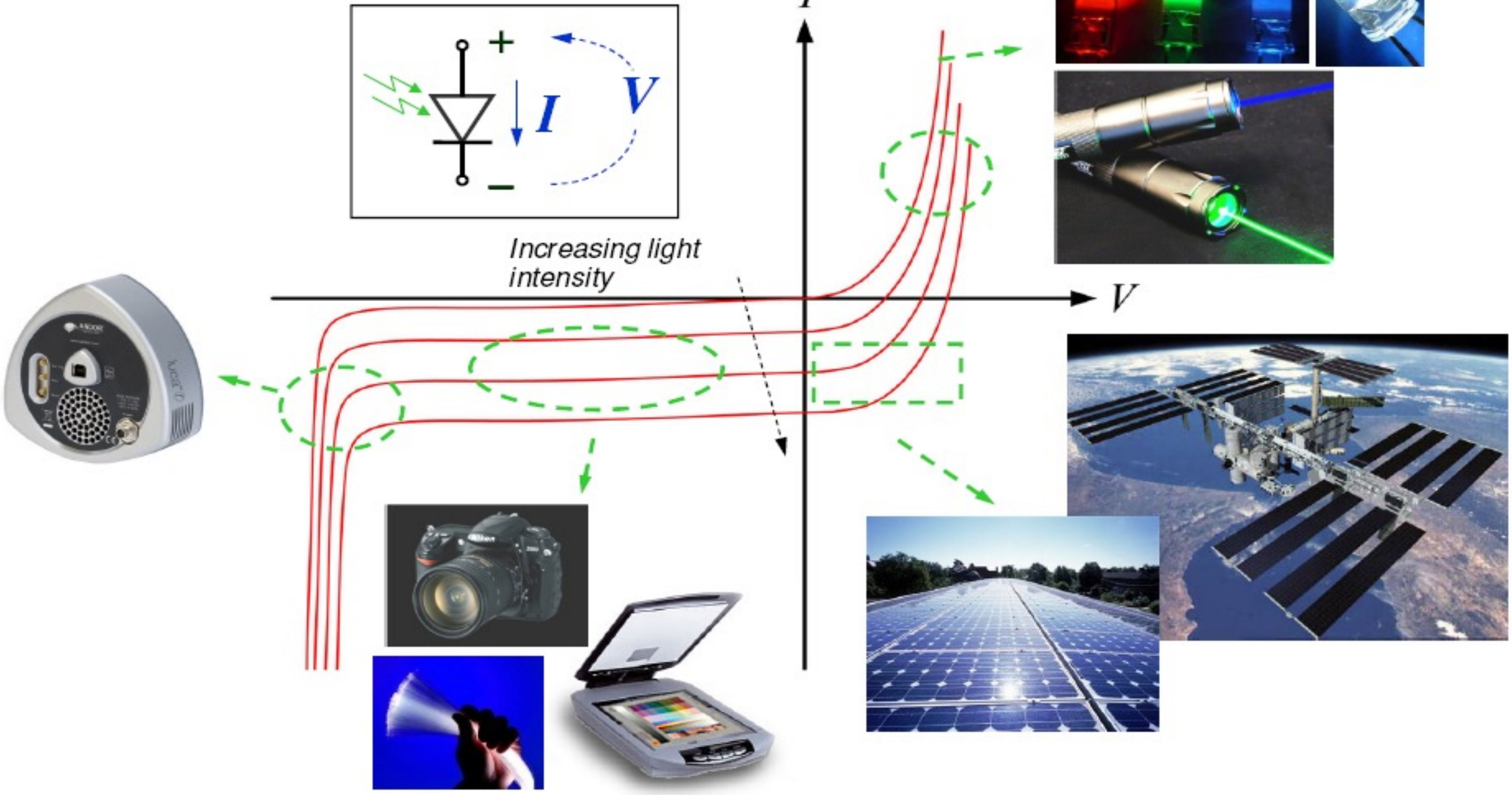
Applications of semiconductors - Microelectronics



Rectifier, switch, and variable capacitor

Applications of semiconductors - Optoelectronics

When light is involved...



Mobile phones

Perfect successful example of the semiconductor technologies

Display

- 5inch Full HD Super AMOLED (1920 x 1080) display, 441 ppi

AP

- 1.9 GHz Quad-Core Processor / 1.6 GHz Octa-Core Processor
- The seletion of AP will be differed by markets

Network

- 2.5G (GSM/ GPRS/ EDGE): 850 / 900 / 1800 / 1900 MHz
- 3G (HSPA+ 42Mbps): 850 / 900 / 1900 / 2100 MHz
- 4G (LTE Cat 3 100/50Mbps) : up to 6 different band sets (Dependent on market)

OS

- Android 4.2.2 (Jelly bean)

Memory

- 16 / 32 / 64GB memory + microSD slot (up to 64GB), 2GB RAM

(User memory approximately 9Gb)*
*User memory is less than the total memory due to storage of the operating system and software used to operate the phones features. Actual user memory will vary depending on the mobile phone operator and may change after software upgrades are performed.
*External Memory may be used to store media (photos, video, and music files) and aplications, which developers implement "storing on SD card" option in.

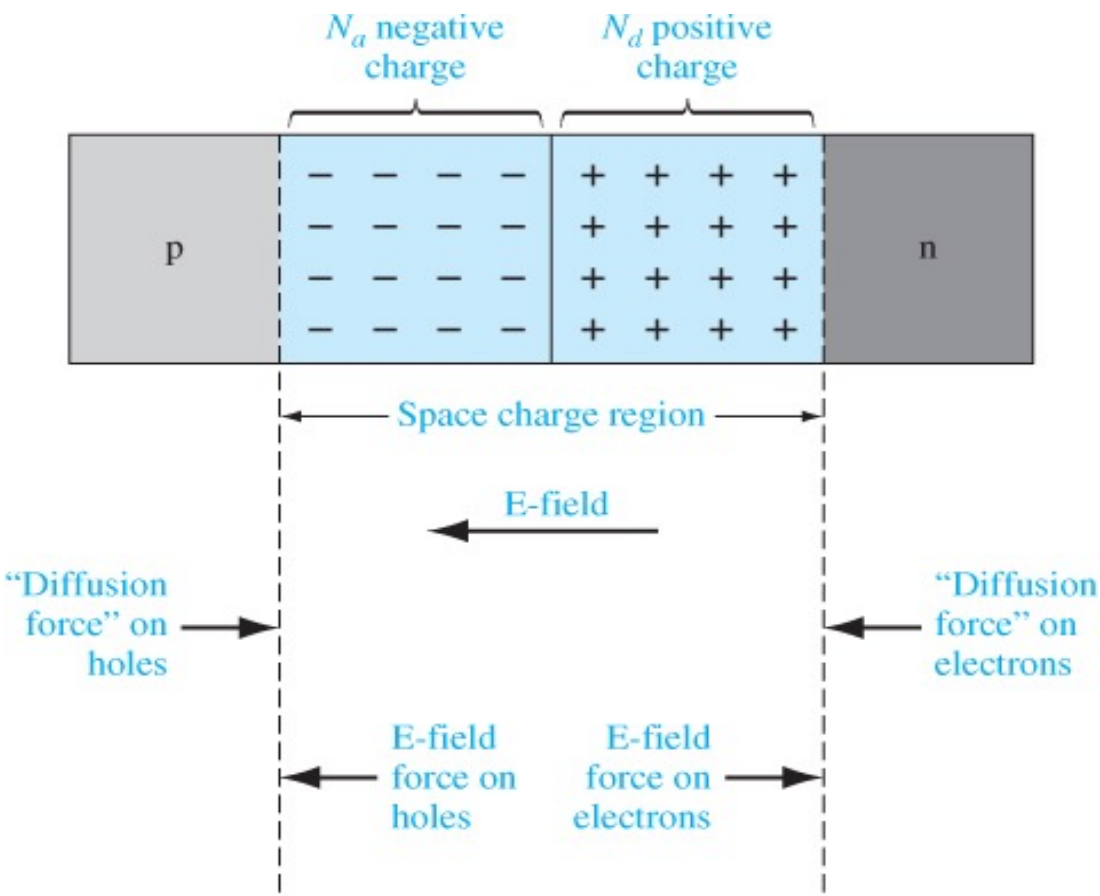
Camera

- Main(Rear): 13 Mega pixel Auto Focus camera with Flash & Zero Shutter Lag, BIS
- Sub (Front): 2 Mega pixel camera, Full HD recording @30fps with Zero Shutter Lag, BIS

Camera Features

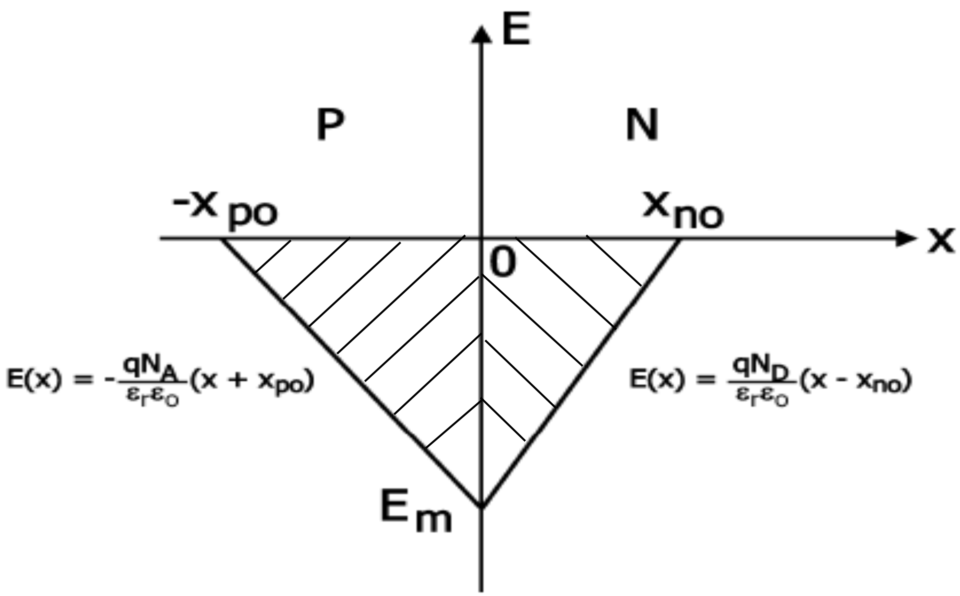
- Dual Shot , Drama Shot, Sound & Shot, 360 Photo, Animated Photo, Eraser, Night, Best Photo, Best Face, Beauty Face, HDR (High Dynamic Range), Panorama, Sports

Recall a pn junction under zero bias



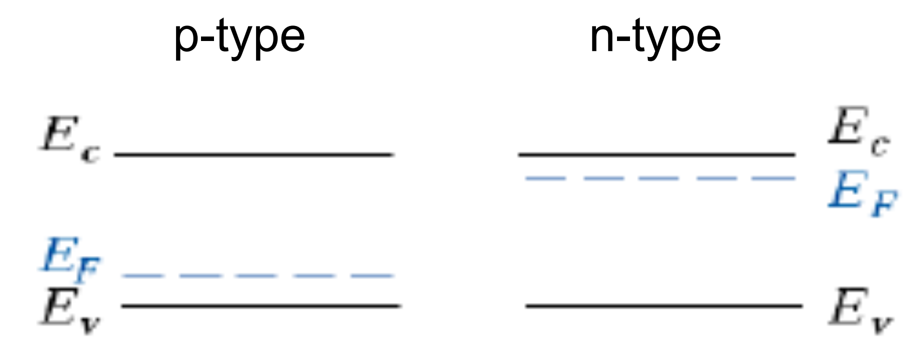
- There is a space charge region at the interface between the n and p regions.
- There is a built in electric field, pointing from n region to the p region.
- The build in electric field is not a constant. The E_{max} occurs at the interface.

Recall a pn junction under zero bias



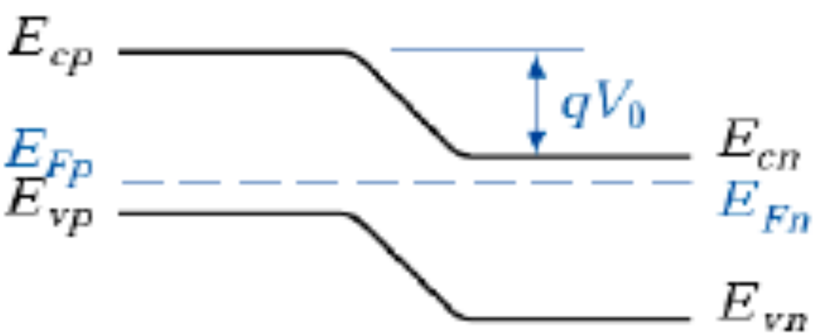
- The build in voltage (or the voltage drop across the pn junction) is the area under the electric field versus distance plot.

Recall a pn junction under zero bias



Before contact

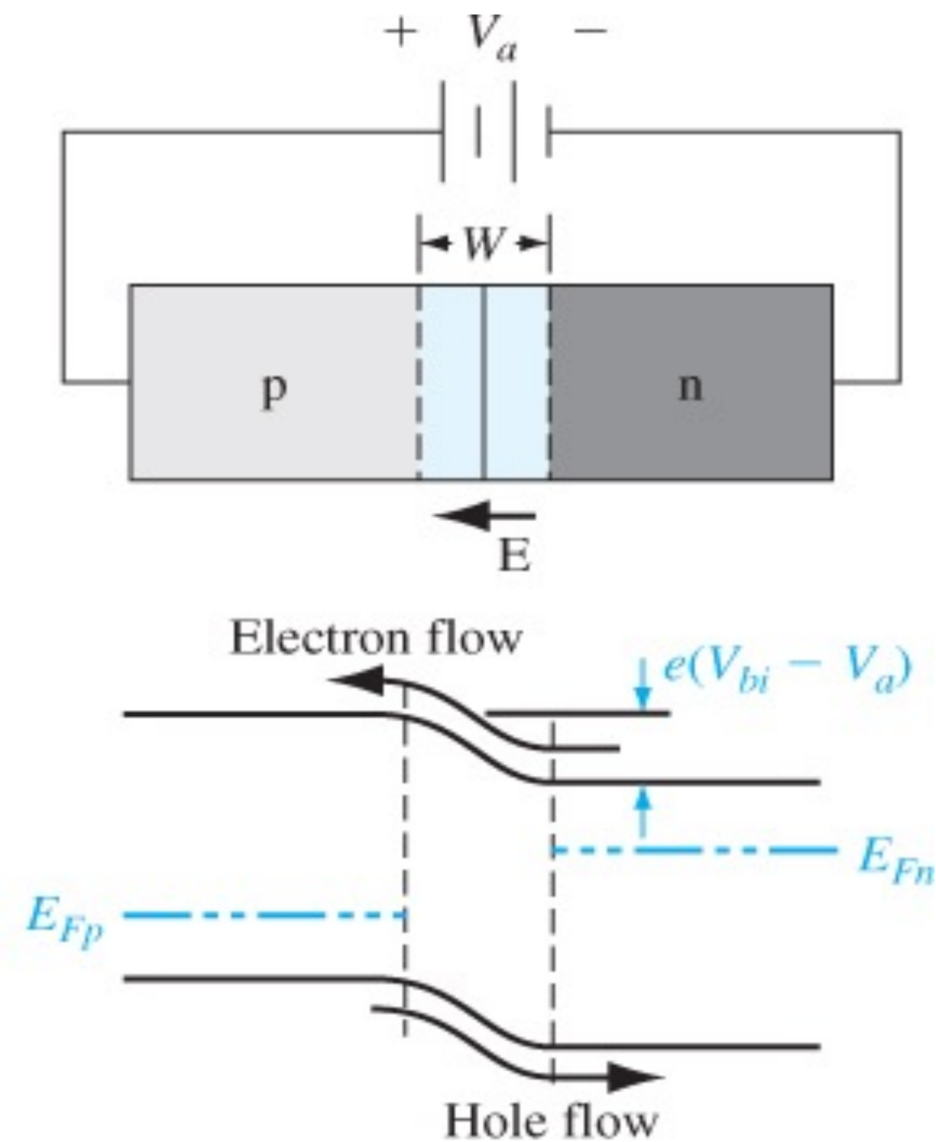
- After contact, under the thermal equilibrium condition, E_F is a constant across the pn junction.



After contact

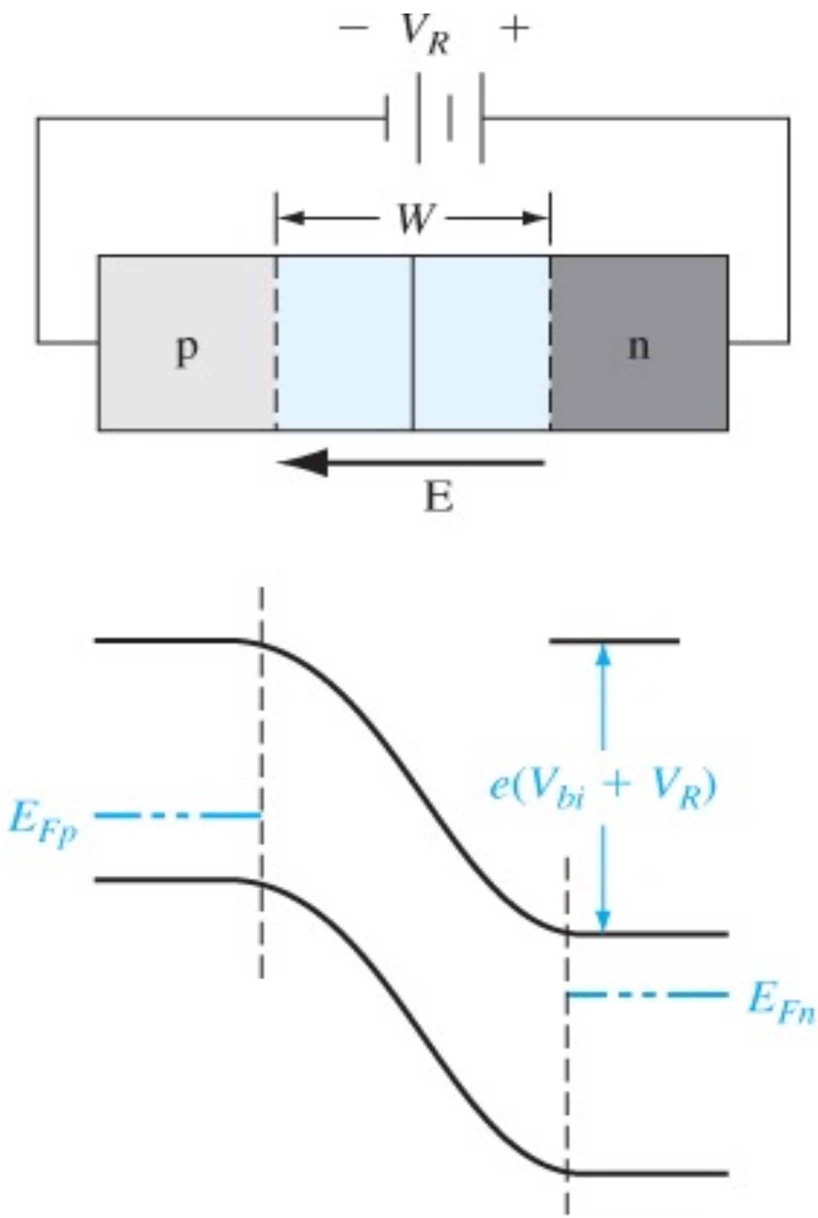
- The potential drop between p and n junction V_0 is equal to the build in voltage.

Recall a pn junction under forward-bias conditions



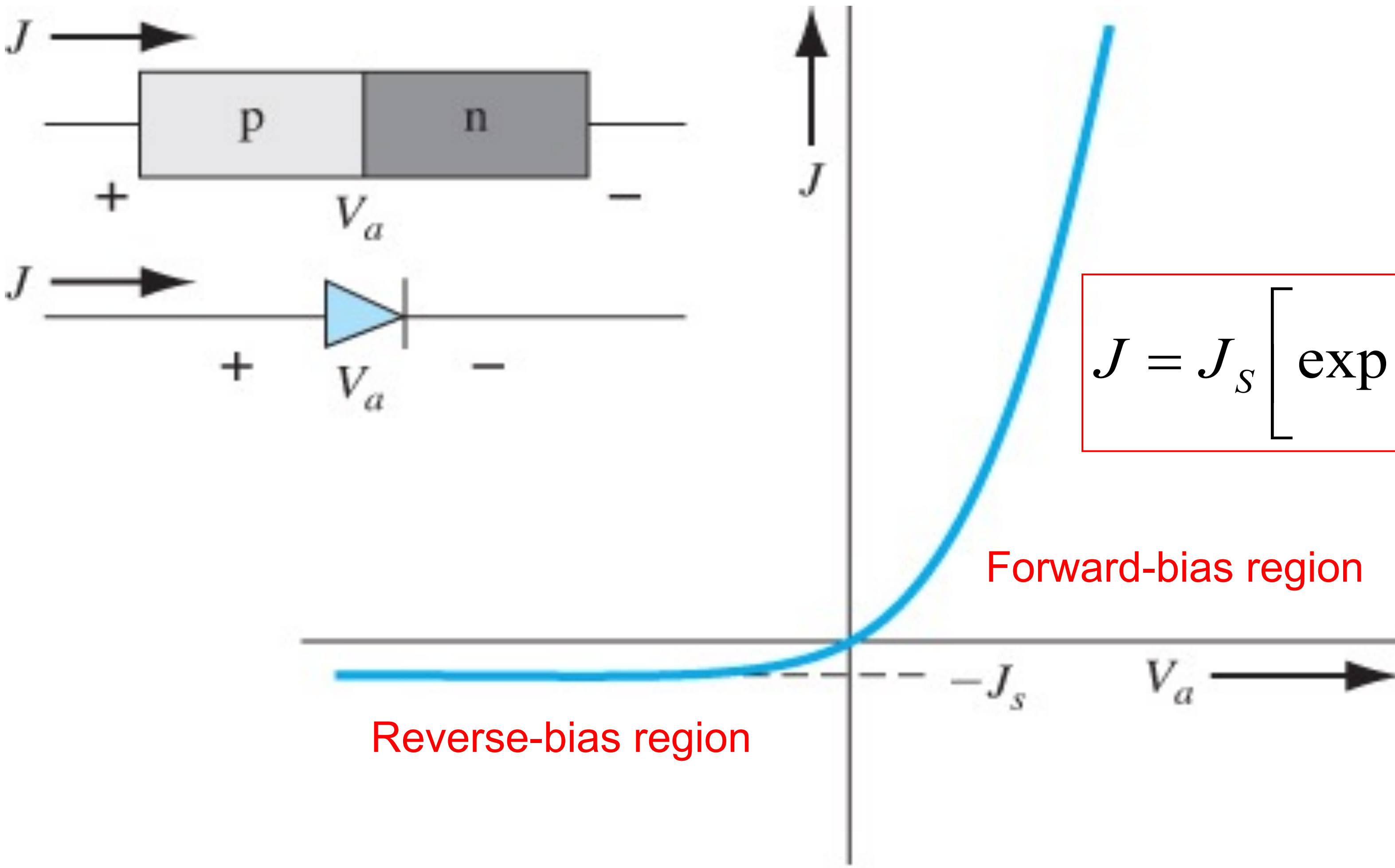
- The applied field opposes the build in field.
- The net electric field becomes smaller. The space charge region width decreases. The potential drop reduces.
- Fermi level is no longer a constant.
- More electrons flow from n to p region; more holes flow from p to n region. → **higher current**

Recall a pn junction under reverse-bias conditions



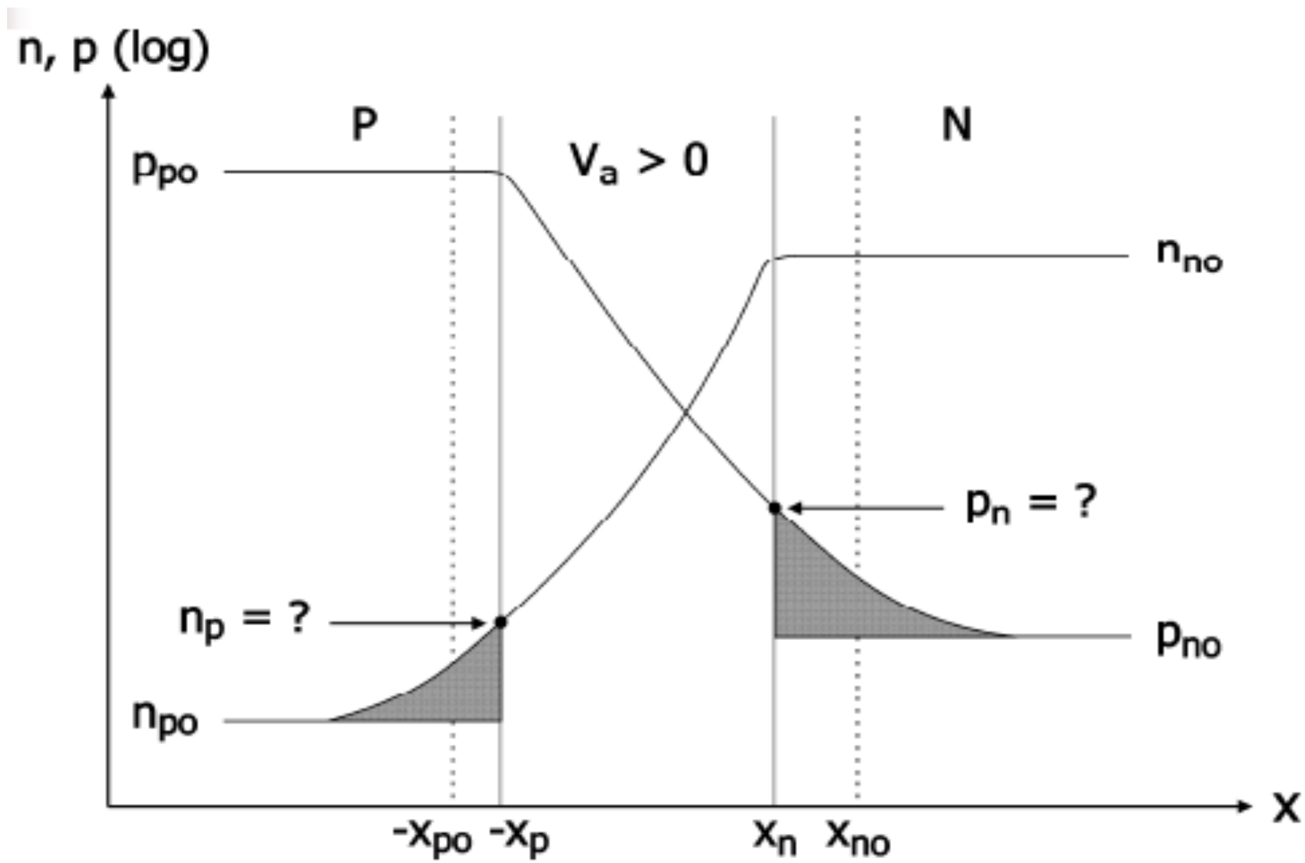
- The direction of the applied field is the same as the build-in field.
- The net electric field becomes larger. The space charge region width increases. The potential drop increases.
- Fermi level is no longer a constant.
- Fewer electrons flow from n to p region; fewer holes flow from p to n region. → **lower current**

Ideal current-voltage characteristics of a pn diode



$$J = J_S\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$$

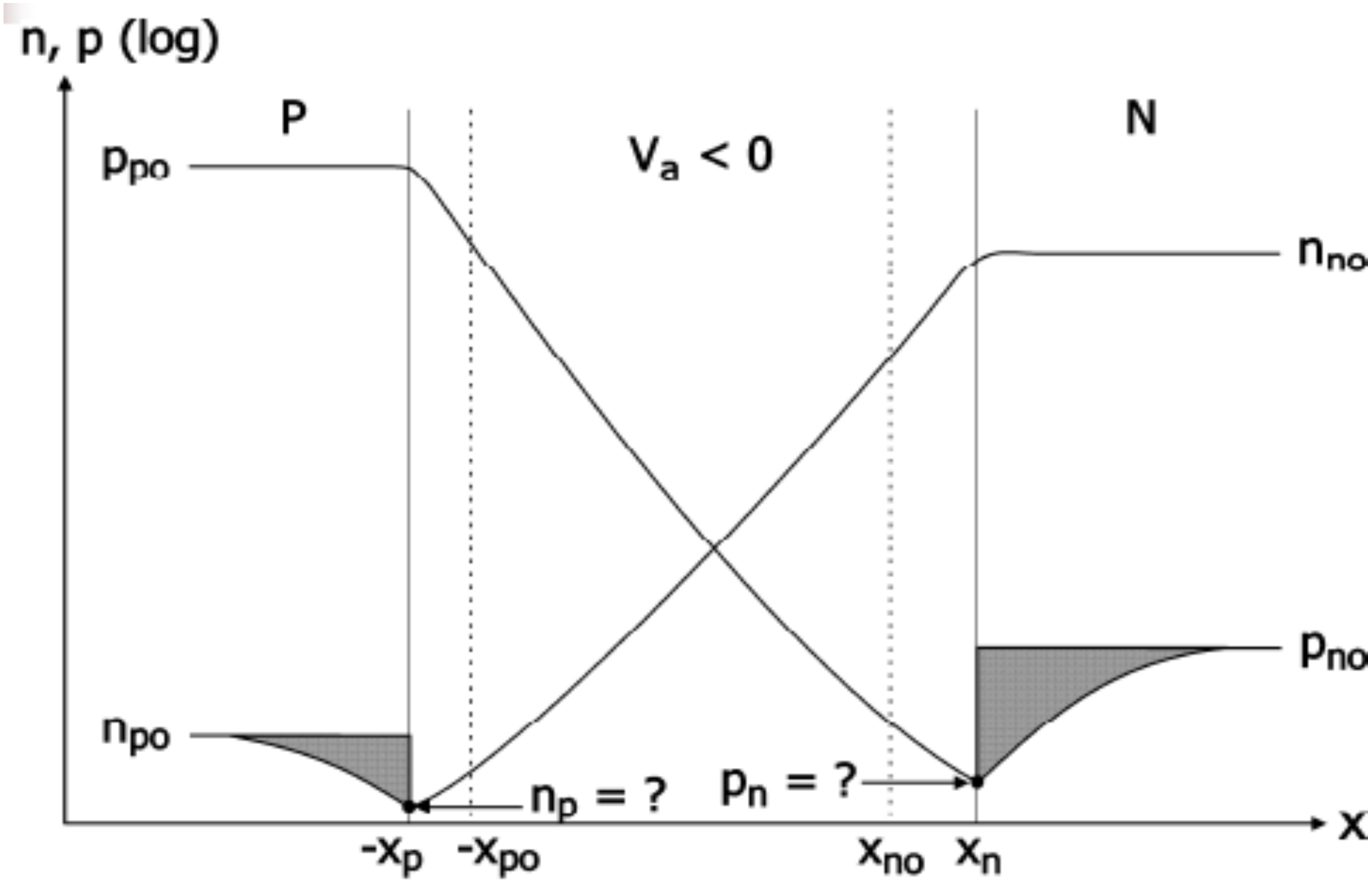
Minority carrier distribution under forward-bias condition



Charge injection

Pay attention to the minority carrier distributions of n_p and p_n outside of the space charge region, higher than the values at thermal equilibrium.

Minority carrier distribution under reverse-bias condition



Charge extraction

Pay attention to the minority carrier distributions of n_p and p_n outside of the space charge region, smaller than the values at thermal equilibrium.

pn junction

Two dominant features of p-n junction are:

- Injection of minority carriers under forward bias.

- Variation of depletion region width W with both forward and reverse biases.

These 2 properties are utilized in transistors.

Introduction of BJT

- Bipolar Junction Transistor (**BJT**) is one of the two major types of transistors.

- The other type is Metal-Oxide-Semiconductor Field-Effect-Transistor (**MOSFET**). (Not covered in this course)

- Two complementary configurations of BJTs, the npn and pnp devices, are widely used.

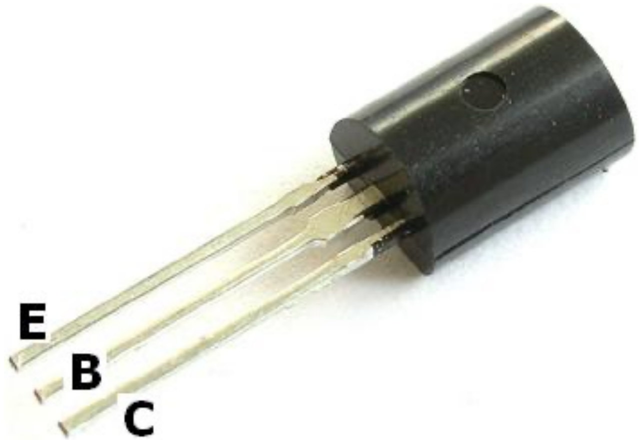
Introduction of BJT

- A BJT has three terminals: base, emitter and collector.

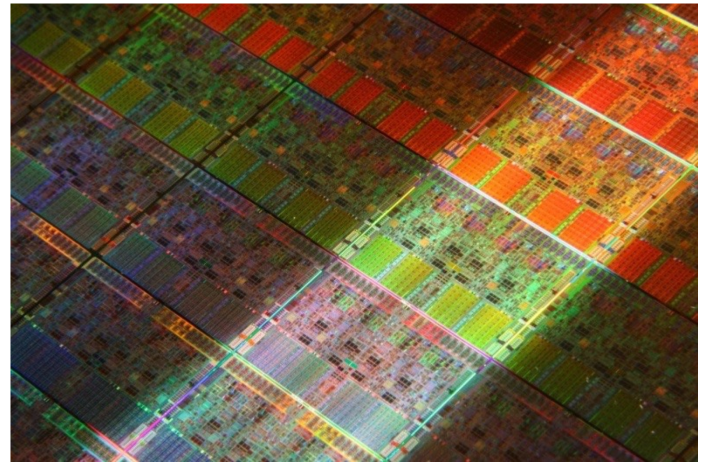
- The basic function of the transistor is that the current at one terminal of the transistor is controlled by the voltage applied across the other two terminals.

- It can perform functions such as amplification and switching, etc.

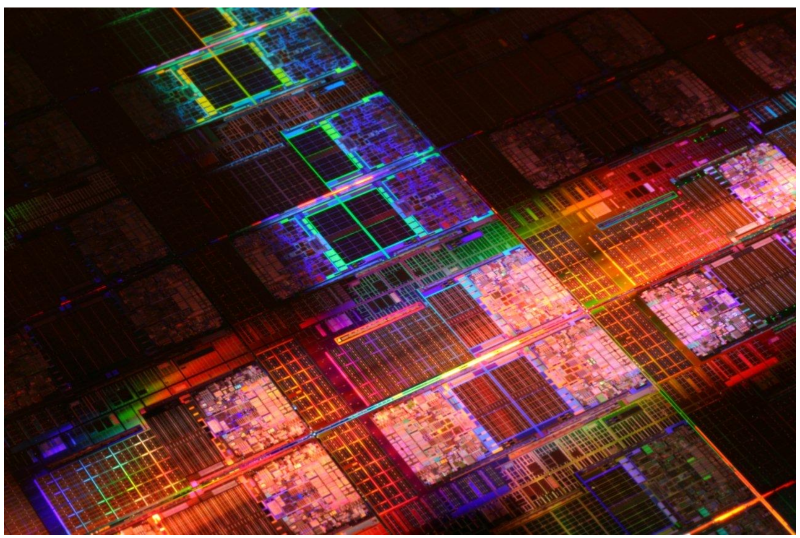
Introduction of BJT



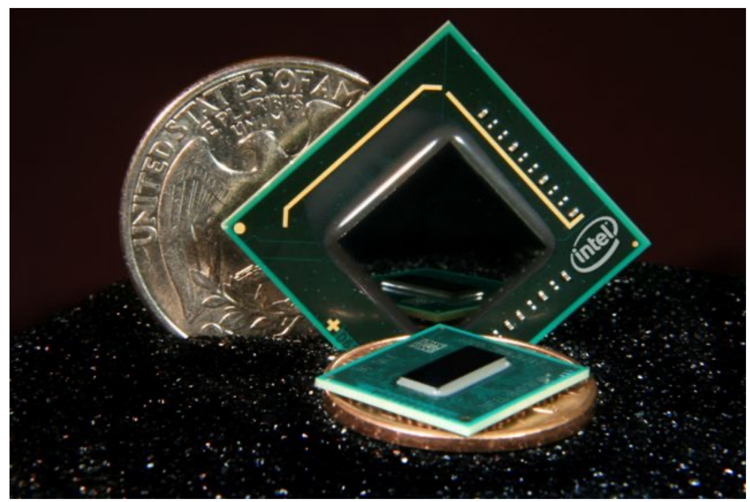
A simple three-terminal transistor



Integrated Semiconductor Device with 45 nm technology



Integrated Semiconductor Device



Semiconductor Chip

Objectives:

- You will study the physical structure of Bipolar Junction Transistor, which consists of two pn junctions put close together.
- You will learn the basic operational principle and current flow in BJT.
- You will study different modes of operations of BJT, with a focus on the forward-active mode.
- You will learn how BJT is applied to applications.

Outline:

1.1 The basic operation principle;

1.2 Simplified transistor current relation;

1.3 The modes of operation;

1.4 Applications: voltage amplification;

How many current components are available in each terminal?

How transistor is used in voltage amplification applications?

Bipolar Transistor Action (npn transistor)

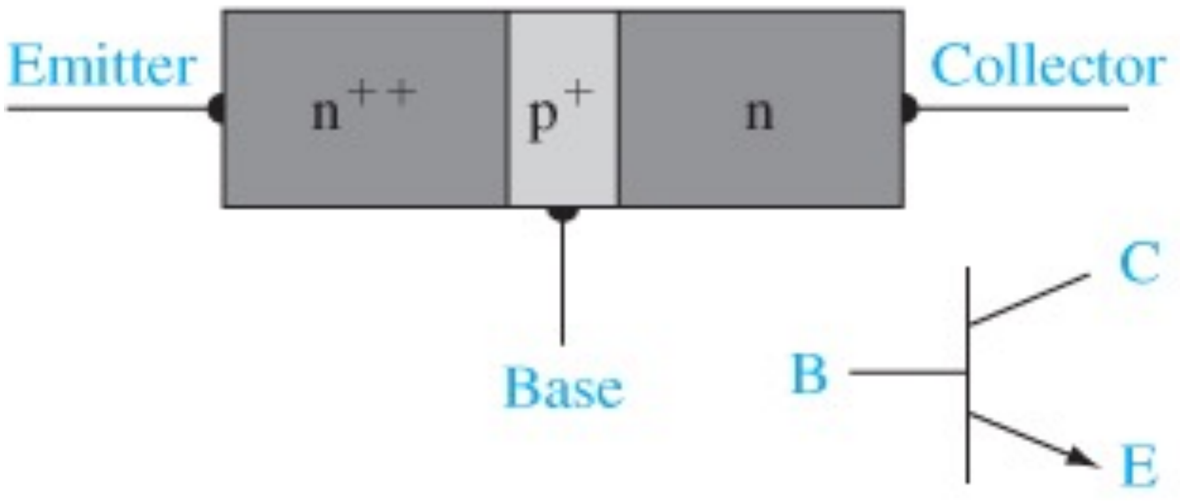


Fig.1.1 Simplified block diagrams and circuit symbols of npn bipolar transistors

- The bipolar transistor has **three separately doped regions** and **two pn junctions**.
- The three terminal connections are called the **emitter**, **base**, and **collector**.
- The arrow in the circuit symbol refers to the current flow direction, meaning electrons are injected through the emitter region.

Bipolar Transistor Action (pnp transistor)

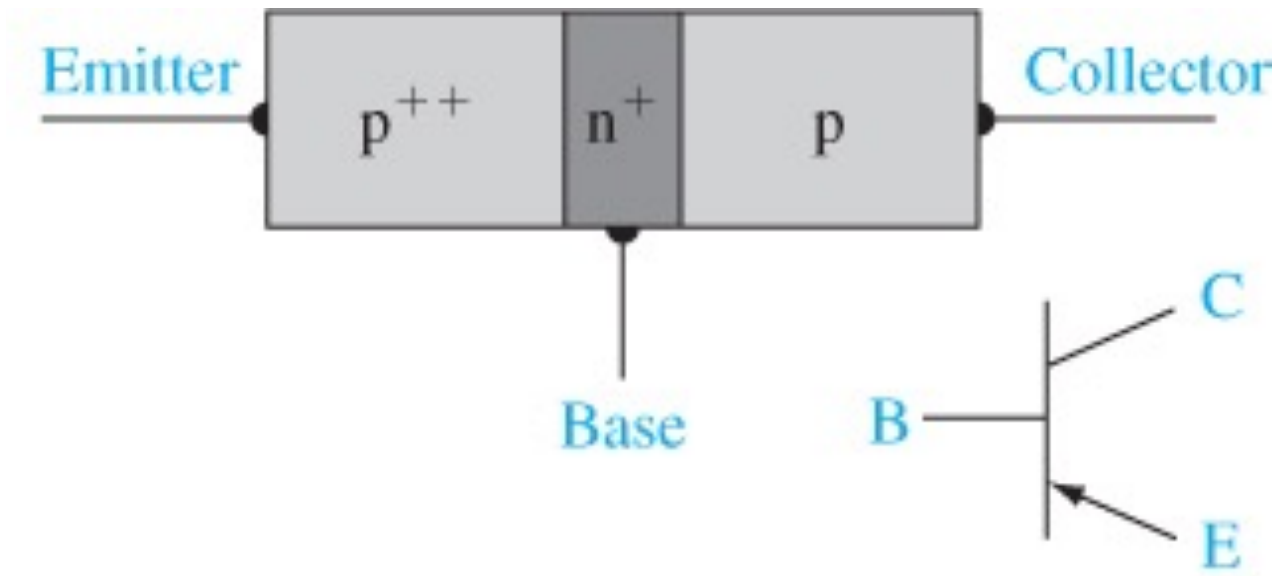


Fig.1.2 Simplified block diagrams and circuit symbols of pnp bipolar transistors

- The concepts for pn junctions ALL applied to bipolar transistors.
- Bipolar transistor is not a symmetrical device (different doping).
- The arrow in the circuit symbol refers to the current flow direction.

Bipolar Transistor Action

(++) and (+) indicate the relative magnitudes of the impurity doping concentrations. (++) → heavily doped; (+) → moderately doped.

The width of the base region is smaller compared to the minority carrier diffusion length;

The emitter region has the largest doping concentration;

The collector region has the smallest doping concentration.

We will explain why the emitter is highly doped and why the base region width is narrow

1.1 The basic principle of operation

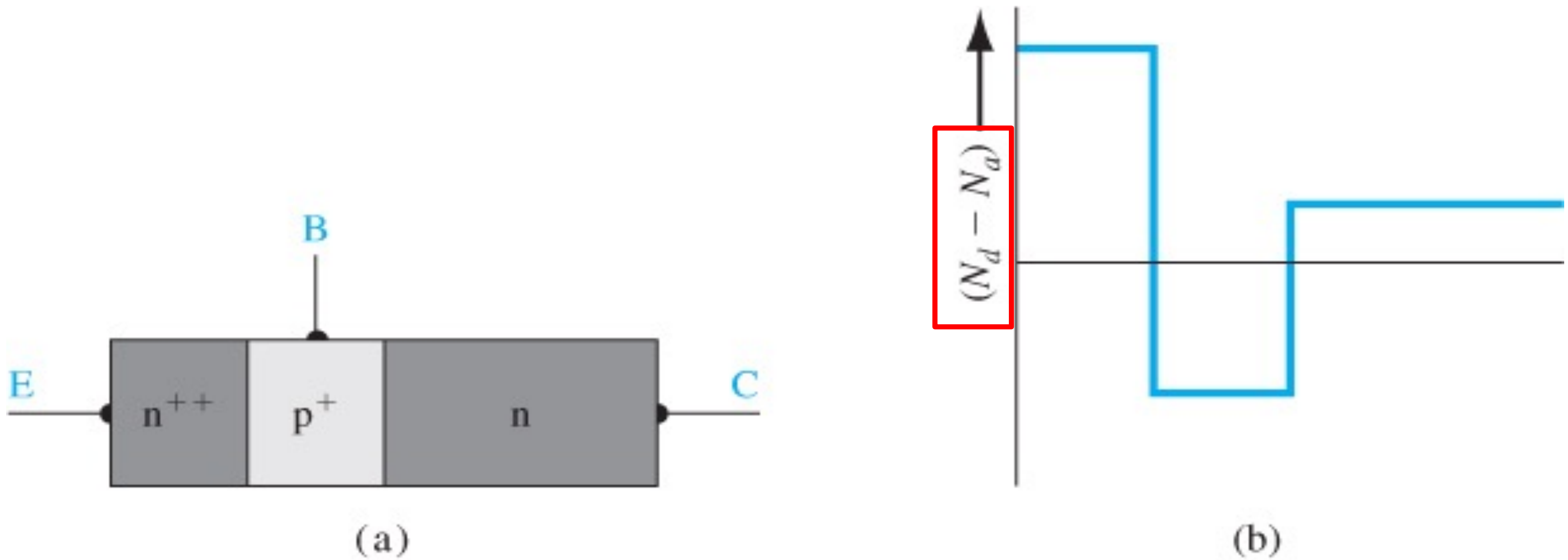


Fig.1.3 Ideal doping profile of a uniformly doped npn bipolar transistor

- The npn and pnp transistors are complementary. The analysis of **npn device** can be applied directly to the **pnp device**.
- Typical doping concentrations in emitter, base, and collector are on the order of 10^{19}, 10^{17}, and 10^{15} cm^{-3}, respectively.

Operational structure of BJT (npn)

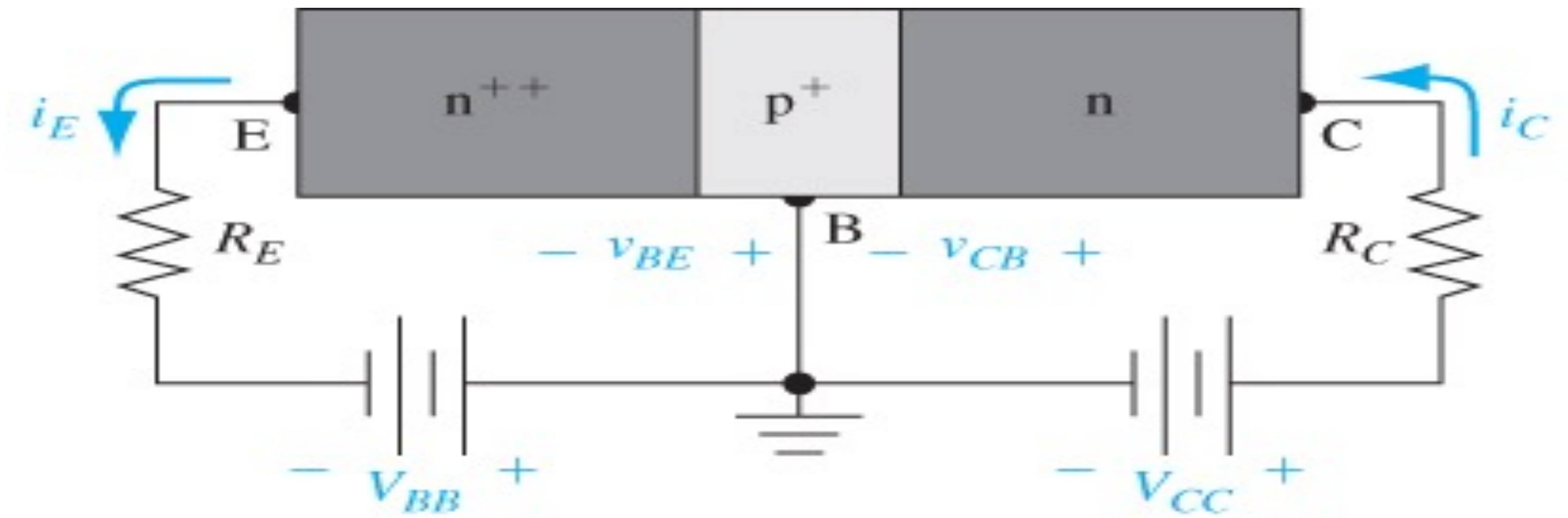
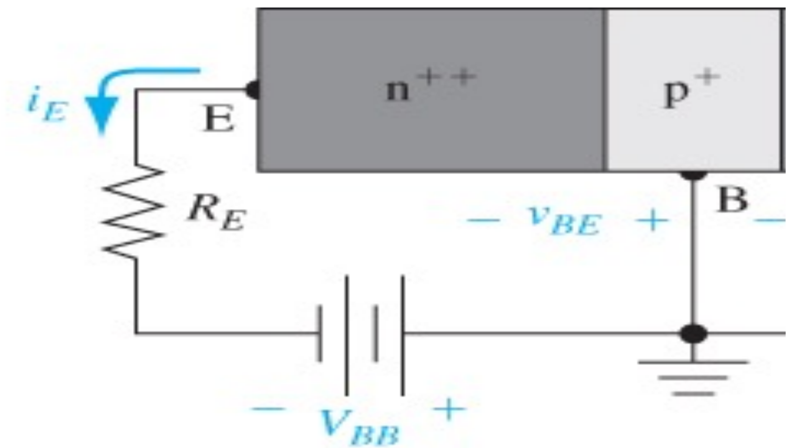


Fig.1.4 npn bipolar transistor in the forward-active mode external biasing

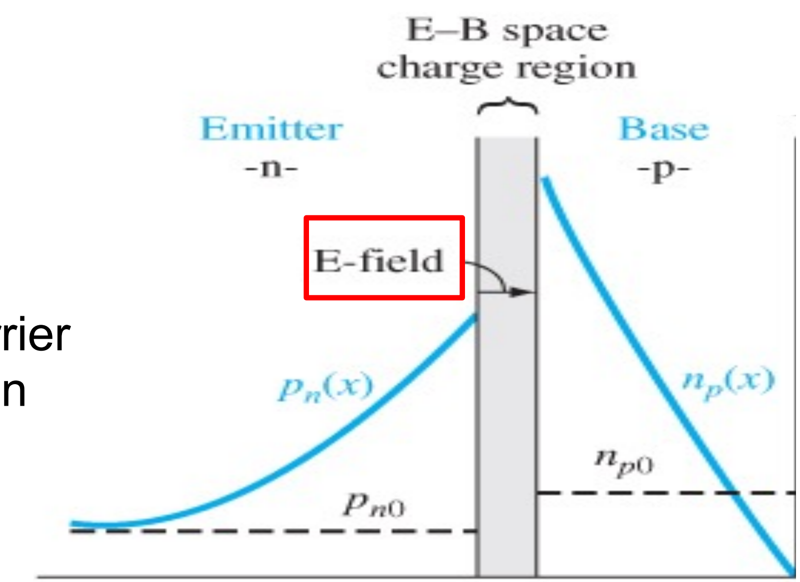
- In a normal bias configuration, the base-emitter (B-E) pn junction is forward biased; and the base-collector (B-C) pn junction is reverse biased.
- This is called the **forward-active operating mode**.

Consider the B-E loop only

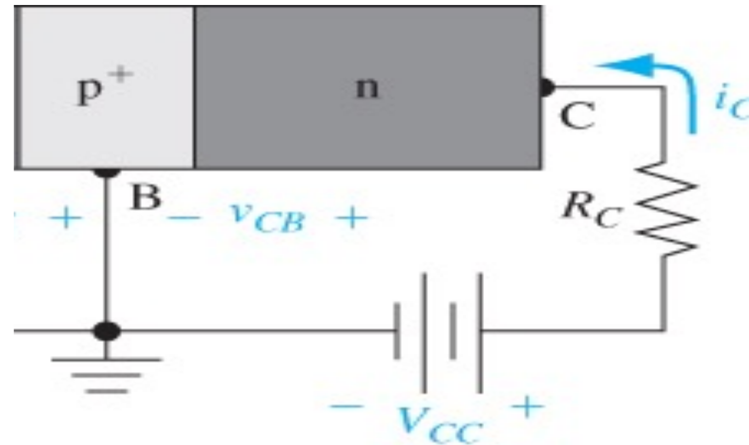


B-E is <u>forward-biased</u>

Minority carrier distribution

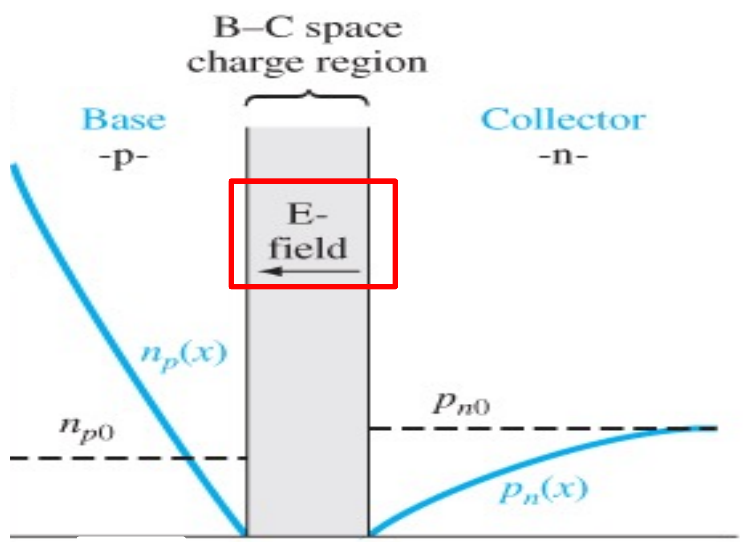


Consider the B-C loop only



B-C is reverse-biased

Minority carrier distribution



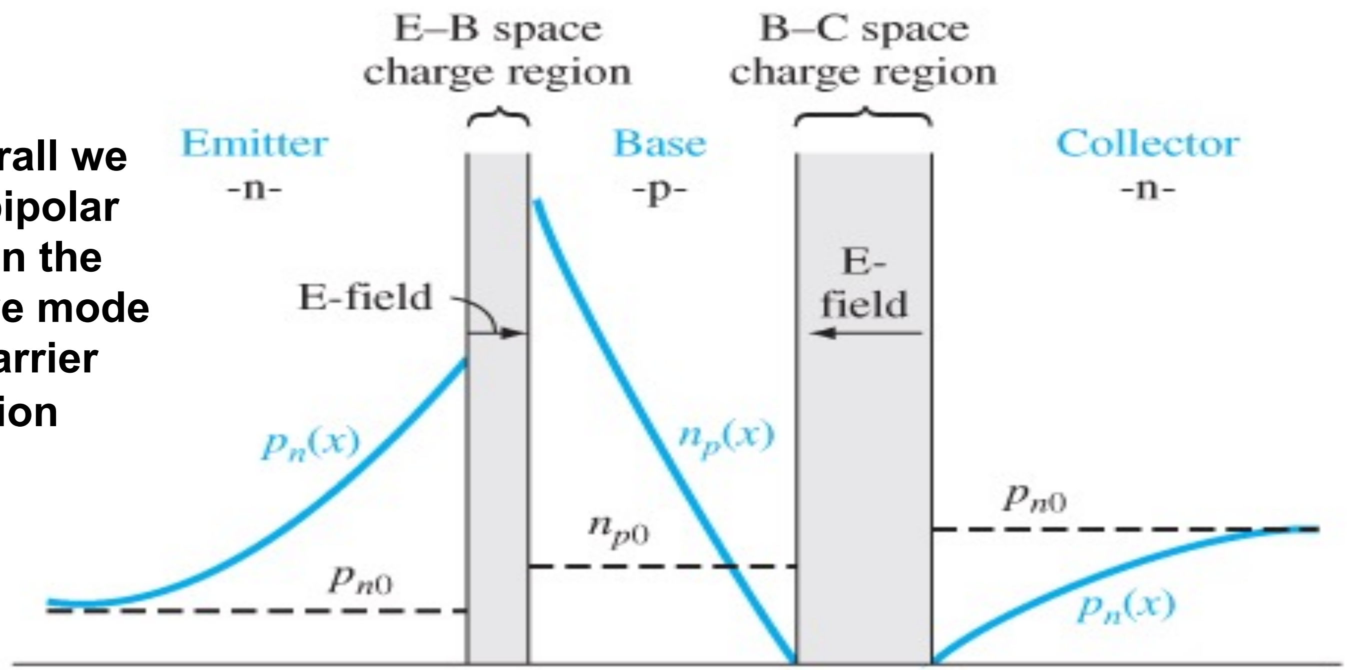
- The B-E junction is forward biased so electrons are injected from the emitter (++ n-type) into the base (p-type), as excess minority carriers.

- The B-C junction is reverse biased, so the electrons at the edge of the B-C junction is zero.

- Due to the large gradient in electron concentration in the base region, the electrons will diffuse across the base region (p-type), and then extracted into the B-C space charge region.

Minority carrier distribution in BJT

Fig. 1.5 Overall we have: npn bipolar transistor in the forward-active mode minority carrier distribution



Overall, the minority carrier concentrations in different regions in npn bipolar junction transistor are shown in Fig. 1.5.

Why p_{n0}, n_{p0}, and p_{n0} in the emitter, base, and collector, respectively, are plotted in different levels??

- Since minority carrier injection involves both electrons and holes, it is called bipolar transistor.

- We want the electrons not to recombine with holes in the base region. Thus, the width of the base region needs to be narrow.

- We want to inject as many as possible electrons from the emitter to the base. Thus, the emitter is highly doped.

- Then, the minority electron concentration in the base is a function of the junction voltage. (we will show the expression in the later part of chapter)

Energy band diagram of BJT

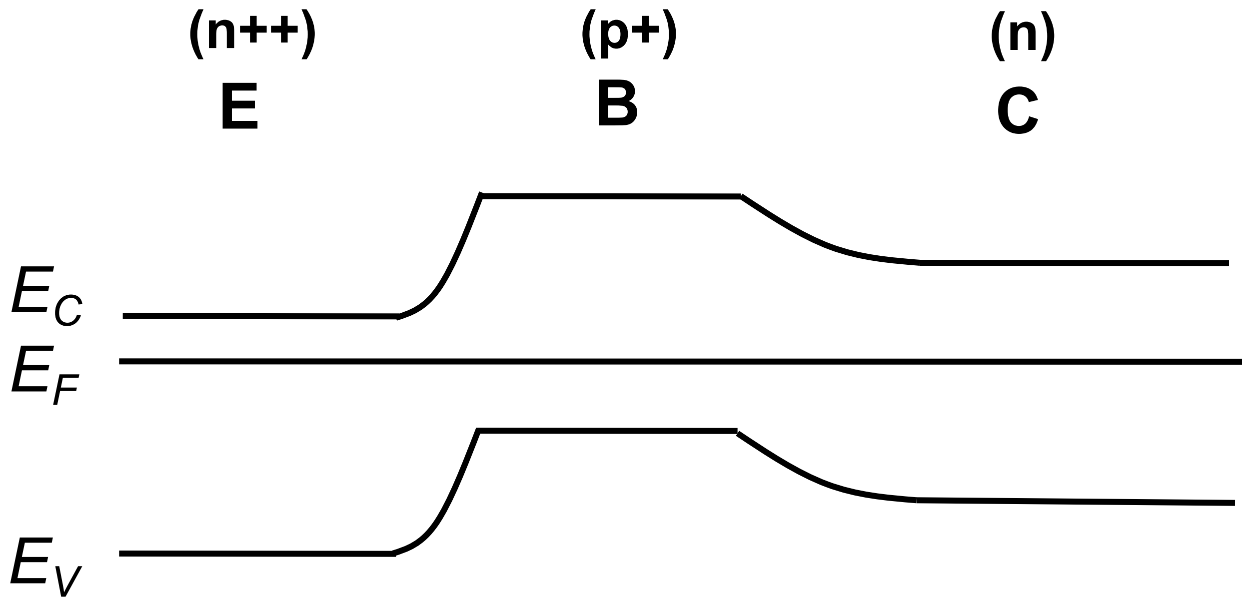


Fig. 1.6 Energy band diagram of the npn BJT under zero bias.

- Fig. 1.6 shows the energy band diagram of npn BJT under zero bias condition. The Fermi energy level is a constant across the whole region.
- Take a note of the Fermi energy levels with respect to the conduction and valence band edges.

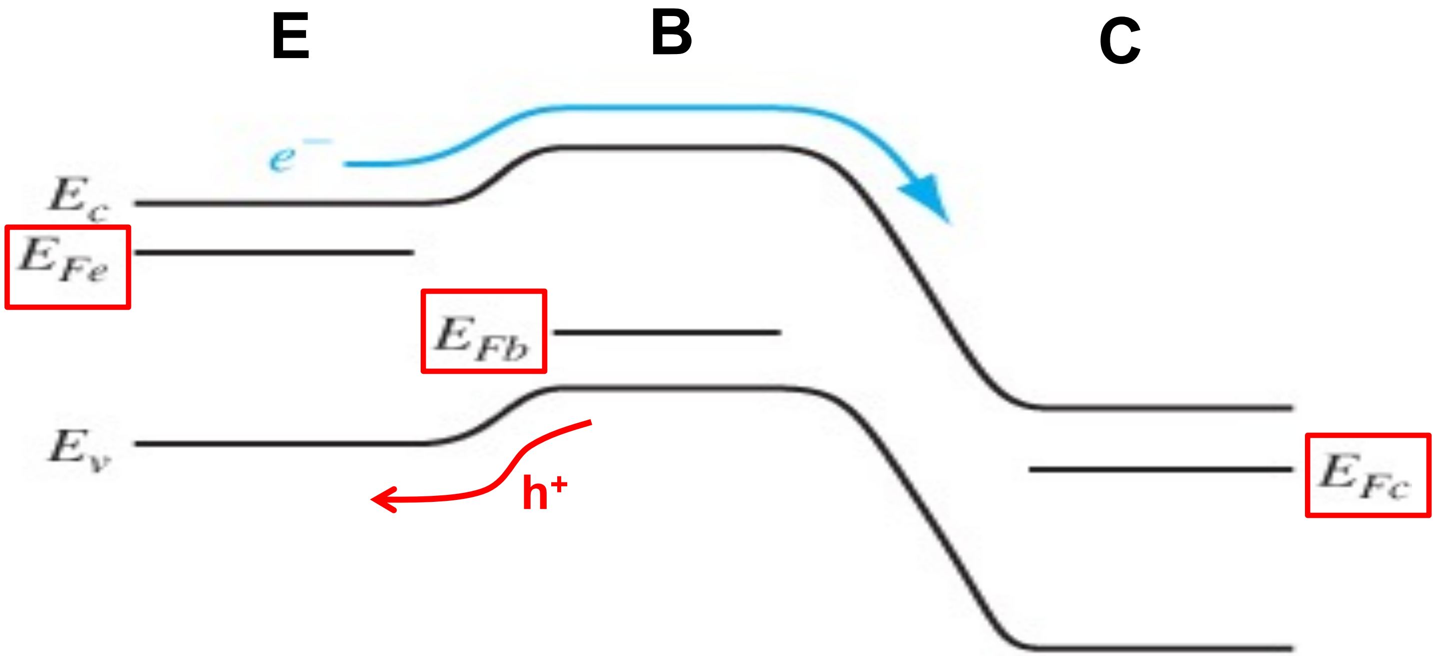


Fig. 1.7 Energy band diagram of npn BJT under forward-active mode biases.

- As the B-E junction is under forward-biased, the potential drop between B-E decreases;
- While as the B-C junction is reversed biased, the potential drop between B-C increases.
- Electrons are easily flow from terminal **E -> B -> C**
- Holes are easily flow from terminal **B -> E.** However, holes only flow through the B-E junction.

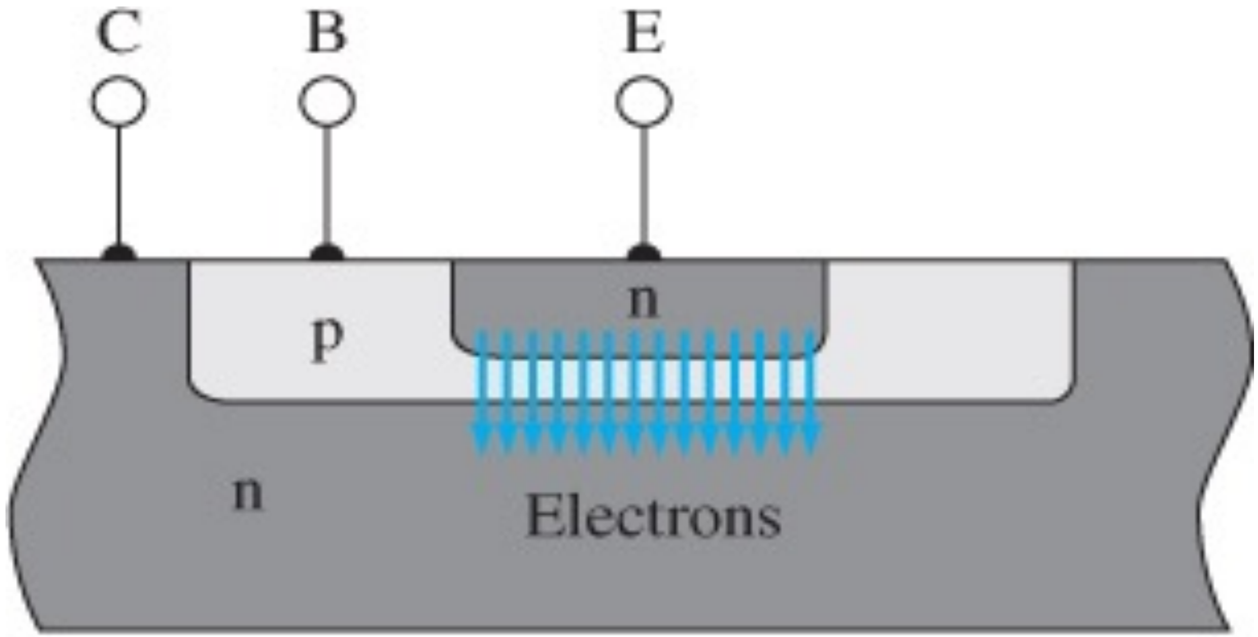


Fig. 1.8 Cross section of an npn bipolar transistor in the forward-active mode

Electrons are injected from the n-type emitter (hence called emitter) and collected from the collector (hence called collector)

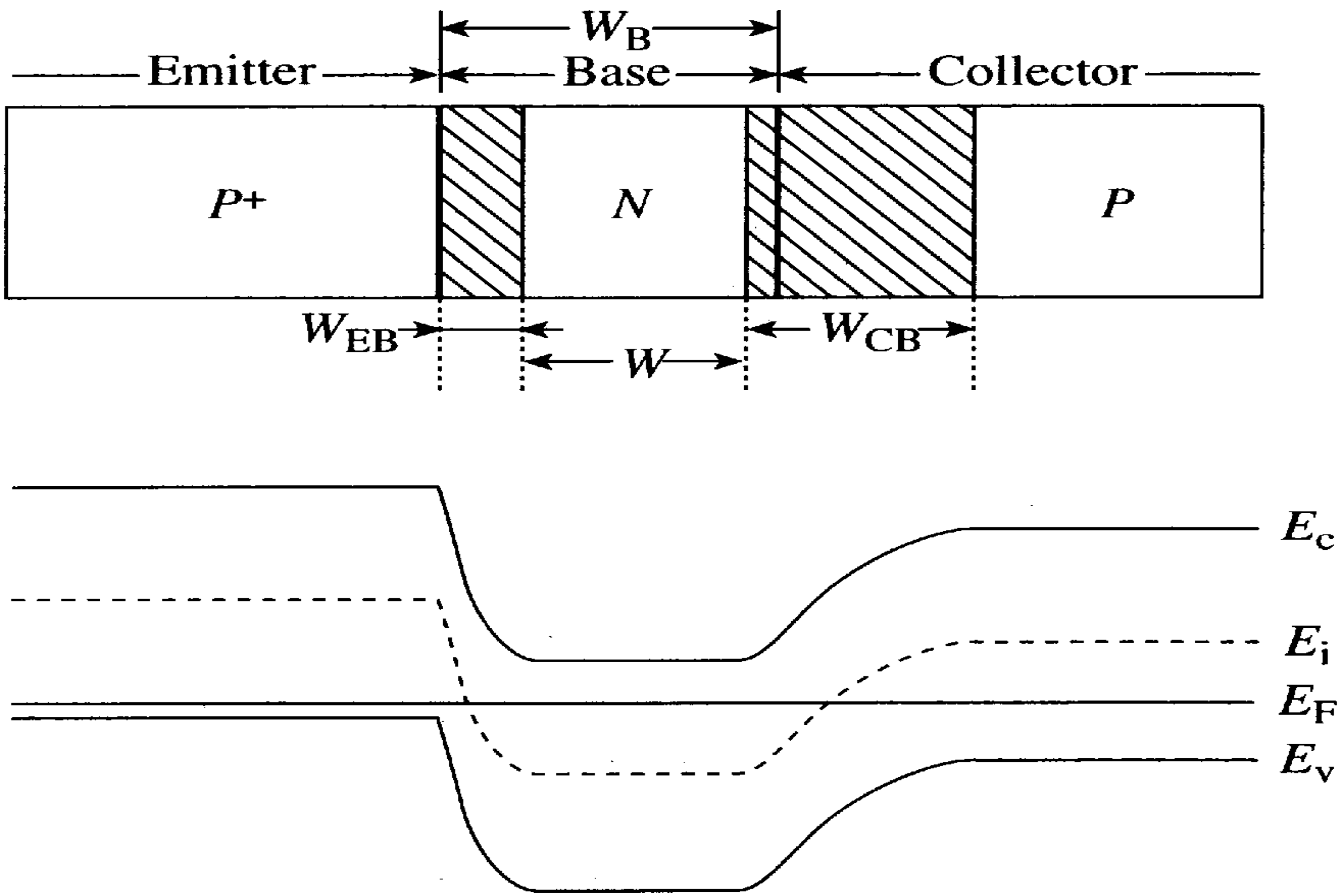
Example 1

For a uniformly doped $\boldsymbol{p^{++}n^{+}p}$ bipolar transistor in the thermal equilibrium condition, the emitter region has the largest doping and the collector region has the smallest doping.

(i) Sketch the schematic structure of the bipolar transistor, marking the space charge width of the B-E and the B-C junctions.

(ii) Sketch the energy band diagram across the emitter region, the base region, and the collector region. Mark the conduction band, the valance band and the Fermi level. Explain your drawings.

Example 1



Example 1

- The B-E junction is highly doped, thus the space charge width is narrower, as space charge width is inverse proportional to the doping concentration.

- Under thermal equilibrium condition, the fermi level is a constant across the whole region.

- Emitter is highly doped, so the Fermi level is closer to the valence band edge.

- In the base region, it is n-doped, thus the Fermi is closer to the conduction band edge.

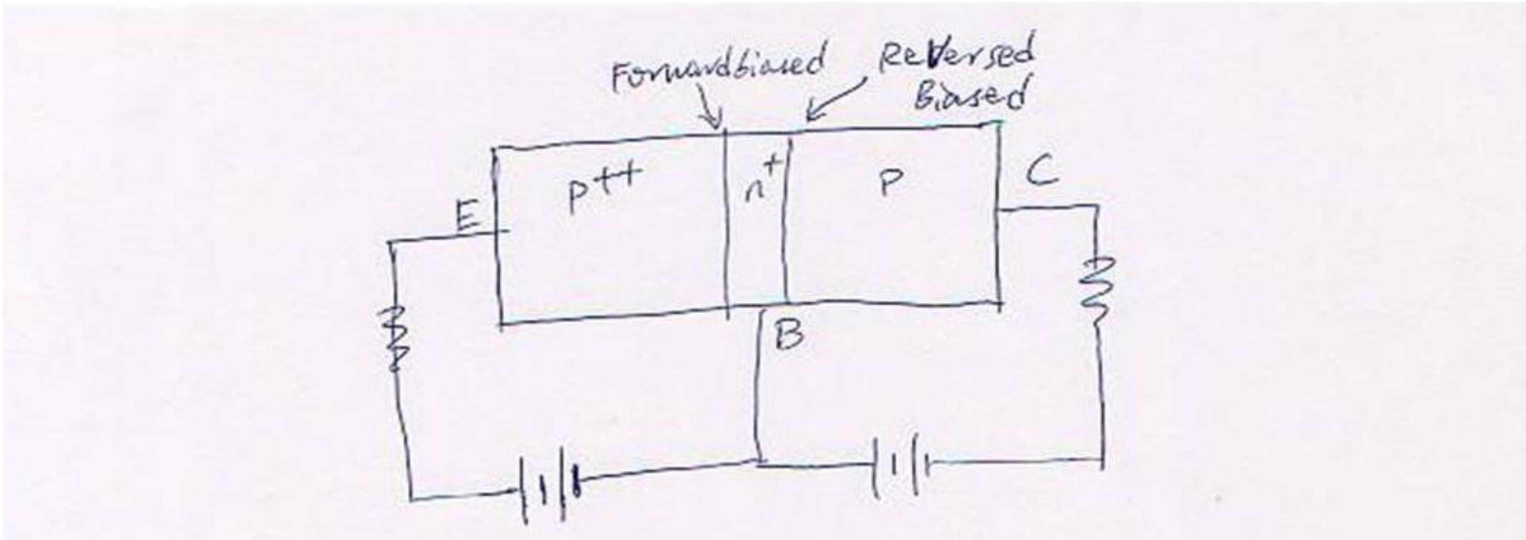
Example 2

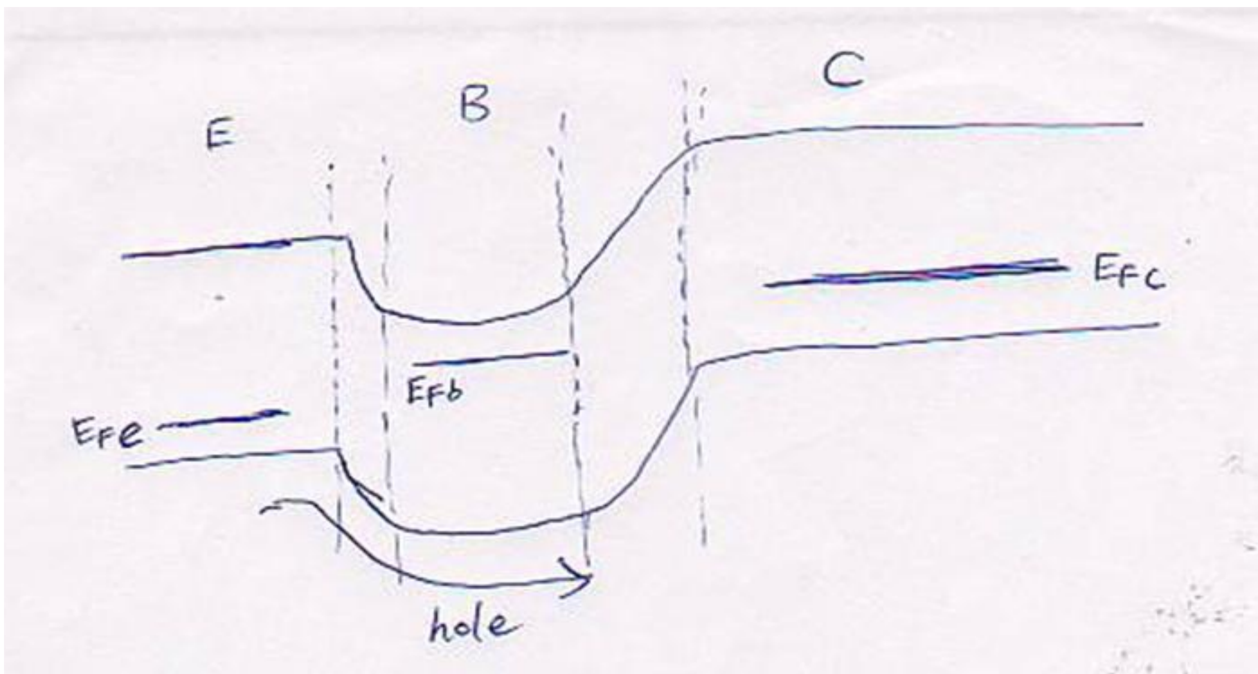
For a uniformly doped $\boldsymbol{p^{++}n^{+}p}$ bipolar transistor in the forward-active region, the emitter region has the largest doping and the collector region has the smallest doping.

(i)Draw the schematic structure of the bipolar transistor with external circuit.

(ii)Sketch the energy band diagram across the emitter region, the base region, and the collector region. Mark the conduction band, the valance band and the Fermi levels.

Example 2





Example 2

- B-E junction is forward-biased, thus a positive potential is connected to the E terminal; while B-C junction is reverse-biased, thus a negative potential is connected to the C terminal.

- The B-E space charge width is narrower due to the high doping; while the B-C space charge width is larger due to the relatively lower doping.

- For B-E junction, under forward-bias, $E_{Fe} < E_{Fb}$;

- For B-C junction, under reverse-bias, $E_{Fb} < E_{Fc}$;

- E_{Fe} is closer to the valence band edge due to the p-doping; E_{Fb} is closer to the conduction band edge due to the n-doping; E_{Fc} is closer to the valence band edge due to the p-doping.

Summary and discussions

- There are two complimentary bipolar transistors – npn and pnp.

- The center region (base) is very narrow, so the two pn junctions are said to be interacting junctions.

- In the forward-active mode, the B-E junction is forward biased and the B-C junction is reverse biased. This applies to both npn and pnp transistors.

- Majority carriers from the emitter are injected into the base where they become minority carriers.

Summary and discussions (cont)

- These minority carriers diffuse across the base into the B-C space charge region where they are extracted into the collector.

- The above analysis can be applied to **pnp transistor** by just changing electron to hole concentrations. And the current directions and voltage polarities also change.

- When a transistor is biased in the forward-active mode of operation, the current at one terminal of the transistor (collector current) is controlled by the voltage applied across the other two terminals of the transistors (base-emitter voltage). **This is the basic transistor action.** (we will show this mathematically in the next session)

You should be able to

- Describe the basic operation of the transistor.
- Sketch the energy bands of both npn and pnp transistors in thermal equilibrium and when biased in the forward-active mode.
- Sketch the minority carrier distribution in npn and pnp bipolar transistors in the forward-active mode.

1.2 Simplified transistor current relation

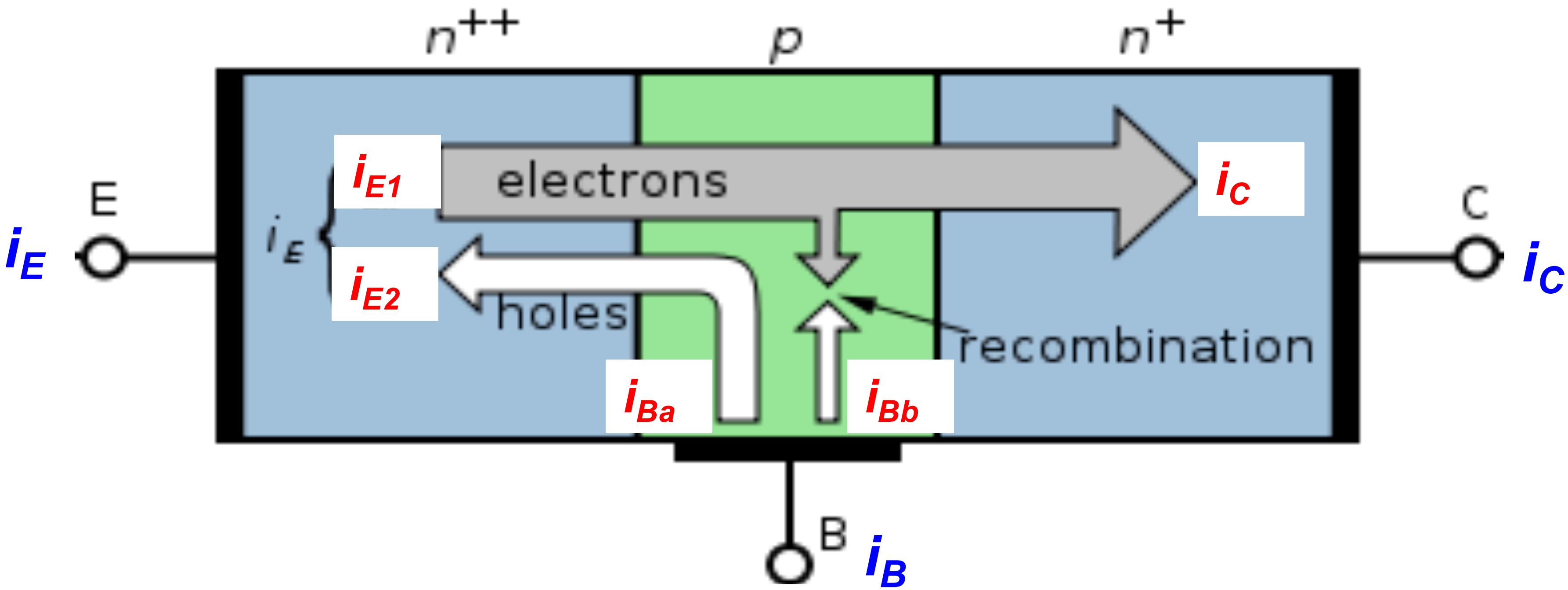


Fig. 1.9 (a) Simplified currents flow in a forward-active npn bipolar transistor

Three currents: i_B, i_C, and i_E

Three voltages: V_{BE}, V_{BC}, and V_{CE}

1.2 Simplified transistor current relation

Ideally, the minority carrier electron concentration in the base is a linear function of distance, as no recombination occurs.

The electrons are injected from the emitter, and diffuse across the base.

Then, the electrons are extracted into the collector by the electric field (E-field) in the B-C space charge region.

A) i_C, has one component

B) i_E, has two components i_{E1} ***and*** i_{E2}

C) i_B, has two components i_{Ba} ***and*** i_{Bb}

More complete transistor current relation

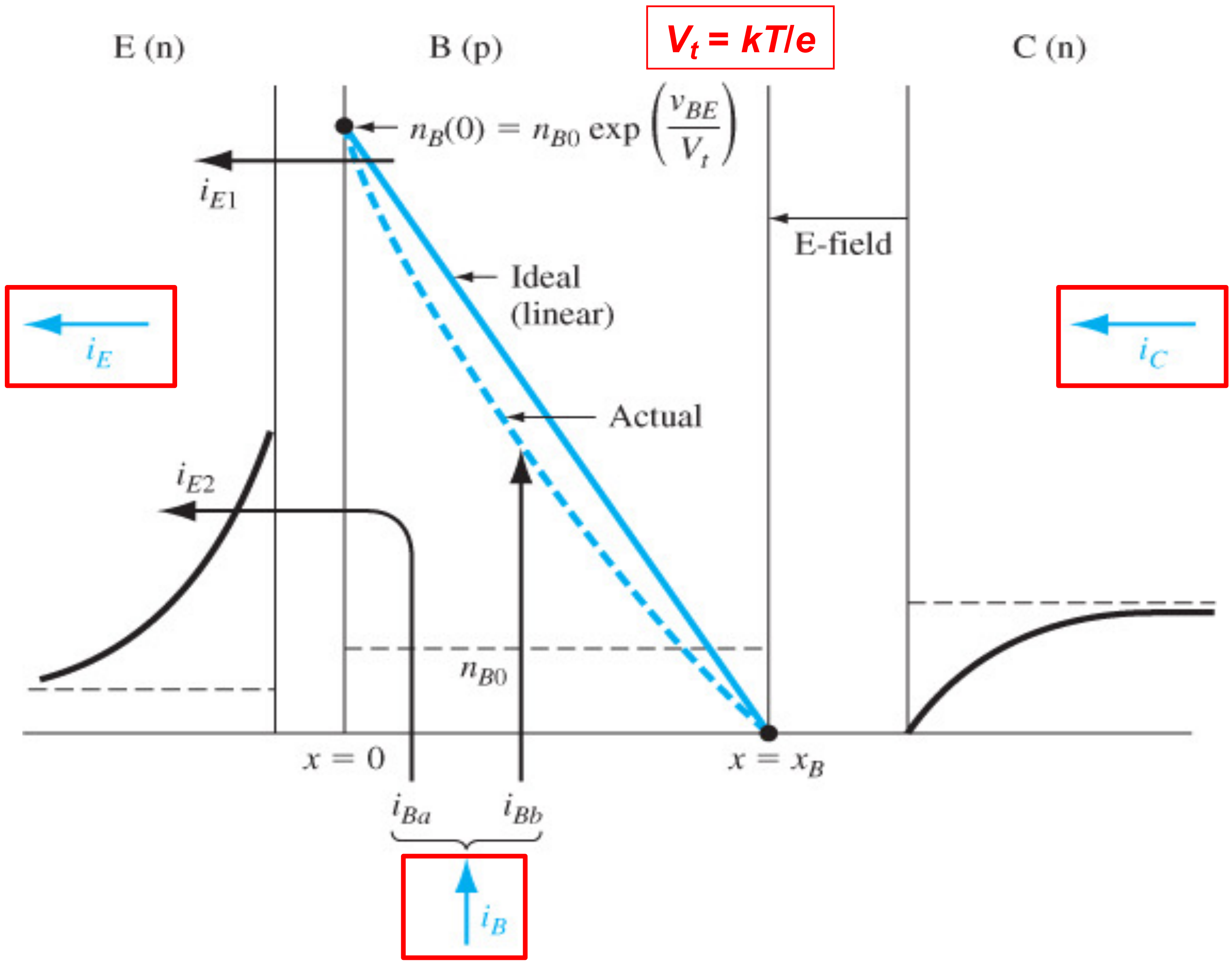


Fig. 1.9 (b) Minority carrier distribution and basic currents in a forward-active npn bipolar transistor

Three currents: i_B, i_C, and i_E will be investigated.

A: Collector Current

Assuming ideal linear electron distribution in the base (i.e. without considering the recombination in the base region), the collector current is determined by the diffusion current in the base. From the diffusion current expression, we have

$$\boxed{\begin{aligned} i_C &= eD_n A_{BE}\frac{dn(x)}{dx} = eD_n A_{BE}\left[\frac{n_B(0)-0}{0-x_B}\right] \\ &= \frac{-eD_n A_{BE}}{x_B}\times n_{B0}\exp\left(\frac{v_{BE}}{kT/e}\right) \end{aligned}} \qquad (1.1)$$

where A_{BE} is the cross-sectional area of the B-E junction;

$n_B(0)$ is the electron concentration in the base at the edge of the B-E junction;

n_{B0} is the thermal-equilibrium electron concentration in the base;

x_B is the width of the base.

See Fig.1.9 (b) for reference.

$$n_B(0) = n_{B0}\exp\left(\frac{v_{BE}}{kT/e}\right)$$

A: Collector Current

Considering magnitudes only,

$$\boxed{i_C = I_S \exp\left(\frac{v_{BE}}{kT/e}\right)} \qquad (1.2)$$

where I_S is the coefficient

$$I_S = \frac{-eD_n A_{BE}}{x_B} n_{B0}$$

The collector current is controlled by the base-emitter voltage V_{BE}; i.e. the basic transistor action.

B: Emitter Current

- The emitter current, $\boldsymbol{i_{E1}}$, shown in Fig.1.9 (a) and (b), is due to the flow of electrons from the emitter to the base. It is then equal to the collector current, $\boldsymbol{i_C}$, given by Eqn. (1.2).

$$i_{E1} = i_C = I_S \exp\left(\frac{v_{BE}}{kT/e}\right)$$

B: Emitter Current

- The majority holes in the base are injected into the emitter, producing a pn junction current, ***i_{E2}***, as shown in Fig.1.9 (a) and (b).

- This current is not part of the collector current, as it is only between B-E junction.

- Since ***i_{E2}*** is a forward-bias pn junction current, we can write

$$i_{E2} = I_{S2} \exp\left(\frac{v_{BE}}{kT/e}\right)$$

where ***I_{S2}*** is a coefficient involving the minority carrier hole parameters in the emitter.

B: Emitter Current

Thus, the total emitter current is, (where ***I_{SE}*** is a coefficient)

$$\boxed{i_E = i_{E1} + i_{E2} = i_c + i_{E2} = I_{SE} \exp\left(\frac{v_{BE}}{kT/e}\right)} \qquad (1.3)$$

B: Emitter Current

Discussions:

Since all current components in Eqn. (1.3) are functions of $\exp\left(v_{BE} / (kT / e)\right)$, then the ratio of the collector current to the emitter current is a constant:

.

$$\boxed{\frac{i_C}{i_E} \equiv \alpha}$$

where α is called the common-base current gain.

As $i_C < i_E$, we have $\alpha < 1$. Since i_{E2} is not part of the basic transistor action, we want it as small as possible, thus α close 1.

C: Base Current

As shown in Fig.1.9 (a) and (b), i_{E2} is a B-E junction current, so a) there is also a base current by

$$i_{Ba} = i_{E2}$$

This component is proportional to $\exp\left(v_{BE} / (kT / e)\right)$

b) there is a second component in the base region, related to the recombination of electrons. Since majority holes in the base are disappearing, positive charges are supplied into the base, as indicated by i_{Bb} in Fig.1.9 (a) and (b). This current is also proportional to $\exp\left(v_{BE} / (kT / e)\right)$

Then, the base current $\boxed{i_B = i_{Ba} + i_{Bb}}$

C: Base Current

Then the ratio of the collector current to the base current is:

$$\boxed{\frac{i_C}{i_B} \equiv \beta}$$

where β is called the common-emitter current gain.

Normally the base current is small, thus **the common-emitter current gain is much larger than 1 (100 or larger)**.

Summary and discussions

The common-base current gain $\alpha = i_C/i_E$, and the common-emitter current gain is $\beta = i_C/i_B$. We have also $i_E = i_B + i_C$, thus we can have the relation,

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

Then we have the relation between α and β.

$$\alpha = \frac{\beta}{1+\beta} \quad \text{or} \quad \beta = \frac{\alpha}{1-\alpha}$$

Example 1

An npn silicon bipolar transistor has the following base parameters: D_n = 22 cm^2/s, x_B = 0.8 μm, and n_{B0} = 2x10^4 cm^{-3}.

(a)The collector current is to be $|i_c|$ = 2 mA when biased at v_{BE} = 0.60 V. What is the required cross-sectional area A_{BE}?

(b)Using the results of (a), what is the value of v_{BE} such that $|i_c|$ = 5 mA?

Example 1

(a) From Eqn (1.1)

$$\left|i_C\right| = \frac{eD_n A_{BE}}{x_B} \cdot n_{B0} \cdot \exp\left(\frac{\upsilon_{BE}}{kT/e}\right)$$

$$2\times10^{-3} = \frac{\left(1.6\times10^{-19}\right)\left(22\right)A_{BE}}{0.80\times10^{-4}} \times \left(2\times10^{4}\right)\exp\left(\frac{0.60}{0.0259}\right)$$

$$\Rightarrow A_{BE} = 1.975\times10^{-4}\,cm^2$$

(b)

$$5\times10^{-3}=\frac{\left(1.6\times10^{-19}\right)\left(22\right)\left(1.975\times10^{-4}\right)}{0.80\times10^{-4}}\times\left(2\times10^{4}\right)\exp\left(\frac{\upsilon_{BE}}{0.0259}\right)$$

$$5\times10^{-3}=\left(1.738\times10^{-13}\right)\exp\left(\frac{\upsilon_{BE}}{0.0259}\right)$$

Then,

$$\upsilon_{BE}=\left(0.0259\right)\ln\left(\frac{5\times10^{-3}}{1.738\times10^{-13}}\right)$$

$$\Rightarrow\upsilon_{BE}=0.6237V$$

Example 2

The parameters of the base region in a silicon npn bipolar transistor are: D_n = 18 cm^2/s, x_B = 0.8 μm, cross-sectional area A_{BE} = 5x10^{-5} cm^2, and n_{B0} = 4x10^3 cm^{-3}.

(a)Calculate the collector current for v_{BE} = 0.58 V.

(b)For a common-base current gain α = 0.9850, determine the common-emitter current gain β, and the emitter and base currents.

Example 2

(a) From Eqn (1.1)

$$\left|i_C\right| = \frac{eD_n A_{BE}}{x_B} \cdot n_{B0} \cdot \exp\left(\frac{\upsilon_{BE}}{kT/e}\right)$$

$$i_C = \frac{\left(1.6\times10^{-19}\right)\left(18\right)\times5\times10^{-5}}{0.80\times10^{-4}}\times\left(4\times10^{3}\right)\exp\left(\frac{0.58}{0.0259}\right)$$

$$\Rightarrow i_C = 3.827\times10^{-5}\,A$$

(b)

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.9850}{1-0.9850} = 65.7$$

$$for \quad i_C = 3.827 \times 10^{-5} A$$

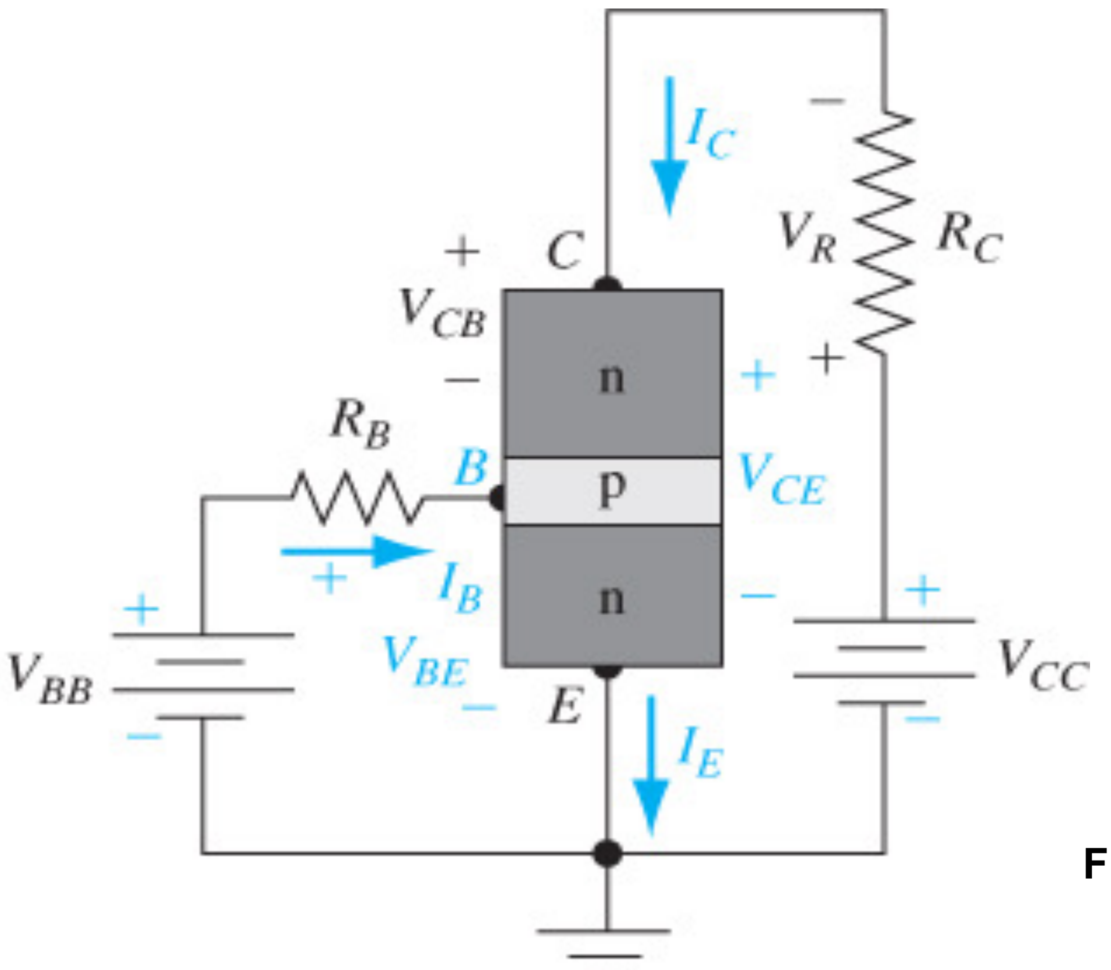
$$I_E = \frac{I_C}{\alpha} = \frac{38.27}{0.9850} = 38.85\,\mu A$$

$$I_B = \frac{I_C}{\beta} = \frac{38.27}{65.67} = 0.5828\,\mu A$$

1.3 The modes of operation

In the configuration (called common-emitter configuration) shown in Fig. 1.10, there are three possible operation modes.

Cutoff mode, forward-active mode, and saturation mode.



We only focus only on the forward-active mode.

Fig. 1.10 An npn bipolar transistor in a common-emitter configuration

Forward-active mode operation

If $\boldsymbol{V_{BE}} > \mathbf{0}$, B-E junction is forward biased, then emitter and collector currents will be generated.

If we look at the collector-emitter loop, If V_{CC} is large enough, then $V_{CB} > 0$, meaning that the B-C junction is reversed biased. This is because

$$V_{CB} = V_{CC} - V_{BE}$$ (neglecting the resistance R_c)

This condition is referred to as **the forward-active** region of operation.

1.4 Example: amplification with bipolar transistor

Voltages and currents can be amplified by bipolar transistors in conjunction with other elements.

We will demonstrate this in the following slides. Fig. 1.11 shows an npn bipolar transistor in a common-emitter configuration, operated in the forward-active mode.

The DC voltage sources, V_{BB} and V_{CC}, are used to bias the transistor in the forward-active mode.

The voltage source v_i represents a time-varying input voltage that needs to be amplified.

1.4 Example: amplification with bipolar transistor

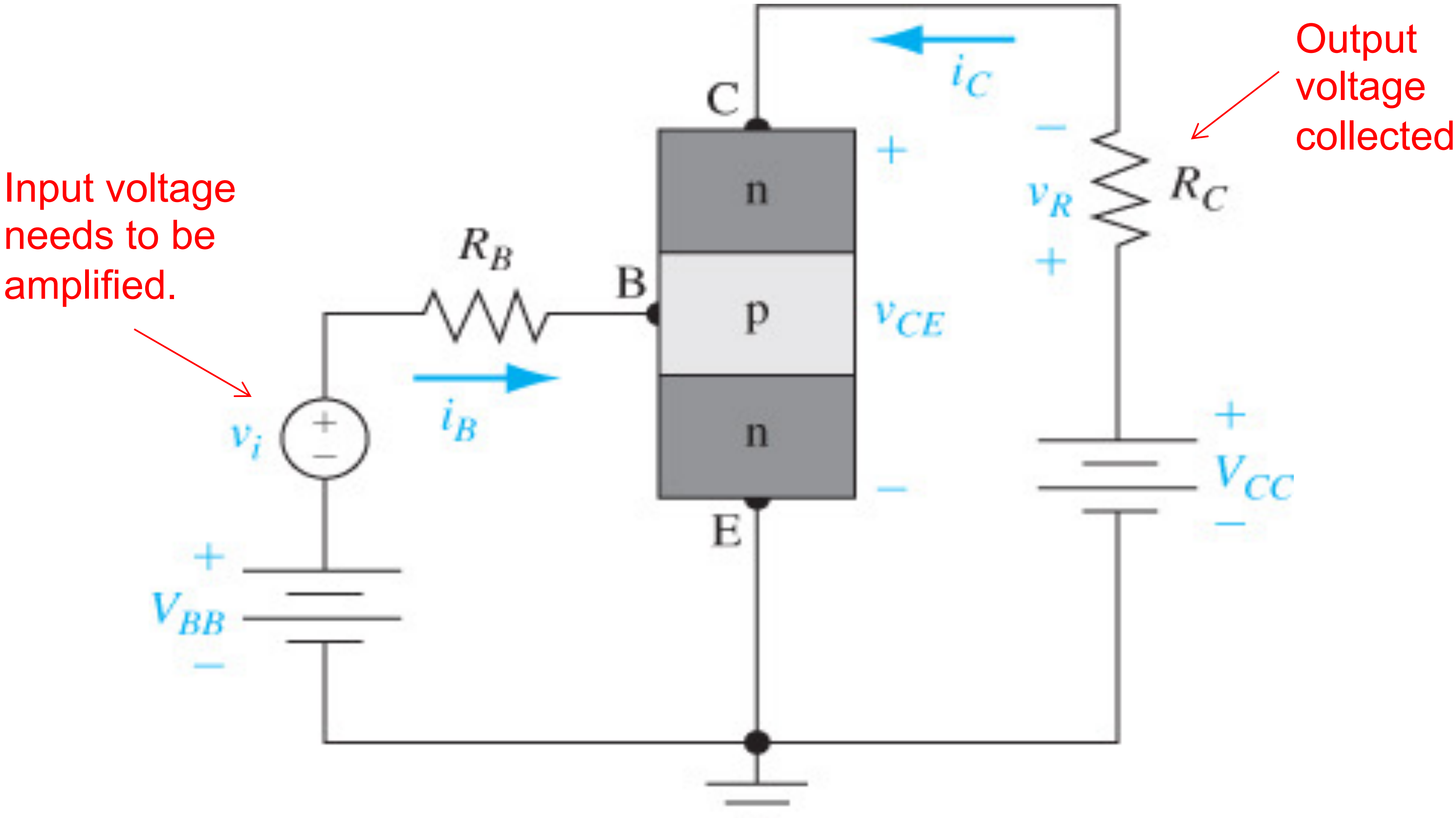


Fig. 1.11 Common-emitter configuration with a time-varying signal voltage v_i, included in the base-emitter loop

This circuit is called the voltage amplifier.

1.4 Example: amplification with bipolar transistor

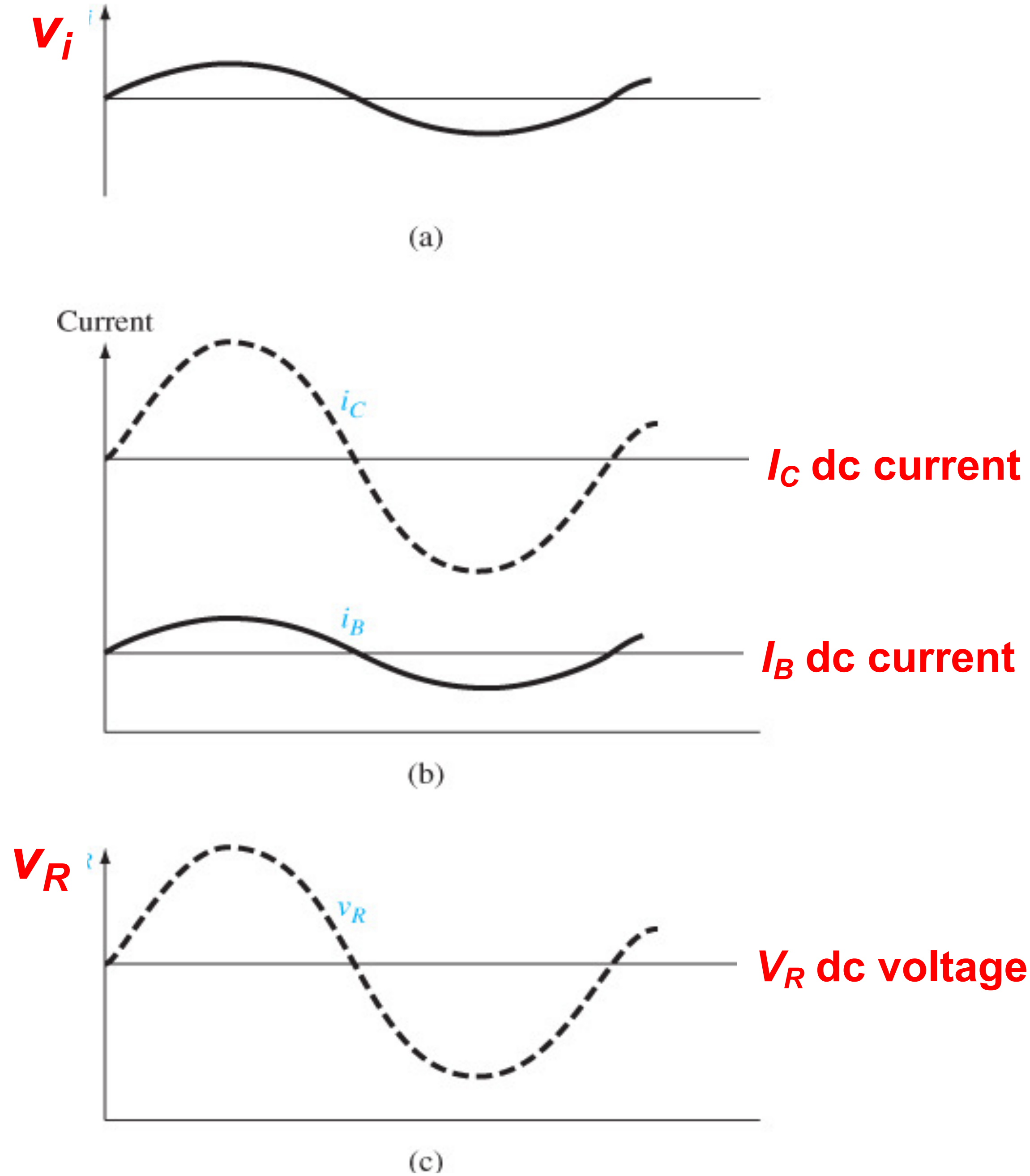


Fig. 1.12 Currents and voltages in Fig. 1.11. (a) Input sinusoidal voltage; (b) base and collector currents superimposed on the dc values; (c) sinusoidal voltage across the R_C resistor superimposed on the dc value.

We will explain the figures in details in the following slides.

1.4 Example: amplification with bipolar transistor

Fig. 1.12 shows the various voltages and currents that are generated in the circuit assuming that v_i is a sinusoidal voltage.

The sinusoidal voltage v_i induces a sinusoidal component of ac base current superimposed on a dc value.

Fig. 1.12 (a)

1.4 Example: amplification with bipolar transistor

Then ac component of $\boldsymbol{i_B}$ has the same shape as v_i , together with a dc current.

As, $\boldsymbol{i_C} = \beta \times \boldsymbol{i_B}$, and $\beta >> 1$, then a relatively large sinusoidal ac collector current is superimposed on a dc value of collector current.

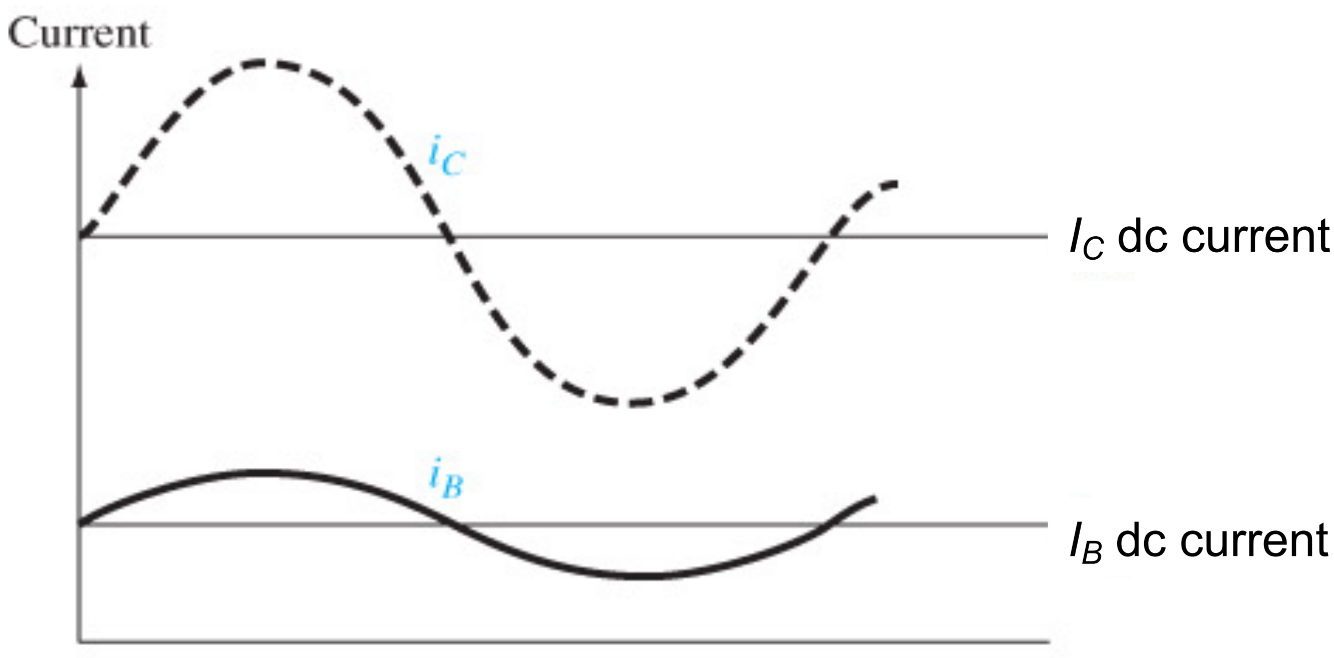


Fig. 1.12 (b)

1.4 Example: amplification with bipolar transistor

The time-varying collector current induces a time-varying voltage across the RC resistor.

This means that an amplified sinusoidal voltage, superimposed on a dc value, exists between the collector and emitter of the bipolar transistor.

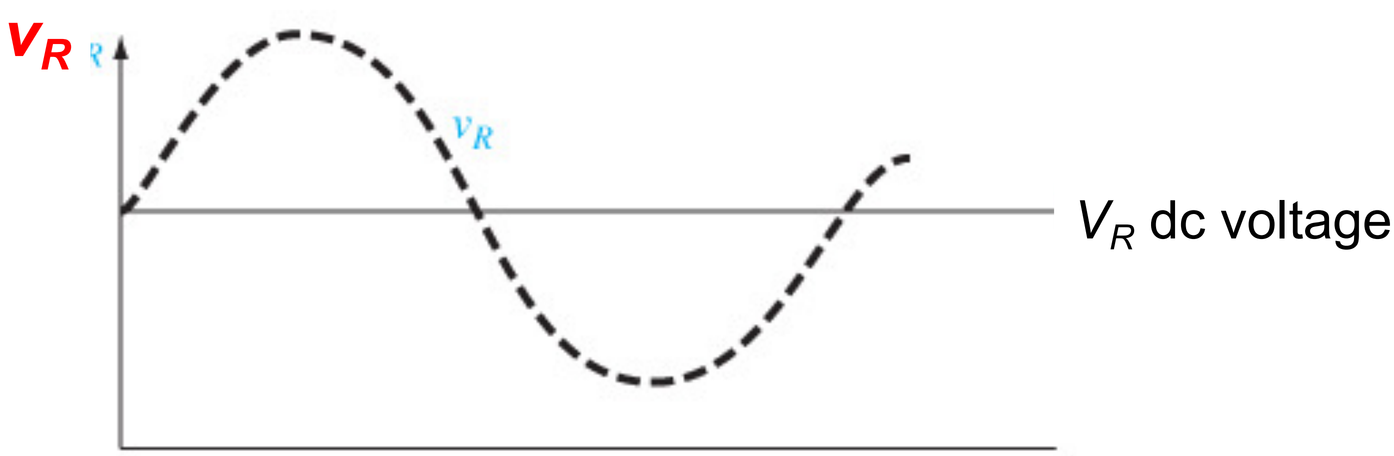


Fig. 1.12 (c)

1.4 Example: amplification with bipolar transistor

In conclusion:

The sinusoidal voltage in the collector-emitter portion of the circuit v_R is larger than the signal input voltage v_i, so that the circuit has produced a voltage gain in the time-varying signals.

Summary and discussions

- In the common-emitter configuration, the bipolar transistor can be operated in the forward-active mode.

- Under the forward-active mode, the B-E junction is forward-biased, while the B-C junction is reversed-biased.

- In such mode, one can amplify the input sinusoidal voltage signal by using the bipolar transistor.

You should be able to

- Calculate the collector current as a function of base-emitter voltage.
- Know the relations among the emitter, base and collector currents.
- Know the operation principles of BJT under the forward-active mode.
- Describe how bipolar transistor in the forward-active mode can be used to amplify voltage signals.