Bipolar Junction Transistor (BJT)

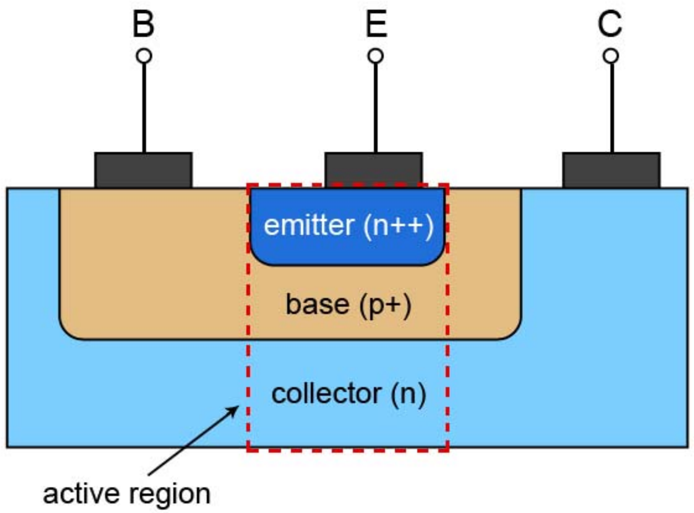
Part 1 :

1. Introduction to the BJT
2. Principles of Operation of the BJT
3. Analysis of the BJT

Reading

- Sedra and Smith, Microelectronic Circuits, Fifth Edition, Oxford (2004), pp. 159 – 168173 - 183, 203 - 226.

1. Introduction to the BJT



- The figure above shows the a simplified schematic cross-sectional view of a bipolar junction transistor (BJT).
- The BJT is constructed in a nested structure, with the emitter surrounded by the base, and the base surrounded by the collector.
- The base of the BJT is designed to be thin.
- The BJT is not a symmetrical device, the geometry and doping of the emitter and the collector are different.
- The "active" region of the BJT is the region under (and including) the emitter. This is the part of the device that provides, for example, the amplifying function of the BJT. The rest of the device is to facilitate the movement of the currents into or out of the transistor. We shall focus our study of the BJT on the active region.

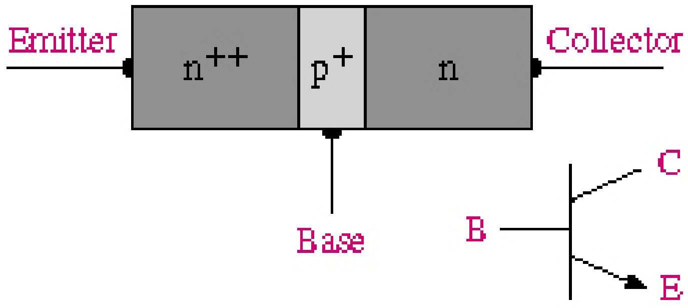
Introduction to the BJT

- The Bipolar Junction Transistor (BJT) is a device comprising two pn junctions which are close enough to each other to interact.

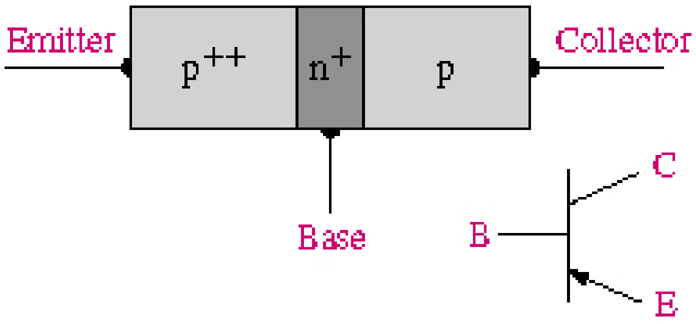
2 types: ***npn*** *or* ***pnp***

3 regions:
emitter, base, collector.

2 junctions:
base-emitter , base-collector



(a)



(b)

Simplified block diagram and circuit symbols of (a) npn and (b) pnp bipolar transistor

Introduction to the BJT

- Since the BJT has 2 pn junctions, and each pn junction can be either forward biased or reverse biased, there are 4 possible permutations of the biasing arrangement for a BJT. These correspond to different modes of operation of the BJT, as shown in the table below*:

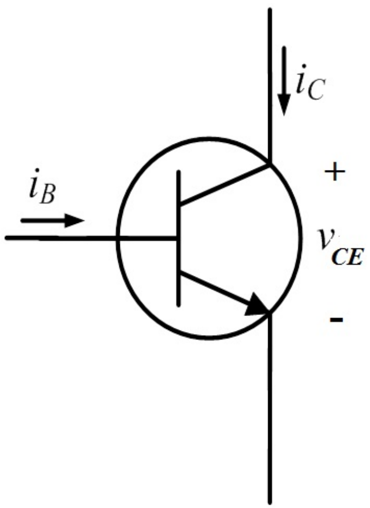
Modes of operation of the **npn** bipolar junction transistor

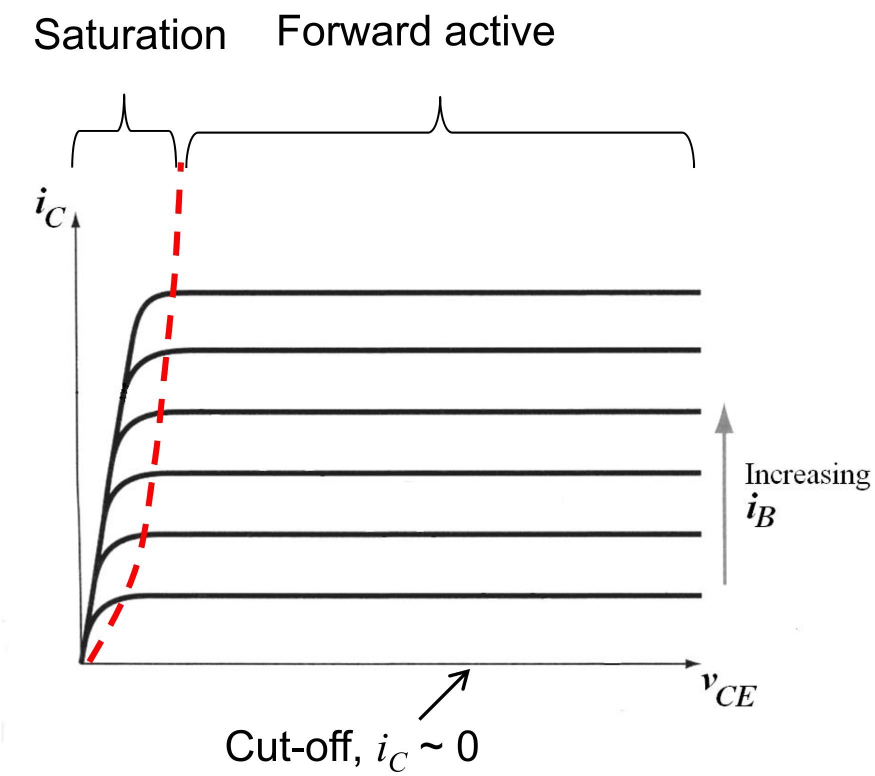
Mode of Operation	Emitter-Base Junction	Collector-Base Junction	Applications
Cut-off	Reverse biased ($V_{BE} < 0$ for npn)	Reverse biased ($V_{BC} < 0$ for npn)	Logic-OFF State
Forward Active	Forward biased ($V_{BE} > 0$ for npn)	Reverse biased ($V_{BC} < 0$ for npn)	Amplifier
Saturation	Forward biased ($V_{BE} > 0$ for npn)	Forward biased ($V_{BC} > 0$ for npn)	Logic - ON State
Reverse Active	Reverse Biased ($V_{BE} < 0$ for npn)	Forward Biased ($V_{BC} > 0$ for npn)	Not used

* A corresponding table for the modes of operation of the pnp bipolar junction transistor is given in the Appendix

Introduction to the BJT (npn)

- The relationship between the collector current i_C, the base current i_B and the collector—emitter voltage v_{CE} of an npn BJT is shown in the plot below.
- The regions on the BJT characteristics corresponding to the forward active, saturation and cut-off modes of operation are as indicated in the plot below.
- We shall be focusing our studies of the BJT on forward active mode of operation.





Introduction to the BJT (npn)

- Consider, as an *example*, an ***npn*** bipolar junction transistor. *Assume* that each region is uniformly* doped, with doping concentrations of N_{DE} =10^{19} cm^{-3}, N_{AB} = 10^{17} cm^{-3}, N_{DC} = 10^{15} cm^{-3}, respectively, in the emitter, base and collector.

Meaning of symbols

N : number of dopant atoms (cm^{-3})

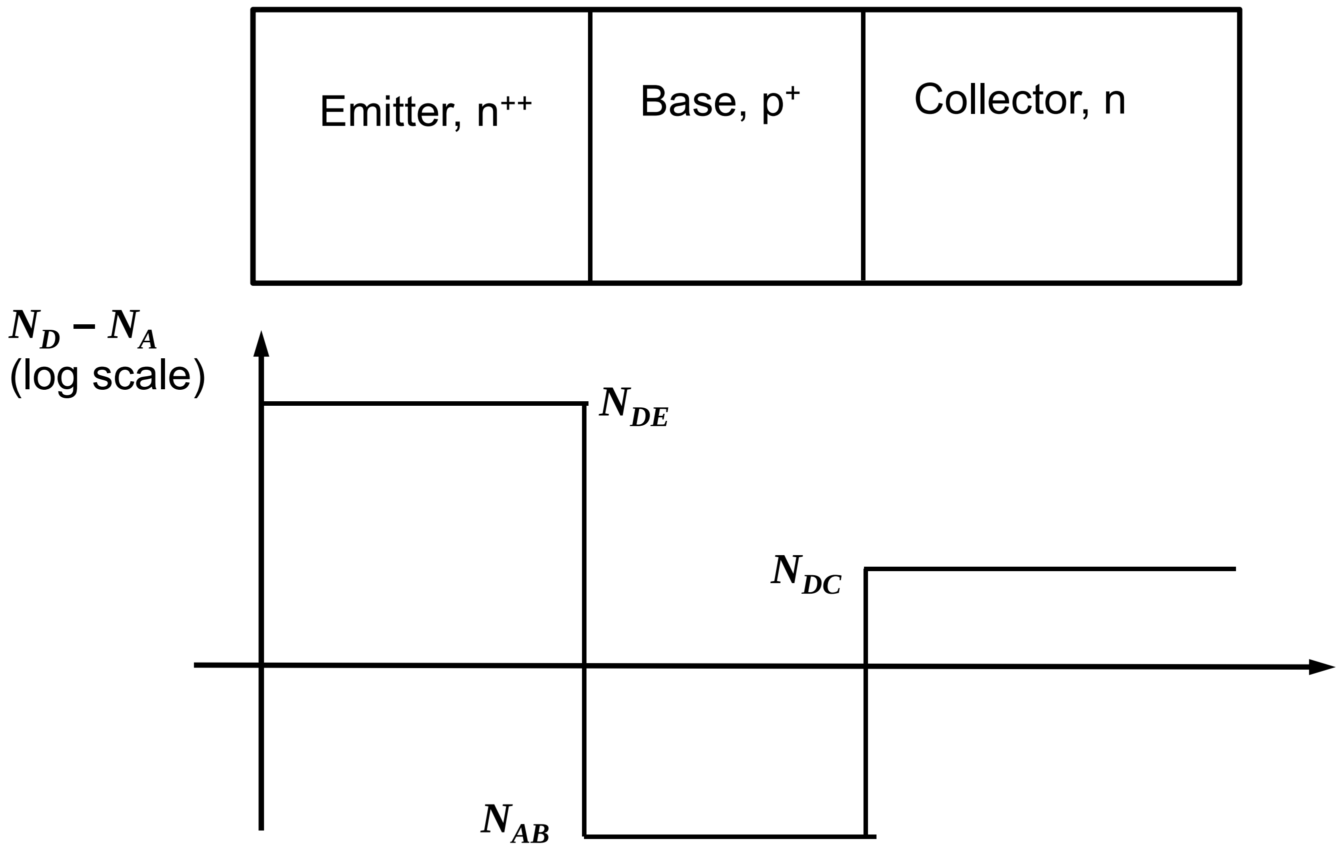
D : donors

A : acceptors

E : emitter

B : base

C : collector



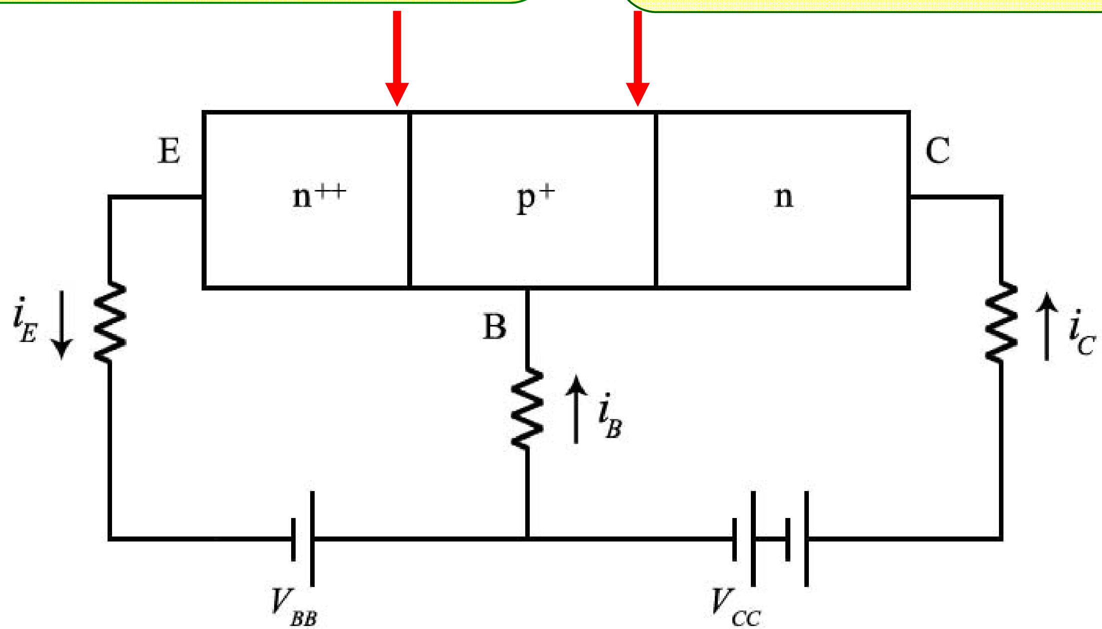
* This assumption is made for simplicity of analysis. In reality, the emitter and base of the bipolar junction transistor are often not uniformly doped.

2. Principles of Operation of the BJT (npn)

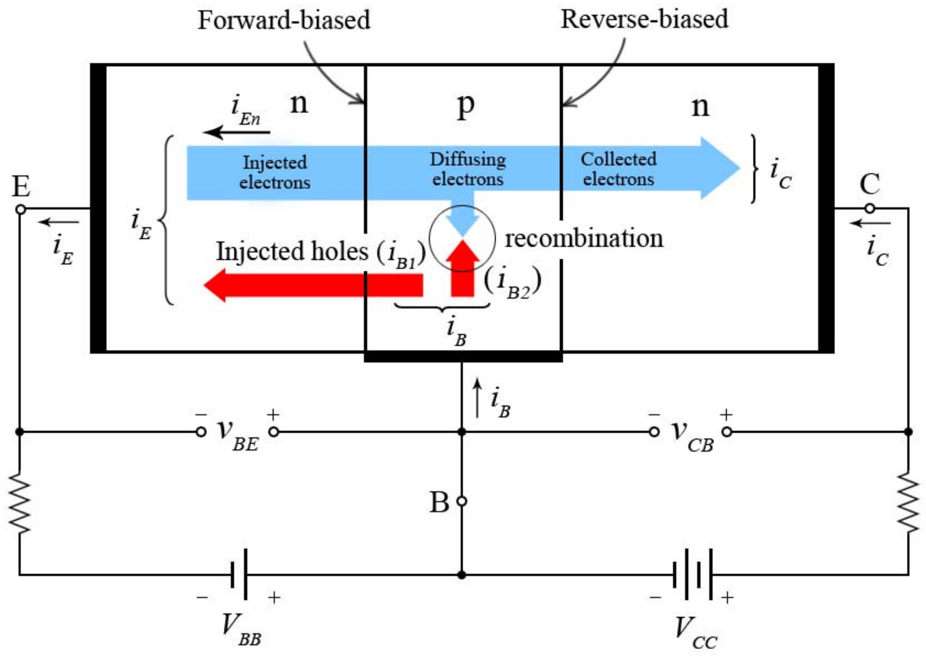
- Consider the *npn* transistor, in the forward active mode where: emitter-base junction is forward biased, collector-base junction is reverse biased.

$V_{BE} > 0$ (forward bias) =>
injection of electrons from E to B,
injection of holes from B to E

$V_{BC} < 0$ (reverse bias) =>
extraction of electrons from B to C
extraction of holes from C to B

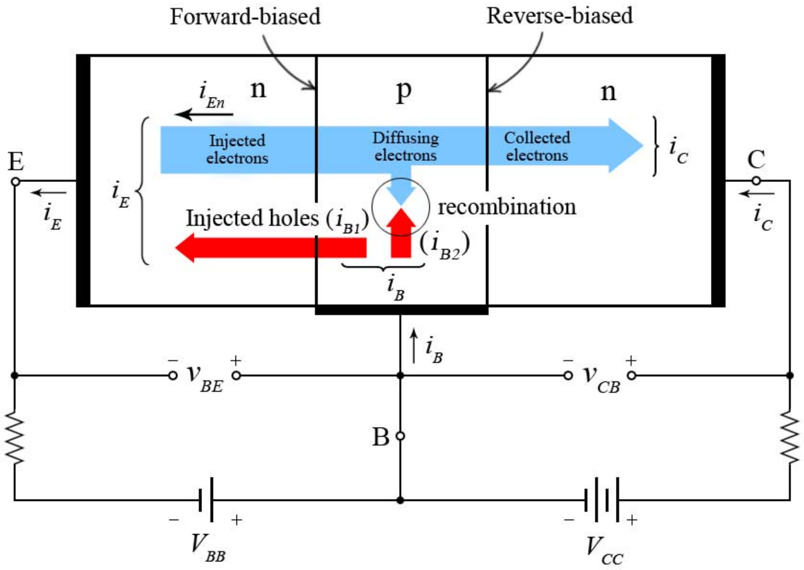


Principles of Operation of the BJT (npn)



- The above diagram shows the flow of electrons and holes in an npn BJT biased in the forward active mode.
- In the above diagram, V_{BB} and V_{CC} are the DC biases applied across the emitter-base junction and the collector junction respectively.
- The potentials across the emitter-base junction and the collector-base junction are denoted by v_{BE} and v_{CB} respectively.
- In the case of a pnp BJT, the roles of the electrons and holes, as well as the polarities of the biases, are reversed.

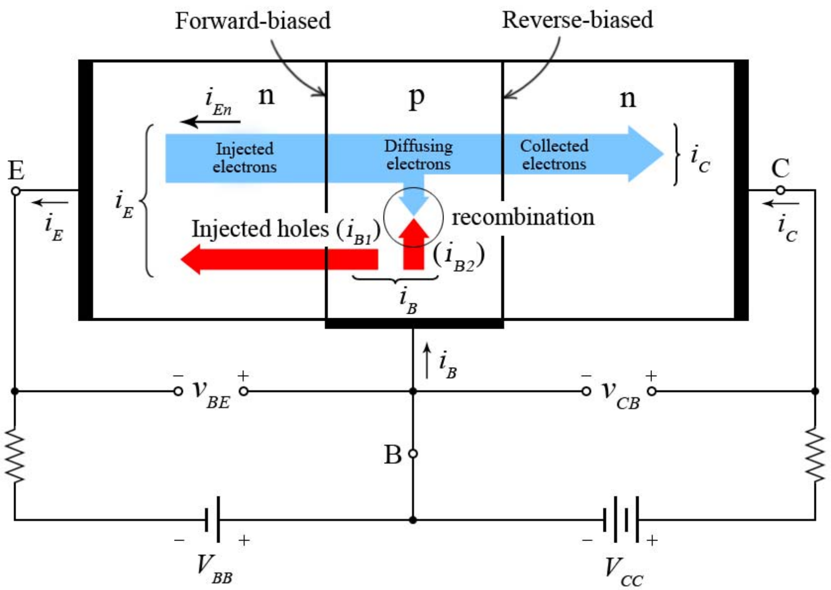
Principles of Operation of the BJT (npn)



At the emitter-base junction :

- Due to the forward bias :
- The potential barrier across the junction is reduced.
  - Net diffusion of excess electrons from emitter into base,
  - Net diffusion of excess holes from base into emitter.
- Emitter doping >> base doping,
  - Most of the charge carriers that cross the junction are electrons that diffuse from the emitter into the base.

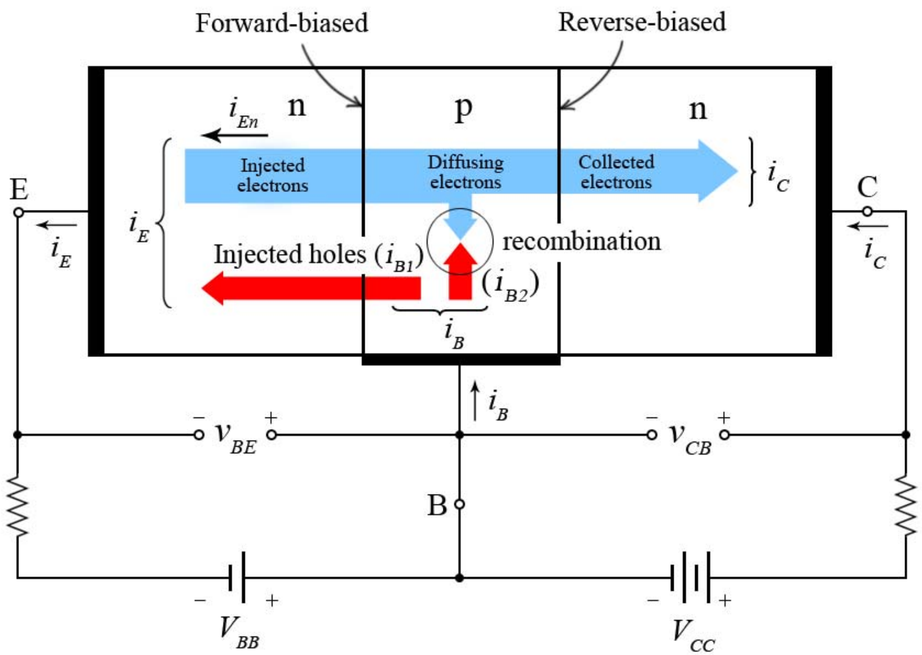
Principles of Operation of the BJT (npn)



<u>In the base region :</u>

- The injected electrons are minority carriers (in npn transistor).
- They diffuse across the base towards to collector-base junction.
- Very few of the electrons recombine with holes in the neutral base, because the base width is much shorter than the minority carrier diffusion length.
- Practically all the injected electrons are able to reach the collector-base space charge region.

Principles of Operation of the BJT (npn)



At the collector-base junction :

- There is a large electric field in the space charge region due to the applied reverse bias.
- The electrons that diffuse through the base are swept by the electric field in the collector-base space charge region into the collector, to give rise to a large collector current.

Principles of Operation of the BJT (npn)

Conceptual View of Amplification in the (npn) Bipolar Junction Transistor

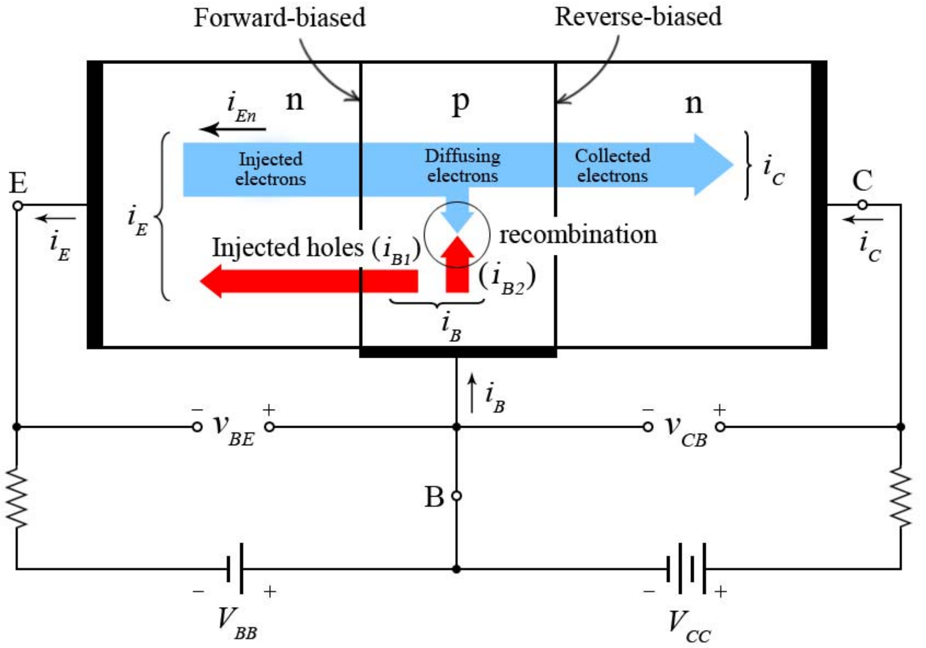
- A forward bias is applied to the base-emitter junction of the BJT.
- This forward bias leads to the reduction of the barrier voltage across the base-emitter pn junction.
- With the reduction of the barrier voltage, holes are injected from the base into the emitter, and electrons are injected from the emitter into the base. Because the emitter is much more heavily doped that the base, there are many more electrons injected from the emitter into the base, than holes injected from the base into the emitter.
- The large number of injected electrons diffuse through the base with little or no recombination and finally enters the collector due to the reverse bias at the collector-base junction to give rise to a large collector current. The collector current is not dependent on the voltage at the collector-base junction, as long as it is reverse biased.
- The injection of holes from the base into the emitter gives rise to a base current. The base current is small because the base is more lightly doped than the emitter.
- Hence the collector current is many times lager than the base current. This is the amplification effect in the BJT.

3. Analysis of the Bipolar Junction Transistor (npn)

Assumptions :

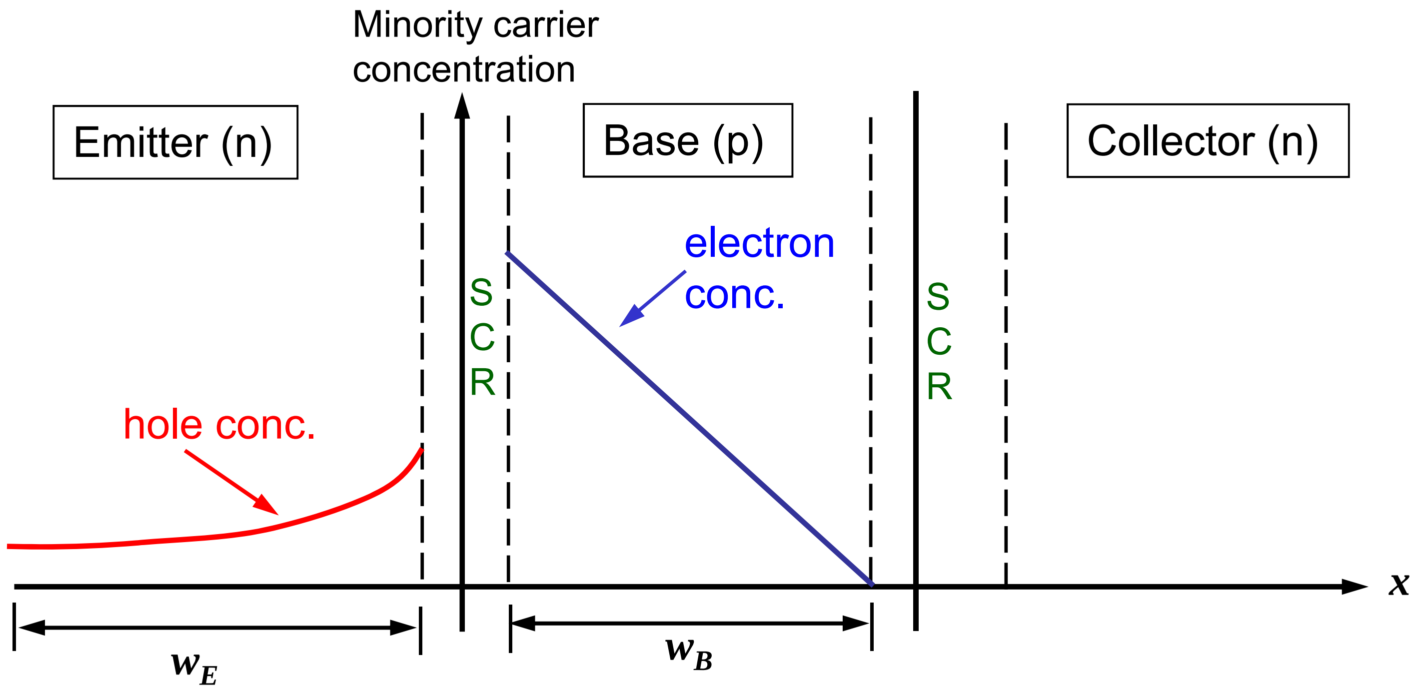
- We use the npn BJT in this analysis. The same method applies to the pnp BJT.
- This analysis is only for the active region of the transistor.
- The emitter, base and collector regions are each uniformly doped.
- The emitter is more heavily doped than the base.
- The width of the neutral part of the base (i.e., excluding the widths of the space charge regions) is much less than the minority carrier diffusion length .
- The transistor is biased in the forward active mode, i.e., the emitter-base junction is forward biased, the collector-base junction is reverse biased.
- The entire bias is applied to the respective p-n junction. The voltage drops in the neutral regions of the transistor are negligibly small.

Analysis of the BJT (npn)



- The major current components in the bipolar transistor are shown in the above diagram.
- i_{En} is the current component that is due to the injection of electrons from the emitter into the base due to the forward bias at the emitter-base junction.
- i_{B1} is the current component that is due to the injection of holes from the base into the emitter due to the forward bias at the emitter-base junction.
- i_{B2} is the current component due to the recombination of electrons and holes in the base. Because the base width is much less than the minority carrier diffusion length, there is very little recombination in the base, and i_{B2} is usually negligible compared to i_{B1} and i_{En}.

Analysis of the BJT (npn)



- The above plot shows the minority carrier concentrations in the emitter and base of an n-p-n bipolar junction transistor. The transistor is biased in the forward active mode, that is, the emitter-base junction is forward biased, the collector-base junction is reverse biased.
- Due to the forward bias at the emitter-base junction, electrons are injected from the emitter into the base, and holes are injected from the base into the emitter.
- The injected electrons and holes then diffuse away from the emitter-base space-charge regions (SCR) into the neutral regions of the base and emitter, respectively.

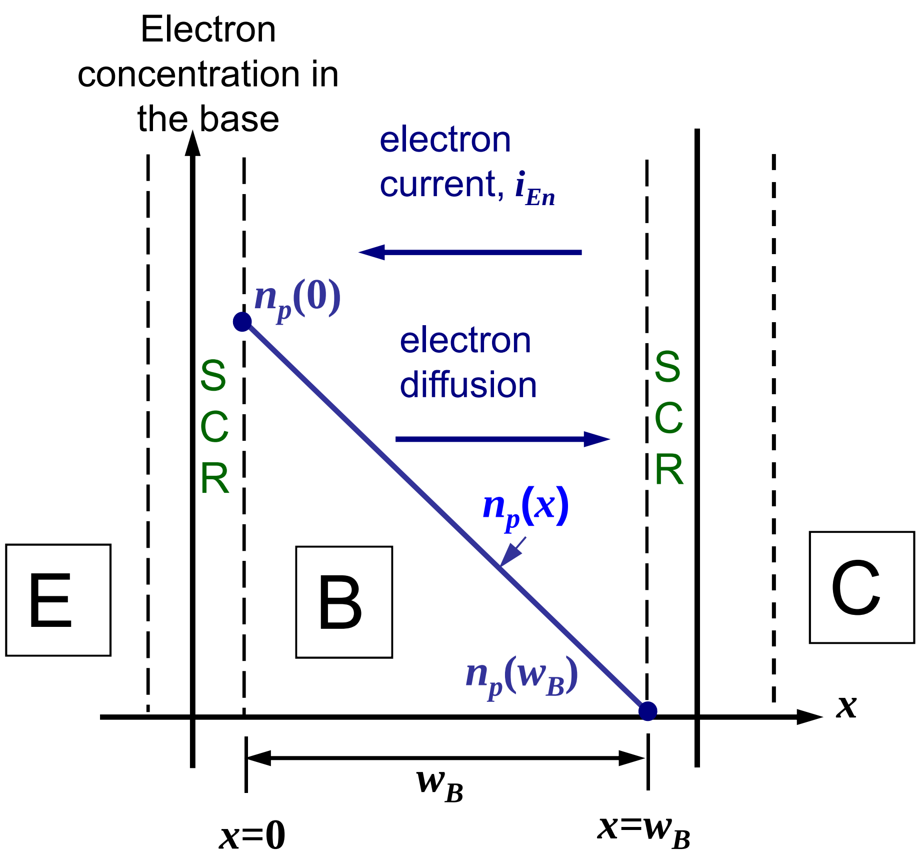
Analysis of the BJT (npn)

- The width of the base in a bipolar transistor is designed to be much shorter than the minority carrier diffusion length, i.e.

$$w_B << L_n,$$

where w_B is the netural base width (width of the base excluding the SCRs) and L_n is the diffusion length of the minority carriers (electrons in the p-type base of an n-p-n transistor).

- Recall that minority carrier diffusion length is the average distance that the minority carriers will diffuse before they recombine with the majority carrier. Since the base width is much shorter than the minority carrier diffusion length, there is negligible recombination in the base of the bipolar transistor.



- The diffusion current in the base is therefore practically constant. Since diffusion current J_n is proportional to dn/dx, the electrons concentration distribution, $n_p(x)$, in the base is therefore a straight line.

Analysis of the BJT (npn)

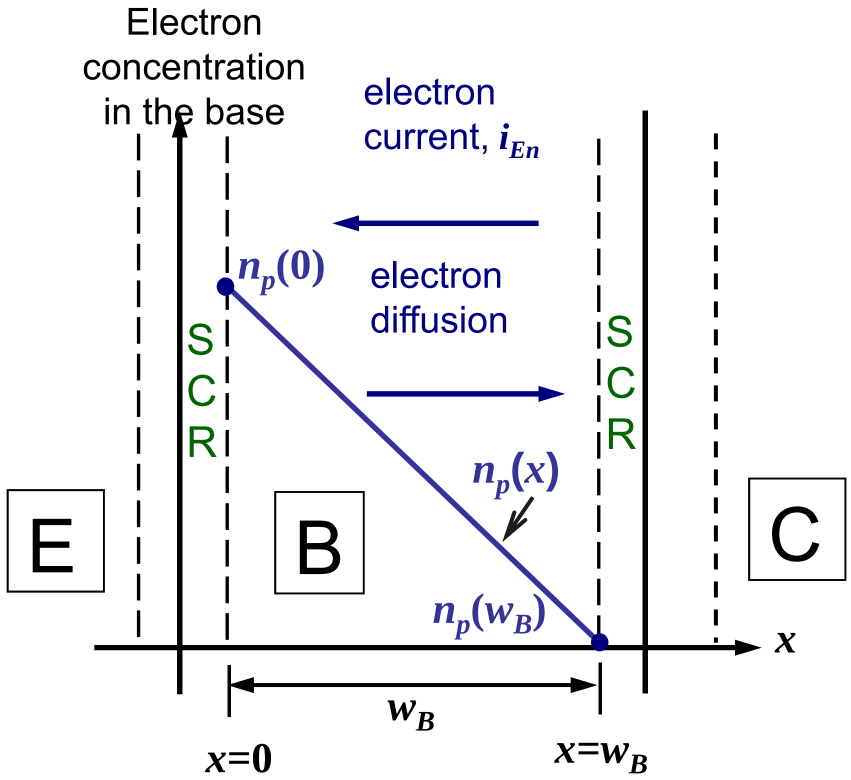
- A forward bias, v_{BE} is applied to the emitter-base junction. The electron (minority carrier) concentration at the edge of the E-B SCR,

$$n_p(x=0) = n_{p0}\, e^{v_{BE}/V_T} \quad . \tag{3.1}$$

where n_{p0} is the equilibrium electron concentration in the base, and the thermal voltage, $V_T = kT/q$.

- A reverse bias, v_{BC} (<0) is applied to the collector-base junction. The electron concentration at the edge of the C-B SCR,

$$n_p(x=w_B) = n_{p0}\, e^{v_{BC}/V_T} = 0 \quad . \tag{3.2}$$



- The current due to electrons that are injected from the emitter into the base

$$|i_{En}| = \left| qAD_n \frac{dn_p(x)}{dx} \right|_{x=0} = \left| qAD_n \frac{n_p(0)-n_p(w_B)}{0-w_B} \right| = qA\frac{D_n}{w_B} n_{p0}\, e^{v_{BE}/V_T} \tag{3.3}$$

where A is the cross-section area of the transistor, and D_n is the electron diffusivity.

Analysis of the BJT (npn)

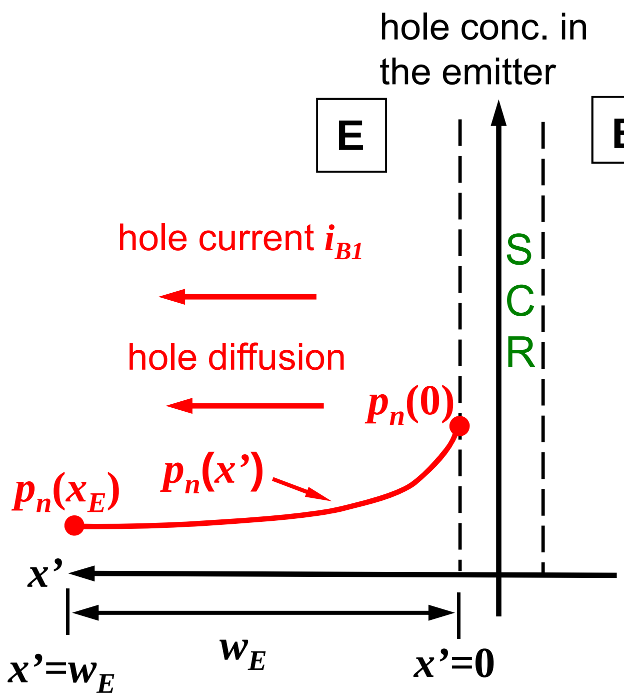
- We assume in this example that the emitter width is much longer than the minority carrier diffusion length, i.e., $w_E >> L_p$.
- Due to the forward bias at the emitter-base junction, the hole concentration at the edge of the E-B SCR is given by

$$p_n(x'=0) = p_{n0}\, e^{v_{BE}/V_T} \qquad (3.4)$$

where p_{n0} is the equilibrium hole concentration in the emitter.

- The hole diffuse into the emitter, and recombine along the way, giving rise to an exponentially decaying distribution (as shown in the p-n junction theory) :

$$p_n(x') = p_{n0} + [p_n(0) - p_{n0}]e^{-x'/L_p} \qquad (3.5)$$



* Note that we have set up an axis x' which is opposite to the x-direction, just to simplify the expression for hole conc. distribution.

- The current due to holes that are injected from the base into the emitter

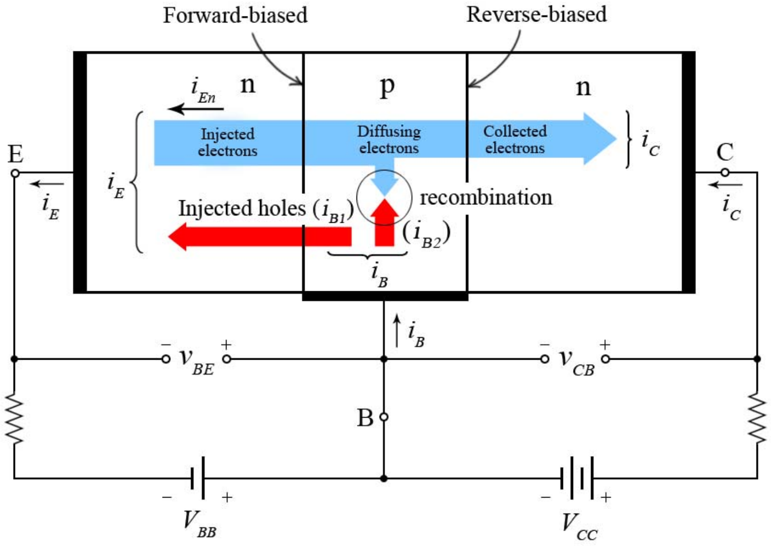
$$|i_{B1}| = \left| -qAD_p \left.\frac{dp_n(x')}{dx'}\right|_{x'=0} \right| = \left| -qAD_p \frac{d}{dx'}\left[\{p_n(0) - p_{n0}\}e^{-x'/L_p}\right]_{x'=0} \right|$$

$$= qA\frac{D_p}{L_p}\{p_n(0) - p_{n0}\} = qA\frac{D_p}{L_p} p_{n0}\left(e^{v_{BE}/V_T} - 1\right) \approx qA\frac{D_p}{L_p} p_{n0}\, e^{v_{BE}/V_T} \quad as \quad v_{BE} >> V_T \qquad (3.6)$$

Analysis of the BJT (npn)

- The collector current is made up of those electrons that are injected from the emitter in the base, that then diffuse through the base and into the collector.

$i_C = i_{En} - i_{B2} \approx i_{En}$ as $i_{B2} << i_{En}$.

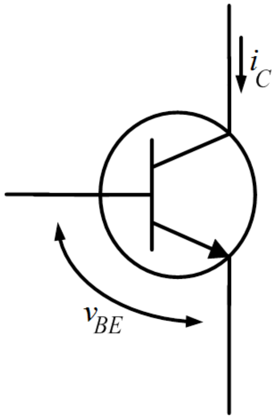


- Therefore

$$i_C = i_{En} = qA\frac{D_n}{w_B} n_{p0}\, e^{v_{BE}/V_T} = I_S e^{v_{BE}/V_T} \qquad (3.7)$$

where $$I_S = qA\frac{D_n}{w_B} n_{p0} = qA\frac{D_n}{w_B}\frac{n_i^2}{N_{AB}} \qquad (3.8)$$

- Equation (3.7) shows that the collector current, i_C, that flows through the collector-base junction, is controlled by the bias voltage v_{BE}, applied at the emitter-base junction. This is the **TRANSISTOR ACTION.**



Analysis of the BJT (npn)

- The base current

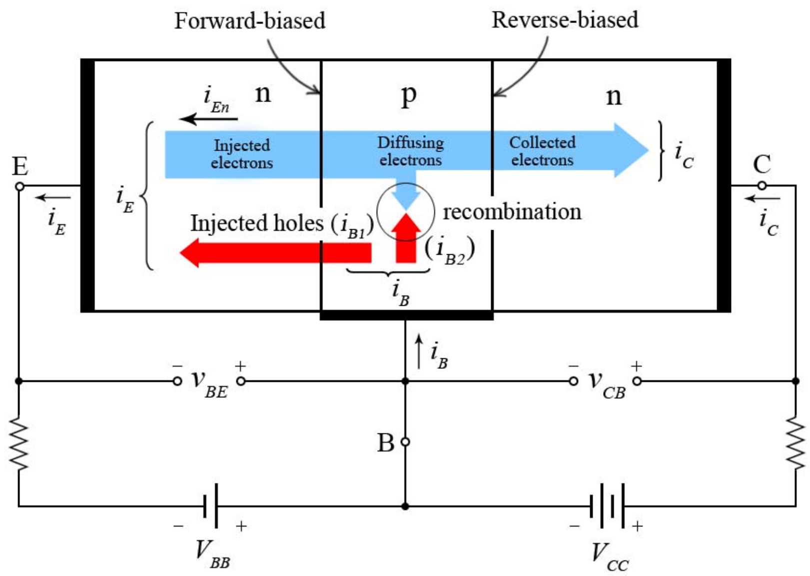
  $i_B = i_{B1} + i_{B2} \approx i_{B1}$ as $i_{B2} << i_{B1}$.

- Therefore

$$i_B = i_{B1} = qA\frac{D_p}{L_p}p_{n0}\,e^{v_{BE}/V_T} \qquad (3.9)$$

- The common emitter current gain, β, is defined as

$$\beta = \frac{i_C}{i_B} \qquad (3.10)$$



$$\beta = \frac{qA\frac{D_n}{w_B}n_{p0}\,e^{v_{BE}/V_T}}{qA\frac{D_p}{L_p}p_{n0}\,e^{v_{BE}/V_T}} = \frac{D_n}{D_p}\frac{L_p}{w_B}\frac{n_{p0}}{p_{n0}} = \frac{D_n}{D_p}\frac{L_p}{w_B}\frac{N_{DE}}{N_{AB}} \qquad (3.11)$$

as
$$n_{p0} = \frac{n_i^2}{N_{AB}}, \quad p_{n0} = \frac{n_i^2}{N_{DE}}.$$

- We note from eqn (3.11) that in order to have a large current gain β, the emitter doping, N_{DE}, much be much higher than the base doping N_{AB}.

Analysis of the BJT (npn)

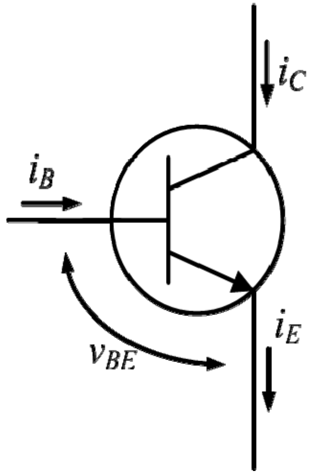
- In summary, the collector current

$$\boxed{i_C = I_S e^{v_{BE}/V_T}} \qquad (3.12)$$

and the base current

$$\boxed{i_B = \frac{I_S}{\beta} e^{v_{BE}/V_T}} \qquad (3.13)$$

where I_s is given by eqn (3.8) and β, by eqn (3.11).



- By Kirchhoff's Current Law (KCL), the emitter current,

$$i_E = i_C + i_B.$$

- The common base current gain, α, is defined as

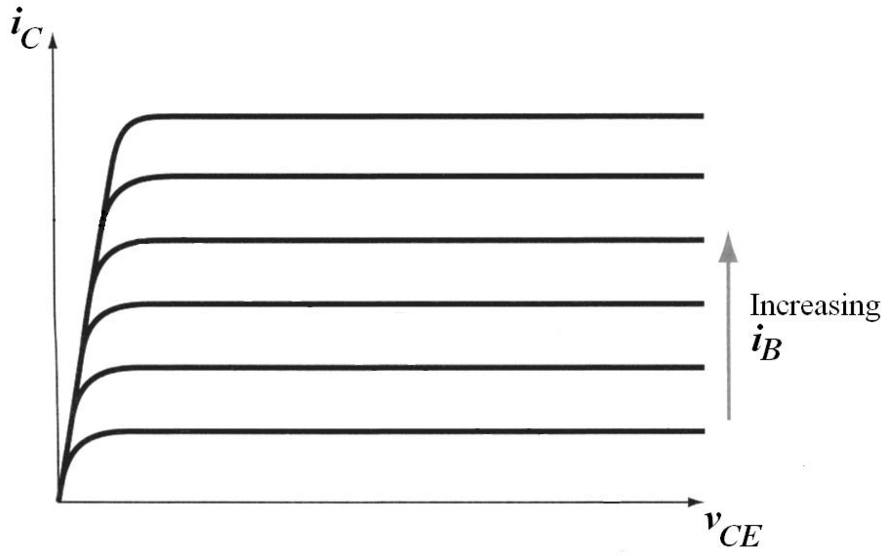
$$\alpha = \frac{i_C}{i_E} \qquad (3.14)$$

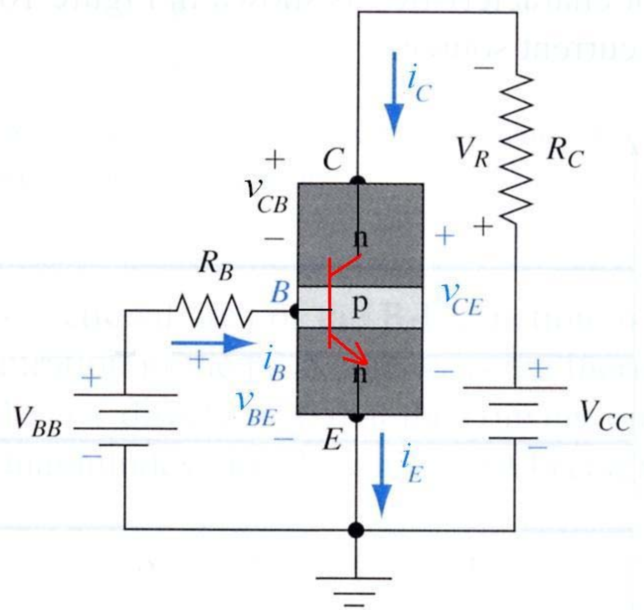
- By simple algebra, it can be shown that

$$\beta = \frac{\alpha}{1-\alpha} \qquad (3.15)$$

Analysis of the BJT (npn)

Ideal I-V characteristics of the BJT

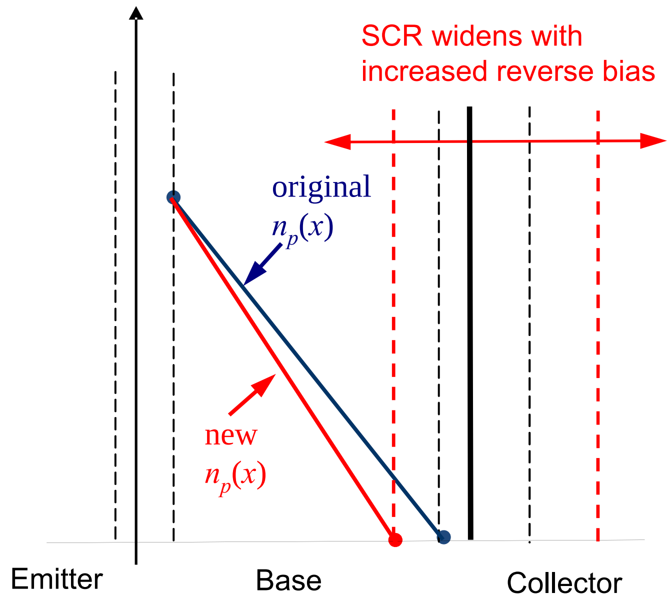




- The plot above shows the collector current, i_C, as a function of the collector-emitter voltage v_{CE} and the base current i_B, for the simple common emitter amplifier circuit shown on the right.
- In the characteristics, i_C is a strong function of i_B.
- $v_{CE} = v_{CB} + v_{BE} \approx v_{CB}$ for $v_{CE} >> v_{BE} \approx 0.7$ V).
- v_{CB} is the reverse bias across the collector-base junction. As discussed before, the value of i_C is not dependent on the bias across the collector-base junction.
- Hence, in the idealized analysis we have done so far, i_C is not a function of v_{CE}.

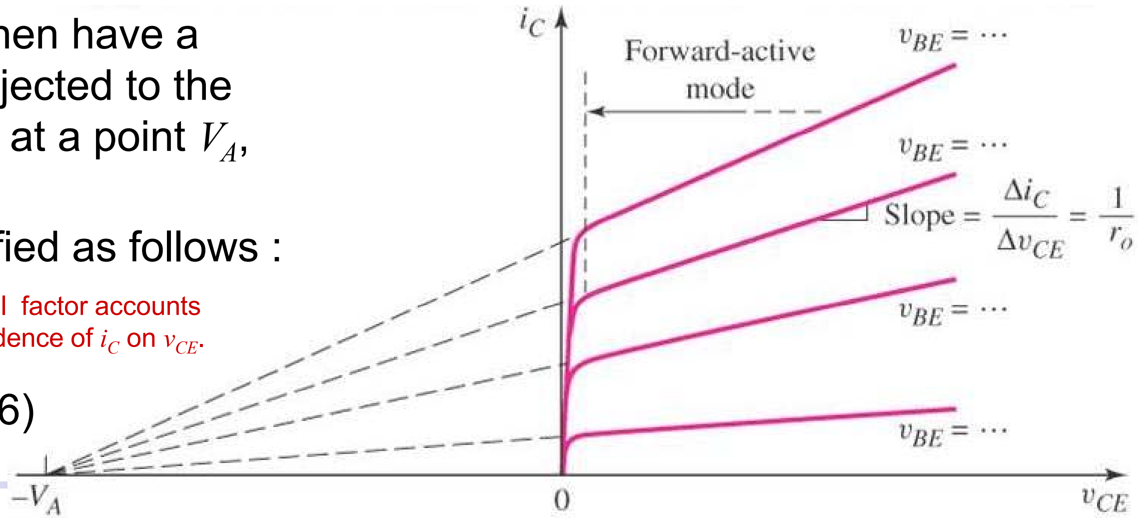
Analysis of the BJT (npn)

- In a real (non-idealized) BJT, there is a slight dependence of i_C on v_{CE}.
- When the reverse bias v_{CB} at the collector base junction is increased, the SCR at that junction widens, and part of it extends further into the base (dotted line in the diagram). The width of the neutral base is reduced slightly, and hence the gradient of the minority carrier concentration profile increases slightly. As the collector current i_C is proportional to the rate of diffusion of the minority carriers in the base, i_C therefore increases slightly.
- This phenomenon is called **base-width modulation**, also know as **Early effect**.
- The i_C - v_{CE} characteristics would then have a slight upward slope, and when projected to the negative axis, meet approximately at a point V_A, called the “Early voltage”.
- The expression for i_C is then modified as follows :



This additional factor accounts for the dependence of i_C on v_{CE}.

$$i_C = I_S\, e^{v_{BE}/V_T}\left(1+\frac{v_{CE}}{V_A}\right) \qquad (3.16)$$



APPENDIX

<u>Modes of operation of the **pnp** bipolar junction transistor</u>

Mode of Operation	Emitter-Base Junction	Collector-Base Junction	Applications
Cut-off	Reverse biased (V_{EB} < 0 for pnp)	Reverse biased (V_{CB} < 0 for pnp)	Logic- OFF State
Forward Active	Forward biased (V_{EB} > 0 for pnp)	Reverse biased (V_{CB} < 0 for pnp)	Amplifier
Saturation	Forward biased (V_{EB} > 0 for pnp)	Forward biased (V_{CB} >0 for pnp)	Logic - ON State
Reverse Active	Reverse Biased (V_{EB} < 0 for pnp)	Forward Biased (V_{CB} > 0 for pnp)	Not used