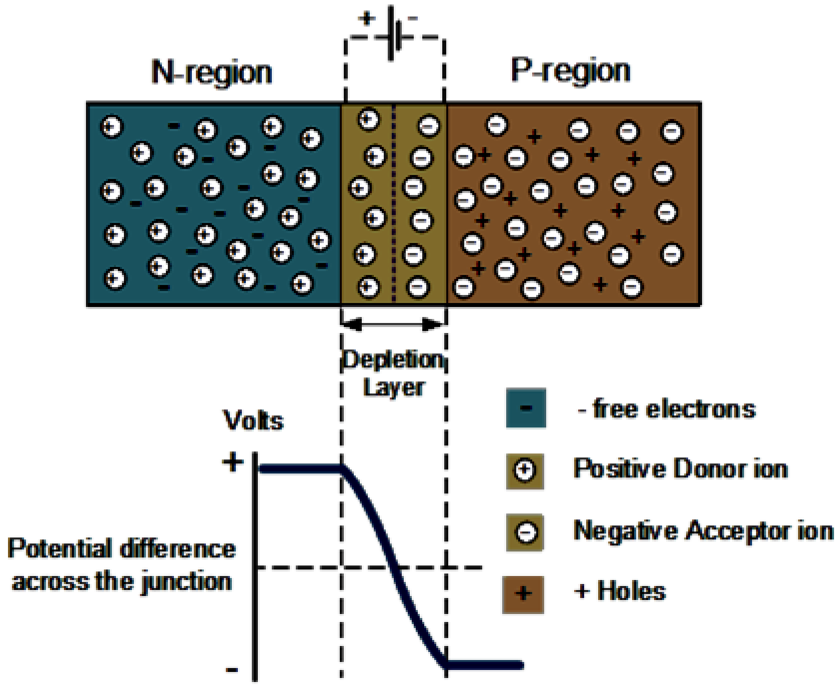
Bipolar Junction Transistors (BJTS

3002 Electronic Devices



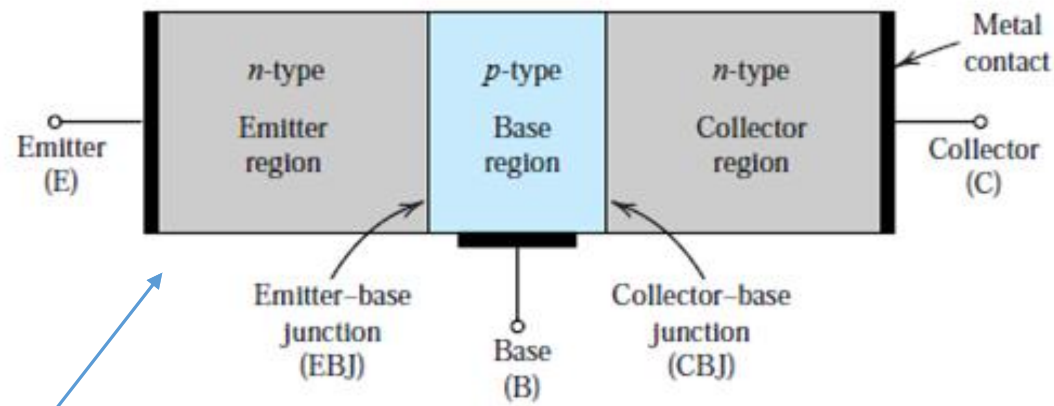
Bipolar Junction Transistor

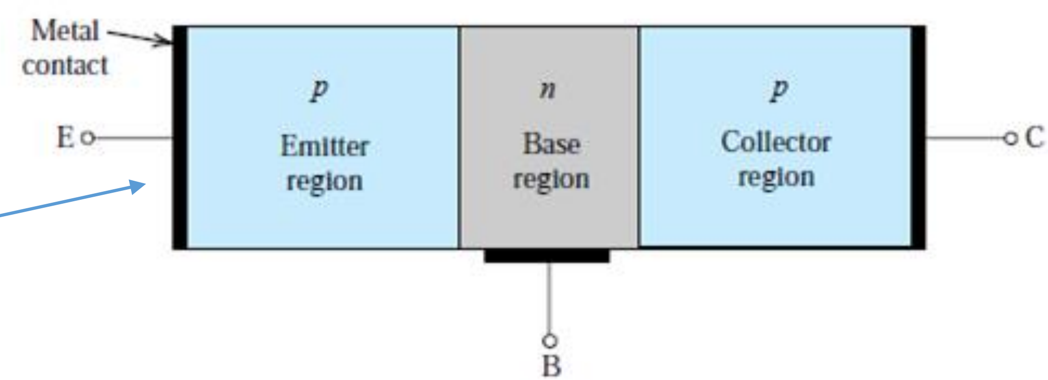
Invention of BJT in 1948 at Bell Labs led to electronics changing the way we work, play, and live.

By 2009, the MOSFET was undoubtedly the most widely used electronic device. CMOS technology became the technology of choice in the design of integrated circuits.

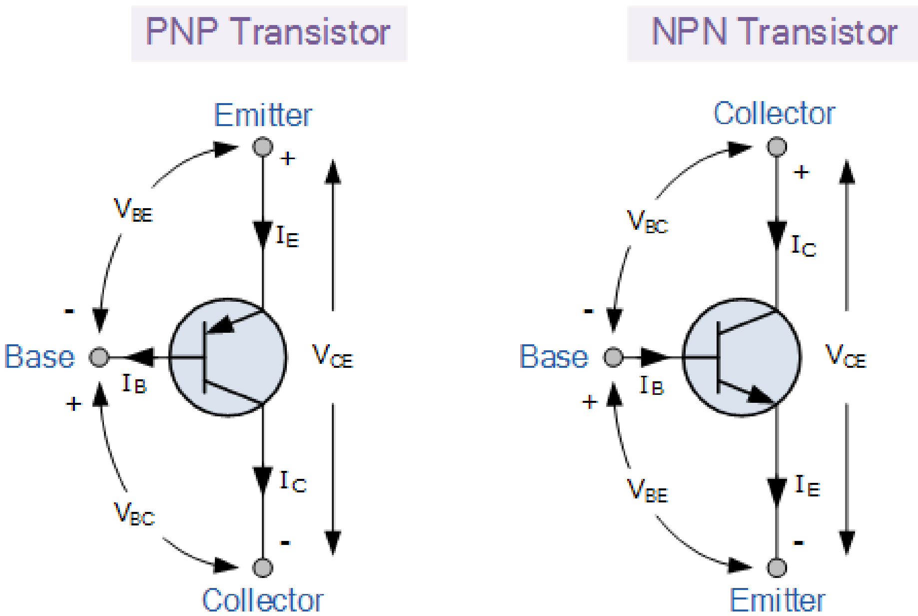
In an ***npn*** transistor, the BJT consists of three semiconductor regions: the emitter region (*n* type), the base region (*p* type), and the collector region (*n* type).

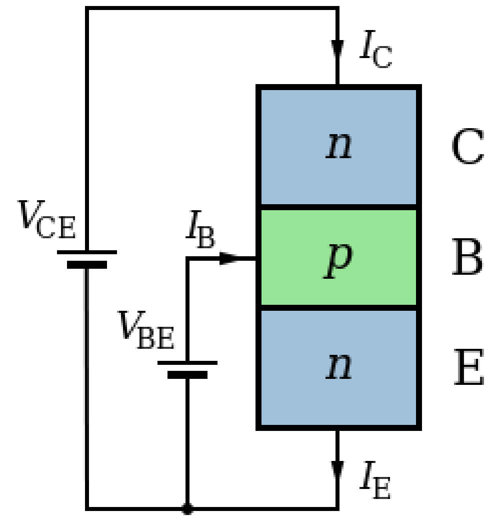
A ***pnp*** transistor has a *p*-type emitter, an *n*-type base, and a *p*-type collector.

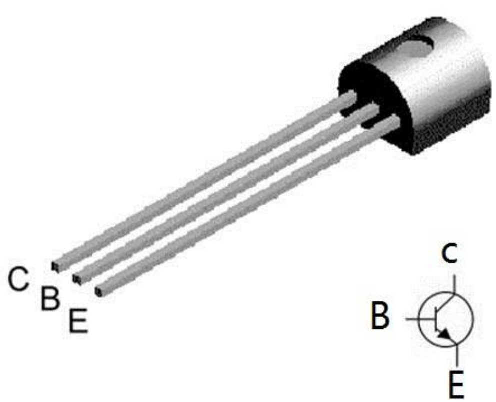


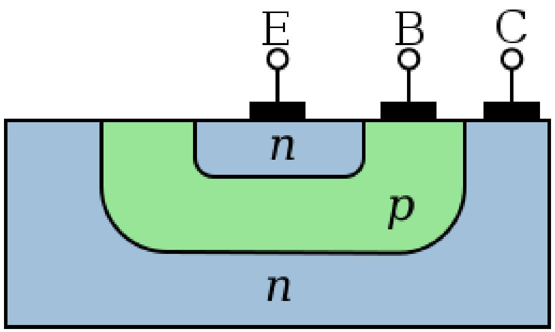


BJT Modes of Operation

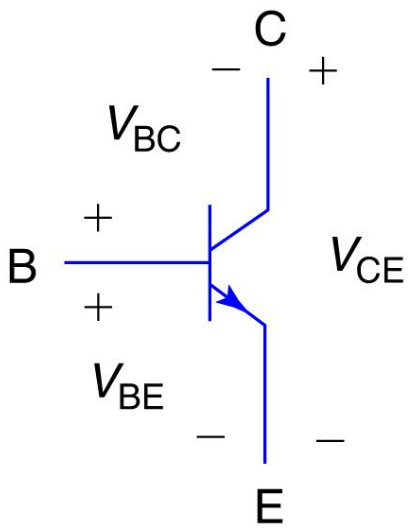


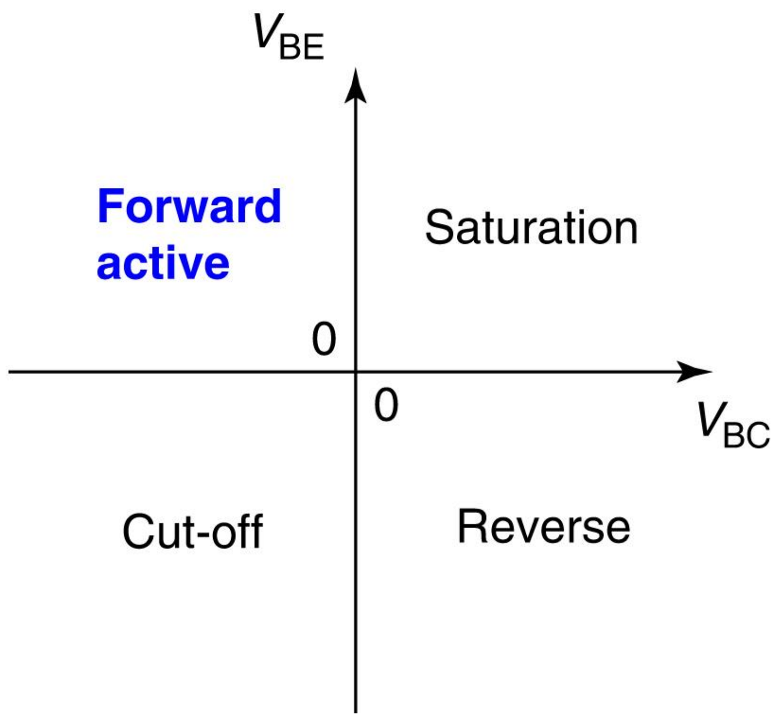


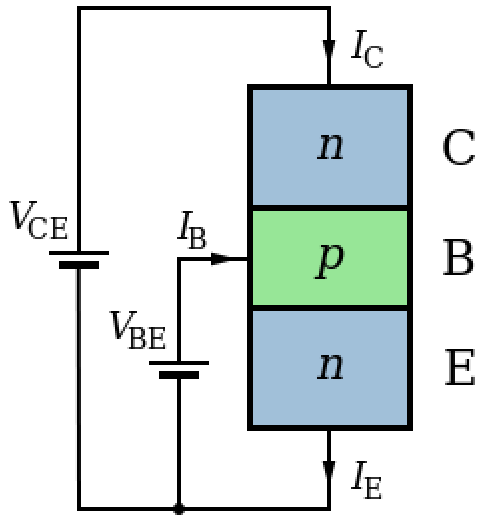


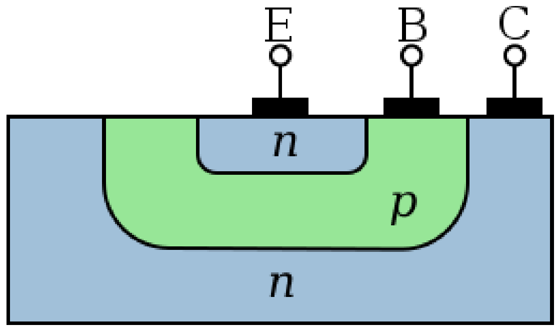


BJT Modes of Operation

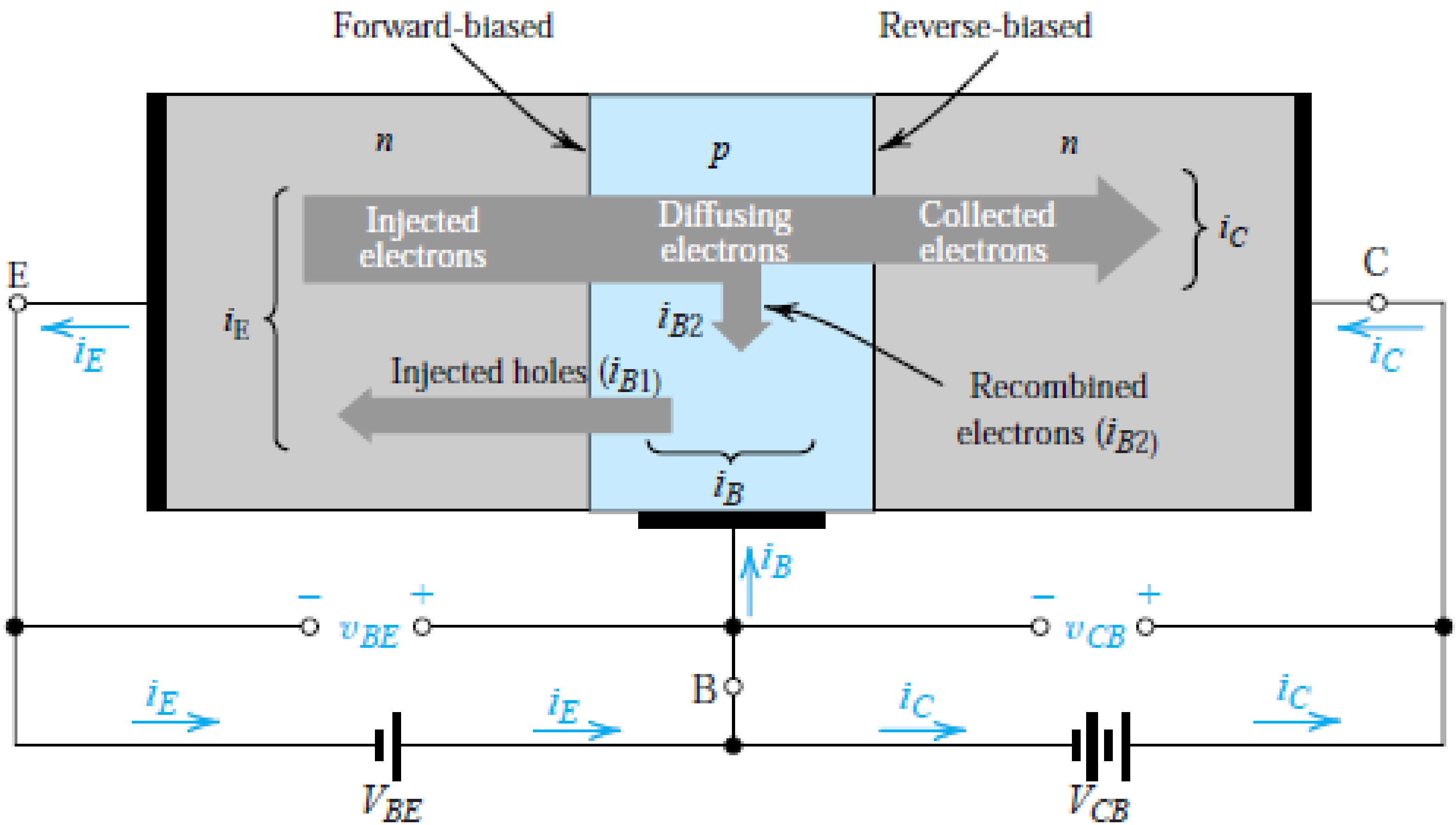




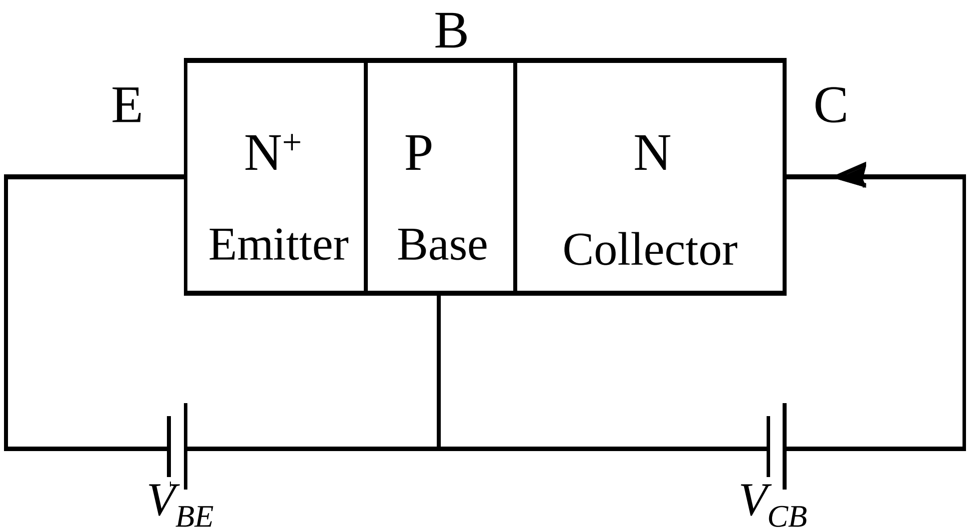


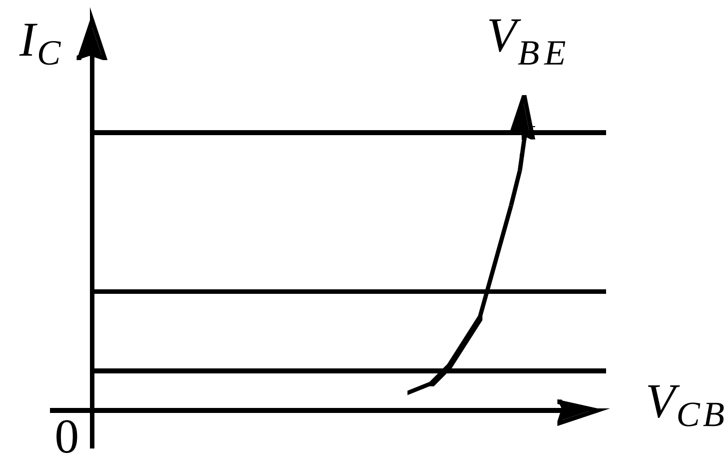


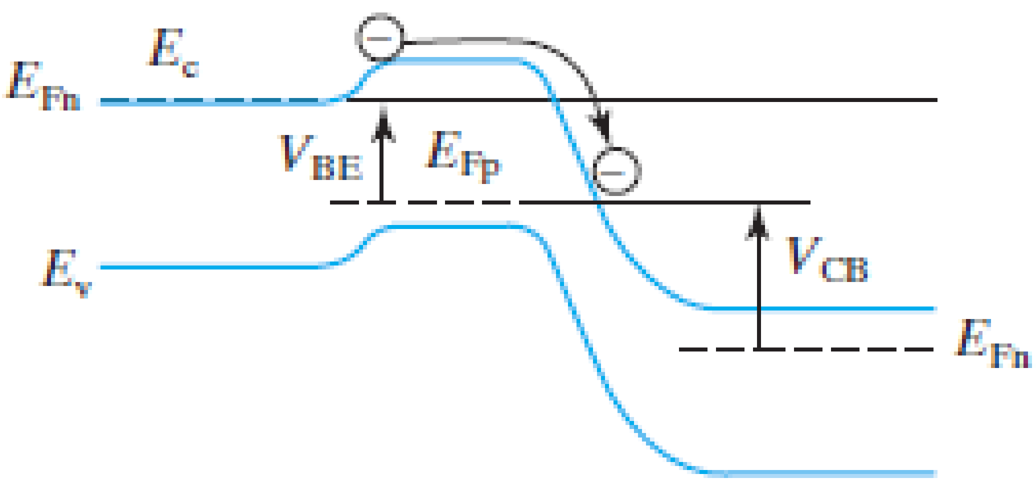
Active Mode npn-BJT



Active Mode npn-BJT







I_C is an exponential function of forward V_{BE} and independent of reverse V_{CB}.

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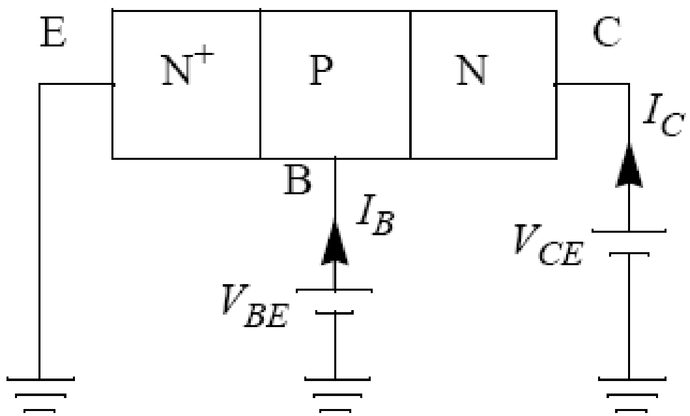
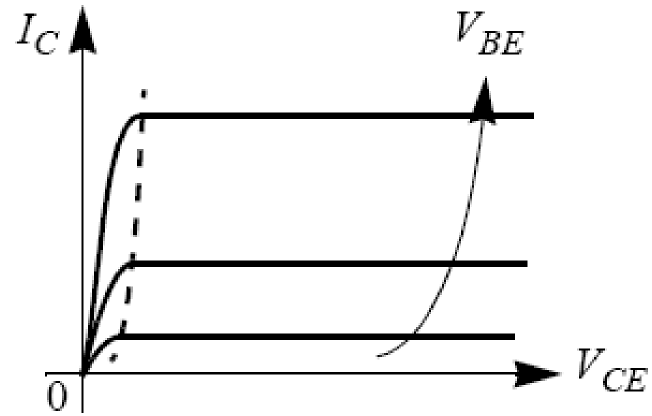
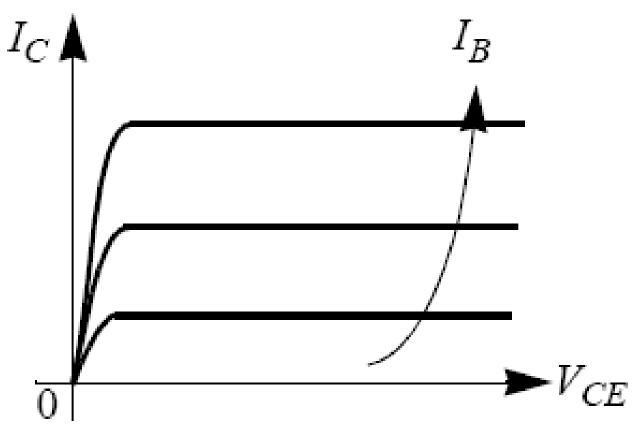
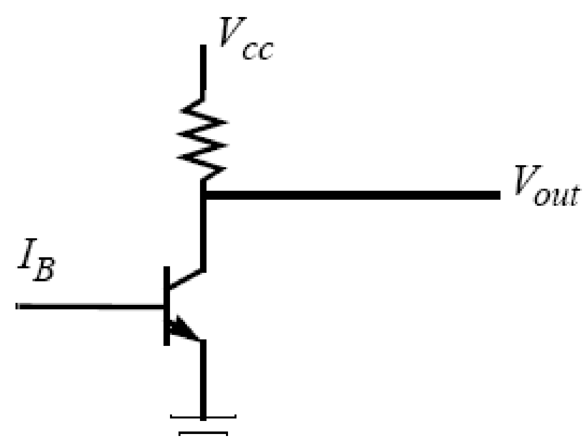
Common-Emitter Configuration









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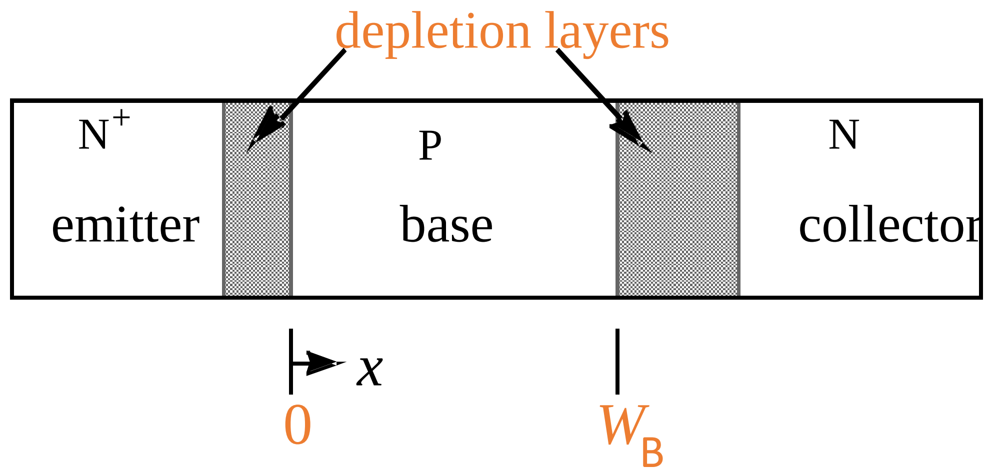
Collector Current

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

τ_B : base recombination lifetime

D_B : base minority carrier (electron) diffusion constant



Boundary conditions :

$$n'(0) = n_{B0}(e^{qV_{BE}/kT} - 1)$$

$$n'(W_B) = n_{B0}(e^{qV_{BC}/kT} - 1) \approx -n_{B0} \approx 0$$

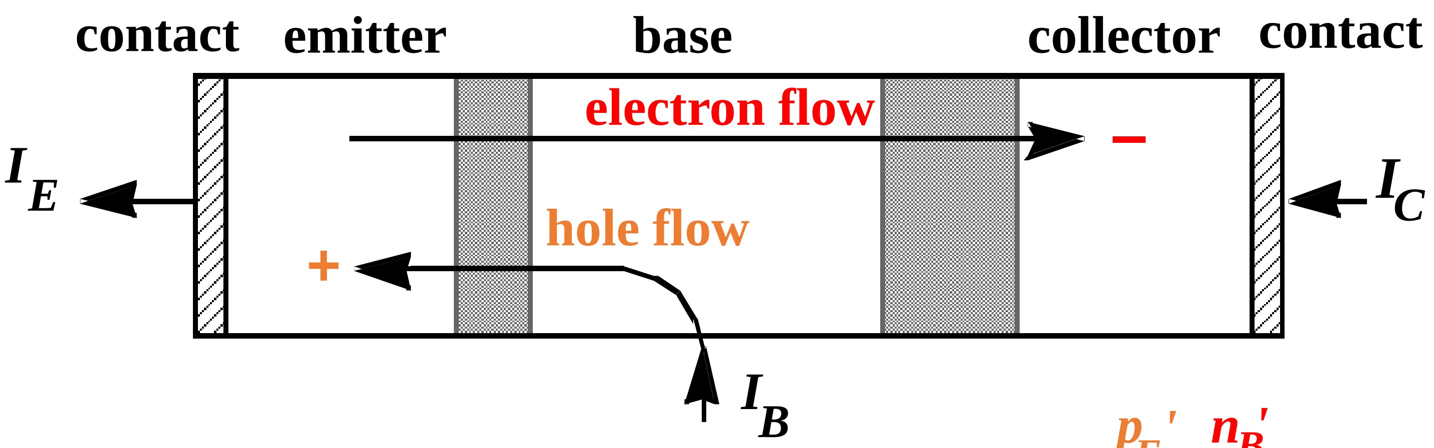
$$I_C = \left| A_E q D_B \frac{dn}{dx} \right|$$

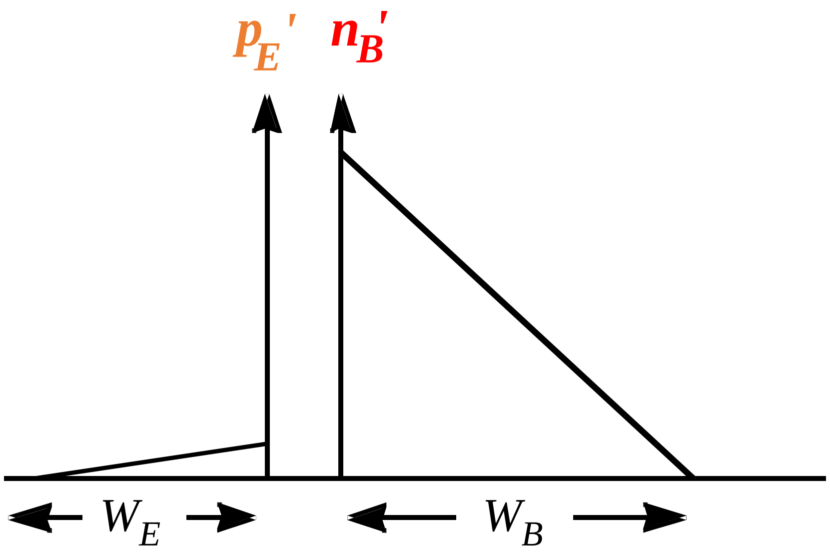
$$= A_E q \frac{D_B}{W_B} \frac{n_{iB}^2}{N_B} (e^{qV_{BE}/kT} - 1)$$

$$\boxed{I_C = I_S (e^{qV_{BE}/kT} - 1)}$$

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 .





For a uniform emitter,

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

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Current Gain

Common-emitter current gain, β_F :

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

Common-base current gain:

$$I_C = \alpha_F I_E$$

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

It can be shown that $\boxed{\beta_F = \frac{\alpha_F}{1 - \alpha_F}}$

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

How can β_F be maximized?

EXAMPLE: Current Gain

A BJT has I_C = 1 mA and I_B = 10 μA. What are I_E, β_F and α_F?

***Solution**:*

EXAMPLE: Current Gain

A BJT has I_C = 1 mA and I_B = 10 μA. What are I_E, β_F and α_F?

***Solution**:*

$$I_E = I_C + I_B = 1\,\mathrm{mA} + 10\,\mu\mathrm{A} = 1.01\,\mathrm{mA}$$

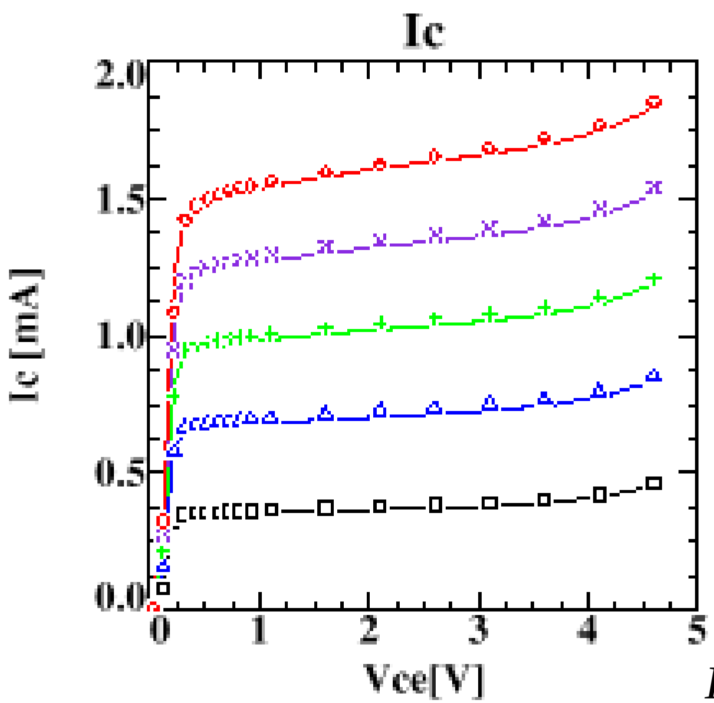
$$\beta_F = I_C / I_B = 1\,\mathrm{mA} / 10\,\mu\mathrm{A} = 100$$

$$\alpha_F = I_C / I_E = 1\,\mathrm{mA} / 1.01\,\mathrm{mA} = 0.9901$$

We can confirm

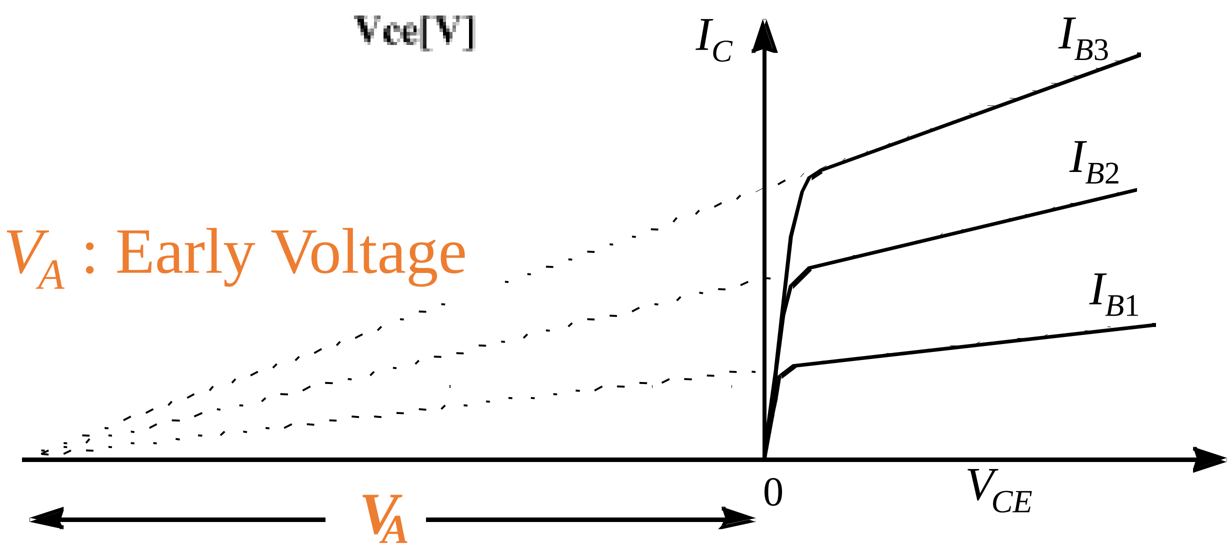
$$\alpha_F = \frac{\beta_F}{1+\beta_F} \quad \text{and} \quad \beta_F = \frac{\alpha_F}{1-\alpha_F}$$

Base-Width Modulation



Output resistance :

$$r_0 \equiv \left(\frac{\partial I_C}{\partial V_{CE}} \right)^{-1} = \frac{V_A}{I_C}$$



Large V_A (large r_o) is desirable for a large voltage gain

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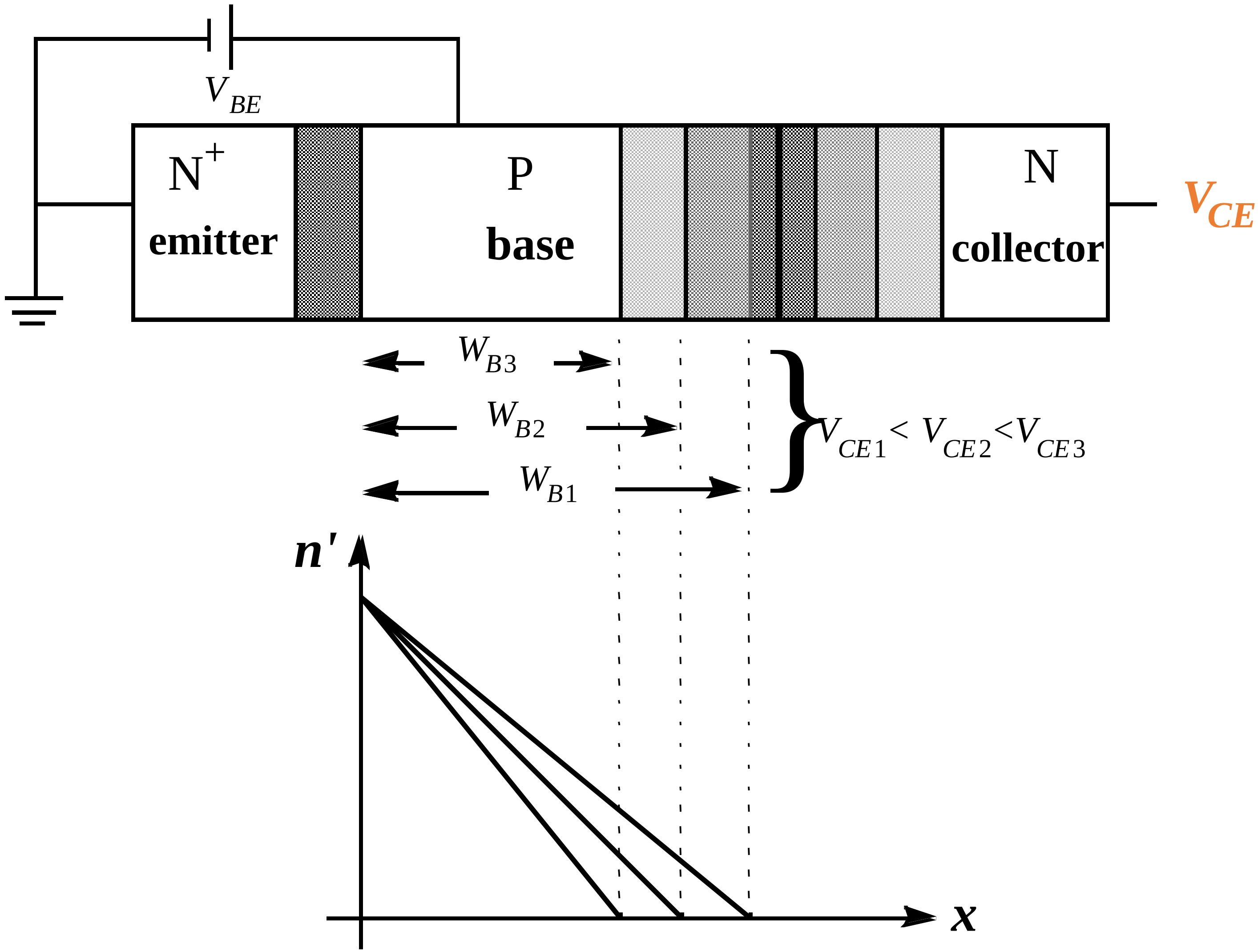
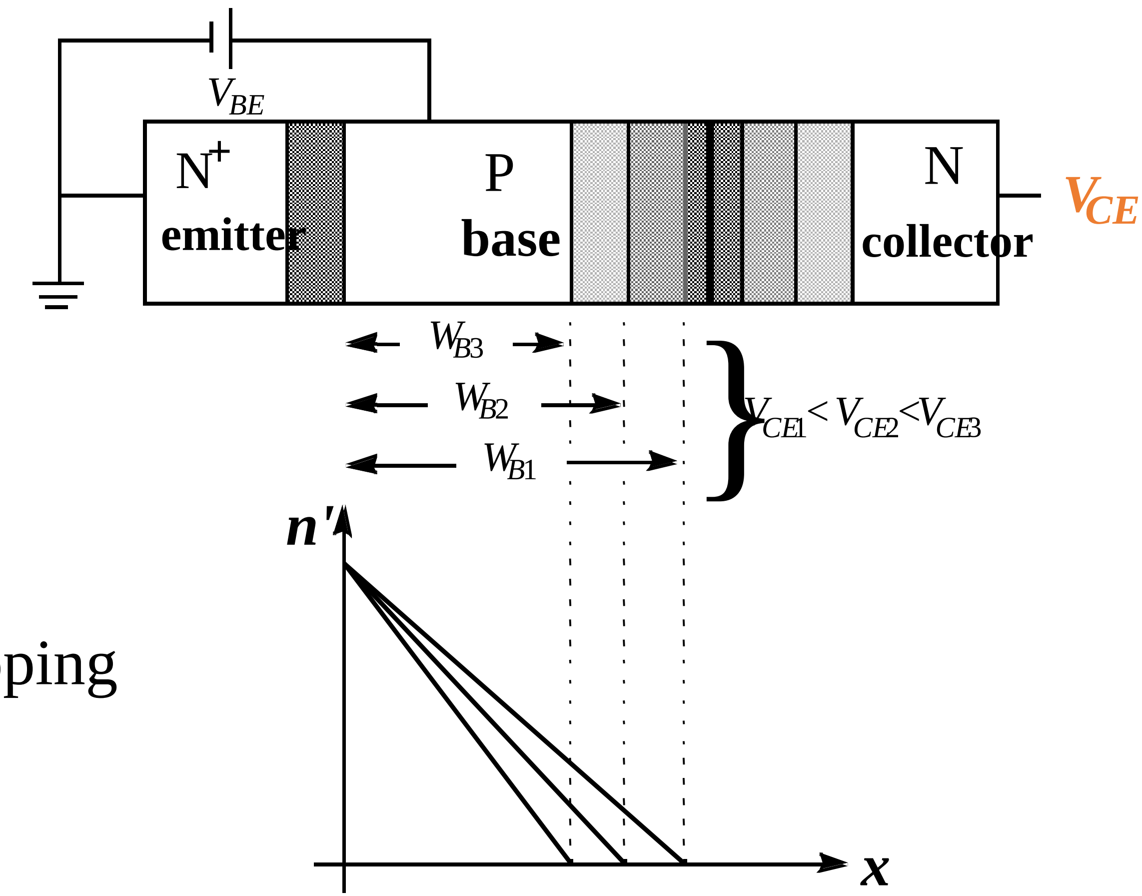
Base-Width Modulation by Collector Voltage



How can we reduce the base-width modulation effect?

Base-Width Modulation by Collector Voltage



The base-width modulation effect is reduced if we

(A) Increase the base width,
(B) Increase the base doping concentration, N_B, or
(C) Decrease the collector doping concentration, N_C.

Which of the above is the most acceptable action?

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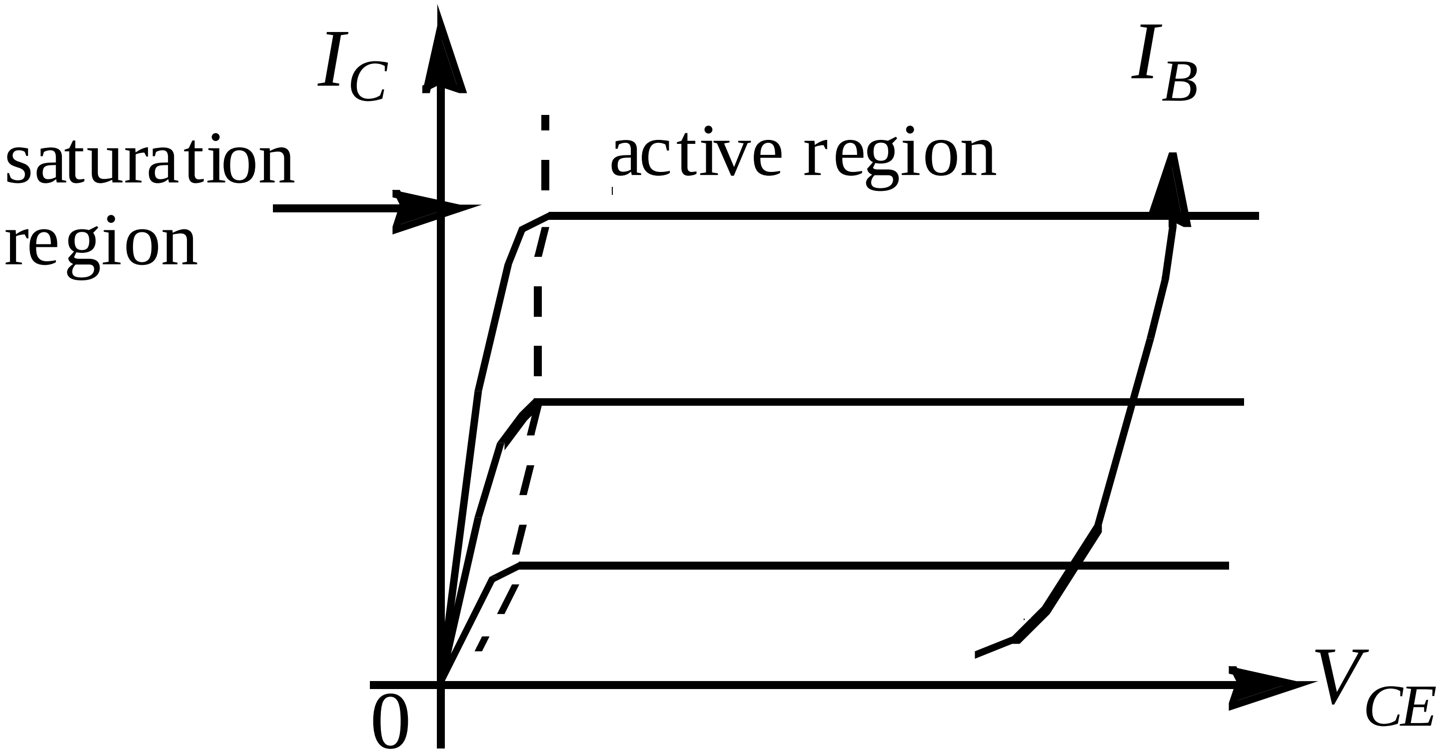
Ebers-Moll Model



The Ebers-Moll model describes both the active and the saturation regions of BJT operation.

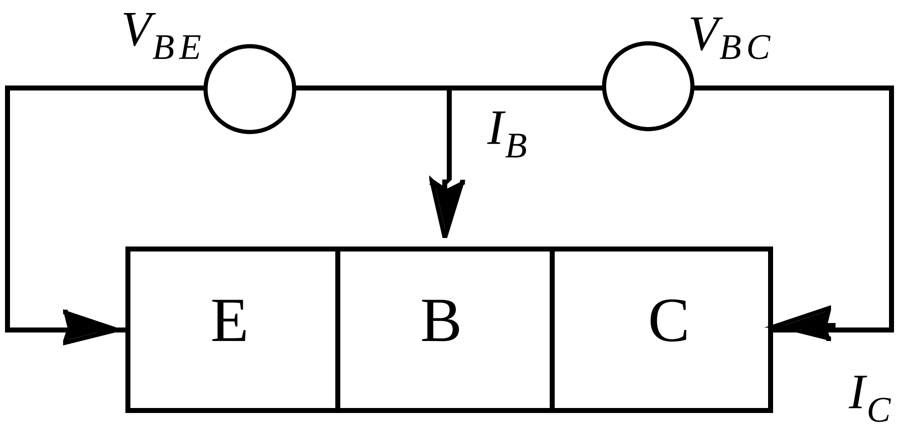
Ebers-Moll Model

I_C is driven by two two forces, V_{BE} and V_{BC} .

When only V_{BE} is present :

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

$$I_B = \frac{I_S}{\beta_F}(e^{qV_{BE}/kT} - 1)$$



Now reverse the roles of emitter and collector.

When only V_{BC} is present :

$$I_E = I_S(e^{qV_{BC}/kT} - 1)$$

$$I_B = \frac{I_S}{\beta_R}(e^{qV_{BC}/kT} - 1)$$

β_R : reverse current gain

β_F : forward current gain

$$I_C = -I_E - I_B = -I_S(1 + \frac{1}{\beta_R})(e^{qV_{BC}/kT} - 1)$$

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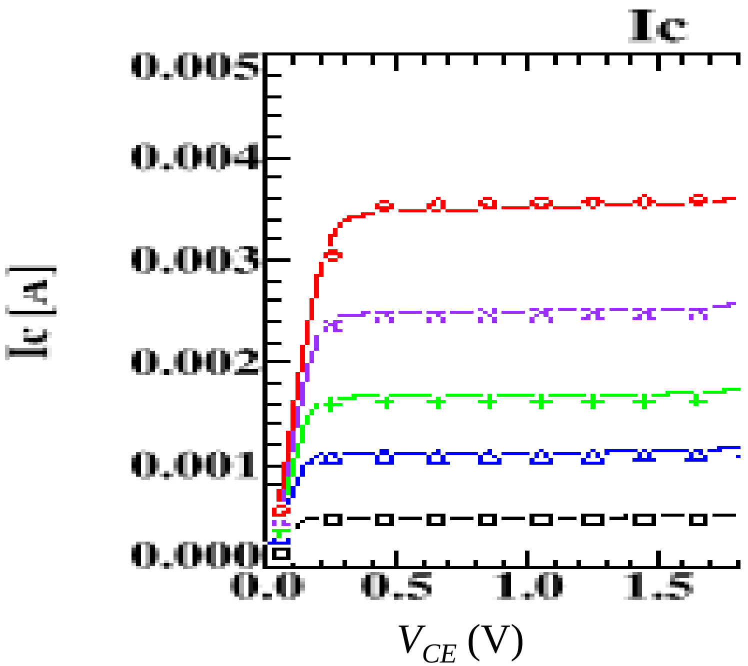
Ebers-Moll Model

In general, both V_{BE} and V_{BC} are present :

$$I_C = I_S(e^{qV_{BE}/kT} - 1) - I_S(1 + \frac{1}{\beta_R})(e^{qV_{BC}/kT} - 1)$$

$$I_B = \frac{I_S}{\beta_F}(e^{qV_{BE}/kT} - 1) + \frac{I_S}{\beta_F}(e^{qV_{BC}/kT} - 1)$$

In saturation, the BC junction becomes forward-biased, too.



V_{BC} causes a lot of holes to be injected into the collector. This uses up much of I_B. As a result, I_C drops.

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Transit Time and Charge Storage

When the BE junction is forward-biased, excess holes are stored in the emitter, the base, and even in the depletion layers.

Q_F is all the stored excess hole charge

$$\boxed{\tau_F \equiv \frac{Q_F}{I_C}}$$

τ_F is difficult to be predicted accurately but can be measured.

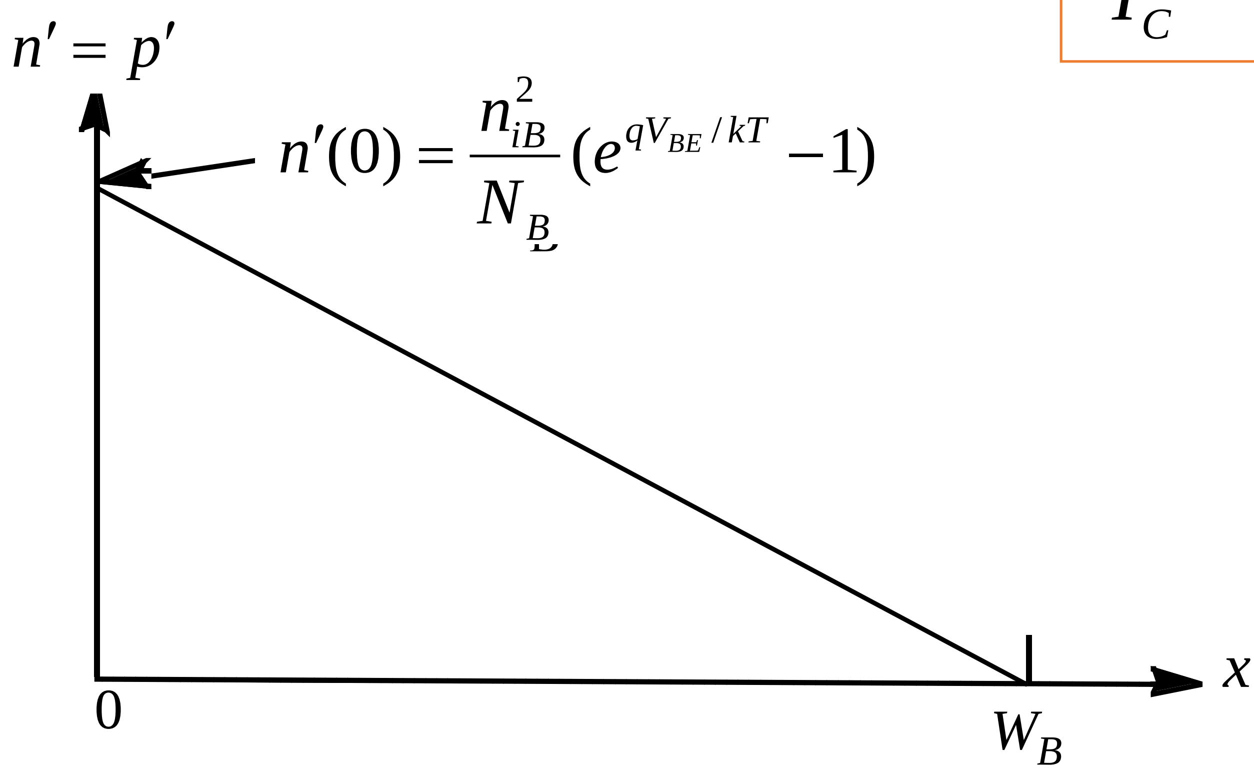
τ_F determines the high-frequency limit of BJT operation.

Base Charge Storage and Base Transit Time

Let's analyze the excess hole charge and transit time in the base only.

$$Q_{FB} = qA_E n'(0) W_B / 2$$

$$\boxed{\frac{Q_{FB}}{I_C} \equiv \tau_{FB} = \frac{W_B^2}{2D_B}}$$



$$n'(0) = \frac{n_{iB}^2}{N_B}\left(e^{qV_{BE}/kT} - 1\right)$$

EXAMPLE: Base Transit Time

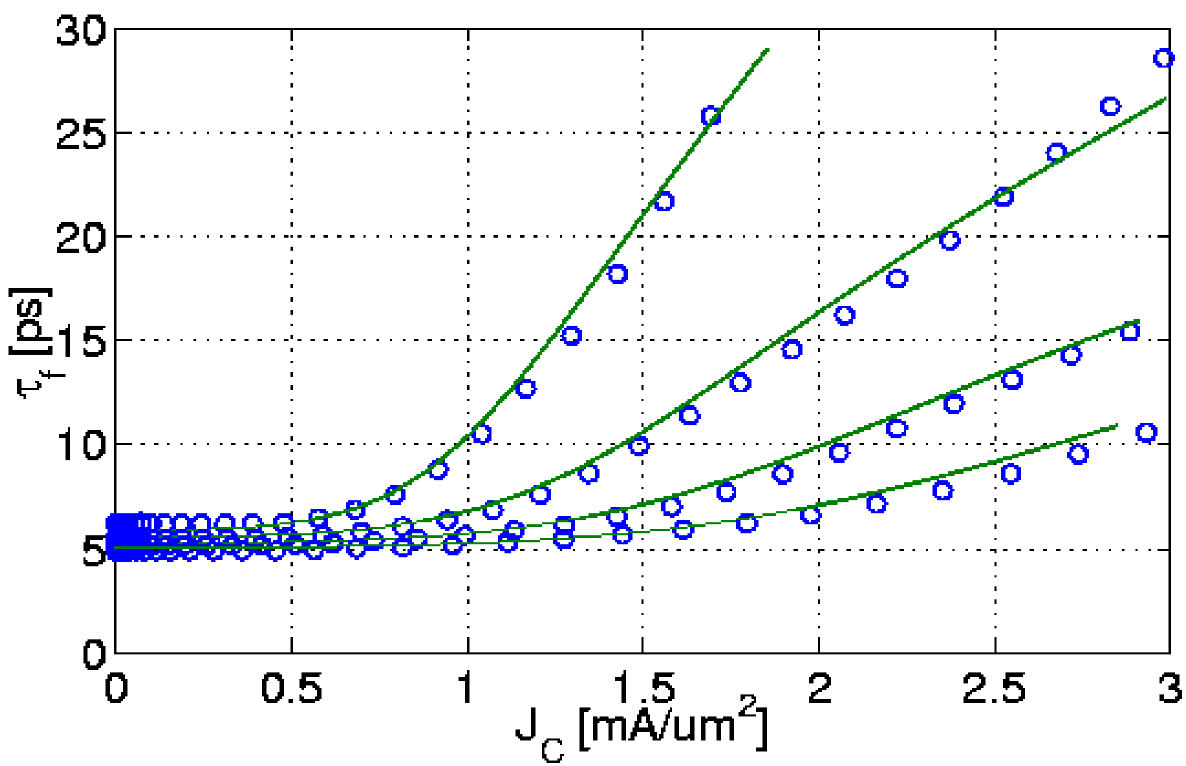
What is τ_{FB} if W_B = 70 nm and D_B = 10 cm^2/s?

Answer:

Emitter-to-Collector Transit Time and Kirk Effect

- To reduce the total transit time, emitter and depletion layers must be thin, too.

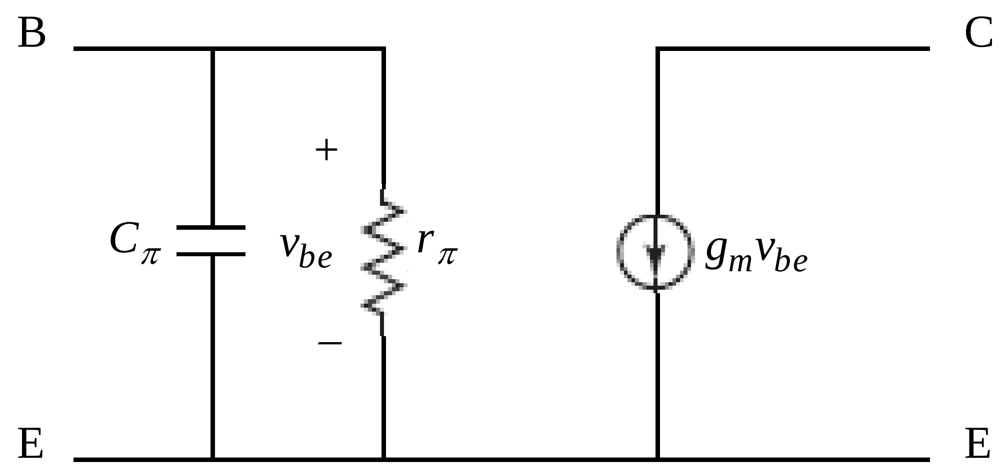
- Kirk effect or base widening: At high I_C the base widens into the collector. Wider base means larger τ_F .



Top to bottom :
V_{CE} = 0.5V, 0.8V, 1.5V, 3V.

Small-Signal Model

$$I_C = I_S e^{qV_{BE}/kT}$$



Transconductance:

$$g_m \equiv \frac{dI_C}{dV_{BE}} = \frac{d}{dV_{BE}}(I_S e^{qV_{BE}/kT})$$

$$= \frac{q}{kT} I_S e^{qV_{BE}/kT} = I_C /(kT/q)$$

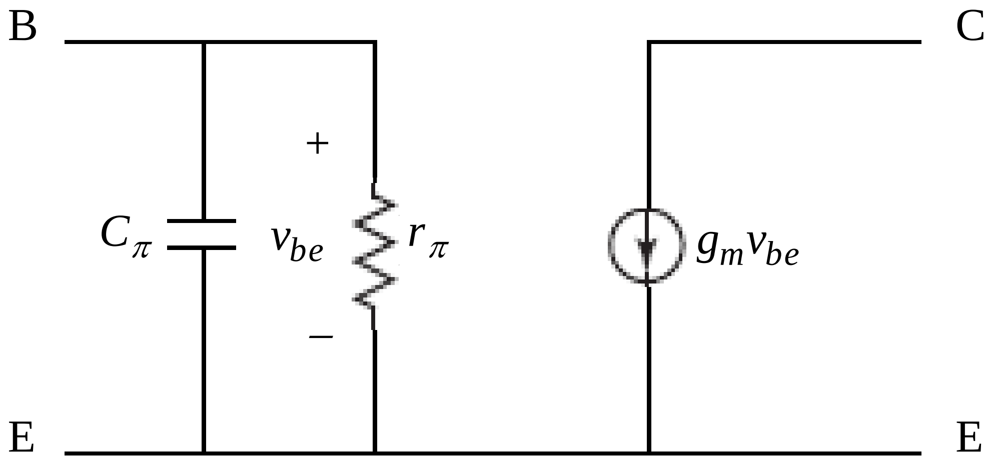
$$\boxed{g_m = I_C /(kT/q)}$$

At 300 K, for example, $g_m = I_C / 26\text{mV}$.

Small-Signal Model

$$\frac{1}{r_\pi} = \frac{dI_B}{dV_{BE}} = \frac{1}{\beta_F}\frac{dI_C}{dV_{BE}} = \frac{g_m}{\beta_F}$$

$$\boxed{r_\pi = \beta_F / g_m}$$



$$C_\pi = \frac{dQ_F}{dV_{BE}} = \frac{d}{dV_{BE}}\tau_F I_C = \tau_F g_m$$

This is the charge-storage capacitance, better known as the ***diffusion capacitance***.

Add the depletion-layer capacitance, C_{dBE} :

$$C_\pi = \tau_F g_m + C_{dBE}$$

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EXAMPLE: Small-Signal Model Parameters

A BJT is biased at I_C = 1 mA and V_{CE} = 3 V. β_F=90, τ_F=5 ps, and T = 300 K. Find (a) g_m, (b) r_π, (c) C_π.

Solution:

(a)

(b)

(c)

Summary

The base-emitter junction is usually forward-biased while the base-collector is reverse-biased. V_{BE} determines the collector current, I_C .

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

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

- G_B is the base Gummel number, which represents all the subtleties of BJT design that affect I_C.

Summary

The base (input) current, I_B, is related to I_C by the common-emitter current gain, β_F. This can be related to the common-base current gain, α_F.

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

In an npn BJT, an emitter is 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:

$$\gamma_E = \frac{I_E - I_B}{I_E} = \frac{I_C}{I_C + I_B} = \frac{1}{1 + D_E W_B N_B n_{iE}^2 / D_B W_E N_E n_{iB}^2}$$

Base-width modulation by V_{CB} results in a significant slope of the I_C vs. V_{CE} curve in the active region (known as the Early effect).

Summary

Due to the forward bias V_{BE} , a BJT stores a certain amount of excess carrier charge Q_F which is proportional to I_C.

$$Q_F \equiv I_C \tau_F$$

τ_F is the forward transit time. If no excess carriers are stored outside the base, then

$$\tau_F = \tau_{FB} = \frac{W_B^2}{2D_B}$$, the base transit time.

- The charge-control model first calculates $Q_F(t)$ from $I_B(t)$ and then calculates $I_C(t)$.

$$\frac{dQ_F}{dt} = I_B(t) - \frac{Q_F}{\tau_F \beta_F}$$

$$I_C(t) = Q_F(t) / \tau_F$$

Summary

The small-signal models employ parameters such as transconductance,

$$g_m \equiv \frac{dI_C}{dV_{BE}} = I_C / \frac{kT}{q}$$

input capacitance,

$$C_\pi = \frac{dQ_F}{dV_{BE}} = \tau_F g_m$$

and input resistance.

$$r_\pi = \frac{dV_{BE}}{dI_B} = \beta_F / g_m$$

EXAMPLE: *A P^+N junction has $N_a = 10^{20}$ cm^{-3} and $N_d = 10^{17}$cm^{-3}. What is a) its built in potential, b)W_{dep} , c)x_N , and d) x_P ?*

Solution:

a)

b)

c)

d)

EXAMPLE: Carrier Injection

A PN junction has $N_a=10^{19}cm^{-3}$ and $N_d=10^{16}cm^{-3}$. The applied voltage is 0.6 V.

***Question**: What are the minority carrier concentrations at the depletion-region edges?*

***Solution**:*

***Question**: What are the excess minority carrier concentrations?*

***Solution**:*

EXAMPLE: Emitter Bandgap Narrowing and SiGe Base

Assume $D_B = 3D_E$, $W_E = 3W_B$, $N_B = 10^{18}$ cm^{-3}, and $n_{iB}^2 = n_i^2$. What is β_F for (a) $N_E = 10^{19}$ cm^{-3} and $\Delta E_{gE} \approx 50$ meV; (b) $N_E = 10^{20}$ cm^{-3} and $\Delta E_{gE} \approx 95$ meV ; (c) $N_E = 10^{20}$ cm^{-3} and a SiGe base with $\Delta E_{gB} = 60$ meV ?

(a) At $N_E = 10^{19}$ cm^{-3}, $\Delta E_{gE} \approx 50$ meV,

(b) At $N_E = 10^{20}$ cm^{-3}, $\Delta E_{gE} \approx 95$ meV

(c)

EXAMPLE: Emitter Bandgap Narrowing and SiGe Base

Assume $D_B = 3D_E$, $W_E = 3W_B$, $N_B = 10^{18}$ cm^{-3}, *and* $n_{iB}^2 = n_i^2$. *What is* β_F *for (a)* $N_E = 10^{19}$ cm^{-3}, *(b)* $N_E = 10^{20}$ cm^{-3}, *and (c)* $N_E = 10^{20}$ cm^{-3} *and a SiGe base with* $\Delta E_{gB} = 60$ *meV ?*

(a) At $N_E = 10^{19}$ cm^{-3}, $\Delta E_{gE} \approx 50$ *meV,*

$$n_{iE}^2 = n_i^2 e^{\Delta E_{gE}/kT} = n_i^2 e^{50\,\mathrm{meV}/26\,\mathrm{meV}} = n_i^2 e^{1.92} = 6.8 n_i^2$$

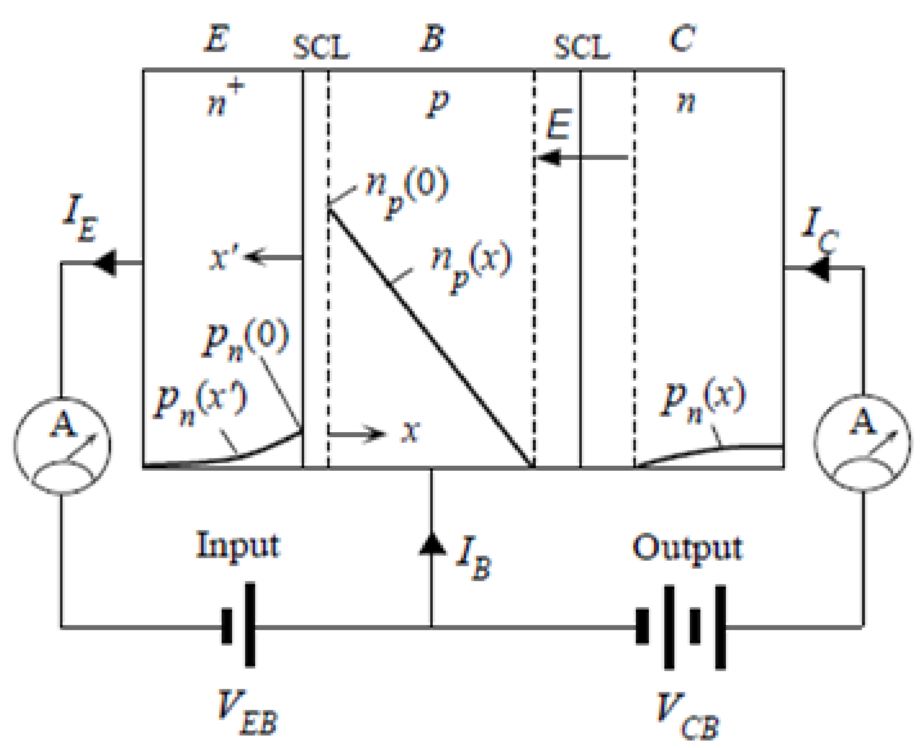
$$\beta_F = \frac{D_B W_E}{D_E W_B} \cdot \frac{N_E n_i^2}{N_B n_{iE}^2} = \frac{9 \cdot 10^{19} \cdot n_i^2}{10^{18} \cdot 6.8 n_i^2} = 13$$

(b) At $N_E = 10^{20}$ cm^{-3}, $\Delta E_{gE} \approx 95$ *meV*

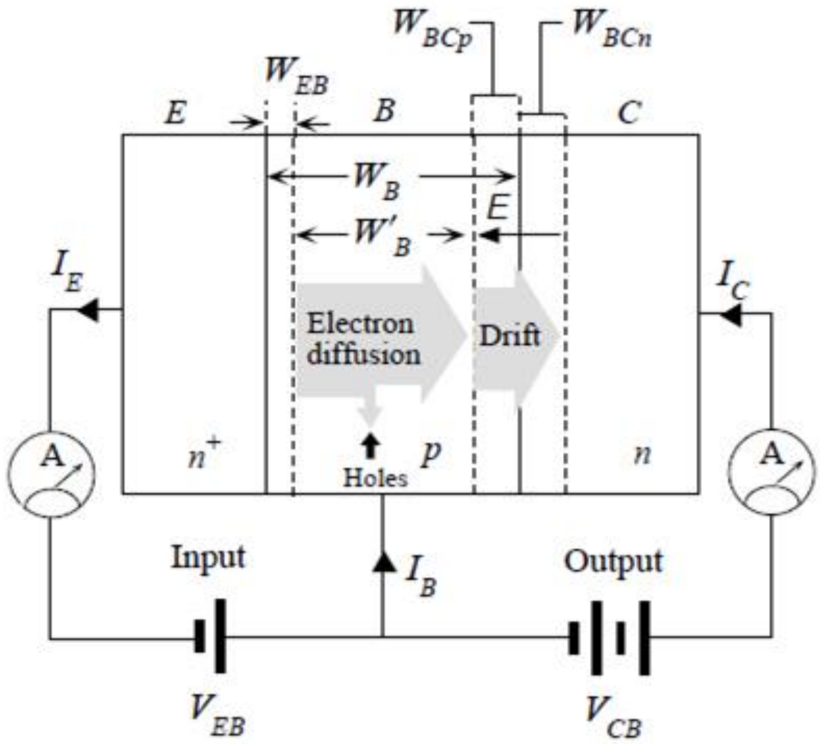
$$n_{iE}^2 = 38 n_i^2 \qquad \beta_F = 24$$

(c) $$n_{iB}^2 = n_i^2 e^{\Delta E_{gB}/kT} = n_i^2 e^{60\,\mathrm{meV}/26\,\mathrm{meV}} = 10 n_i^2 \qquad \beta_F = 237$$

BJT npn Solved Example



Minority carrier concentration profiles in the emitter, base and collector of an ***npn*** BJT. Depletion regions marked as **SCL** (Space Charge Layer). ***E*** is the electric field in the collector junction SCL.



Depletion regions in an ***npn*** transistor operated in the common base (CB) configuration.

BJT npn Solved Example

Consider an idealized silicon *npn* bipolar transistor with the properties listed below in Table 1. The base region has a relatively uniform doping. The emitter and collector donor concentrations are mean values. The cross-sectional area is 100 μm × 100 μm. The transistor is biased to operate in the normal active mode. The base-emitter forward bias voltage is 0.6 V and the reverse bias base-collector voltage is 18 V.

Table 1

Properties of an *npn* bipolar transistor.

Emitter width	Emitter doping	Hole lifetime in emitter	Base width	Base doping	Electron lifetime in base	Collector doping
10 μm	2×10^{18} cm^{-3}	10 ns	4 μm	1×10^{16} cm^{-3}	400 ns	1×10^{16} cm^{-3}

(a) Calculate the depletion layer width extending from the collector into the base and also from the emitter into the base. What is the width of the neutral base region?

(b) Calculate α and hence β for this transistor assuming unity emitter injection efficiency. How do α and β change with V_{CB}?

(c) What is the emitter injection efficiency and what are α and β taking into account the emitter injection efficiency is not unity?

BJT npn Solved Example

the base-collector junction $V_r = V_{BC} + V_o \approx V_{BC}$. Thus, the depletion layer W_{BC} at the base-collector junction is given by;

$$W_{BC} \approx \left[\frac{2\varepsilon(N_a + N_d)V_{BC}}{eN_aN_d}\right]^{1/2}$$

i.e.

$$W_{BC} = \left[\frac{2(8.854\times10^{-12}\ \mathrm{F\,m^{-1}})(11.9)(10^{22}\ \mathrm{m^{-3}} + 10^{22}\ \mathrm{m^{-3}})(18\ \mathrm{V})}{(1.6\times10^{-19}\ \mathrm{C})(10^{22}\ \mathrm{m^{-3}})(10^{22}\ \mathrm{m^{-3}})}\right]^{1/2}$$

$$W_{BC} = 2.18\times10^{-6}\ \mathrm{m}\ \text{or}\ 2.18\ \mu\mathrm{m}$$

Only a portion of W_{BC} is in the base side. Suppose that W_{BCp} and W_{BCn} are the depletion widths in the base and collector sides of the SCL respectively. Since the total charge on the *p* and *n*-sides of the SCL must be the same

$$N_aW_{BCp} = N_dW_{BCn}$$

and since

$$W_{BC} = W_{BCp} + W_{BCn}$$

we can find W_{BCp},

$$W_{BCp} = \frac{N_d}{N_a + N_d}W_{BC} = \frac{10^{16}}{10^{16} + 10^{16}}(2.17\ \mu\mathrm{m}) = 1.09$$

Since $N_d(E) >> N_a(B)$, the depletion layer width W_{EB} is almost totally in the *p*-side (in the base). With forward bias, $V_{EB} = 0.6$ V across the emitter-base junction, W_{EB} is given by

$$W_{EB} = \left[\frac{2\varepsilon(V_o - V_{EB})}{eN_a}\right]^{1/2}$$

BJT npn Solved Example

We first need to calculate the built-in voltage V_o between the emitter and base,

$$V_o = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\ \text{V})\ln\left[\frac{(2\times10^{18}\ \text{cm}^{-3})(1\times10^{16}\ \text{cm}^{-3})}{(1.5\times10^{10}\ \text{cm}^{-3})^2}\right]$$

i.e. $V_o = 0.830\ \text{V}$

Then, $$W_{EB} = \left[\frac{2\varepsilon(V_o - V_{EB})}{eN_a}\right]^{1/2}$$

i.e. $$W_{EB} = \left[\frac{2(8.854\times10^{-12}\ \text{F m}^{-1})(11.9)(0.830\ \text{V} \pm 0.6\ \text{V})}{(1.6\times10^{-19}\ \text{C})(10^{22}\ \text{m}^{-3})}\right]^{1/2}$$

or $W_{EB} = 1.74\times10^{-7}$ m or $0.174\ \mu\text{m}$

Notice that due to the forward bias across the *EB* junction, W_{EB} is an order of magnitude smaller than W_{BCp}.

If W_B is the base width between emitter and collector metallurgical junctions, then the width W'_B of the neutral region in the base between the depletion regions is given by,

$$W'_B = W_B - W_{BCp} - W_{EB}$$

so that $W'_B = 4\ \mu\text{m} - 1.09\ \mu\text{m} - 0.174\ \mu\text{m} = 2.74\ \mu\text{m}$

BJT npn Solved Example

(b) The electron drift mobility μ_e in the base is determined by the dopant (acceptor) concentration here. For $N_a = 1 \times 10^{16}$ cm^{-3}, $\mu_e = 1250$ cm^2 V^{-1} s^{-1} and the diffusion coefficient D_e from the Einstein relationship is,

$$D_e = kT\mu_e/e = (0.02585 \text{ V})(1250 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}) = 3.23 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$$

The electron diffusion length L_e in the base is

$$L_e = (D_e\tau_e)^{1/2} = [(3.23 \times 10^{-3} \text{ m}^2 \text{ s}^{-1})(400 \times 10^{-9} \text{ s})]^{1/2}$$

i.e. $$L_e = 36.0 \times 10^{-6} \text{ m } (= 36.0\ \mu\text{m})$$

In order to calculate α, first we need to find the transit (diffusion) time τ_t through the base

$$\tau_t = \frac{W_B'^2}{2D_e} = \frac{(2.74 \times 10^{-6} \text{ m})^2}{2(3.23 \times 10^{-3} \text{ m}^2 \text{ s}^{-1})} = 1.161 \times 10^{-9} \text{ s}$$

If we assume unity injection ($\gamma = 1$), then $\alpha = \alpha_B$, base transport factor:

$$\alpha = \alpha_B = 1 - \frac{\text{Transit (diffusion) time across base}}{\text{Minority carrier recombination time in base}} = 1 - \frac{\tau_t}{\tau_e}$$

i.e. $$\alpha = 1 - (1.161 \text{ ns})/(400 \text{ ns}) = 0.99710$$

BJT npn Solved Example

The current gain β is

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.9971}{1-0.9971} = 343$$

(c) The hole drift mobility μ_h in the emitter is determined by the dopant (donor) concentration here. For $N_d = 2 \times 10^{18}$ cm^{-3}, $\mu_h \approx 100$ cm^2 V^{-1} s^{-1} and the diffusion coefficient D_h from the Einstein relationship is,

$$D_h = kT\mu_h/e = (0.02585 \text{ V})(100 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}) = 2.59 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$$

The hole diffusion length L_h in the base is

$$L_h = (D_h\tau_h)^{1/2} = [(2.59 \times 10^{-4} \text{ m}^2 \text{ s}^{-1})(10 \times 10^{-9} \text{ s})]^{1/2}$$

$$L_h = 1.61 \times 10^{-6} \ (= 1.61 \ \mu\text{m})$$

Thus the hole diffusion length is much shorter than the emitter width.

The emitter current is given by electron diffusion in the base and hole diffusion in the emitter so that

$$I_E = I_{E(\text{electron})} + I_{E(\text{hole})}$$

where for electrons diffusing in the base,

$$I_{E(\text{electron})} = I_{soe} \exp\left(\frac{eV_{EB}}{kT}\right); \qquad I_{soe} = \frac{eAD_e n_i^2}{N_a W_B}$$

BJT npn Solved Example

and holes diffusing in the emitter,

$$I_{E(\text{hole})} = I_{soh} \exp\left(\frac{eV_{EB}}{kT}\right); \qquad I_{soh} = \frac{eAD_h n_i^2}{N_d L_h}$$

where we used L_h instead of W_E because $W_E >> L_h$ (emitter width is 10 µm and hole diffusion length is 1.62 µm)

Substituting the values we find,

$$I_{soe} = \frac{(1.601\times10^{-19}\,\text{C})(1\times10^{-8}\ \text{m}^2)(3.23\times10^{-3}\ \text{m}^2\ \text{s}^{-1})(1.5\times10^{16}\ \text{m}^{-3})^2}{(1\times10^{22}\ \text{m}^{-3})(2.74\times10^{-6}\ \text{m})}$$

i.e. $I_{soe} = 4.267 \times 10^{-14}$ A or 42.67 fA

and $$I_{soh} = \frac{(1.601\times10^{-19}\,\text{C})(1\times10^{-8}\ \text{m}^2)(2.59\times10^{-4}\ \text{m}^2\ \text{s}^{-1})(1.5\times10^{16}\ \text{m}^{-3})^2}{(2\times10^{24}\ \text{m}^{-3})(1.61\times10^{-6}\ \text{m})}$$

i.e. $I_{soh} = 2.93 \times 10^{-17}$ A or 0.0293 fA

The emitter injection efficiency is the fraction of the emitter current that is due to minority carriers injected into the base; those that diffuse across the base towards the collector.

$$\gamma = \frac{I_{E(\text{electron})}}{I_{E(\text{electron})} + I_{E(\text{hole})}} = \frac{I_{soe}}{I_{soe} + I_{soh}}$$

i.e. $$\gamma = \frac{4.267\times10^{-14}\ \text{A}}{4.267\times10^{-14}\ \text{A} + 2.93\times10^{-17}\ \text{A}} = 0.99931$$

The current gains, taking into account the emitter injection efficiency, are

BJT npn Solved Example

$$\alpha = \gamma\alpha_B = (0.99931)(0.9971) = 0.99641$$

and

$$\beta = \alpha/(1-\alpha)= 0.99641/(1-0.99641) = 278$$

(d) The emitter current with $V_{EB} = 0.6$ V is

$$I_E = (I_{soe} + I_{soh})\exp(eV_{EB}/kT)$$

$$I_E = (4.267 \times 10^{-14} \text{ A} + 2.93 \times 10^{-17} \text{ A})\exp[(0.6 \text{ V})/(0.2585 \text{ V})]$$

$$I_E = 5.13 \times 10^{-4} \text{ A or } 0.513 \text{ mA}$$

The collector current is determined by those minority carriers in the base that reach the collector junction. Only γI_E of I_E is injected into the base as minority carriers and only a fraction α_B make it to the collector,

$$I_C = \alpha_B\gamma I_E = \alpha I_E = (0.99641)(0.513 \text{ mA}) = 0.511 \text{ mA}$$

The base current is given by,

$$I_B = I_C/\beta = (0.511 \text{ mA})/278 = 1.83 \times 10^{-3} \text{ mA} = 1.83\ \mu\text{A}$$