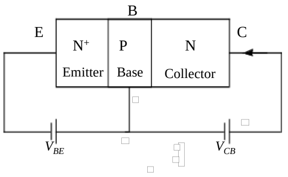
Chapter 8 Bipolar Junction Transistors

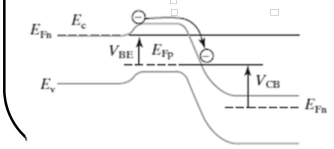
- Since 1970, the high density and low-power advantage of the MOS technology steadily eroded the BJT’s early dominance.
- BJTs are still preferred in some high-frequency and analog applications because of their high speed and high power output.

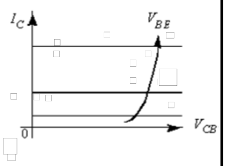
Question: What is the meaning of “bipolar” ?

8.1 Introduction to the BJT

NPN BJT:

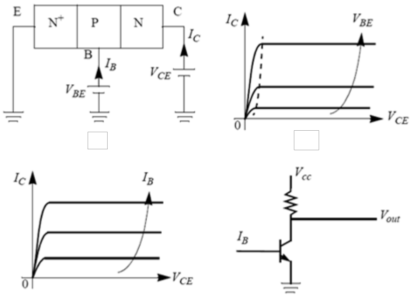






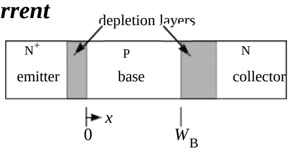
I_C is an exponential function of forward V_{BE} and independent of reverse V_{CB}.

Common-Emitter Configuration



Question: Why is I_B often preferred as a parameter over V_{BE}?

8.2 Collector Current



$$\frac{d^2n'}{dx^2}=\frac{n'}{L_B^2}$$

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

τ_B : base recombination lifetime

D_B : base minority carrier (electron) diffusion constant

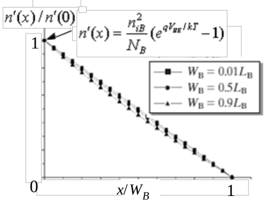
Boundary conditions :

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

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

8.2 Collector Current

$$n'(x)=n_{B0}(e^{qV_{BE}/kT}-1)\frac{\sinh\left(\frac{W_B-x}{L_B}\right)}{\sinh(W_B/L_B)}$$



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

$$\boxed{\begin{aligned}n'(x)&=n'(0)(1-x/W_B)\\&=\frac{n_{iB}^2}{N_B}(e^{qV_{BE}/kT}-1)(1-x/W_B)\end{aligned}}$$

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

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

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

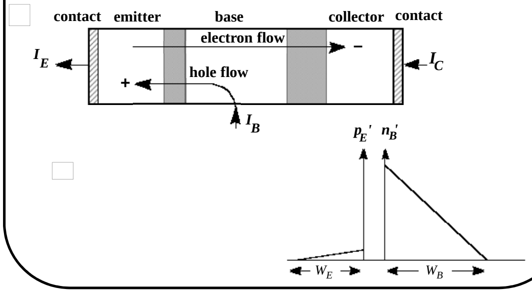
It can be shown

$$\boxed{\begin{aligned}I_C&=A_E\frac{qn_i^2}{G_B}(e^{qV_{BE}/kT}-1)\\G_B&\equiv\int_0^{W_B}\frac{n_i^2}{n_{iB}^2}\frac{p}{D_B}dx\end{aligned}}$$

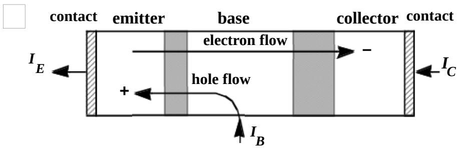
G_B (s·cm^4) is the ***base Gummel number***

8.3 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 .



8.3 Base Current



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

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

For a uniform emitter,

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

Is a large I_B desirable? Why?

8.4 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:

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

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

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

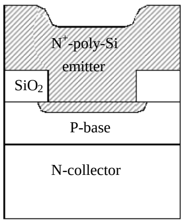
We can confirm

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

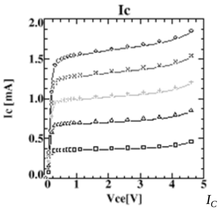
8.4.3 Poly-Silicon Emitter

A high-performance BJT typically has a layer of As-doped N$^+$ poly-silicon film in the emitter.

β_F is larger due to the large W_E , mostly made of the N$^+$ poly-silicon. (A deep diffused emitter junction tends to cause emitter-collector shorts.)

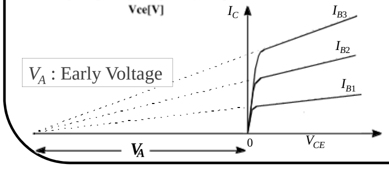


8.5 Base-Width Modulation by Collector Voltage



Output resistance :

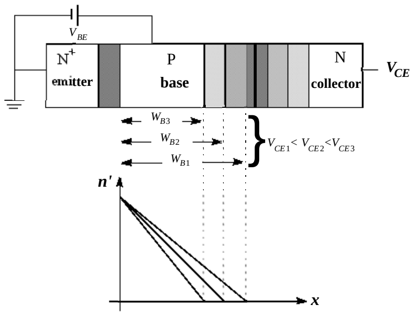
$$\boxed{r_0 \equiv \left(\frac{\partial I_C}{\partial V_{CE}}\right)^{-1} = \frac{V_A}{I_C}}$$



V_A : Early Voltage

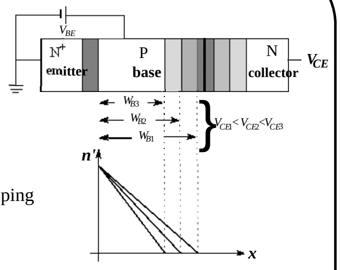
Large V_A (large r_o) is desirable for a large voltage gain

8.5 Base-Width Modulation by Collector Voltage



How can we reduce the base-width modulation effect?

8.5 Base-Width Modulation by Collector Voltage

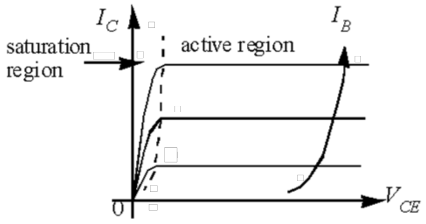


The base-width modulation effect is reduced if we

(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?

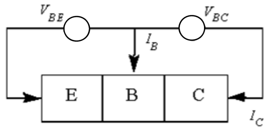
8.6 Ebers-Moll Model



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

8.6 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

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

8.6 Ebers-Moll Model

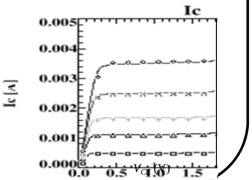
In general, both V_{BE} and V_{BC} are present :

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

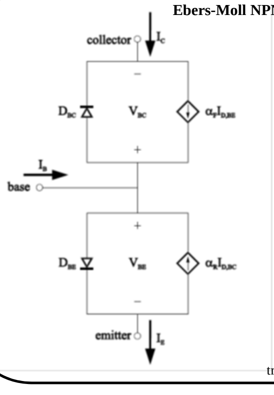
$$I_B = \frac{I_S}{\beta_F}(e^{qV_{BE}/kT} - 1) + \frac{I_S}{\beta_F}(e^{qV_{BC}/kT} - 1)$$

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

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



Ebers-Moll NPN BJT Model



$$\boxed{I_E = I_{D,BE} - \alpha_R I_{D,BC}}$$

$$\boxed{I_C = \alpha_F I_{D,BE} - I_{D,BC}}$$

$$\boxed{I_B = I_E - I_C}$$

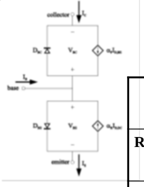
$$I_{D,BE} = I_{ES}(e^{V_{BE}/V_T} - 1)$$

$$I_{D,BC} = I_{CS}(e^{V_{BC}/V_T} - 1)$$

Reciprocity theorem

$$I_S = \boxed{\alpha_F I_{ES} = \alpha_R I_{CS}}$$

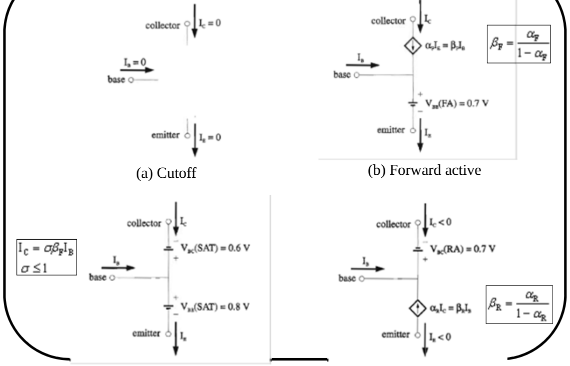
transport saturation current



BJT Modes of Operation

BE junction	BC junction	Mode
Reverse	**Reverse**	**Cutoff (OFF)**
Forward	**Reverse**	**Forward active (FA)**
Forward	**Forward**	**Saturation (SAT)**
Reverse	**Forward**	**Reverse active (RA)**

Reduced models of the operation modes



(a) Cutoff (b) Forward active

(c) Saturation (d) Reverse active

8.7 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.

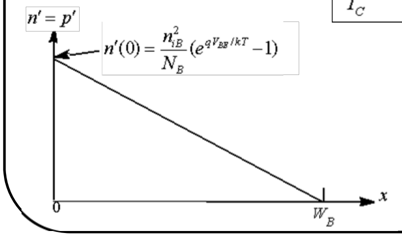
τ_F determines the high-frequency limit of BJT operation.

8.7.1 Base Charge Storage and Base Transit Time

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

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

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



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

EXAMPLE: Base Transit Time

What is τ_{FB} if W_B = 70 nm and D_B = 10 cm²/s?

Answer:

$$\tau_{FB} = \frac{W_B^2}{2D_B} = \frac{(7\times10^{-6}\ \text{cm})^2}{2\times10\ \text{cm}^2/\text{s}} = 2.5\times10^{-12}\ \text{s} = 2.5\ \text{ps}$$

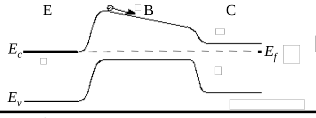
2.5 ps is a very short time. Since light speed is 3×10^8 m/s, light travels only 1.5 mm in 5 ps.

8.7.2 Drift Transistor–Built-in Base Field

The base transit time can be reduced by building into the base a drift field that aids the flow of electrons. Two methods:

- Fixed E_{gB}, N_B decreases from emitter end to collector end.

- Fixed N_B, E_{gB} decreases from emitter end to collector end.



$$\mathbf{E} = \frac{1}{q}\frac{dE_c}{dx}$$

8.12 Chapter 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.

8.12 Chapter 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.

$$\beta_F = \frac{I_C}{I_B} \approx \frac{G_E}{G_B} \qquad \alpha_F = \frac{I_C}{I_E} = \frac{\beta_F}{1+\beta_F}$$

- The Gummel plot shows that β_F falls off in the high I_C region due to high-level injection in the base. It also falls off in the low I_C region due to excess base current.
- 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).

8.12 Chapter 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.