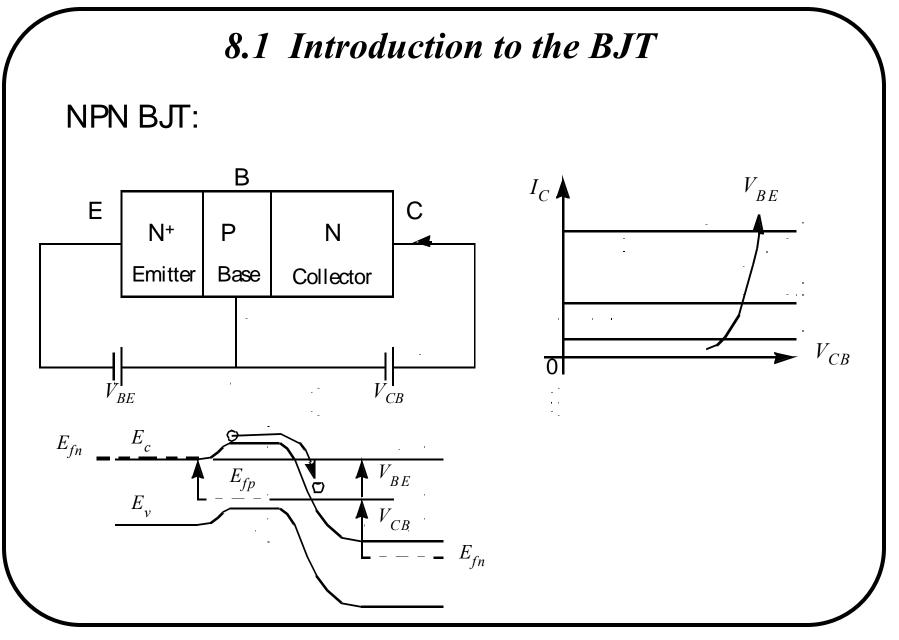
Chapter 8 Bipolar Junction Transistors

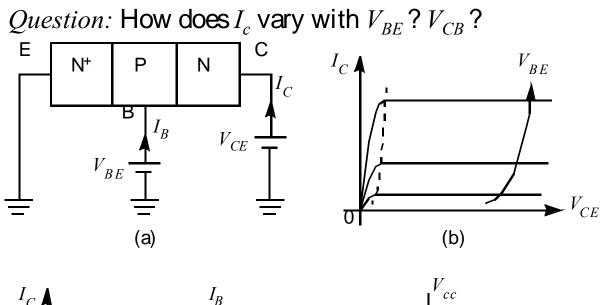
- Since 1970, the high density and low-power advantage of the MOS technology steadily eroded the BJT's early dominance.
- BJTs are still preferred in some high-frequency and analog applications because of their high transconductance and high speed.

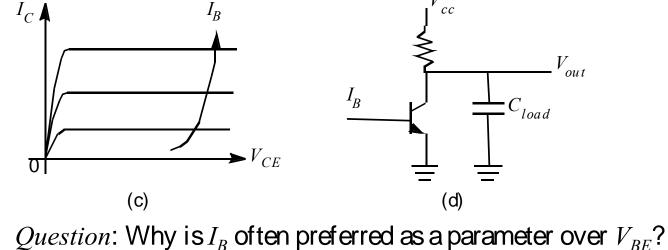
Question: What is the meaning of "bipolar"?



Semiconductor Devices for Integrated Circuits (C. Hu)

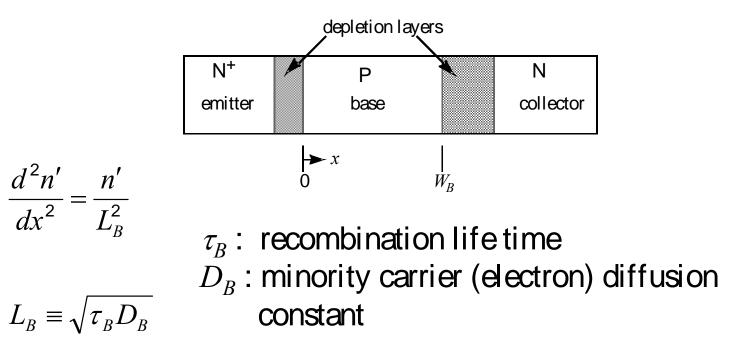
Common-Emitter Configuration





Slide 8-3

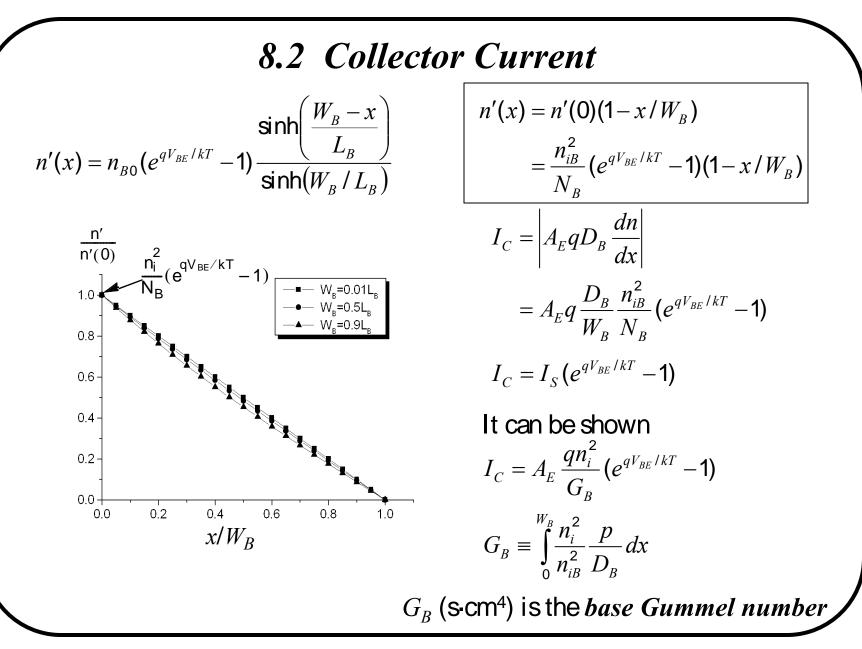
8.2 Collector Current



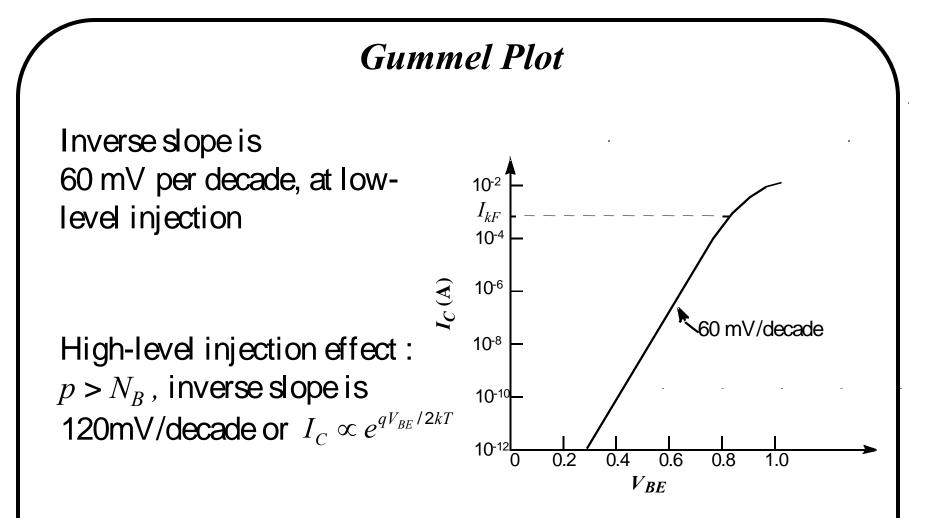
Boundary conditions:

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

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



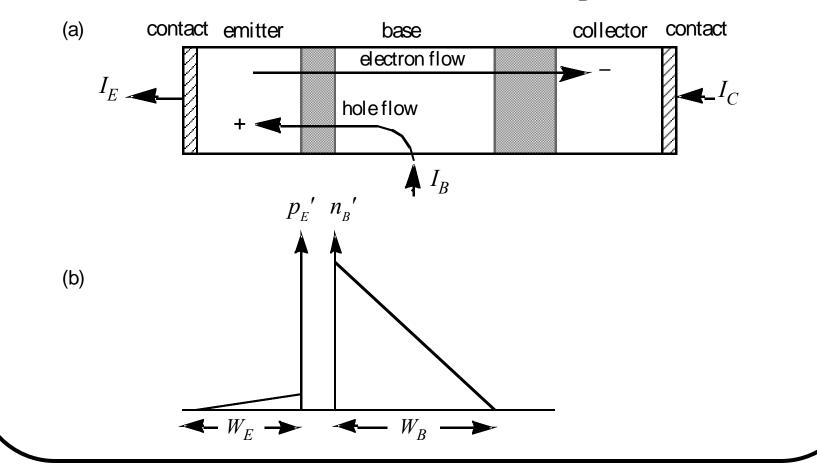
Semiconductor Devices for Integrated Circuits (C. Hu)



The IR drop across parasitic series resistance increases V_{BE} at high I_C and further flattens the curve.

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_R .



Semiconductor Devices for Integrated Circuits (C. Hu)

8.3 Base Current contact emitter base collector contact electron flow holeflow I_R $I_B = A_E \frac{q n_i^2}{G_F} (e^{q V_{BE}/kT} - 1)$ For a uniform emitter, $I_{B} = A_{E}q \frac{D_{E}n_{iE}^{2}}{W_{E}N_{E}} (e^{qV_{BE}/kT} - 1)$ $G_E \equiv \int_{0}^{W_E} \frac{n_i^2}{n_{iE}^2} \frac{n}{D_E} dx$

Question: Is a large I_B desirable? Why?

8.4 Current Gain

Common-emitter current gain, β_F :

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

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 $\beta_F = \frac{\alpha_F}{1 - \alpha_F}$

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

How can β_F be maximized?

EXAMPLE: Current Gain

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

Solution:

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

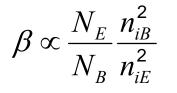
 $\beta_F = I_C / I_B = 1 \text{ mA} / 10 \mu\text{A} = 100$
 $\alpha_F = I_C / I_E = 1 \text{ mA} / 1.01 \text{ mA} = 0.9901$

We can confirm

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

Semiconductor Devices for Integrated Circuits (C. Hu)

8.4.1 Emitter Bandgap Narrowing



To raise β_F , N_E is typically very large. Unfortunately, large N_E makes $n_{iE}^2 > n_i^2$ (called the heavy doping effect).

$$n_i^2 = N_C N_V e^{-E_g/kT}$$

Since n_i is related to E_g , this effect is also known as band-gap narrowing.

$$n_{iE}^2 = n_i^2 e^{\Delta E_{gE}/kT}$$

 ΔE_{gE} is negligible for $N_E < 10^{18}$ cm⁻³, is 50 meV at 10^{19} cm⁻³, 95 meV at 10^{20} cm⁻³, and 140 meV at 10^{21} cm⁻³.

Emitter bandgap narrowing makes it difficult to raise β_F by doping the emitter very heavily.

Semiconductor Devices for Integrated Circuits (C. Hu)

8.4.2 Narrow-Bandgap (SiGe) Base

$$\beta \propto \frac{N_E}{N_B} \frac{n_{iB}^2}{n_{iE}^2}$$
 To further elevate β_F , we can raise n_{iB} by using an epitaxial Si_{1- η} Ge _{η} base.

With $\eta = 0.2$, E_{gB} is reduced by 0.1eV and n_{iE}^2 by 30x.

EXAMPLE: Emitter Bandgap Narrowing and SiGe Base

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

(a) At
$$N_E = 10^{19} \text{ cm}^{-3}$$
, $\Delta E_{gE} \approx 50 \text{ meV}$,
 $n_{iE}^2 = n_i^2 e^{\Delta E_{gE}/kT} = n_i^2 e^{50 \text{ meV}/26 \text{ meV}} = n_i^2 e^{1.92} = 6.8 n_i^2$
 $\beta_F = \frac{D_B W_E}{D_E W_B} \cdot \frac{N_E n_i^2}{N_B n_{iE}^2} = \frac{9 \cdot 10^{19} \cdot n_i^2}{10^{18} \cdot 6.8 n_i^2} = 13$

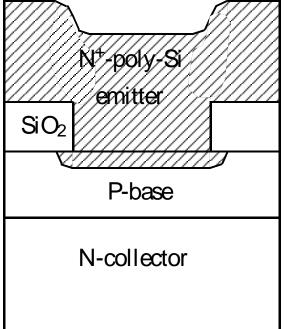
(b)
$$At N_E = 10^{20} cm^{-3}$$
, $\Delta E_{gE} \approx 95 meV$
 $n_{iE}^2 = 38n_i^2$ $\beta_F = 24$
(c) $n_{iB}^2 = n_i^2 e^{\Delta E_{gB}/kT} = n_i^2 e^{60 meV/26 meV} = 10n_i^2$ $\beta_F = 237$

Semiconductor Devices for Integrated Circuits (C. Hu)

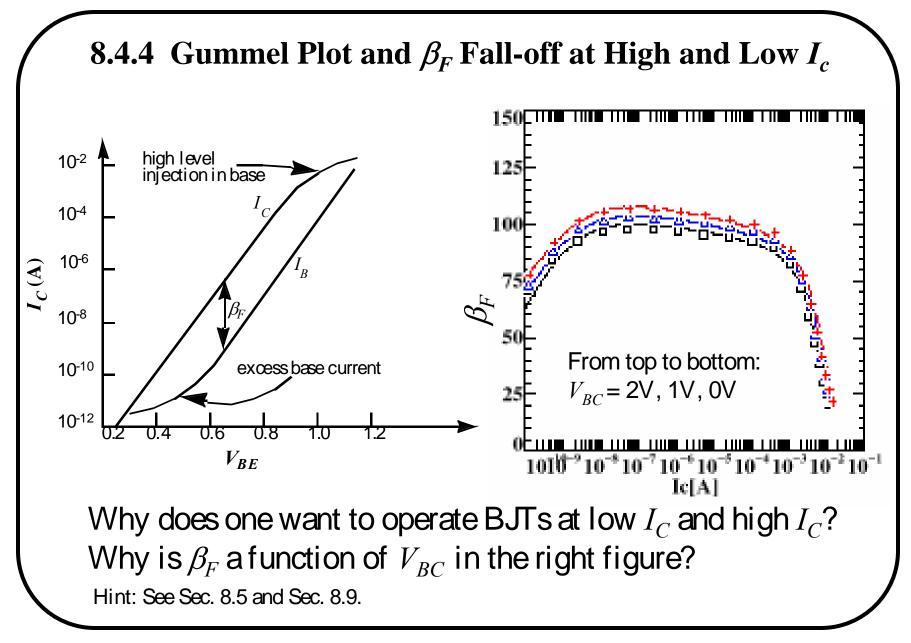
8.4.3 Poly-Silicon Emitter

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

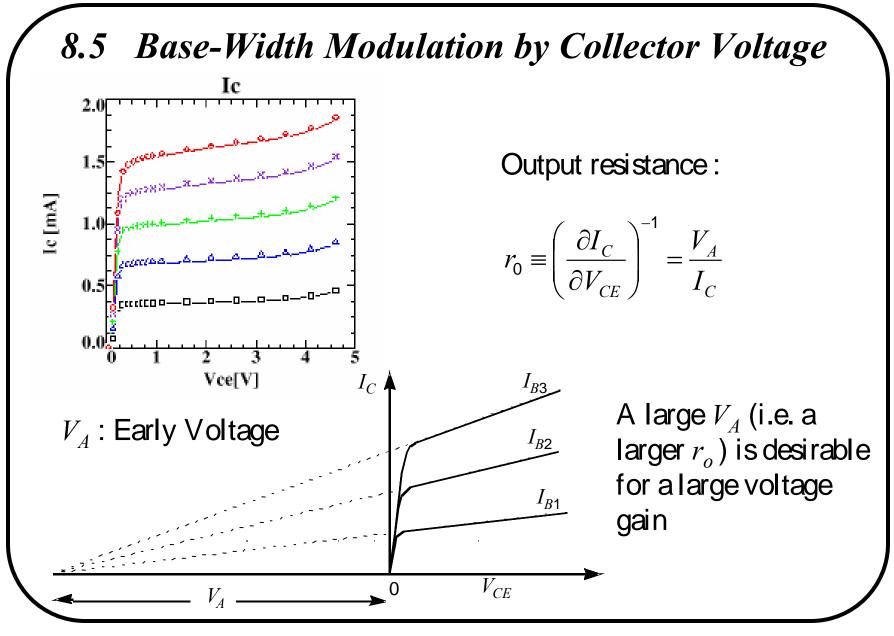
 β_F is larger due to the large W_E , mostly made of the N⁺ polysilicon. (A deep diffused emitter junction tends to cause emitter-collector shorts.)



Semiconductor Devices for Integrated Circuits (C. Hu)

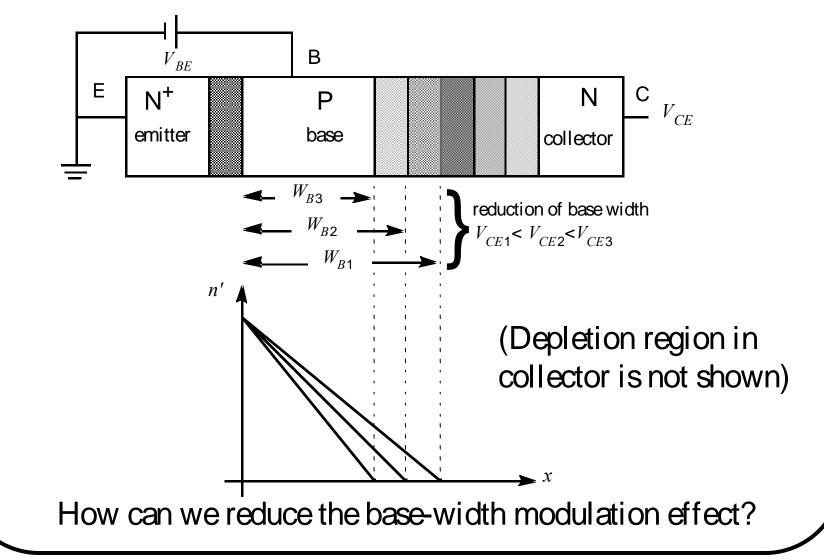


Slide 8-15



Semiconductor Devices for Integrated Circuits (C. Hu)

8.5 Base-Width Modulation by Collector Voltage



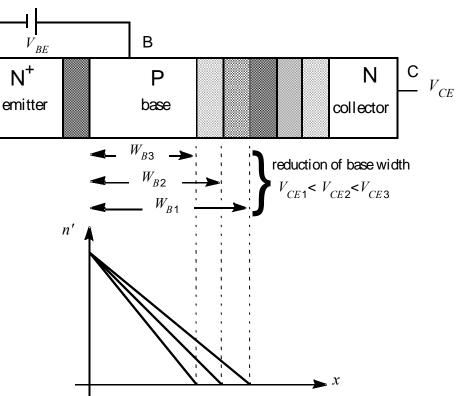
Slide 8-17

8.5 Base-Width Modulation by Collector Voltage

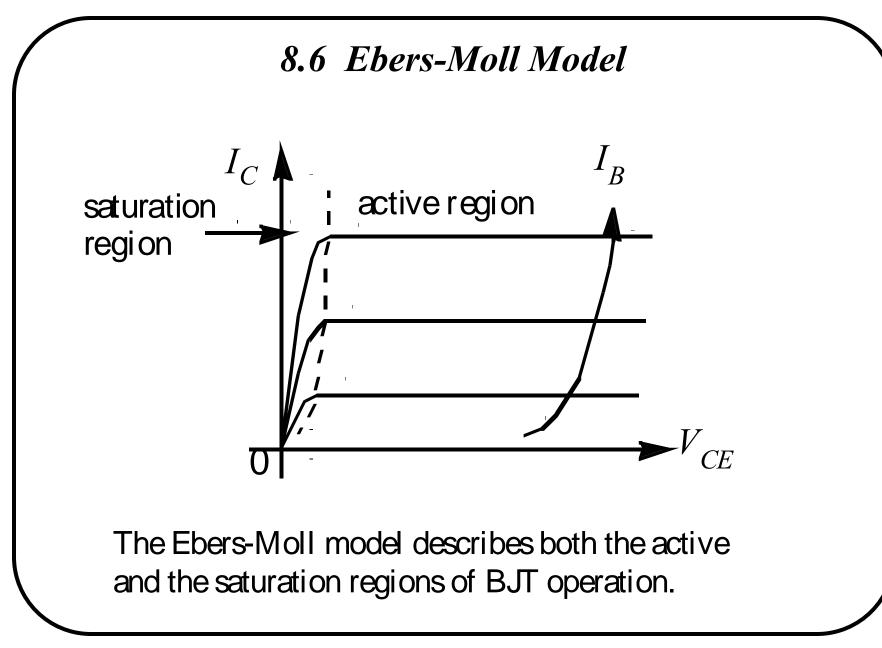
Е

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 .



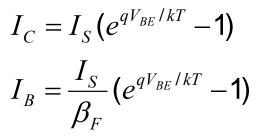
Which of the above is the most acceptable action?

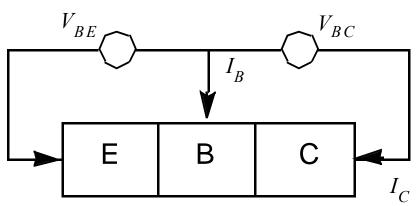


8.6 Ebers-Moll Model

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

When only V_{BE} is present :





Now reverse the roles of emitter and collector.

When only V_{BC} is present :

 $I_{E} = I_{S} (e^{qV_{BC}/kT} - 1) \qquad \beta_{R} : \text{reverse current gain} \\ I_{B} = \frac{I_{S}}{\beta_{R}} (e^{qV_{BC}/kT} - 1) \qquad \beta_{F} : \text{forward current gain} \end{cases}$

$$I_{C} = -I_{E} - I_{B} = -I_{S} (1 + \frac{1}{\beta_{R}}) (e^{qV_{BC}/kT} - 1)$$

Slide 8-20

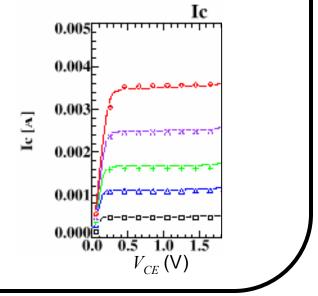
8.6 Ebers-Moll Model

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

$$I_{C} = I_{S} \left(e^{qV_{BE}/kT} - 1 \right) - I_{S} \left(1 + \frac{1}{\beta_{R}} \right) \left(e^{qV_{BC}/kT} - 1 \right)$$
$$I_{B} = \frac{I_{S}}{\beta_{F}} \left(e^{qV_{BE}/kT} - 1 \right) + \frac{I_{S}}{\beta_{F}} \left(e^{qV_{BC}/kT} - 1 \right)$$

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.



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

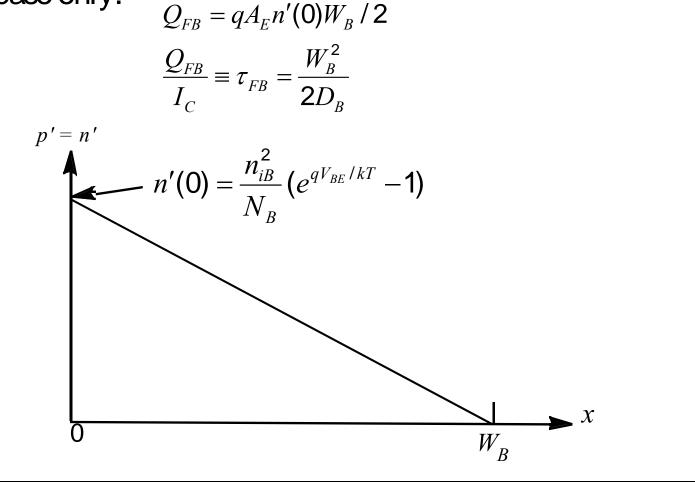
$$\tau_F \equiv \frac{Q_F}{I_C}$$

 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.



Slide 8-23

EXAMPLE: Base Transit Time

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

Answer:

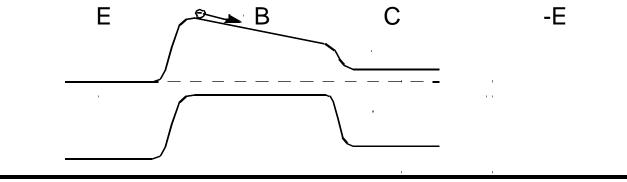
$$\tau_{FB} = \frac{W_B^2}{2D_B} = \frac{(7 \times 10^{-6} \text{ cm})^2}{2 \times 10 \text{ cm}^2/\text{s}} = 2.5 \times 10^{-12} \text{s} = 2.5 \text{ ps}$$

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.

The base transit time can b a drift field that aids the f

• Fixed E_{gB} , N_B decrease



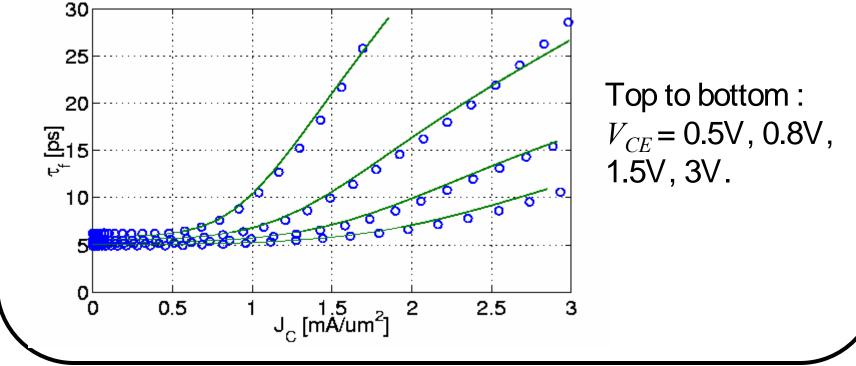


Semiconductor Devices for Integrated Circuits (C. Hu)

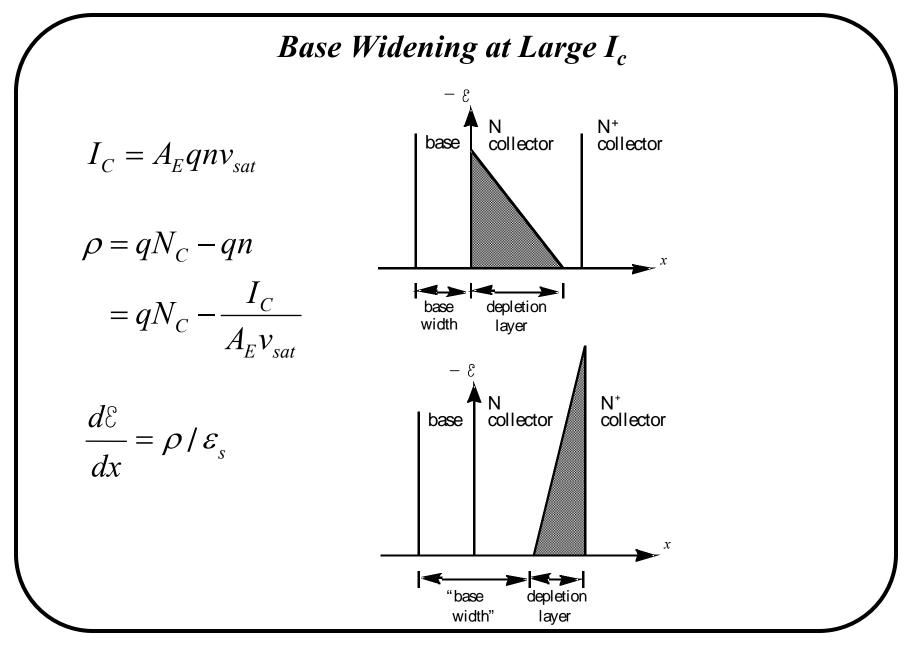
8.7.3 Emitter-to-Collector Transit Time and Kirk Effect

• To reduce the total transit time, the emitter as well as the depletion layers must be kept thin as well.

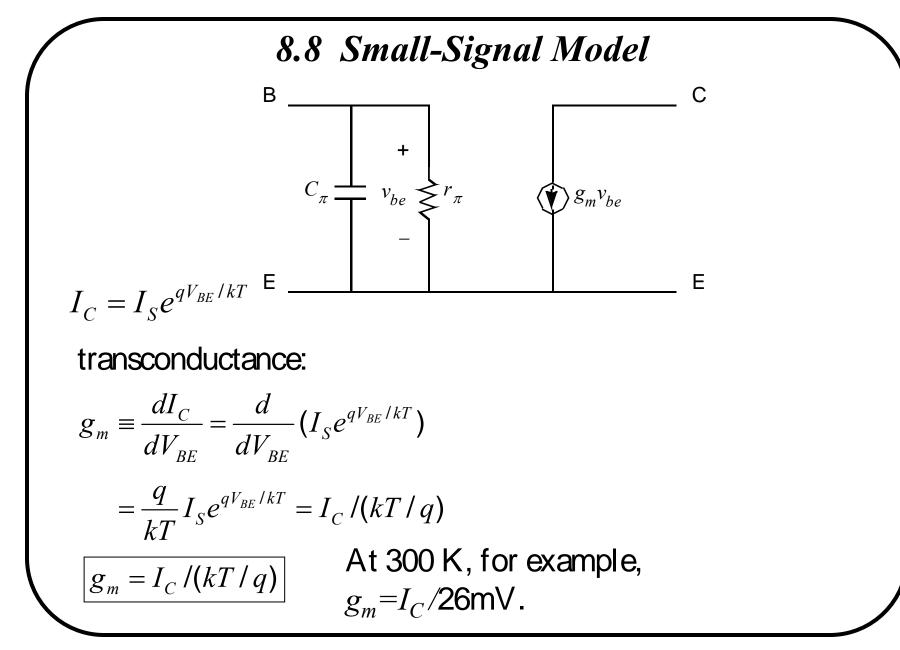
• Kirk effect or base widening: electron density in the collector $(n = N_C)$ is insufficient to support the collector current even if the electrons move at the saturation velocity-the base widens into the collector. Wider base means larger τ_F .



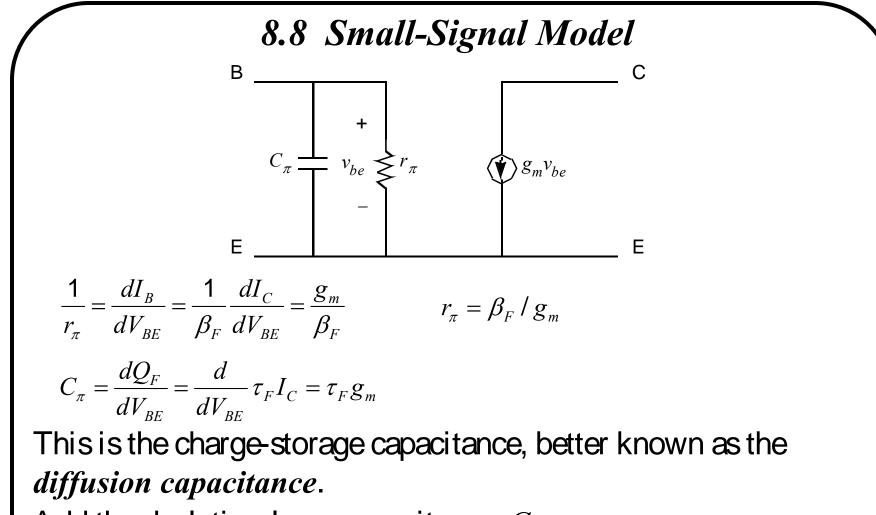
Semiconductor Devices for Integrated Circuits (C. Hu)



Semiconductor Devices for Integrated Circuits (C. Hu)



Slide 8-28



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

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

EXAMPLE: Small-Signal Model Parameters

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

Solution:

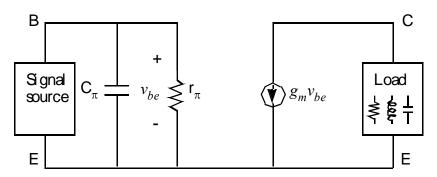
(a)
$$g_m = I_C / (kT/q) = \frac{1 \text{ mA}}{26 \text{ mV}} = 39 \frac{\text{mA}}{\text{V}} = 39 \text{ mS} (milli siemens)$$

(b)
$$r_{\pi} = \beta_F / g_m = \frac{90}{39 \,\mathrm{mS}} = 2.3 \,\mathrm{k}\Omega$$

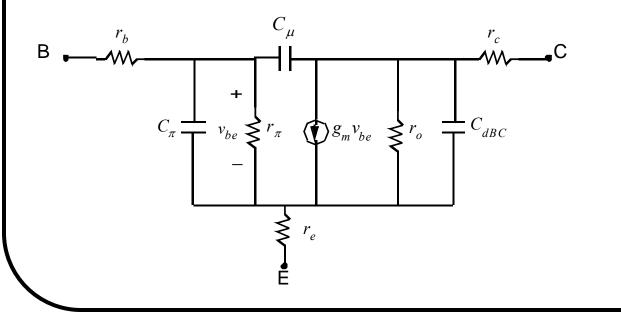
(c) $C_{\pi} = \tau_F g_m = 5 \times 10^{-12} \times 0.039 \approx 1.9 \times 10^{-14} \text{ F} = 19 \text{ fF} (femto farad)$

Slide 8-30

Once the model parameters have been determined, one can analyze circuits with arbitrary source and load impedance.



The parameters are routinely determined through comprehensive measurement of the BJT AC and DC characteristics.



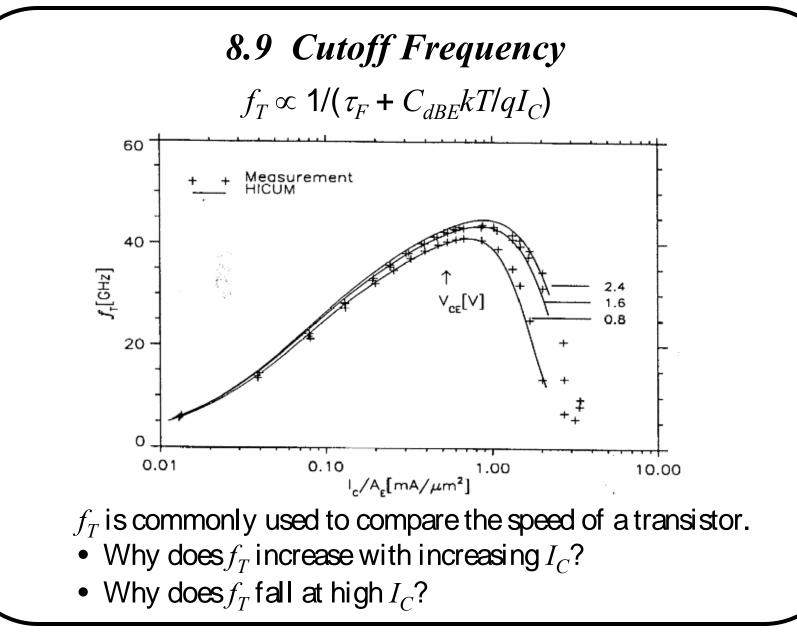
Semiconductor Devices for Integrated Circuits (C. Hu)

8.9 Cutoff Frequency

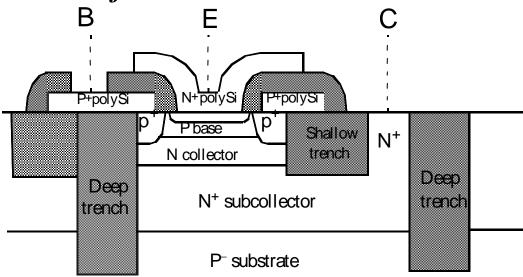
$$\begin{array}{c} \overset{\mathsf{B}}{\underset{\mathsf{source}}{\mathsf{Signal}}} & \overset{\mathsf{F}}{\underset{\mathsf{source}}{\mathsf{Signal}}} \\ \overset{\mathsf{C}}{\underset{\mathsf{a}}{\mathsf{f}}} & \overset{\mathsf{F}}{\underset{\mathsf{a}}{\mathsf{f}}} \\ \overset{\mathsf{Signal}}{\underset{\mathsf{source}}{\mathsf{source}}} \\ \overset{\mathsf{C}}{\underset{\mathsf{a}}{\mathsf{f}}} & \overset{\mathsf{F}}{\underset{\mathsf{a}}{\mathsf{f}}} \\ \overset{\mathsf{Load}}{\underset{\mathsf{a}}{\mathsf{f}}} \\ \overset{\mathsf{Load}}{\underset{\mathsf{a}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{a}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \end{array} \\ \begin{array}{c} \beta \\ \end{array} \\ \overset{\mathsf{I}}{\underset{\mathsf{a}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \end{array} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}} \\ \overset{\mathsf{I}}}{ \atop {f}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}} \\ \overset{\mathsf{I}}}{ \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}} \\ \overset{\mathsf{I}}{ \atop f}} \\ \overset{\mathsf{I}}{ \atop } \\ \overset{\mathsf{I}}}{ \atop I}} \\ \overset{\mathsf{I}}{\underset{\mathsf{f}}} \\ \overset{\mathsf{I}}}{ \overset{\mathsf{I}}}{ \atop I}} \\ \overset{\mathsf{I}}{ \atop I} \\ \overset{\mathsf{I}}}{ \atop I}} \\$$

The load is a short circuit. The signal source is a current source, i_b , at frequency, *f*. At what frequency does the current gain $\beta (\equiv i_c / i_b)$ fall to unity?

$$v_{be} = \frac{i_b}{\text{input admittance}} = \frac{i_b}{1/r_{\pi} + j\omega C_{\pi}} , \quad C_{\pi} = \tau_F g_m + C_{dBE}$$
$$i_c = g_m v_{be}$$
$$\beta(\omega) = \left|\frac{i_c}{i_b}\right| = \frac{g_m}{|1/r_{\pi} + j\omega C_{\pi}|} = \frac{1}{|1/\beta_F + j\omega \tau_F + j\omega C_{dBE} kT/qI_C|}$$



BJT Structure for Minimum Parasitics and High Speed



- Poly-Si emitter
- Thin base
- Self-aligned poly-Si base contact
- Narrow emitter opening
- Lightly-doped collector
- Heavily-doped epitaxial subcollector
- Shallow trench and deep trench for electrical isolation

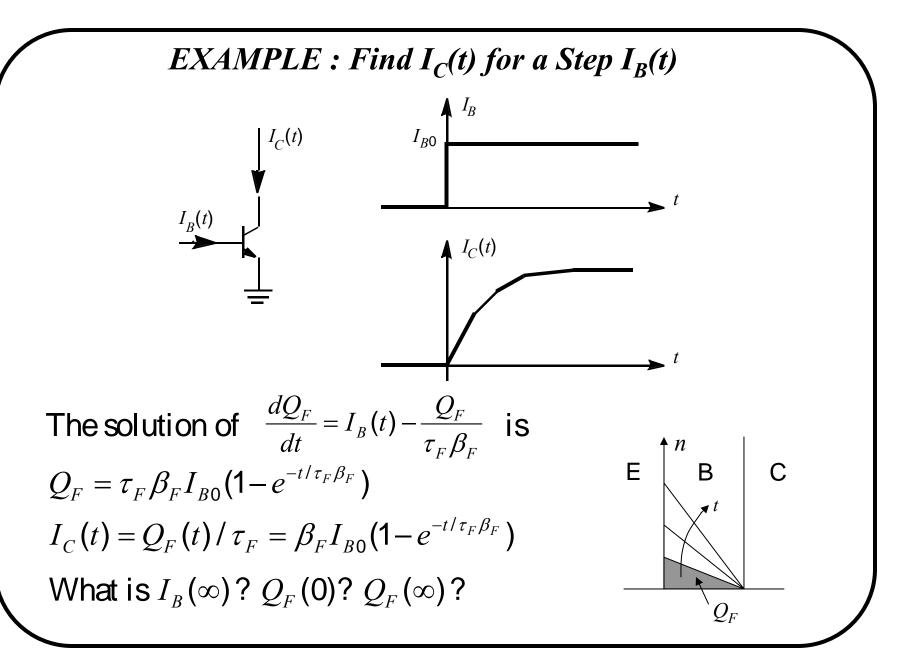
8.10 Charge Control Model

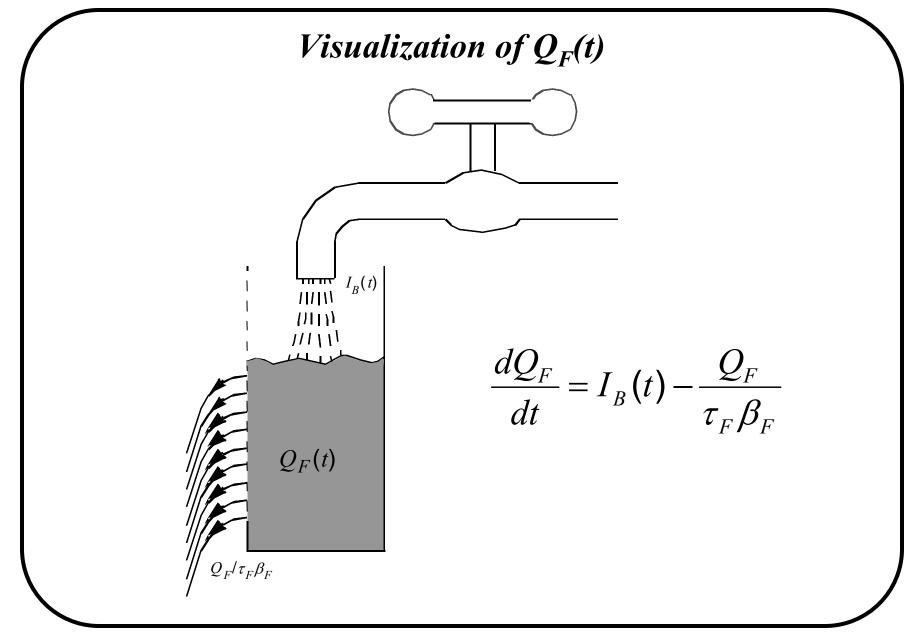
For the DC condition, $I_B = I_C / \beta_F = \frac{Q_F}{\tau_F \beta_F}$

In order to sustain a constant excess hole charge in the transistor, holes must be supplied to the transistor through I_B to replenish the holes lost to recombination at the above rate. What if I_B is larger than $Q_F / \tau_F \beta_F$?

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

Can find $Q_F(t)$ for any given $I_B(t)$. Can then find $I_C(t)$ through $I_C(t) = Q_F(t)/\tau_F$.





Semiconductor Devices for Integrated Circuits (C. Hu)

8.11 Model for Large-Signal Circuit Simulation

B

- Model contains dozens of parameters, mostly determined from measured BJT data.
- Circuits containing tens of thousands of transistors can be simulated.
- Compact model is a "contract" between device/manufacturing engineers and circuit designers.

$$I_{C} = I_{S}' \left(e^{qV_{BE}/kT} - e^{qV_{BC}/kT} \right) \left(1 + \frac{V_{CB}}{V_{A}} \right) - \frac{I_{S}}{\beta_{F}} \left(e^{qV_{BC}/kT} - 1 \right)$$

Semiconductor Devices for Integrated Circuits (C. Hu)

 r_{C}

 C_{BC}

 \sim_{BE}

8.11 Model for Large-Signal Circuit Simulation

A commonly used BJT circuit simulation model is the Gummel-Poon model, consisting of

- Ebers-Moll model (two diodes and two driving forces for I_C)
- Enhancements for high-level injection and Early effect
- Voltage-dependent capacitances representing charge storage
- Parasitic resistances

• 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 .

• 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 .

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

- 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).

• 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 W^2

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

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

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

Semiconductor Devices for Integrated Circuits (C. Hu)

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.

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

Semiconductor Devices for Integrated Circuits (C. Hu)