Bipolar Junction Transistor: Model limitations

- Base narrowing: Early Effect (Collector Bias)

- Low level injection: - Recombination in the base space charge region

  ⇓

  Current gain degradation

- High level injection: - Base-Emitter Junction

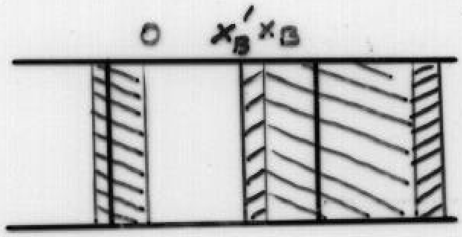
  $I_C \propto \exp\left(\frac{qV_{BE}}{2kT}\right)$: gain degradation

  - Base resistance: current crowding

  - Kirk Effect: Base-Collector Junction base widening.

- Base transit time: High level injection effect (Webster effect)

EARLY EFFECT (BASE NARROWING)



$$\int_0^{x_B} p(x)\,dx \rightarrow \int_0^{x_B'} p(x)\,dx.$$

GN DECREASES WITH V_{CB}

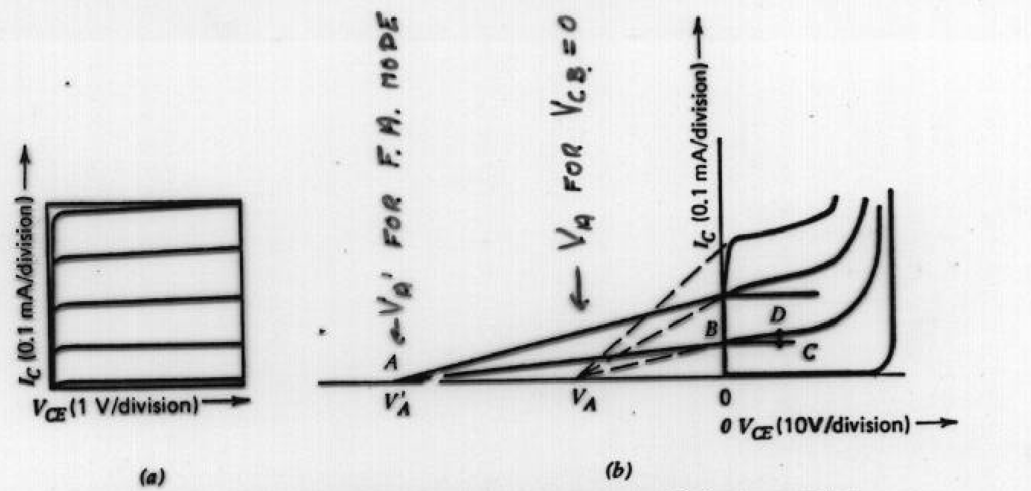
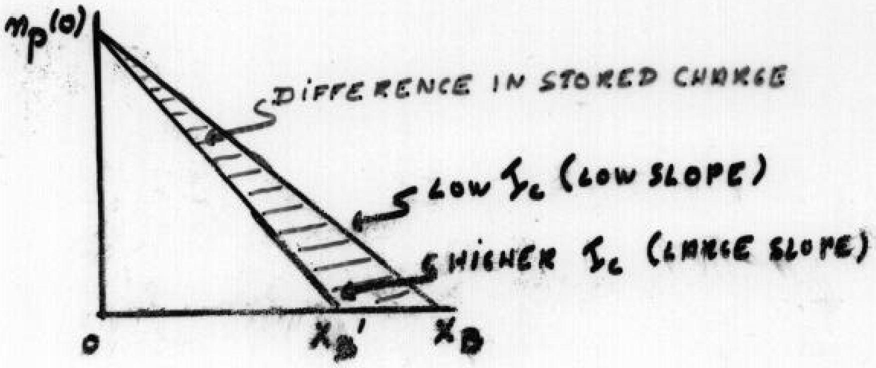


Figure 7.1 Measured output characteristics for an amplifying transistor: collector current versus V_{CE}. (*a*) vertical 0.1 mA/div., horizontal 1 V/div. (*b*) vertical 0.1 mA/div., horizontal 10 V/div.; tangents to the measured curves (at the edge of saturation) are extended to the voltage axis (dashed lines) to determine the Early Voltage V_A. Extension of lines drawn approximately tangential to the characteristic in the active region intersects the voltage axis at V_A' (solid lines).



LOW EMITTER BIAS

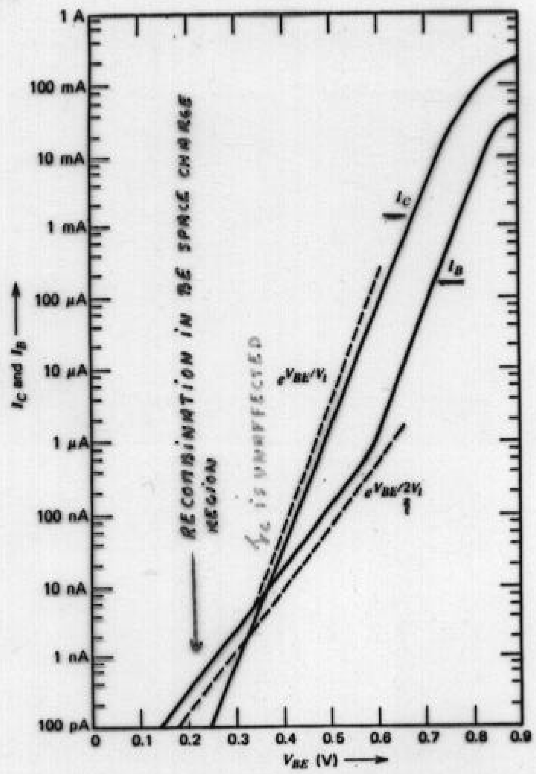
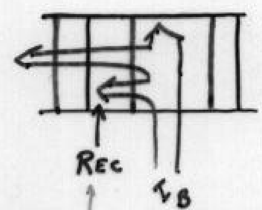


Figure 7.3 Typical behavior of collector and base currents as functions of base-emitter voltage for bias in the forward–active region.

$$I_B = I_o e^{\frac{qV_{BE}}{n kT}}$$

$1 \leq n \leq 2$



DOMINATES AT LOW JUNCTION BIAS.

GAIN DEGRADATION

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

I_B INCREASES AT LOW BIAS

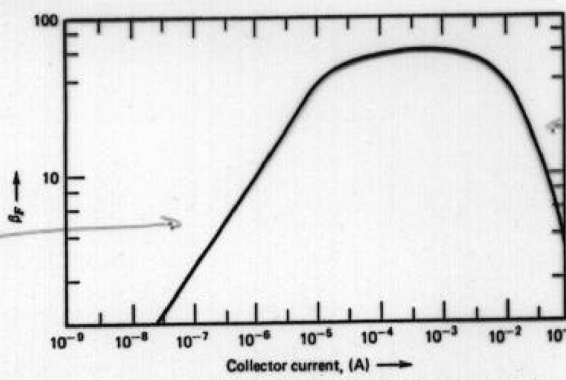


Figure 7.4 Current gain (β_F) as a function of collector current for the transistor of Figure 7.3.

I_C DECREASES AT HIGH BIAS

$$I_C \propto \frac{1}{\int_0^{x_B} p \, dx}$$

WITH HIGH INJECTION.

$p = N_A + n$ ← SIGNIFICANT

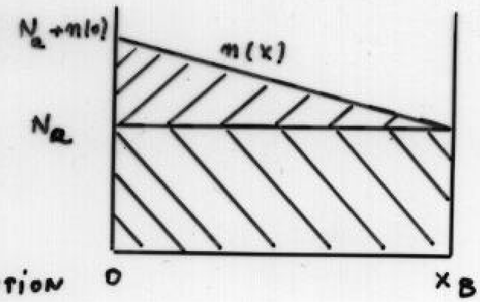
N_A: BASE DOPING

n: HOLE RECOMB WITH INJECTED ELECTRONS

$n \geq N_A$ FOR HIGH LEVEL INJECTION

HIGH-LEVEL INJECTION : BASE EMITTER JUNCTION

BASE QUASI NEUTRALITY

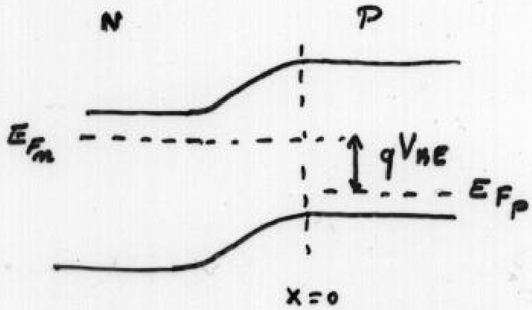


$$\int_0^{x_B} p(x)\,dx = \int_0^{x_B} dx\left[N_a(x) + n(x)\right]$$

$n(0)$: DOMINANT CONTRIBUTION

BUT :

$$\begin{cases} p(0)\,n(0) = n_i^2\, e^{\frac{qV_{BE}}{kT}} \\ p(0) = N_a(0) + n(0) \end{cases}$$



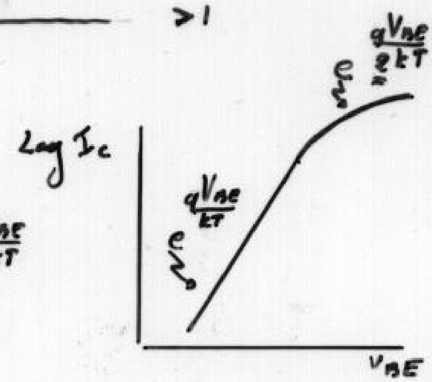
$$\Rightarrow \quad n(0) = \frac{N_a(0)}{2}\left[\sqrt{1 + \frac{4n_i^2}{N_a^2(0)}\exp\left(\frac{qV_{BE}}{kT}\right)} - 1\right]$$

$$\simeq \frac{n_i^2}{N_a(0)}\, e^{\frac{qV_{BE}}{kT}} \qquad \text{IF} \quad \frac{4n_i^2}{N_a(0)}\exp\left(\frac{qV_{BE}}{kT}\right) \ll 1$$

$$\simeq n_i \exp\left(\frac{qV_{BE}}{2kT}\right) \qquad \text{IF} \quad \text{———} \gg 1$$

CONSEQUENCES:

$$I_C = \frac{q\tilde{D}_n n_i^2 A_E \exp\left(\frac{qV_{BE}}{kT}\right)}{\int_0^{x_B} p(x)\,dx} \propto \frac{e^{\frac{qV_{BE}}{kT}}}{e^{\frac{qV_{BE}}{2kT}}} \propto e^{\frac{qV_{BE}}{2kT}}$$



BASE RESISTANCE (HIGH INJECTION)

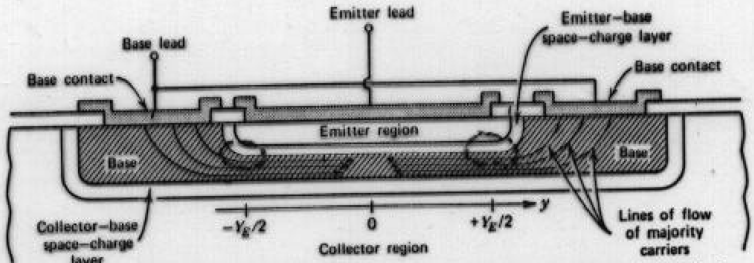


Figure 7.9 Cross section of a transistor under active bias. The base current is supplied from two side base contacts and flows toward the center of the emitter causing the base-emitter voltage to vary with position.

CURRENT CROWDING

V AND n INCREASE FROM 0 TO $\pm Y_E/2$

BASE SPREADING RESISTANCE R_B

$$I_C = I_S \exp\left[\frac{q(V_{BE} - I_B R_B)}{kT}\right]$$

R_B VARIES W/ I_C.

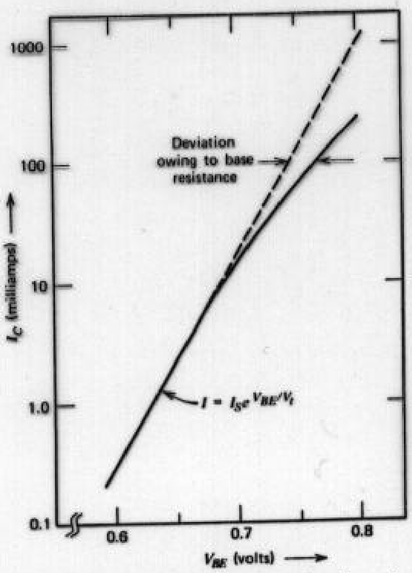
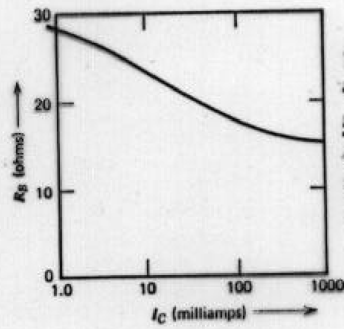


Figure 7.10 Collector current as a function of base-emitter voltage showing the deviation from ideal behavior at high currents.



DECREASES BECAUSE OF THE DECREASING PATH LENGTH FROM BASE ELECTRODE TO ACTIVE REGION

Figure 7.11 Base resistance in the transistor of Figure 7.10. Values of R_B obtained using measured data in Equation 7.2.13.