Lecture 28

• Last time:
  – DC and small-signal model of the forward-biased diode

• Today:
  – the npn bipolar junction transistor (BJT): large-signal characteristics
nnp Bipolar Transistor Structure
nnp Bipolar Transistor Layout

- (base)
- (emitter)
- edge of n buried layer
- field oxide
- p^+
- p
- n^+
- n^+ emitter area, A_E
- (intrinsic npn transistor)
- (collector)
BJT Symbol
Measuring the BJT’s Collector Characteristics

\[ I_C = I_C(I_B, V_{CE}) \]
Collector Characteristics

I_C (μA)

I_B = 2.5 μA
I_B = 2 μA
I_B = 1.5 μA
I_B = 1 μA
I_B = 0.5 μA
I_B = 500 nA
I_B = 1 mA
I_B = 2 mA

V_CE (V)

(saturation)
(forward active)
(reverse active)
(cutoff)
Base-Emitter Voltage Control

Diagram showing the relationship between collector current ($I_C$) and collector-emitter voltage ($V_{CE}$) with base-emitter voltage ($V_{BE}$) as a parameter. The diagram illustrates different regions of operation based on $V_{BE}$:

- **Saturation** region:
  - $V_{BE} < 0.7$ (cutoff)

- **Forward active** region:
  - $V_{BE} > 0.7$

- **Reverse active** region:
  - $V_{BE}$ negative values

The diagram also shows the scale for $I_C$ in microamperes ($\mu$A) and the scale for $V_{CE}$ in volts (V).
“Transistor Action”
Diffusion Currents
BJT Currents

Collector current is nearly identical to the (magnitude) of the emitter current ... define

\[ I_C = -\alpha_F I_E \]

Kirchhoff:

\[ -I_E = I_C + I_B \]

DC Current Gain:
Origin of $\alpha_F$

Base-emitter junction: some reverse injection of holes into the emitter $\rightarrow$ base current isn’t zero

Typical $\alpha_F$
Collector Current

Diffusion of electrons across base results in

\[ J_n^{\text{diff}} = qD_n \frac{dn_p}{dx} = \]

\[ I_C = I_S e^{V_{BE}/V_{th}} \]
Base Current

Diffusion of holes across emitter results in

\[ J_{p}^{\text{diff}} = -qD_p \frac{dp_{nE}}{dx} = \]

\[ I_B = \]
Current Gain $\beta_F$

$$\beta_F = \frac{I_C}{I_B} = \frac{\left(\frac{qD_n n_{pBo} A_E}{W_B}\right)}{\left(\frac{qD_p p_{nEo} A_E}{W_E}\right)} =$$

Parameter sensitivities:
Ebers-Moll Equations

Exp. 6: measure E-M parameters
Derivation: write emitter and collector currents in terms of internal currents at two junctions

\[ I_E = -I_{ES} \left( e^{\frac{V_{BE}}{V_{th}}} - 1 \right) + \alpha_R I_{CS} \left( e^{\frac{V_{BC}}{V_{th}}} - 1 \right) \]

\[ I_C = \alpha_F I_{ES} \left( e^{\frac{V_{BE}}{V_{th}}} - 1 \right) - I_{CS} \left( e^{\frac{V_{BC}}{V_{th}}} - 1 \right) \]

\[ \alpha_F I_{ES} = \alpha_R I_{CS} \]
Ebers-Moll Equivalent Circuit

Building blocks: diodes and $I$-controlled $I$ sources

Diode Currents:
- $I_F = I_{ES}(e^{V_{BE}/V_{th}} - 1)$
- $I_R = I_{CS}(e^{V_{BC}/V_{th}} - 1)$
Forward-Active Model

B-C junction is not forward-biased $\Rightarrow I_R$ is very small
Simplified Ebers-Moll (Cont.)

Forward-Active Case

Saturation: both diodes are forward-biases → batteries
Small-Signal Model

Analogy from MOSFET s.s. model:

\[ i_D = f(v_{GS}, v_{DS}, v_{BS}) \quad i_C = f(v_{BE}, v_{CE}) \]
Transconductance $g_m$