Lecture 11

Michael Brodskiy
Professor: M. Onabajo

October 16, 2024

- npn Bipolar Junction Transistors
  - The collector "collects" electrons, and causes current to flow through the emitter
- npn Structure without Bias
  - At zero bias ($V_{be} = V_{bc} = 0$), neither electrons nor holes can overcome this built-in voltage barrier of $\approx .7$[V] (for Si)
    * $I_B = I_C = 0$ (cutoff)
- npn Structure with Forward-Biased EBJ
  - When ($V_{be} = .65$[V], $V_c > V_b$), electrons and holes can overcome the built-in voltage barrier between the base and emitter
    * $I_b > 0$ and $I_e > I_b$ (due to n^+ emitter doping)
  - If the base region is very thin, the electrons injected by the emitter are collected by the positive voltage applied at V_c
    * $I_c \approx I_E >> I_B$ (active region)
  - If the base region is too thick, many electrons injected at the emitter are lost by recombining with holes in the base before the voltage applied at V_c can collect them
    * $I_c < I_E$ (active region with low α and $\beta \rightarrow$ low gain)
- Achievement of high β during Fabrication
  - Thin base region
    * Increases the collection efficiency for injected electrons
    * Reduces the chance of electron recombination in the base
  - Heavily-doped emitter

    * $I_E/I_B \propto n(\text{emitter})/p(\text{base}) \propto \beta$
  - Doping concentrations are difficult to control precisely
    * Current gain is not uniform among BJTs (exception: when the BJTs are all fabricated on the same integrated circuit $\rightarrow$ small variations)

- The Early Effect
  - As V_c increases, the depletion width of the B-C junction widens
    * Base width becomes more narrow
    * Increased collection efficiency
    * Finally, I_c/I_b increases (higher β)

- Summary: Regions of Operation
  - CBJ: Collector-Base Junction
  - EBJ: Emitter-Base Junction
  - RB: Reverse-Biased
  - FB: Forward-Biased

EBJ	CBJ	Mode
FB	RB	Active
FB	FB	Saturation
RB	RB	Cutoff

  - When designing amplifers: make sure the BJT is in active mode

- npn BJT Model for the Active Region
  - Current gain: $\beta = I_C/I_B$ (range: 10-1000, typical: 100-200)
  - Model usage:
    * Assume (gues) a region of operation
    * Replace the BJT with the appropriate model
    * Perform standard circuit analysis
    * Check that the conditions for the region of operation are met (if the conditions are not met: change the accumption and repeat the analysis)
    * From KVL: $V_{BC} = V_{BE} - V_{CE}$
    * Assuming $V_{BE} = .7$ (forward-biased)
      · $V_{BC} = V_{BE} - V_{CE(min)} = .7 - .2 = .5$[V] $<$ .7[V] (ensures that CBJ remains reverse-biased)
      · $V_{CE\downarrow} \rightarrow V_{BC\uparrow} \rightarrow$ CBJ becomes forward-biased $\rightarrow$ saturation
      · Note: in some models (other books), $V_{CE} > .3$[V] is assumed as condition for the active mode of operation

- npn BJT Model for the Saturation Region
  - Forward Voltage Drop of .7[V] [V_{BE}] (note for all models: depends on BJT type, some models use different assumptions, such as .6[V])
- npn BJT Model for the Cutoff Region
  - BJT forms an open circuit since both diodes are in reverse bias
- Key Equations:

$$I_E = I_C + I_B$$

  - When the base-emitter junction is forward-biased:

$$I_E = I_{ES}[e^{V_{BE}/V_T} - 1]$$

  - Valid only in the active region:

$$I_C = \alpha I_E$$
$$I_C = \alpha I_{ES}[e^{V_{BE}/V_T} - 1]$$
$$I_B = (1 - \alpha) I_E$$
$$I_C = \beta I_B$$
$$I_S = \alpha I_{ES}$$
$$\beta = \frac{\alpha}{1 - \alpha} \quad \text{and} \quad \alpha = \frac{\beta}{1 + \beta}$$

  - Typical (with high β): α is near unity