Bipolar Junction Transistors

Recall diodes

\[ \text{P} \quad \text{n} \]

\[ \text{I} \quad \text{I} \]

current flows on forward biasing

\[ \text{I} \quad \text{I} \]

Transistor is like a diode with another junction added
- middle part is very thick

Two types

\[ \text{P} \quad \text{n} \quad \text{p} \]
\[ \text{n} \quad \text{p} \quad \text{n} \]

Three leads: Emitter, Base, Collector

Arrow goes on the emitter!
Basic operation

1. Forward bias EB "diode"
2. Emitter then emits charges which are collected by collector

- Current flows from E → C
  (or C → E for npn)
- Current flows in direction of arrow

Nomenclature

\[ V_E, V_B, V_C \] voltage at lead

\[ V_{EB}, V_{BE}, V_{BC}, V_{EC} \] voltage difference

\[ V_{EB} = V_E - V_B \]

\[ V_{EE}, V_{BB}, V_{CC} \] power supply voltage to lead (through resistor)
Applications
- Switches
- Amplifiers
- Variable resistors
- Impedence changing
- Current source

First Model

1. Forward bias \( E_B \) \( V_{EB} = 0.6 \text{ V} \) (pnp)
   \( V_{EB} = -0.6 \text{ V} \) (nnp)

2. \( I_C = I_E \) (\( I_C = \alpha I_E \), \( \alpha \leq 1 \))

Second Model

1. Forward bias \( E_B \) \( V_{BE} = 0.6 \text{ V} \)

2. \( I_C = \beta I_B \), \( 25 \beta \leq 250 \)
   Small \( I_B \) controls large \( I_C \)
Watch out for $\beta$!
- Depends on $I_B$
- Depends on $T$
- Depends on doping details (varies from one sample to the next)

**Characteristic Curves**

$I_C$ vs. $V_{EB}$

$(I_C \neq I_E$ so $I_E$ like a diode $)$

Show slide

$I_C$ vs. $V_{EC}$

- Active
- Saturation
- Cutoff
- $V_{EC} > 0.2$, $I_C = \beta I_B$
- $I_C$ independent (ish) of $V_{EC}$
- Cutoff
  - $V_{EB} < 0.6 V$, $I_C = 0$
- Saturation
  - $V_{EC} = 0.2$, $V_{RR} = 0.6 V$

Questions
**Another use of transistor-as-switch**

**NOT Gate**

\[ V_{cc} = +5 \text{ V} \]

\[ 2k\Omega \]

\[ 20k \]

\[ V_{in} \rightarrow V_{out} \]

1. \( V_{in} < 0.4 \text{ V} \) **Cutoff**, transistor **OFF**
   
   \[ V_{out} = V_{cc} = 5 \text{ V} \]

2. \( V_{in} = 5 \text{ V} \) **Saturation**, transistor **ON**
   
   \[ V_{out} = 0.2 \text{ V} \]

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**NOR Gate**

\[ V_{cc} \]

\[ V_{1} \rightarrow V_{2} \rightarrow V_{out} \]

\[ V_{EE} = 0 \]
Load Line Analysis

\[ V_C = 7.5 \text{ V} \]

- \( I_B = 40 \mu \text{A}, \quad V_C = 8.6, \quad I_C = 6.3 \text{ mA} \)
- \( I_B = 50 \mu \text{A}, \quad V_C = 6.8, \quad I_C = 8.1 \text{ mA} \)

\[ \beta_{re} = \frac{\Delta I_C}{\Delta I_B} \bigg|_{I_B = 45} = 180 \]

So the transistor works as an amplifier!

Small changes in \( i_B (V_B) \) result in large changes in \( (V_{out})(v) \)

But!

Need to bias input
Blasing Circuits

Fixed Bias

\[ i_B = \frac{V_C - 0.6}{R_B} \]

Voltage Divider Bias (Fixed)

Problems

1) Amplification depends directly on \( \beta \)
   (and \( \beta \) is variable)

2) Thermal runaway

\[ I_C = I_C_0 (e^{\frac{V_T}{4}} - 1) \]

\( I_C_0 \) increases with temperature
\( I_C \) dissipates heat raising temp
dissipating more heat, etc.
Non-Fixed Biasing

\[ i_B = \frac{V_{CB}}{R_B} \]

\[ V_{OB} = 0.6 \approx V_c - 0.6 \]

\[ V_{CC} - V_c = (\frac{V_c - V_c}{1 + \beta})R_c = V_{OUT} \]

\[ V_{CC} - V_c = \frac{(\beta + 1)V_B}{R_B} = V_{CC} - V_{OUT} \]

\[ = \frac{(\beta + 1)(V_{OUT} - 0.6)R_c}{R_B} = V_{CC} - V_{OUT} \]

\[ (1 + \frac{\beta + 1}{R_B R_c})V_{OUT} = (1 + \frac{0.6(\beta + 1)}{V_c R_B})V_c \]

\[ V_{OUT} = \frac{1 + \frac{0.6(\beta + 1)}{V_c R_B}}{1 + (\beta + 1)} V_c \]

\[ \approx \frac{1 + 0.6}{\beta} V_c \]

\[ \approx \left( \frac{0.6}{V_c} + \frac{1}{\beta} \right) V_c \]
\[ i_B = \frac{V_{CB}}{R_B} = \frac{i_C}{\beta} \]

\[ V_C = V_{cc} - \frac{(1+\beta)i_B R_C}{R_B} \]

\[ V_{CB} = V_C - V_B = V_C - V_{BE} \]

\[ i_B = \frac{V_{CB}}{R_B} = \frac{V_C - V_{BE}}{R_B} = \frac{V_{cc} - (1+\beta)i_B R_C - V_{BE}}{R_B} \]

\[ i_B R_B = V_C - V_{BE} - (1+\beta)i_B R_C \]

\[ (R_B + (1+\beta)R_C)i_B = V_C - V_{BE} \]

\[ i_B = \frac{V_C - V_{BE}}{R_B + (1+\beta)R_C} \]

\[ \frac{di_B}{d\beta} = -\frac{i_B}{(R_B + (1+\beta)R_C)} \cdot R_C \]
Self Biasing

\[ i_B = \frac{V_{BB} - V_{BE}}{R_B + (1+\beta)R_E} \]

Biasing Circuit Design

(Guiescent Point of Amplifier)

1. Determine \( I_{CQ} \) (= \( I_{EQ} \))

   (horizontal line on \( I_C \) vs \( V_{CE} \))

2. Determine \( V_{CC} \) (12V supply)

3. Pick \( V_E = \frac{1}{10} V_{CC} \)
   
   \( R_E = \frac{1}{10} \frac{V_{CC}}{I_{CQ}} \)

   Thermal Stability, Gain
   \( \beta \) variability

4. Determine \( V_B \)
   
   \( V_{BE} = 0.7 \) V (0.3 for Ge)
   
   \( V_B = V_E + V_{BE} \)

5. Pick output voltage divider current
   
   \( I_2 = \frac{1}{10} I_C \)
(3) Follows from 1/10th rule of input & output impedances
with \( \beta = 100 \), don't have to account for \( I_B \)!

(6) Calculate \( R_2 \)
\[ V_B = I_{12} \cdot R_2 \]

(7) Calculate \( R_1 \)
\[ (V_{CC} - V_B) = I_{12} \cdot R_1 \]

(8) Pick \( V_c = \frac{V_{CC}}{2} \)

(9) Calculate \( R_c = \)
\[ V_{CC} - V_c = \frac{I_c}{R_c} = \frac{V_{CC}}{2} \]