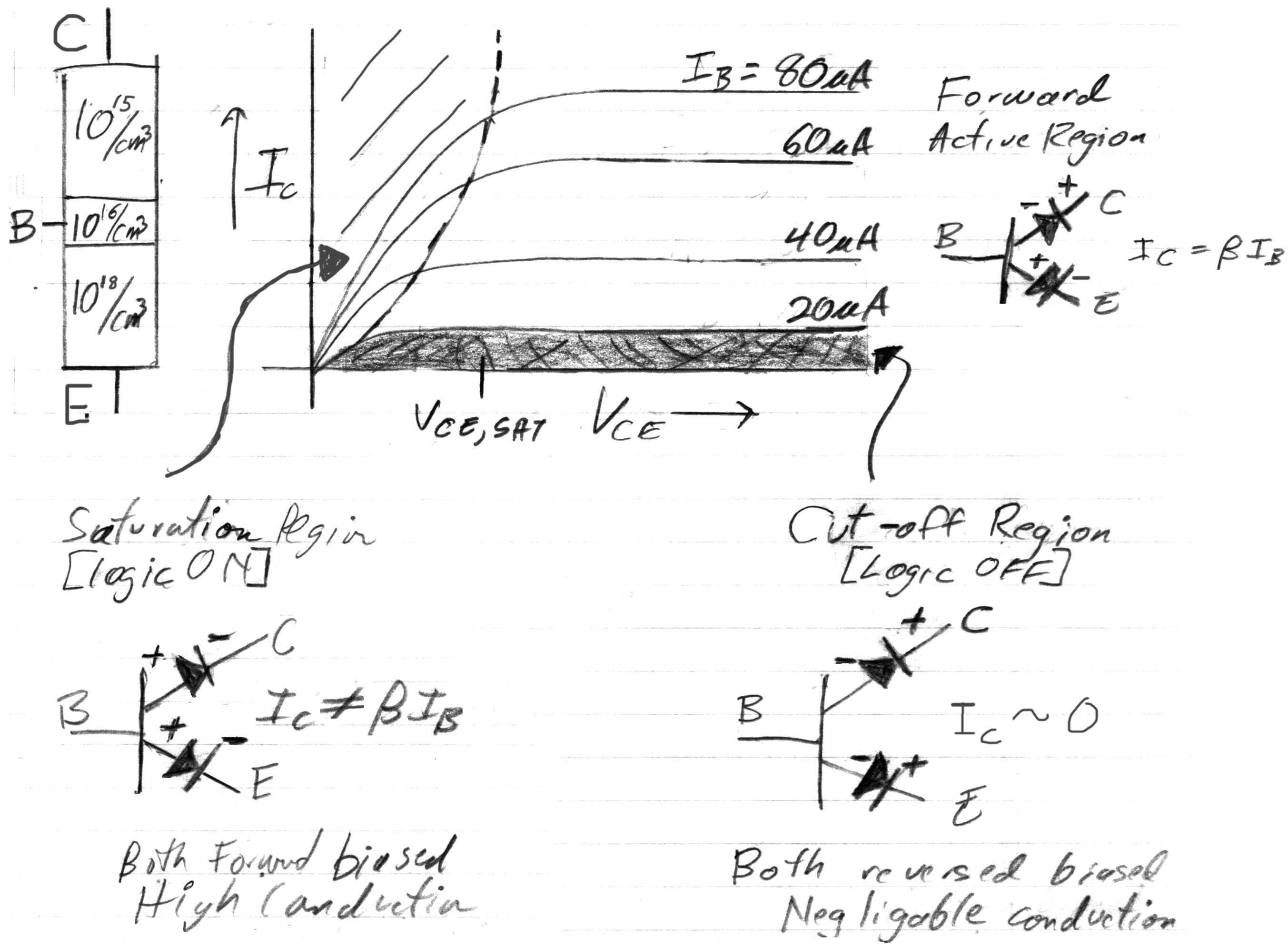
Notes on NPN transistors - David Kleinfeld - Spring 2018

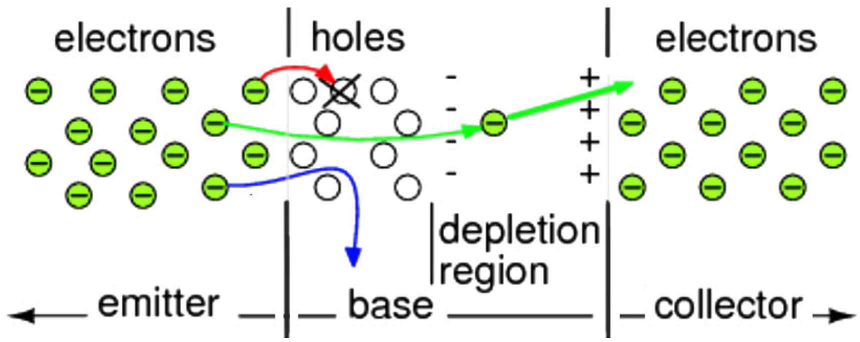
1. Introduction

The bipolar junction transistor consists of three regions. The emitter has the greatest level of doping, $N_n \sim 10^{18}/cm^3$ (recall that the number density of Si is $6 \times 10^{21}/cm^3$), while that in the base is $N_p \sim 10^{16}/cm^3$ and that in the collector is $N_n \sim 10^{15}/cm^3$. The current flows from collector to emitter, which means that the electrons, which are the majority carrier, flow from the emitter to the collector.



2. Active zone

The base/emitter junction is forward biased, with $I_C = I_o[exp(qV_{BE}/kT) - 1]$, while the base/collector junction is reverse biased. A critical point is that the base is extremely thin so that electrons from the emitter will diffuse through the base, only to be transported in the depletion zone formed by the reverse bias and then swept into the collector. The thinness of the base ensures that the depletion zone entails a significant fraction of the thickness of the base, so that most electrons from the emitter are swept into the collector rather than leaving through the base or lost via recombination with holes.



Electrons in the emitter suffer one of three fates:
(1) Recombination with holes in the base
(2) Exiting the base through the external lead
(3) Drift into the collector; this is the major current by a factor, denoted β, of β ~ 100!

3. Constitutive relations

Collector current:

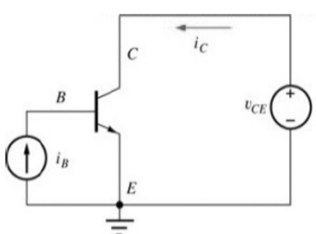
$$i_C = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$

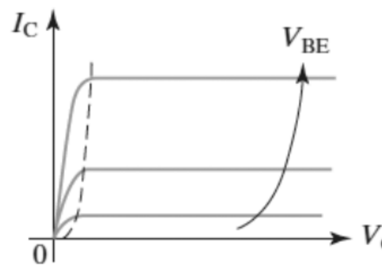
$$V_T = \frac{kT}{q} \quad \text{(26mV at room temp)}$$

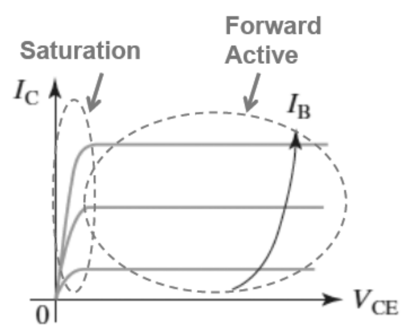
I_S : BJT saturation current

Collect current increases exponentially with V_{BE}

Collect current increases linearly with I_B



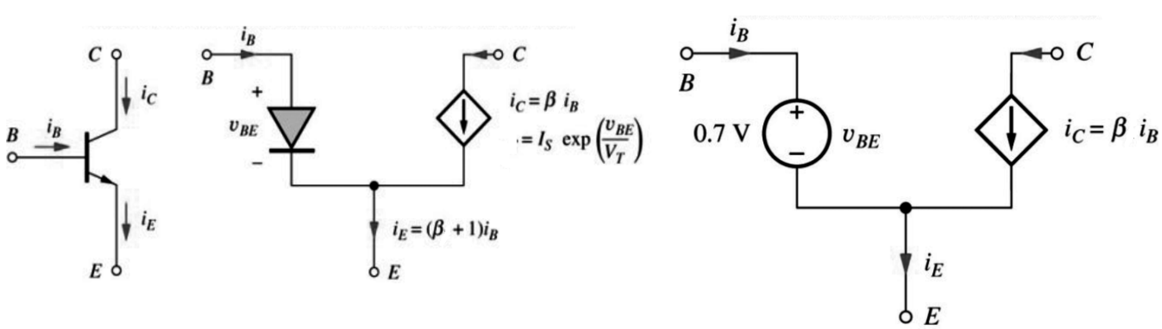




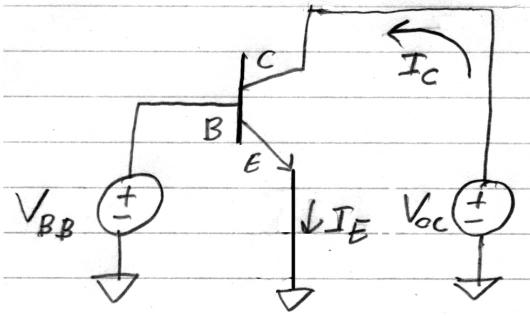
$$\mathbf{I_C = \beta\, I_B} \text{ and } \mathbf{I_E = I_C + I_B}$$
$$\text{so that } \mathbf{I_E = (1+\beta)\, I_B = (1+\beta)/\beta\ I_C}$$

4. Simplified model of transistor in active zone

We see that V_{BE} ~ 0.7 V. A brutal model is to replace the transistor, when operating in the Active region, with a model in which the base is connected to a battery and the collector is connected to a dependent current source.



4. Voltage controlled circuit



Impose: $V_{BB} = +5V$

$V_{oc} = +10V$

$\beta = 20$

Measure: $I_E = 100\mu A$

Question: Is transistor in active zone?

Check Base-Collector bias

$V_{CB} = V_C - V_B = 10 - 5 = 5V$

So, B-C junction is reverse biased!

$$I_C = \frac{\beta}{1+\beta} I_E = \frac{20}{21} \times 100\mu A \simeq 95\mu A$$

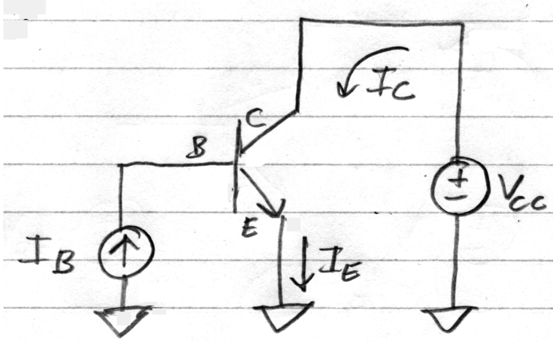
$$I_B = \frac{95\mu A}{20} \simeq 5\mu A$$

$$I_c = I_o\left(e^{eV_{BE}/kT} - 1\right) \Rightarrow V_B = \frac{k_B T}{e} \log \frac{I_c}{I_o}$$

but $I_o \simeq 1 \times 10^{-16} A \Rightarrow V_{BE} = 0.69V$

So, B-E junction is forward biased!

5. Current controlled circuit



Imposed: $V_{cc} = 5V$

$\beta = 20$

$I_B = 100\mu A$

Check voltages

$I_C = \beta I_B = 2mA$

$$V_{BE} = \frac{kT}{e} \log \frac{I_c}{I_o}$$

I_o: $1 \times 10^{-16} A$

" $= 0.77V$

$V_{CB} = V_c - V_B$

$= V_C - V_{BE}$

$= 5V - 0.8V$

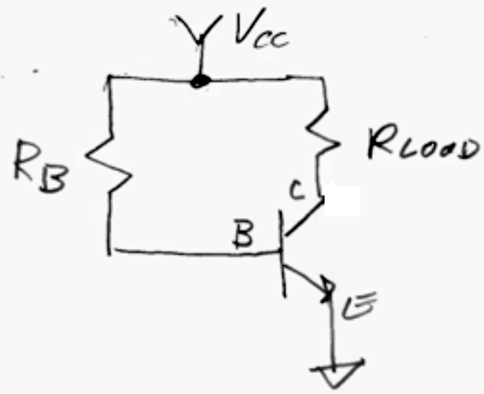
$= 4.2V$

Properly reverse biased

Properly forward biased

6. Analysis of a simple driver circuit

A common emitter driver circuit to pass a fixed current independent of the load.



① $V_{CC} = I_B R_B + V_{BE}$

② $V_{CC} = I_C R_L + V_{CE}$

③ $I_C = \beta I_B$ for $V_{CE} > V_{CE,SAT}$

④=①+③ $$I_C = \frac{V_{CC} - V_{BE}}{R_B/\beta}$$

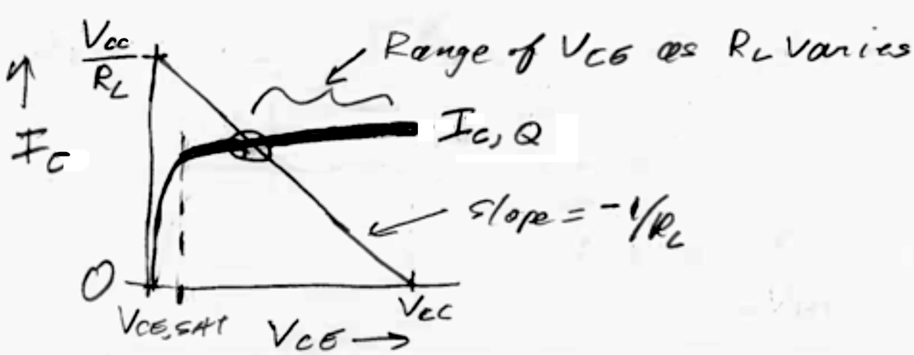
Use to choose R_B to set current: $R_B = \beta \dfrac{V_{CC} - V_{BE}}{I_{C,Q}}$

⑤=③+④ $$V_{CE} = V_{CC} - I_{CQ} R_{LOAD}$$

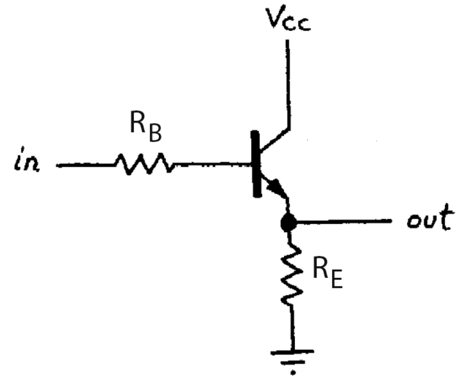
$$'' \quad = V_{CC} - \beta \frac{R_{LOAD}}{R_B}(V_{CC} - V_{BE})$$

$$\therefore \; V_{CC} - \beta \frac{R_{LOAD}}{R_B}(V_{CC} - V_{BE}) \geq V_{CE,SAT}$$

$$0 < R_{Load} < \frac{R_B}{\beta} \underbrace{\left[\frac{V_{CC} - V_{CE,SAT}}{V_{CC} - V_{BE}}\right]}_{\text{Close to but } < 1}$$



7. Analysis of a the emitter-follower, a unity gain impedance buffer



This circuit can be understood by applying Kirchhoff's voltage law to the left-hand loop. We have:

$-V_{in} + I_B R_B + V_{BE} + I_E R_E = 0.$

In the linear regime, $I_E = (1+\beta)I_B$ so:

$$V_{out} = I_E R_E = (V_{in} - V_{BE}) R_E /[R_E + R_B / (1+\beta)] = (V_{in} - V_{BE}) /[1 + R_B /(1+\beta)R_E]$$

$$\approx V_{in} - V_{BE}$$

since $\beta >> 1$. To within an offset of V_{BE}, the magnitude of output is the same as that of the input.

The input resistance is found by replacing the transistor with the Active Zone model (panel 4) and performing a Thevenin equivalence analysis, i.e., opening the dependent current source I_C and shorting the voltage drop $V_{BE.}$ Thus:

$$R_{in} = V_B / I_B = V_{BE.} + I_E R_E /I_B = 0 + (1+\beta)R_E = (1+\beta)R_E$$

So we see that the emitter-follower functions with a high(-ish) impedance input.

The output resistance, found similarly by opening the dependent current source Ic and shorting the voltage sources V_{BE} and V_{in}, is just

$$R_{out} = V_E / I_E = I_B R_B /I_E - V_{BE} = R_B/(1+\beta) - 0 = R_B/(1+\beta).$$

This is just the resistance of the source divided by the gain.

Both relations generalize to

$$Z_{in} = (1+\beta) Z_E$$

and

$$Z_{out} = Z_{source} /(1+\beta)$$

so that

$$Z_{in} Z_{out} = Z_E Z_{source} .$$