VE320 Intro to Semiconductor Devices

Chapter 12. The Bipolar Transistor (BJT)

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Contents

Objective

1. Learn the working principle for BJT
    1.1 BJT structure
    1.2 Basic principle of operation
    1.3 Different operation modes
    1.4 Minority carrier distribution
2. Learn the non-ideal effect: early effect
3. Practice how to apply the concepts and formulas in solving problems

BJT Structure

1. BJT has three doped regions and two pn junction
2. Three terminal connections: emitter, base, and collector

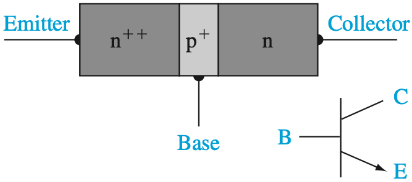


Figure: npn BJT

BJT Structure

3. The (++) and (+) notation indicates the relative magnitudes of the impurity doping concentrations
4. The width of the base region is small compared to the minority carrier diffusion length

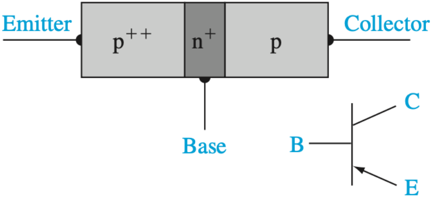


Figure: pnp BJT

1. Typical impurity doping concentrations in the emitter, base, and collector may be on the order of 10^{19} cm^{-3}, 10^{17} cm^{-3}, and 10^{15} cm^{-3}

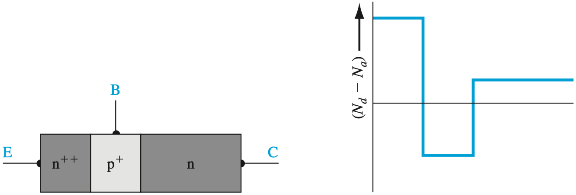


Figure: Idealized doping profile of a npn BJT

Basic Principle of Operation

2. In the normal bias configuration: the B-E pn junction is forward biased and the B-C pn junction is reversed biased (**forward-active** operation mode)

- **Brainstorm**: Can you explain how electrons move in this mode?

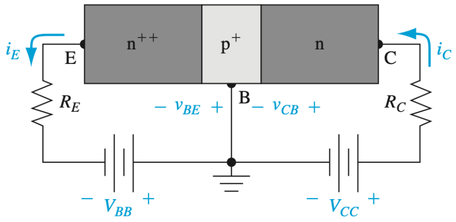
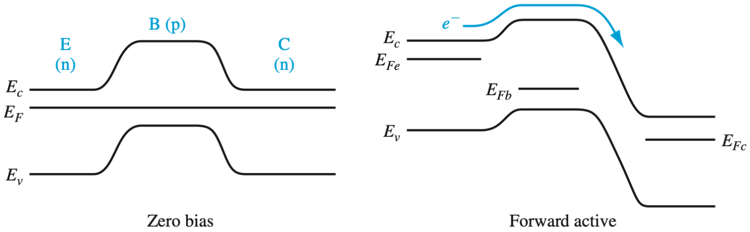


Figure: Biasing of an npn BJT in the forward-active mode

Basic Principle of Operation

3. Energy-band diagram of npn BJT:

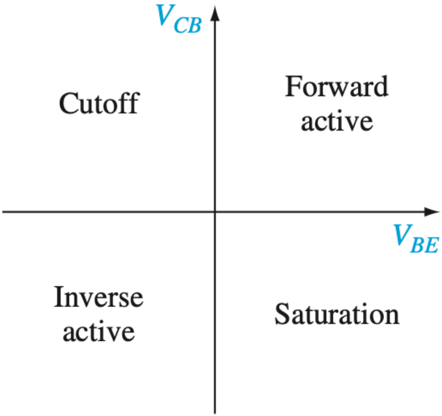


Basic Principle of Operation

4. **Quiz:** Energy-band diagram of pnp BJT:

Operation Mode

1. Cutoff: $V_{BE} \leq 0$, so $i_E = i_C = 0$
2. Forward-active: $V_{BE} > 0$, V_{CB}>0, so $i_C = \beta i_B$
3. Saturation: $V_{BE} > 0$, $V_{CB} \leq 0$, both pn junction are forward biased, i_C doesn't depend on V_{BE}



Current-Voltage Characteristic

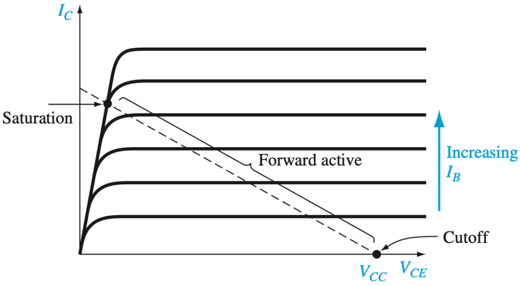


Figure: BJT common-emitter current–voltage characteristics

Minority Carrier Distribution

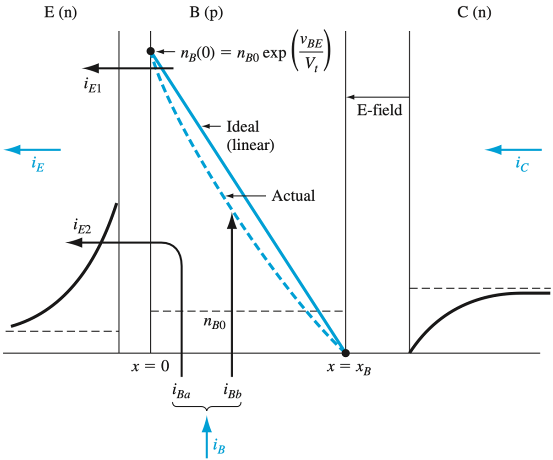


Figure: Minority carrier distributions and basic currents in a forward-biased npn BJT

Minority Carrier Distribution

1. Parameters:

$$\begin{cases} \alpha: & \text{common-base current gain } (\alpha \sim 1) \\ \beta: & \text{common-emitter current gain } (\beta \gg 1) \end{cases}$$

2. Collector current: i_C is controlled by v_{BE}

$$|J_C| = \frac{eD_B n_{B0}}{x_B} \exp\left(\frac{V_{BE}}{V_t}\right)$$

$$i_C = \frac{-eD_n A_{BE}}{x_B} n_{B0} \exp\left(\frac{v_{BE}}{V_t}\right) = I_s \exp\left(\frac{v_{BE}}{V_t}\right)$$

3. Emitter current: $\frac{i_C}{i_E} = \alpha$. $i_E = I_{SE} \exp\left(\frac{v_{BE}}{V_t}\right)$
4. Base current: $\frac{i_C}{i_B} = \beta$. $i_B \propto \exp\left(\frac{v_{BE}}{V_t}\right)$

Early Effect

- Previous assumption: base width x_B is constant
- In reality: x_B changes with V_{CB}. The width of the space charge region extending into the base region varies with B–C voltage, i.e.,

$$V_{CB} \uparrow \Longrightarrow \text{BC space charge region width } \uparrow \Longrightarrow x_B \downarrow$$

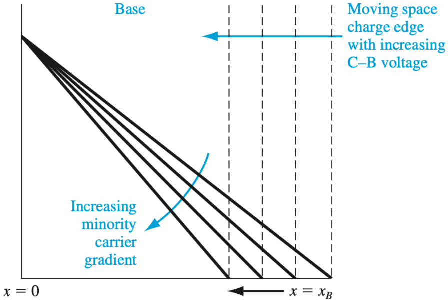


Figure: Change of x_B and minority carrier gradient as the B–C space charge width changes

Early Effect

1. Current-voltage characteristic: I_C changes with V_{CE}/V_{CB}
2. g_o: output conductance, r_o: output resistance:

$$\begin{cases} \frac{dI_C}{dV_{CE}} & \equiv & g_o = \frac{I_C}{V_{CE}+V_A} = \frac{1}{r_o} \\ I_C & = & g_o(V_{CE}+V_A) = \frac{1}{r_o}(V_{CE}+V_A) \end{cases}$$

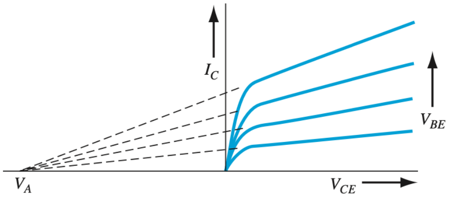


Figure: The collector current versus C-E voltage showing the Early effect and Early voltage.

Exercise

Early Effect

A uniformly doped silicon npn bipolar transistor at T=300 K has parameters $N_E = 2 \times 10^{18}\text{cm}^{-3}$, $N_B = 2 \times 10^{16}\text{cm}^{-3}$, $N_C = 2 \times 10^{15}\text{cm}^{-3}$, $x_{B0} = 0.85\mu\text{m}$, and $D_B = 25\ \text{m}^2/\text{s}$. Assume $x_{B0} \ll L_B$ and let $V_{BE} = 0.650\,V$.

(a) Determine the electron diffusion current density for $V_{CB} = 4\,V$ and $V_{CB} = 12\,V$.

(b) Estimate the Early voltage.

Answer

(a) $J_C = 52.16A/cm^2$ for $V_{CB} = 4\,V$
$J_C = 61.85A/cm^2$ for $V_{CB} = 12\,V$

(b) $V_A = 38.4A$

Answer

Answer

Exercise

Homework 7.5 (9.30 in textbook)

9.30 A metal–semiconductor junction is formed between a metal with a work function of 4.3 eV and p-type silicon with an electron affinity of 4.0 eV. The acceptor doping concentration in the silicon is $N_a = 5 \times 10^{16}$ cm^{-3}. Assume $T = 300$ K. (*a*) Sketch the thermal equilibrium energy-band diagram. (*b*) Determine the height of the Schottky barrier. (*c*) Sketch the energy-band diagram with an applied reverse-biased voltage of $V_R = 3$ V. (*d*) Sketch the energy-band diagram with an applied forward-bias voltage of $V_a = 0.25$ V.

Answer

Answer

Conclusion

- **Minute paper**: Please take a piece of paper and list all the concepts we talk about today as much as possible.