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

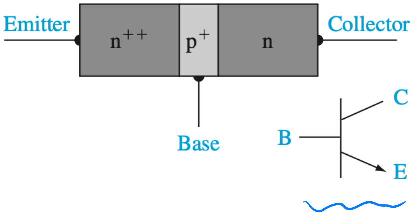


Figure: npn BJT

circuit symbol

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

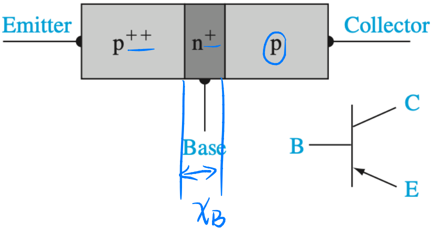


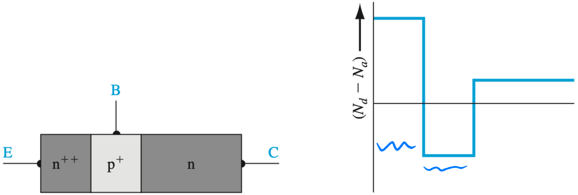
Figure: pnp BJT

Basic Principle of Operation

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}

$N_d - N_a$

++ and +



emitter : $N_d = 10^{19}\,cm^{-3}$ $N_a = 0$

Figure: Idealized doping profile of a npn BJT

base : $N_d = 0$ $N_a = 10^{5}\,cm^{-3}$

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?

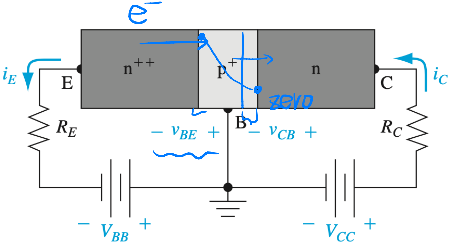


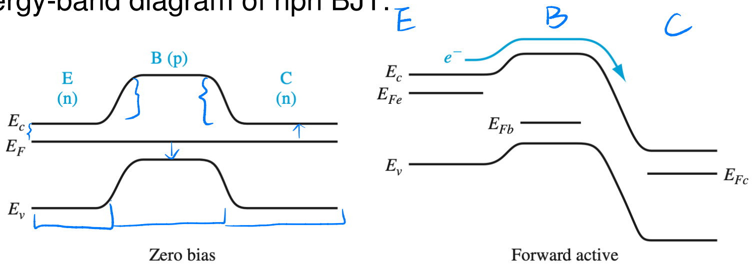
Figure: Biasing of an npn BJT in the forward-active mode

Basic Principle of Operation

B-E junction forward biased
voltage barrier ↓

B-C reversed biased

3. Energy-band diagram of npn BJT:

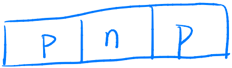


① E_F is flat

② electrons in the emitter or in the collector can not enter the base region

Basic Principle of Operation

pnp

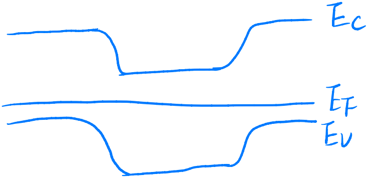


B-E forward biased

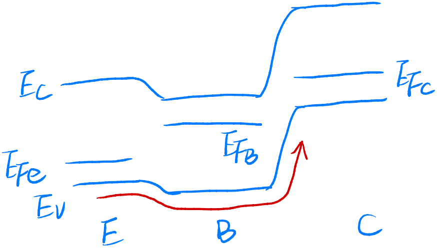
B-C reversed biased

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

① zero bias



② forward-active

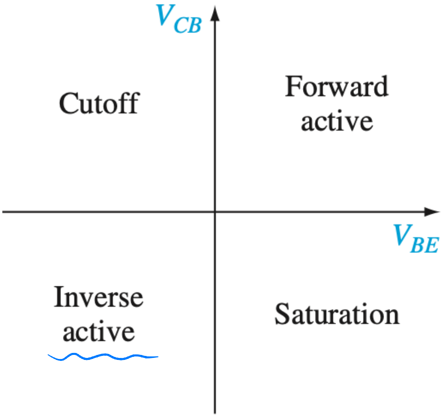


Operation Mode

npn E_F B-E reversed biased

$V_{BE}=0$ $V_{BE}<0$

1. Cutoff: $V_{BE} \leq 0$, so $i_E = i_C = 0$
   E B C
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}



possible

B-E reversed

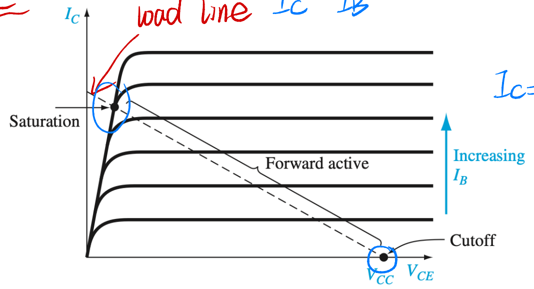
B-C forward

Current-Voltage Characteristic

We need to use Kirchhoff's voltage law.

$V_{CE} = V_{CC} - I_C R_C$

load line I_C I_B



$I_C = \beta \cdot I_B$

$V_{CE} = V_{CC}$ $I_C = 0$

Figure: BJT common-emitter current–voltage characteristics

Minority Carrier Distribution

i_{E1}: electrons

i_{E2}: holes

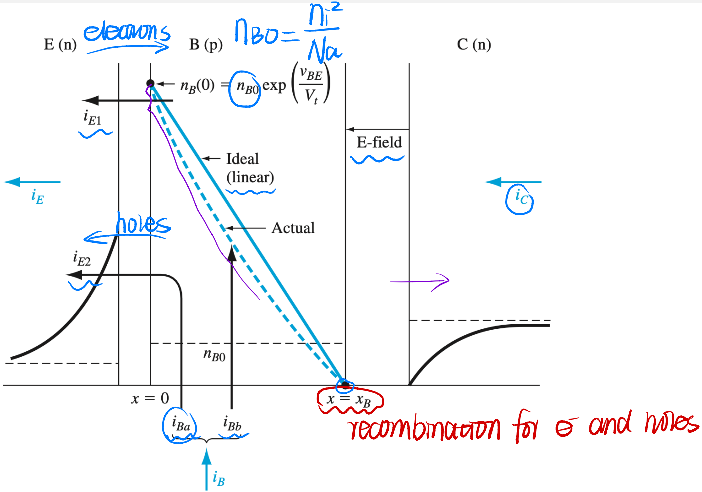


Figure: Minority carrier distributions and basic currents in a forward-biased npn BJT

Minority Carrier Distribution

1. Parameters:

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

$\frac{i_C}{i_E} = \alpha$

$\frac{i_C}{i_B} = \beta$

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: $\frac{i_C}{i_E} = \alpha$. $i_E = I_{SE} \exp\left(\frac{v_{BE}}{V_t}\right)$ $\quad i_E = i_{E1} + i_{E2}$
4. Base current: $\frac{i_C}{i_B} = \beta$. $i_B \propto \exp\left(\frac{v_{BE}}{V_t}\right)$ $\quad i_B = i_{Ba} + i_{Bb}$

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.,

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

⇓

gradient ↑

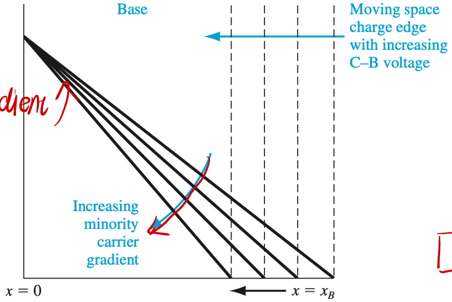
⇓

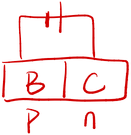
diffusion current ↑

x_B ↓

e^- concentration gradient ↑

diffusion current ↑



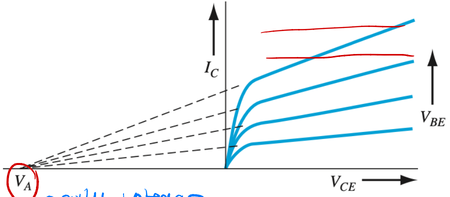


V_{CB} ↑

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

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

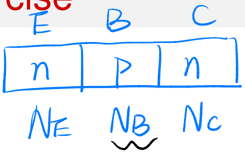
$$\begin{cases} \dfrac{dI_C}{dV_{CE}} \equiv \overset{=0}{g_o} = \dfrac{I_C}{V_{CE}+V_A} = \dfrac{1}{r_o} \\ I_C = g_o(V_{CE}+V_A) = \dfrac{1}{r_o}(V_{CE}+V_A) \end{cases}$$



early voltage

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. V_a

a> $|J_C| = \dfrac{eD_B n_{B0}}{x_B} \exp\left(\dfrac{V_{BE}}{V_t}\right)$, $\quad n_{B0} = \dfrac{n_i^2}{N_B}$

b> $\dfrac{dI_C}{dV_{CE}} = \dfrac{I_C}{V_{CE}+V_A}$

Answer

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

(b) $V_A = 38.4 A$

Answer

a> $|J_C| = \frac{e D_B n_{B0}}{x_B} \exp\left(\frac{V_{BE}}{V_t}\right)$

B-C reversed biased.

$$x_{dB} = \left\{ \frac{2\varepsilon_s (V_{bi} + V_{CB})}{e} \left[\frac{N_C}{N_B} \frac{1}{(N_B + N_C)} \right] \right\}^{1/2}$$

$$= \left\{ \frac{2 \times 11.7 \times 8.85 \times 10^{-14} (V_{bi} + 4)}{1.6 \times 10^{-19}} \left[\frac{2 \times 10^{15}}{2 \times 10^{16}} \frac{1}{(2 \times 10^{16} + 2 \times 10^{15})} \right] \right\}^{1/2}$$

$$V_{bi} = V_t \ln\left(\frac{N_B N_C}{n_i^2}\right) = 0.6709\ V$$

$$x_{dB} = 0.1658\ \mu m$$

b> Early effect: $x_B \downarrow$

$$x_B = x_{B0} - x_{dB} = 0.6842\ \mu m$$

Answer

c) J_C

$$n_{B0} = \frac{n_i^2}{N_B} = 1.25 \times 10^4\ cm^{-3}$$

$$J_C = \frac{n_{B0}}{x_B} = 52.16\ A/cm^2$$

$V_{CB} = 12\ V$. $J_{C(12)} = 61.85\ A/cm^2$

2) $$\frac{dI_C}{dV_{CE}} = \frac{J_C}{V_{CE} + V_A}$$ $$\frac{\Delta I_C}{\Delta V_{CE}} = \frac{J_C}{V_{CB} + V_{BE} + V_A}$$

$$\frac{61.85 - 52.16}{12 - 4} = \frac{52.16}{4 + 0.65 + V_A} \Rightarrow V_A = 38.4\ V$$

Exercise

ϕ_m ϕ_s

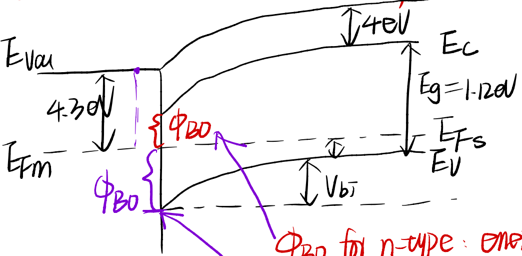
Homework 7.5 (9.30 in textbook)

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. ϕ_{B0}

① Determine it is a schottky diode

$$E_F - E_V = -kT\ln\frac{N_a}{N_v}$$

$$= 0.138\ \text{eV}$$



ϕ_{B0} for n-type: energy difference between E_F and E_c

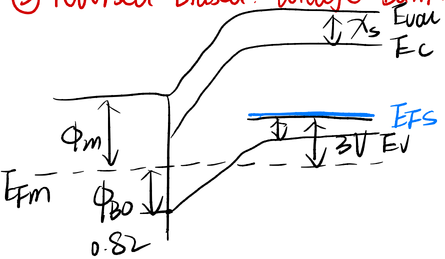
② schottky barrier

ϕ_{B0} for p-type: energy difference between E_F and E_V

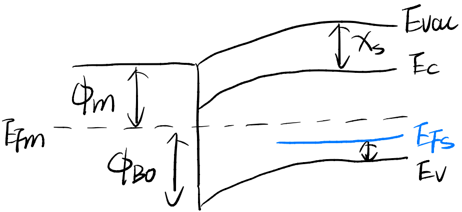
$$\phi_{B0} = \chi_s + E_g - \phi_m = 0.82\ \text{V}$$

Answer

③ reversed biased: voltage barrier ↑. ϕ_{B0} remains the same



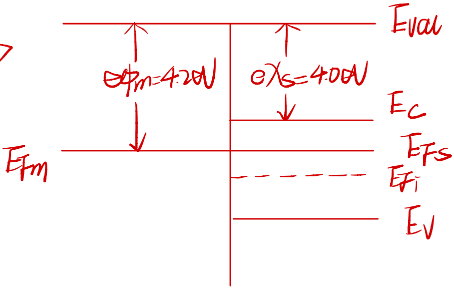
④ forward biased: voltage barrier ↓. ϕ_{B0} —.



Answer

Homework 7.4

a>



please notice in the question, it says no space region exists

Conclusion

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