Introduction to: Bipolar Junction Transistors (BJTs)

(Ch. 10: pp. 371 – 385)

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Outline

1) Introduction
2) Review of PN junctions under bias
3) IV Characteristics
SiGe HBTs

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Circuit board of an Iphone 5

Digital processor (CMOS)
16 GByte Memory (CMOS)
Power Management
RF front-end (analog modules for communication)

MOS transistors

n-channel enhancement mode MOSFET

\[ I_D \approx 0 \]

saturation

linear region

Lundstrom 11.24.14
bipolar transistors

C: collector
B: base
E: emitter

NPN BJT

(forward) active region

saturation region

I_C

V_CE

I_C

V_{BE}, I_{B1}

understanding MOSFETs

To understand this device, we should first draw an Energy Band Diagram.
equilibrium energy band diagram

$V_G$

$E$

$E_C$

$E_F$

$E_Y$

source channel drain

Lundstrom ECE 305 F14

how transistors work

2007 N-MOSFET

$L = 100 \text{ nm}$

$Lundstrom ECE 305 F14$
NPN bipolar transistor

KCL:

\[ I_b + I_c = I_E \]

KVL:

\[ V_{BE} + V_{CB} = V_{CE} \]
transistor structures

**double diffused BJT**

common base (active region)

BE: FB $V_{EB} < 0$

BC: RB $V_{CB} > 0$
To understand this device, we should first draw an Energy Band Diagram.
final result: one semiconductor with 3 regions

how bipolar transistors work
1) Introduction
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NP junction in equilibrium

\[ P_0 = e^{-qV_{bi}/k_BT} \]

\[ J_1 = J_0 \]
NP junction in FB

\[ J_1 = J_0 e^{\frac{qV_A}{k_B T}} \]

\[ J_0 \]

\[ J = J_1 - J_0 = J_0 \left( e^{\frac{qV_A}{k_B T}} - 1 \right) \]

NP junction in RB

\[ J_1 = J_0 e^{\frac{qV_A}{k_B T}} \]

\[ J_1 \ll J_0 \]

\[ J = J_1 - J_0 \approx -J_0 \]
**NP junction in RB**

\[ J = J_0 \left( e^{V_{bi}/kT} - 1 \right) \]

**NP junction in FB**

Examine the minority electron concentration in the neutral p-region assuming a short p-type region (short base).
NP junction in FB

\[ \Delta n(x) = \frac{n_i^2}{N_A} \left( e^{qV_A/k_B T} - 1 \right) \]

\[ J_n = qD_n \frac{d\Delta n(x)}{dx} \bigg|_{x=0} \]

\[ J_n = q \frac{D_n}{W_B} \Delta n(0) \]

\[ J_n = q \frac{D_n}{W_B} n_i^2 \left( e^{qV_A/k_B T} - 1 \right) \]

NP junction in FB

\[ J_p = q \frac{D_p}{W_E} n_i^2 \left( e^{qV_A/k_B T} - 1 \right) \]
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NPN BJT operation

The large current that flows from the collector to emitter is due to electrons.
NPN BJT operation ($I_C$)

FB/RB  FB/RB

\[ I_1 = q \frac{D_n}{W_B} n_i^2 (e^{\frac{V_{BE}}{kT}} - 1) \quad I_2 = q \frac{D_n}{W_B} n_i^2 (e^{\frac{V_{BC}}{kT}} - 1) \quad I_C = (I_1 - I_2) \]

\[ I_C = I_0 (e^{\frac{V_{BE}}{kT}} - e^{\frac{V_{BC}}{kT}}) \quad I_0 = q \frac{D_n}{W_B} n_i^2 \]

(forward) active region

\[ I_C = I_0 (e^{\frac{V_{BC}}{kT}} - e^{\frac{V_{BC} - V_{CE}}{kT}}) \]

\[ V_{CE} = V_{BE} + V_{CB} \]

\[ V_{CE} = V_{BE} - V_{BC} \]

\[ V_{BC} = V_{BE} - V_{CE} \]

\[ I_C = I_0 (e^{\frac{V_{BC}}{kT}} - e^{\frac{V_{BC} - V_{CE}}{kT}}) \]

\[ I_C = I_0 e^{\frac{V_{BC}}{kT}} (1 - e^{-qV_{CE}/kT}) \]
NPN BJT operation (forward active $I_C$)

\[ I_C = I_0 e^{V_{BE}/kT} \]

\[ I_0 = \frac{q D_n n_t^2}{W_B N_{AB}} \]

(forward) active region

\[ I_C = I_0 \left( e^{V_{BE}/kT} - e^{V_{EC}/kT} \right) \]

\[ I_C = I_0 e^{V_{BE}/kT} \left( 1 - e^{-V_{CE}/kT} \right) \]

\[ V_{BC} = V_{BE} - V_{CE} \]
NPN BJT operation (saturation)

$$I_C = I_0 e^{\frac{\phi_{sc}}{kT}} \left( 1 - e^{-\frac{qV_{CE}}{kT}} \right)$$

$$I_0 = q \frac{D_n}{W_B} \frac{n_i^2}{N_{AB}}$$

BJT operation: base current (active region)

$$I_p = q \frac{D_p}{W_E} \frac{n_i^2}{N_{DE}} \left( e^{\frac{\phi_{sc}}{kT}} - 1 \right)$$
beta in the (forward) active region

\[ I_B = I_p = q \frac{D_{pe} n_i^2}{W_E N_{DE}} (e^{\frac{qV_{BE}}{kT}} - 1) \]

\[ I_C = I_n = q \frac{D_{ne} n_i^2}{W_B N_{AB}} e^{\frac{qV_{BE}}{kT}} \]

\[ \beta_{dc} = \frac{I_C}{I_B} = \frac{D_{ne} N_{DE} W_E}{D_{pe} N_{AB} W_B} \]

\[ I_B = \frac{I_0}{\beta_{dc}} e^{\frac{qV_{BE}}{kT}} \]

\[ I_0 = q \frac{D_{ne} n_i^2}{W_B N_{AB}} \]

common emitter (active region)

\[ I_C = I_0 e^{\frac{qV_{BE}}{kT}} \]

\[ I_0 = q \frac{D_{ne} n_i^2}{W_B N_{AB}} \]

\[ I_B = \frac{I_0}{\beta_{dc}} e^{\frac{qV_{BE}}{kT}} \]
NPN bipolar transistor

\[ I_C = \beta I_B \]

\[ I_E = I_B + I_C = I_C \left( 1 + \frac{1}{\beta_{dc}} \right) \]

\[ I_C = \frac{I_E}{1 + 1/\beta_{dc}} = \frac{\beta_{dc}}{\beta_{dc} + 1} I_E \]

\[ I_C = \alpha_{dc} I_E \]

\[ \alpha_{dc} = \frac{\beta_{dc}}{\beta_{dc} + 1} < 1 \quad \beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}} >> 1 \]

BE: FB \quad V_{BE} > 0

BC: RB \quad V_{CB} = V_{CE} - V_{BE} > 0

 invert active

common base (active region)

Pierret, Fig. 10.4
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