Bipolar Junction Transistors (BJTs)

(Sedra and Smith, 7th Ed., Sec. 6.1)

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BJT’s

1) Transistors
2) PN junction review
3) BJT structures
4) Energy band treatment
5) BJT IV: active region
6) BJT IV: saturation region
Transistor as a “black box”

A small current (or voltage) on the control terminal controls a much larger current through two other terminals.
IV characteristics: resistor

\[ I = \frac{V}{R} \]

Lundström: 2019
IV characteristics: ideal current source

\[ I = I_0 \]

\[ V \]

Lundstrom: 2019
IV characteristics: transistors

C: collector
B: base
E: emitter

NPN BJT

$I_C$ vs $V_{CE}$

“output characteristics”

$V_{BE1}, I_{B1}$

“I”, “saturation region”

“resistor”, base controlled current source “active region”
IV characteristics: real current sources

\[ I = I_0 + \frac{V}{R_0} \]

\( R_0 \): output resistance
IV characteristics: transistors

C: collector
B: base
E: emitter

NPN BJT

output characteristics

output resistance

$L_B$, $I_{B1}$

$L_{BE1}$

$L_{CE}$
Applications of BJT’s

symbol

C: collector

B: base

E: emitter

NPN BJT

I_C

I_B

I_E

Lundstrom: 2019
HBTs

Circuit board of an iPhone 5
Double diffused BJT

Silicon wafer

Lundstrom: 2019
To understand this device, we just need to understand PN junctions.
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This is not a BJT
NP Junction in equilibrium

\[ \Delta E = qV_{bi} \]

\[ V_{bi} = \frac{k_B T}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right) \]

\[ n_n = N_D \]

\[ p_p = N_A \]

N-type

P-type

Lundstrom: 2019
A forward biased junction (FB) injects electrons from the N-side across the junction and into the P-side.

A FB junction also injects holes from the P-side across the junction and into the N-side.
A reverse biased junction (RB junction) collects minority carrier electrons from the P-side.

\[ V_R = -V_A \]

\[ q(V_{bi} - V_A) \]

A reverse biased junction collects minority carrier holes from the N-side.

Lundstrom: 2019
BJT: equilibrium energy band diagram

$E_x$ \quad $E_C(x)$ \quad $E_V(x)$

$qV_{bi1}$ \quad $qV_{bi2}$

N-type emitter \quad P-type base \quad N-type collector

Lundstrom: 2019
Energy band diagrams

https://www.pbs.org/wgbh/americanexperience/features/silicon-timeline-silicon/
BJT: active region energy band diagram

**FB** emitter-base junction injects electrons in the base

**RB** collector-base junction collects electrons that diffuse across the base
BJT: active region energy band diagram

\[ I_C = I_s e^{\frac{V_{BE}}{V_T}} \]

almost independent of collector voltage

Lundström: 2019
Forward biased NP junction

\[ I_n \propto \frac{n_i^2}{N_A} e^{V_D/V_T} \]

\[ I_p \propto \frac{n_i^2}{N_D} e^{V_D/V_T} \]
NPN BJT operation (general)

In general, four currents, two for each junction

Lundstrom: 2019
NPN BJT operation (active)

\[ I_{En} \propto \frac{n_i^2 e^{V_{BE}/V_T}}{N_{AB}} \]

\[ I_{Ep} \propto \frac{n_i^2 e^{V_{BE}/V_T}}{N_{DE}} \]

\[ I_{En} \gg I_{Ep} \quad (N_{DE} \gg N_{AB}) \]

\[ I_C \approx I_{En} \]

\[ I_C = I_S e^{qV_{BE}/k_BT} \]

Lundstrom: 2019
BJT in active region

C: collector
B: base
E: emitter

NPN BJT

Early effect: \[ I_C = I_S e^{V_{BE}/V_T} \left(1 + V_{CE}/V_A \right) \]

Lundstrom: 2019
Base current

\[ I_C = I_{En} \approx \frac{n_i^2}{N_{AB}} e^{V_{BE}/V_T} \]

\[ I_B \approx I_{Ep} \approx \frac{n_i^2}{N_{DE}} e^{V_{BE}/V_T} \ll I_C \]

\[ I_B = \frac{I_S}{\beta} e^{V_{BE}/V_T} \ll I_C \]

10 < \beta < 1000

Lundstrom: 2019
BJT in active region (beta = 100)

\[ I_C = I_S e^{V_{BE}/V_T} \]

NPN BJT

\[ I_C = \frac{I_S}{\beta} e^{V_{BE}/V_T} \]

active region
EB: FB, BC: RB

\[ V_{CE} \]
BJTs at low $V_{CE}$

What happens here (at low $V_{CE}$)?

Lundstrom: 2019
NPN BJT at low $V_{CE}$

KVL:

$$V_{BE} + V_{CB} = V_{CE}$$

Active region:

$$V_{BE} \approx 0.7 \text{ V}$$

If:

$$V_{CE} < V_{BE}$$

$$V_{CB} < 0$$

The base-collector junction is forward biased!

Lundstrom: 2019
NPN BJT operation (saturation)

Lundstrom: 2019
BJT at low $V_{CE}$

NPN BJT

$E$: emitter
$B$: base
$C$: collector

$I_E$, $I_B$, $I_C$

saturation region
$EB$: $FB$, $BC$: $FB$

$I_C < I_S e^{qV_{BE}/k_B T}$
$I_B > \frac{I_C}{\beta}$

Lundstrom: 2019
Three regions

C: collector
B: base
E: emitter

NPN BJT

$V_{CE}$

$I_C$

Active region
EB: FB, BC: RB

Saturation region
EB: FB, BC: FB

Cut-off region
EB: RB, BC: RB

Lundstrom: 2019
A BJT consists of two, interacting PN junctions.

BJTs come in two flavors – NPN and PNP.

In the active region, the EB junction is forward biased and the BC junction is reverse biased.

In the active region, a small base current produces a much larger collector current.
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