BJT Intro and Large Signal Model
VLSI Chip Manufacturing Process

Fabrication involves many repetitions of four basic steps:
- Photolithography: transfer mask patterns to the chip
- Diffusion or Ion Implantation: selective doping of Si
- Oxidation: SiO₂ growth
- Deposition: Al, polysilicon and Si₃N₄ (silicon nitride) thin films
0.35 mm SiGe BiCMOS Layout for RF (3.5 GHz) Two-Stage Power Amplifier

Each transistor above is realized as net of four heterojunction bipolar transistors (HBT)
Why BJT?

What's the competition to BJT and bipolar technologies?

What advantages does the competition have over BJT?

What advantages does BJT and bipolar technologies have over their competition?

What circuit applications benefit from BJT and bipolar technologies?
Why BJT

What's the competition to BJT and bipolar technologies?
MOSFET, in particular CMOS is the leading competitor.

What advantages does the competition have over BJT?
Small size (die area), low cost and low power dissipation.

What advantages does BJT and bipolar technologies have over their competition?
High frequency operation, high current drive, high reliability in severe environmental conditions.

What circuit applications benefit from BJT and bipolar technologies?
RF analog and digital circuits, power electronics and power amplifiers, automobile electronics, radiation hardened electronics.
BJT Physical Configuration

NPN

Each transistor looks like two back-to-back diodes, but each behaves much differently!

Closer to actual layout

PNP

2010 by Kenneth R. Laker, update 15Sep10 KRL
BJT Symbols and Conventions

NPN

PNP

\[ I_E = I_C + I_B \]

Note reversal in current directions and voltage signs for PNP vs. NPN!
NPN BJT Modes of Operation

Forward-Active Mode
EBJ forward bias \( (V_{BE} > 0) \)
CBJ reverse bias \( (V_{BC} < 0) \)

\[
\begin{align*}
i_E &= i_C + i_B \\
v_{CE} &= v_{CB} + v_{BE} \\
v_{XY} &= V_{XY} + v_{xy}
\end{align*}
\]

Not Useful!

\[
V_{BC} = -V_{CB}
\]

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**NPN BJT Modes of Operation**

- **Saturation region**
- **Forward-Active region**

### Mode

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*Not Useful!*
NPN BJT Forward-Active Current Flow

Forward-biased

Injected electrons

Injected holes ($i_{B1}$)

Injected electrons

Collected electrons ($i_{B2}$)

Recombined electrons

$V_{BE}$

$V_{CB}$

$V_{BE}$

$V_{CB}$

$E$

$C$

$B$

$i_E$

$i_C$

$i_B$

$i_{E1}$

$i_{E2}$

$i_B = i_{B1} + i_{B2}$

$i_E = i_C + i_B$
NPN BJT Forward-Active Mode Basic Model

Collector-base diode is reverse biased
\[ V_{CB} > 0 \quad ( \text{or} \quad V_{BC} < 0) \]

Base-emitter diode is forward biased
\[ V_{BE} \approx 0.7 \]
\[ I_s = \frac{A_E q D_n n_i^2}{N_A W} \]

\[ i_C \approx I_s e^{\frac{V_{BE}}{V_T}} \]
\[ V_T = \frac{kT}{q} \approx 25 \text{mV} @ 25^\circ C \]
\[ i_B = \frac{i_C}{\beta} \]
\[ i_E = i_B + i_C = (\beta + 1)i_B \]

- \( A_E \) Area of base-emitter junction
- \( W \) Width of base region
- \( N_A \) Doping concentration in base
- \( D_n \) Electron diffusion constant
- \( n_i \) Intrinsic carrier concentration = f(T)

\( \beta = \text{common-emitter current gain} \)
**NPN BJT Forward-Active Beta ($\beta$)**

\[
\beta = \frac{1}{\frac{D_p}{D_n} \frac{N_A}{N_D} \frac{W}{L_p} + \frac{1}{2} \frac{W^2}{D_n \tau_b}}
\]

- $A_E$ -> Area of base-emitter junction
- $W$ -> Width of base region
- $N_A$ -> Doping concentration in base
- $N_D$ -> Doping concentration in emitter
- $D_n$ -> Electron diffusion constant
- $D_p$ -> Hole diffusion constant
- $L_p$ -> Hole diffusion length in emitter
- $\tau_b$ -> Minority-carrier lifetime
- $n_i$ -> Intrinsic carrier concentration = $f(T)$

Large $\beta$ =>
- $N_A$ -> small
- $N_D$ -> large
- $W$ -> small
Note that the $i_C$ equation looks like that of a forward-biased diode collector-base. Is it?

$$i_C = I_S(e^{\frac{v_{BE}}{V_T}} - 1)$$

Using Eqs. $i_E = i_B + i_C$ and $i_C = \beta i_B$ we can answer this question, i.e.

$$i_E = i_B + i_C = \left(\frac{1}{\beta} + 1\right)i_C = \frac{\beta + 1}{\beta}i_C$$

and write:

$$i_E = \frac{\beta + 1}{\beta} I_S \left(e^{\frac{v_{BE}}{V_T}} - 1\right) = \frac{1}{\alpha} I_S \left(e^{\frac{v_{BE}}{V_T}} - 1\right) = \frac{i_C}{\alpha}$$

where $\alpha = \frac{\beta}{1 + \beta}$

AhHa! This $i_E$ equation describes a forward-biased emitter-base “diode”.
So the new set of equations are:

\[ i_E = \frac{I_S v_{BE}}{\alpha} (e^{\frac{v_{BE}}{V_T}} - 1) \]

\[ i_C = I_S (e^{\frac{v_{BE}}{V_T}} - 1) = \alpha i_E \]

\[ i_B = \frac{i_C}{\beta} \]

\[ I_s = \frac{A_E q D_n n_i^2}{N_A W} \]

Where:

\[ \alpha = \frac{\beta}{\beta + 1} \]

Typically:

\[ 50 < \beta < 200 \Rightarrow 0.980 < \alpha < 0.995 \]

\[ 10^{-18} < I_s < 10^{-12} \text{ A.} \]

\( I_s \) is strongly temperature-dependent, doubling for a 5 degree Celsius increase in ambient temperature!
Two equivalent large signal circuit models for the \textit{forward-active mode} NPN BJT:

\[ i_C = I_S \left( e^{v_{BE}/V_T} - 1 \right) \approx I_S \frac{v_{BE}}{V_T} \]

\[ i_C \approx I_s e^{v_{BE}/V_T} = \alpha_F i_E \]

\[ i_E \approx \frac{I_S}{I_{SE}} e^{v_{BE}/V_T} \]

\[ i_B = i_E - i_C = \frac{1}{\beta} i_C \]

Key Eqs.
Yet another NPN BJT large signal model

\[ i_C = \beta i_B \approx I_S e^{\frac{v_{BE}}{V_T}} \Rightarrow i_B \approx \frac{I_S}{\beta} e^{\frac{v_{BE}}{V_T}} \]

This “looks like” a diode between base and emitter and the equivalent circuit becomes:

Note that in this model, the diode current is represented in terms of the base current. In the previous ones, it was represented in terms of the emitter current.
NPN BJT Operating in the Reverse-Active Mode

Recall for NPN Reverse-Active Mode $V_{BE} < 0 \& V_{BC} > 0$

- Weak transistor action if we:
  - Forward bias the base-collector junction and
  - Reverse bias the base-emitter junction
  - Collector and emitter reverse roles
- The physical construction of the transistor results
  - Weak reverse-active performance
    - Small values of $\beta$ on the order of $0.01$ to $1$
    - Correspondingly smaller values of $\alpha$, e.g.

$$\alpha_R = \frac{\beta_R}{\beta_R + 1} \approx \frac{0.1}{1.1} \approx 0.091 \text{ for } \beta_R = 0.1$$
The equivalent large signal circuit model for the **reverse-active mode** NPN BJT:

**Key Eqs.**

- Collector and emitter reverse roles

- Key Eqs.

- BJT is non-symmetrical:
  \[ \alpha_R \ll \alpha_F \quad \beta_R \ll \beta_F \]

- Note that the directions of the reverse-active currents are the reverse of the forward-active currents; hence the “minus” signs.
The Ebers-Moll Large Signal Model

The E-M model combines the FWD & RVRS Active equivalent circuits:

\[
\begin{align*}
    i_C &= \alpha_F i_{DE} - i_{DC} \\
    i_E &= i_{DE} - \alpha_R i_{DC} \\
    i_B &= (1 - \alpha_F) I_{DE} + (1 - \alpha_R) I_{DC}
\end{align*}
\]

\[
\begin{align*}
    i_{DE} &= \frac{I_S}{\alpha_F} \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) \\
    i_{DC} &= \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right)
\end{align*}
\]

Note that the lower left diode and the upper right controlled current source form the forward-active mode model, while the upper left diode and the lower right source represent the reverse-active mode model.
Operation in the Saturation Mode

Recall for Saturation Mode \( v_{BE} > 0 \) & \( v_{BC} > 0 \) (or \( v_{CB} < 0 \))

Consider the E-M model for collector current.

\[
i_C = \alpha_F i_{DE} - i_{DC}
\]

\[
i_C = I_S \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right)
\]

The first term is the forward mode collector current:

\[
\alpha_F i_{DE} = I_S \left( e^{\frac{v_{BE}}{V_T}} - 1 \right)
\]

The second is the reverse mode collector current:

\[
i_{DC} = \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right)
\]
Combining terms:

\[ i_C = I_S \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right) \]

Using typical values:

\[ \beta_R = 0.1 \]
\[ I_S = 10^{-14} \, A \]
\[ V_T = 0.025 \, V \]

We obtain:

\[ i_C = \left[ \left( e^{40v_{BE}} - 1 \right) - 11 \left( e^{-40v_{CB}} - 1 \right) \right] 10^{-14} \]

Let's plot \( i_C \) vs. \( v_{BC} \) (or \( v_{CB} \)) with \( v_{BE} = 0.7 \, V \)
Scilab Saturation Mode Calculation

//Calculate and plot npn BJT collector
//current in saturation mode
vBE=0.7;
VsubT=0.025;
VTinv=1/VsubT;
betaR=0.1;
IsubS=1E-14;
alphaR=betaR/(betaR+1);
alphaInv=1/alphaR;
ForwardExp=exp(VTinv*vBE)-1;
vCB=-0.7:0.001:-0.1;
vBC=-vCB;
ReverseExp=alphaInv*(exp(VTinv*vBC)-1);
iC=(ForwardExp-ReverseExp)*IsubS;
signiC=sign(iC);
iCplus=(iC+signiC.*iC)/2; //Zero negative values
plot(vCB,1000*iCplus);  //Current in mA.

\[ i_C = I_S \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right) \]
Saturation Mode Plot

Saturation Mode Collector Current

Recall for Sat. Mode
\( v_{BE} > 0 \)
\&
\( v_{BC} > 0 \)
(or \( v_{CB} < 0 \))

Note: forward-active NPN operation continues for negative \( v_{CB} \)
down to \( -0.5V \); i.e. \( v_{CB} > -0.5V \)

Forward-active

\[ i_C = [(e^{40v_{BE}} - 1) - 11(e^{-40v_{CB}} - 1)] \times 10^{-14} A \]

\[ v_{BE} = 0.7V \]

\( v_{CB}(V) \)
Scilab Plot of NPN Characteristic  

\[ (i_C \text{ vs. } v_{CE} \text{ and } v_{BE}) \]

//Calculate and plot npn BJT collector  
//characteristic using Ebers-Moll model  
VsubT=0.025;  
VTinv=1/VsubT;  
betaR=0.1;  
alphaInv=(betaR+1)/betaR;  
IsubS=1E-14;  
for vBE=0.6:0.02:0.68  
    ForwardExp=exp(VTinv*vBE)-1;  
    vCE=-0:0.001:10;  
    vBC=vBE-vCE;  
    ReverseExp=alphaInv*(exp(VTinv*vBC)-1);  
    IC=(ForwardExp-ReverseExp)*IsubS;  
    signiC=sign(IC);  
    ICplus=(IC+signiC.*IC)/2; //Zero negative vals  
    plot(vCE,1000*ICplus);    //Current in mA.  
end  

\[ i_C = I_S \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right) \]
Plot Output

NPN Transistor Collector Characteristic

Early effect not included.

@ start of saturation $V_{CEsat} = v_{CE} = v_{CB} + v_{BE} \approx -0.4V + 0.7V = 0.3V$

$\begin{align*}
\phi &= 0.68 V \\
\phi &= 0.66 V \\
\phi &= 0.64 V \\
\phi &= 0.62 V
\end{align*}$
More on NPN Saturation

- The base-collector diode has much larger area than the base-emitter one.
- Therefore, with the same applied voltage, it will conduct a much larger forward current than will the base-emitter diode.

\[ i_C = I_S \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right) \text{ where } \alpha_R \ll 1 \]

- When the collector-emitter voltage drops below the base-emitter voltage, the base-collector diode is forward biased and conducts heavily.

\[ v_{CB} = v_{CE} - v_{BE} \quad \Rightarrow \quad v_{CE} \approx V_{CESat} = v_{CB} + v_{BE} \approx 0.3 V \]
More on NPN Saturation - cont.

- In saturation the forward-biased the current through the collector-base junction increases $i_B$ and decreases $i_C$ as $v_{BC}$ increases.

$$\beta_{\text{sat}} = \beta_{\text{forced}} = \left(\frac{i_C}{i_{B \text{ sat}}}\right) \leq \beta$$

- Test for saturation mode operation
  - $v_{CE} = V_{CE\text{sat}} = 0.1$ to $0.3 \text{ V}$ => collector-base junction is forward biased
  - Current ratio $\left(\frac{i_C}{i_{B \text{ sat}}}\right) \leq \beta$ => collector-base junction is forward biased
Note that the collector current is zero at about $v_{CE} = 0.06 \, V$, not $0 \, V$!

Also note the large reverse collector-base current for $v_{CE} < 0.06 \, V$. 

Diode forward voltage

$\begin{align*}
  v_{BE} &= 0.68 \, V, \\
  v_{CE} &= 0.25 \, V, \\
  v_{BC} &= v_{BE} - v_{CE} = 0.43 \, V
\end{align*}$
Voltage at Zero Collector Current

\[ i_C = I_S \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right) \]

\[ \alpha_R \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) = \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) \]

\[ \alpha_R \left( 1 - e^{-\frac{v_{BE}}{V_T}} \right) = \left( e^{\frac{v_{BE}}{V_T}} - e^{-\frac{v_{BE}}{V_T}} \right) \]

\[ \frac{V_{BE}}{V_T} \approx 40 \times 0.7 \Rightarrow e^{-\frac{v_{BE}}{V_T}} \ll 1 \]

\[ \alpha_R = e^{-\frac{v_{CE}}{V_T}} \Rightarrow v_{CE} = -V_T \ln(\alpha_R) \]

For \( \beta_R = 0.1 \Rightarrow \alpha_R = 0.09 \Rightarrow v_{CE} = -0.06 \text{ V} \]
The PNP Transistor

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$V_{CB} = -V_{BC}$

Not Useful!
PNP BJT Forward-Active Mode Basic Model

Collector-base diode is reverse biased

\[ V_{BC} > 0 \]

Emitter-base diode is forward biased

\[ V_{EB} \approx 0.7 \]

Note reversal in voltage polarity and in current directions!

\[ i_C = I_S \left( e^{\frac{V_{EB}}{V_T}} - 1 \right) \]

\[ i_B = \frac{i_C}{\beta} \]

\[ i_E = i_B + i_C = (\beta + 1) i_B \]
PNP BJT Large Signal Model

FWD. Active

Note reversal in current directions!

Substituting, as in the npn case, we get:

\[ i_E = i_B + i_C = (\beta + 1) i_B \]
Yet another PNP BJT large signal model

\[ i_C = \beta i_B = I_S (e^{\frac{V_{EB}}{V_T}} - 1) \Rightarrow i_B = \frac{I_S}{\beta} (e^{\frac{V_{EB}}{V_T}} - 1) \approx \frac{I_S}{\beta} e^{\frac{V_{EB}}{V_T}} \]

This “looks like” a diode between base and emitter and the equivalent circuit becomes:

Again, in this model, the diode carries only base current, not emitter current.