BJT Intro and Large Signal Model
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 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 have over their competitors?
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!

PNP

Closer to actual layout
BJT Symbols and Conventions

NPN

PNP

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

<table>
<thead>
<tr>
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**Equations:**

- $i_E = i_C + i_B$
- $V_{CE} = V_{CB} + V_{BE}$

**Diagrams:**

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

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**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

\[ V_{BE} \approx 0.7 \]

saturation current

\[ i_C \approx I_S \left( \frac{v_{BE}}{V_T} \right) \]

\[ V_T = \frac{kT}{q} \approx 25 \text{ mV} \at 25^\circ \text{C} \]

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

\[ i_E = i_B + i_C = (\beta + 1)i_B \]

\[ \beta = \text{common-emitter current gain} \]

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Area of base-emitter junction

Width of base region

Doping concentration in base

Electron diffusion constant

Intrinsic carrier concentration = f(T)

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Note that the $i_C$ equation looks like that of a forward-biased diode.

$$i_C \approx I_S e^{\frac{v_{BE}}{V_T}}$$

Is it?

Also, $i_C$ is independent of $v_{CB}$?
Note that the $i_C$ equation looks like that of a forward-biased diode. Is it?

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

By using the other two equations the question can be answered

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

and write:

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

AhHa! This $i_E$ equation describes a forward-biased emitter-base “diode”.

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So the new set of equations is:

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

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

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

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

Where:

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

Typically:

\[ 50 < \beta < 200 \]

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

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

(a) Nonlinear VCCS

(b) Nonlinear CCCS

Key Eqs.

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

\[ i_E \approx I_S \frac{v_{BE}}{V_T} e^{-\frac{v_{BE}}{V_T}} \]

\[ \alpha = \alpha_F \]
Yet another NPN BJT large signal model

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

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 $V_{BE} < 0$ & $V_{BC} > 0$

- We also have transistor action if we:
  - Forward bias the base-collector junction and
  - Reverse bias the base emitter junction
- The physical construction of the transistor, however, leads to betas on the order of 0.01 to 1 and correspondingly smaller values of alpha, e.g.:

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

\[ i_C \approx -I_S e^{\frac{v_{BC}}{V_T}} \]

\[ i_E \approx -I_S e^{\frac{v_{BC}}{V_T}} \]

Sat. or Scale Current Eq.

\[ \alpha_F I_{SE} = \alpha_R I_{SC} = I_S \]

Key Eqs.

BJT is non-symmetrical

\[ \alpha_R \ll \alpha_F \quad \beta_R \ll \beta_F \]

\[ A_C > A_E \]
The Ebers-Moll Large Signal Model

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

\[ i_C = \alpha_F i_{DE} - i_{DC} \]
\[ i_E = i_{DE} - \alpha_R i_{DC} \]
\[ i_b = (1 - \alpha_F) I_{DE} + (1 - \alpha_R) I_{DC} \]

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.

\[ i_{DE} = I_{SE} \left( e^{\frac{v_{BE}}{V_T}} - 1 \right) \]
\[ i_{DC} = I_{SC} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right) \]
\[ \alpha_F I_{SE} = \alpha_R I_{SC} = I_S \]
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. We will include the “$-I_S$” term in the ideal diode equation.

$$i_C = \alpha_F i_{DE} - i_{DC}$$

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

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:

\[ \beta_R = 0.1 \]

\[ I_S = 10^{-14} \text{ A.} \]

\[ V_T = 0.025 \text{ V.} \]

We obtain:

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

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

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

\[ i_C = \left[ (e^{40V_{BE}} - 1) - 11(e^{-40V_{CB}} - 1) \right] \times 10^{-14} A \]
The PNP Transistor

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**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!

\[
\begin{align*}
i_C &= I_S \left( e^{\frac{V_{EB}}{V_T}} - 1 \right) \\
i_B &= \frac{i_C}{\beta} \\
i_E &= i_B + i_C = (\beta + 1)i_B
\end{align*}
\]
PNP BJT Large Signal Model
FWD. Active

Note reversal in current directions!

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

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

\[ i_E = i_B + i_C = (\beta + 1) i_B \]

Substituting, as in the npn case, we get:

\[ i_E = I_S \frac{v_{EB}}{\alpha} \left( e^{\frac{v_{EB}}{V_T}} - 1 \right) \]
Yet another PNP BJT large signal model

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

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.
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

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

where

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

\[i_{DC} = I_{SC} \left( e^{\frac{v_{BC}}{V_T}} - 1 \right)\]

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

No Early effect
Plot Output

NPN Transistor Collector Characteristic

$I_C$ (mA) vs $V_{CE}$ (V)

Saturation mode

Forward-active mode

Early effect not included.

$v_{BE} = 0.68 \text{V}$

$v_{BE} = 0.66 \text{V}$

$v_{BE} = 0.64 \text{V}$
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.
- When the collector-emitter voltage drops below the base-emitter voltage, the base-collector diode is forward biased and conducts heavily.

\[ v_{CB} = v_{CE} - v_{BE} \quad \text{when} \quad v_{CE} \approx V_{CE} (\text{sat}) \]
$I_C$ Expansion Around Zero $V_{CE}$

Note that the collector current is zero at about $V_{CE} \approx 0.06 \text{ V}.$, not 0 V.!
Also note the large reverse collector-base current below 0.06 V.
Voltage at Zero Collector Current

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

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

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

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

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

\[ v_{CE} = -0.025 \cdot \ln \left( \frac{0.1}{0.1 + 1} \right) = 0.0599 \text{V.} \]