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

by Kenneth R. Laker, update 04Sep13 KRL
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?
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RF analog & digital circuits, power electronics, wireless communications, automobile electronics, rad hard electronics.
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MOSFET, in particular CMOS is the leading competitor

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Moore's Law

Curve shows transistor count doubling every two years
Moore's Law and Moore Equivalent Scaling

International Technology Road Map for Semiconductors

by Kenneth R. Laker, update 04Sep13 KRL
0.35 μm SiGe BiCMOS Layout for RF (3.5 GHz) Two-Stage Power Amplifier

Each transistor above is realized as a net of four parallel HBTs

“Design of a SiGe BiCMOS Power Amplifier for WiMAX Application” by Cheng-Chi Yu, Yao-Tien Chang, Meng-Hsiang Huang, Luen-Kang Lin, and Hsiao-Hua Yeh, 2009
0.35 \( \mu \text{m} \) SiGe BiCMOS Layout for RF (3.5 GHz) Two-Stage Power Amplifier
BJT Physical Configuration

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

Closer to actual layout
BJT Symbols and Conventions

NPN

PNP

Note reversal in current directions and voltage signs for PNP vs. NPN!

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### NPN BJT Modes of Operation

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

**Reverse-Active Mode**
- Not Useful!

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**Diagrams:**
- Forward-Active Mode: 
  - $i_E = i_C + i_B$
  - $v_{CE} = v_{CB} + v_{BE}$
- Reverse-Active Mode: 
  - $V_{BC} = -V_{CB}$

**Equations:**
- $v_{XY} = V_{XY} + v_{xy}$
- $v_{CE} = v_{CB} + v_{BE}$
- $i_E = i_C + i_B$
### NPN BJT Modes of Operation

**Saturation region**

**Forward-Active region**

\[ I_E = I_C + I_B \]

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

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

Not Useful!
NPN BJT Forward-Active Current Flow

\[ i_E = i_B + i_C \]

Emitters-base junction (EBJ)

Collector-base junction (CBJ)

Metal contact

Emitter (E)

Base (B)

Collector (C)

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NPN BJT Forward-Active Current Flow

\[ n_p(0) = n_{p0} e^{\frac{v_{BE}}{V_T}} \]

Forward-biased \( n_p(W) = 0 \)

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

Injected holes \( (i_{B1}) \)
Recombined electrons \( (i_{B2}) \)
Injected electrons
Collected electrons

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NPN BJT Forward-Active Mode Basic Model

Collector-base diode is reverse biased

\[ V_{CB} \geq 0 \quad \text{or} \quad V_{BC} \leq 0 \]

Base-emitter diode is forward biased

\[ V_{BE} \approx 0.7 \]

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

Saturation or scale current

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

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

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

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

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

\[ A_E \text{ Area of base-emitter junction} \]

\[ W \text{ Width of base region} \]

\[ N_A \text{ Doping concentration in base} \]

\[ D_n \text{ Electron diffusion constant} \]

\[ n_i \text{ Intrinsic carrier concentration } = f(T) \]
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
With \( i_C > 0 \) one might conclude that the collector – base junction or diode is forward-biased - hmm!. BUT, we know the collector-base junction is reverse bias. What gives?

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

Using Eqs. \( i_E = i_B + i_C \) and \( i_C = \beta i_B \) to derive \( i_E \), i.e.

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

\( \beta = \text{common-emitter current gain} \)

\( \alpha = \text{common-base current gain} \)

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 \( \alpha = \frac{\beta}{1 + \beta} \)

With \( i_E > 0 \) the emitter-base “diode” is forward-biased.
The basic BJT Fwd. Act. equations (model) are:

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

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

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

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

Where:

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

Typically:

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

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

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

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

**Nonlinear VCCS**

**Nonlinear CCCS**

Key Eqs.

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

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

\[ i_C = \frac{1}{\beta} i_C \]

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

by Kenneth R. Laker, update 04Sep13 KRL
Yet another NPN BJT large signal model

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

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

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

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

Note \( \beta \gg 1 \Rightarrow \alpha \approx 1 \)

Sometimes used approximation:

\[ \beta = \infty \Rightarrow \alpha = 1 \]

Hence:

\[ i_E = i_C \Rightarrow i_B = 0 \]

1. At this limit the BJT resembles an MOS.
2. Be careful when using this approximation – important details are lost.
$i_C = I_S \left( e^{V_{BE}/V_T} - 1 \right)$

Tangent point ($i_C$ vs. $V_{BE}$)

$0.6 \leq V_{BE} \leq 0.8V$

Another approximation: $V_{BE} \approx 0.7V$  Fwd. Act. BJT

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Forward Active BJT Model Configuration Options

“T” Configuration

“Π” Configuration
NPN BJT Operating in the Reverse-Active Mode

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

- 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.

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

Key Eqs.

$$i_C \approx -I_S e^{\frac{v_{BC}}{V_T}} = -I_S e^{\frac{v_{BC}}{V_T}}$$

$$i_E \approx -I_S e^{\frac{v_{BE}}{V_T}} = \alpha_R i_C$$

BJT is non-symmetrical

$$\alpha_R \ll \alpha_F$$

$$\beta_R \ll \beta_F$$

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:

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.

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

- $i_C$: Collector current
- $v_{BE}$: Base-emitter voltage
- $I_S$: Saturation current
- $\alpha_F$: Forward current gain
- $\beta$: Early voltage gain
- $v_{BE}$: Base-emitter voltage
- $I_{SE}$: Saturation current
- $D_E$: Emitter junction diode

Symbols:
- $\downarrow$: Current out
- $\uparrow$: Current in
Operation in the Saturation Mode

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

Consider the E-M model for collector current.

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

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

The first term is the forward mode collector current:

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

The second is the reverse mode collector current.

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

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

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

\[ \frac{1}{\alpha_R} = \frac{\beta_R + 1}{\beta_R} \]

We obtain:

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

Using typical values:

\[ \beta_R = 0.1 \]

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

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

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;

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

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 \( v_{CB} < 0 \))

Note: forward-active NPN operation continues for positive \( v_{BC} \) up to about 0.5V; or \( v_{CB} \geq -0.5V \)

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

\[ v_{BE} = 0.7V \]

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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
Early effect not included.

@ start of saturation $V_{CEsat} = V_{CE} = -V_{BC} + V_{BE} \approx -0.5 \, V + 0.7 \, V \approx 0.2 \, V$
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.

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

where \( \alpha_R << 1 \)

- When \( v_{CE} \) drops below \( v_{BE} \), the base-collector diode is forward biased \( (v_{BC} > 0) \) and conducts heavily.

Let \( V_{BE} = 0.7 \text{ V} \) & \( V_{CE} = 0.2 \text{ V} \) \( \Rightarrow \) \( v_{BC} = v_{BE} - v_{CE} \approx 0.5 \text{ V} \)
More on NPN Saturation - cont.

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

$$\beta_{sat} = \beta_{forced} = \left( \frac{i_C}{i_B} \right)_{sat} \leq \beta$$

- Test for saturation mode operation
  - $V_{CE} = V_{CESat} = 0.2$ to $0.3$ $V$ => collector-base junction is forward biased
  - or
  - Current ratio $\left( \frac{i_C}{i_B} \right)_{sat} \leq \beta$ => collector-base junction is forward biased
More on NPN Saturation - cont.

Does $i_C = 0 A \Rightarrow v_{CE} = 0 V$?
Voltage at Zero Collector Current

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

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

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

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

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

For \( \beta_R = 0.1 \Rightarrow \alpha_R = 0.09 \Rightarrow v_{CE} = 0.06 \, 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

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

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

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

Substituting, as in the npn case, we get:

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

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

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