05 Bipolar Junction Transistors (BJTs) basics

The first bipolar transistor was realized in 1947 by Brattain, Bardeen and Shockley. The three of them received the Nobel prize in 1956 for their invention. The bipolar transistor is composed of two PN junctions and hence is also called the "Bipolar Junction Transistor" (BJT).
There are two types of bipolar transistors: the NPN transistor, in which a P-type region is sandwiched between two N-type regions, and the PNP transistor, where N-type silicon is confined between two P-type regions.
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Long-base device
If the width of the neutral base, is large enough, all the electrons injected by the emitter into the base recombine in the P-type material, because the base width is larger than the electron diffusion length in the base. There is no interaction between both junctions and therefore no current flowing between emitter and collector. Neglecting the small reverse current in the collector-base junction, the only current flowing through the device is between the base and the emitter:
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**Short-base device**

The term "short base" implies that the neutral base width is smaller than the electron diffusion length: $W_B < L_{nB}$

Let the emitter-base junction be forward biased $V_{BE} = V_B - V_E > 0$ and the collector-base junction be reverse biased $V_{BC} = V_B - V_C < 0$

Because the length of the neutral base is smaller than the diffusion length for electrons in the base, a number of electrons injected from the emitter into the base can diffuse to the collector-base junction depletion region, at $x = W_B$

Once there, they are accelerated by the electric field of the depletion region and transported into the collector.
In modern BJTs 99% or more of the electrons injected by the emitter into the base reach the collector.

The magnitude of current flowing in the collector does not depend on magnitude of the collector voltage; the collector-base junction simply needs to be reverse biased.

This effect, in which the current in a junction is controlled by the bias applied to another junction, is called "transistor effect".
Symbolic representation, applied bias, and currents in an NPN bipolar transistor.
A BJT transistor with a forward-biased emitter-base junction and a reverse-biased collector-base junction is said to operate in the **forward active mode**.

If both junctions are forward biased the transistor is said to be in **saturation**. In that case electrons are injected from the emitter through the base into the collector and from the collector through the base into the emitter.

If both junctions are reverse biased there is no current flow at all and the device is in the **cut-off mode**.

If the emitter junction is reverse biased and the collector junction is forward biased the transistor operates in the **reverse active mode**.
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BJT Current gain

The current flowing through the emitter junction is given by the sum of the hole current injected from the base into the emitter and the electron current injected from the emitter into the base. The ratio between these two current components

\[
\frac{I_{nE}}{I_{pE}} = \frac{D_n n_p o L_p}{D_p p_n o L_n} = \sqrt{\frac{\mu_n \tau_p}{\mu_p \tau_n}} \frac{N_{dE}}{N_{aB}}
\]

where \( N_{aB} \) and \( N_{dE} \) are the doping concentrations in the base and the emitter, respectively.
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BJT circuit configurations

Common-base configuration

Common-emitter configuration
BJT Currents

The collector current, $I_{nC}$ is due to the diffusion through the base of electrons injected by the emitter into the base.

$$I_{nC} = I_{nE} - I_{rB},$$

where $I_{rB}$ is the current due to the recombination of electrons in the base.

The base current is equal to

$$I_{pE} + I_{rB};$$

For the convention for current direction as shown

$$I_C + I_B + I_E = 0$$
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BJT Current Gain

Common base gain, $\alpha_F$

$$I_C = - \alpha_F I_E$$

or,

$$I_C = \frac{\alpha_F}{1 - \alpha_F} I_B$$

Common emitter gain, $\beta_F$

$$I_C = \beta_F I_B$$

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

The value of $\alpha_F$ in typical bipolar transistors is approximately 0.99. As a result, the value of the current gain, $\beta_F$, usually ranges between 50 and 300. There are, however, transistors called "super-$\beta$ transistors" which have current gains higher than 1,000 or even 10,000.
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BJT fabrication

[Diagram showing a P-type substrate with labeled regions E, B, and C, and impurity concentration graphs for N+ (arsenic), P (boron), N (arsenic), N+ (antimony), and P-type substrate (boron) as functions of depth, x.]
Amplification using a bipolar transistor

\[ V_{in} = R_S I_B + V_{BE} \quad \text{and} \quad V_{CC} = R_L I_C + V_{CE} \]

For typical Si BJT in the forward active mode,

\[ V_{BE} = 0.7 \, V \quad \text{and} \quad I_C = \beta_F I_B \]

\[ V_{out} = V_{CE} = V_{CC} - \beta_F \frac{R_L}{R_S} (V_{in} - 0.7V) \]

\[ \Delta V_{out} = -\beta_F \frac{R_L}{R_S} \Delta V_{in} \]
Amplification using a bipolar transistor

\[ V_{CC} = R_L I_C + V_{CE} \times I_C = \]

\[ I_C V_{CC} = R_L I_C^2 + I_C V_{CE} \]

- power supplied by the power supply
- power dissipated in the load resistor
- power loss (the price one has to pay to obtain amplification by the transistor.)
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Ebers-Moll model

\[ n(x) = n_{0B} \left\{ 1 + \left[ \exp\left(\frac{qV_{BE}}{kT}\right) -1 \right] \frac{\sinh\left(\frac{w_{B}-x}{L_{nB}}\right)}{\sinh\left(\frac{w_{B}}{L_{nB}}\right)} + \left[ \exp\left(\frac{qV_{BC}}{kT}\right) -1 \right] \frac{\sinh\left(\frac{x}{L_{nB}}\right)}{\sinh\left(\frac{w_{B}}{L_{nB}}\right)} \right\} \]
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Ebers-Moll model

\[ J_{nE} = qD_{nB} \left. \frac{dn}{dx} \right|_{x=0} \]

\[ = - \frac{qD_{nB} n_{oB}}{L_{nB} \tanh \left( \frac{w_B}{L_{nB}} \right)} \left[ \exp \left( \frac{qV_{BE}}{kT} \right) - 1 \right] + \frac{qD_{nB} n_{oB}}{L_{nB} \sinh \left( \frac{w_B}{L_{nB}} \right)} \left[ \exp \left( \frac{qV_{BC}}{kT} \right) - 1 \right] \]

\[ J_{nC} = qD_{nB} \left. \frac{dn}{dx} \right|_{x=w_B} \]

\[ = - \frac{qD_{nB} n_{oB}}{L_{nB} \sinh \left( \frac{w_B}{L_{nB}} \right)} \left[ \exp \left( \frac{qV_{BE}}{kT} \right) - 1 \right] + \frac{qD_{nB} n_{oB}}{L_{nB} \tanh \left( \frac{w_B}{L_{nB}} \right)} \left[ \exp \left( \frac{qV_{BC}}{kT} \right) - 1 \right] \]

\[ I_E = A(J_{pE} + J_{nE}) \]
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Ebers-Moll model

\[ I_E = A(J_{pE} + J_{nE}) \]

\[ I_E = -\left[ \frac{AqD_{pE}p_{pE}}{L_{pE}} + \frac{AqD_{nB}n_{nB}}{L_{nB}tanh\left(\frac{w_B}{L_{nB}}\right)} \right] \left( \exp\left(\frac{qV_{BE}}{kT}\right) - 1 \right) \]

\[ + \frac{AqD_{nB}n_{nB}}{L_{nB}b\sinh\left(\frac{w_B}{L_{nB}}\right)} \left( \exp\left(\frac{qV_{BC}}{kT}\right) - 1 \right) \]

\[ I_C = \frac{AqD_{nB}n_{nB}}{L_{nB}b\sinh\left(\frac{w_B}{L_{nB}}\right)} \left( \exp\left(\frac{qV_{BE}}{kT}\right) - 1 \right) \]

\[ - \left[ \frac{AqD_{nB}n_{nB}}{L_{nB}tanh\left(\frac{w_B}{L_{nB}}\right)} + \frac{AqD_{pC}p_{pC}}{L_{pC}} \right] \left( \exp\left(\frac{qV_{BC}}{kT}\right) - 1 \right) \]
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Ebers-Moll model

Defining the emitter and the collector junctions reverse saturation currents

\[ I_{ES} = \frac{AqD_p E_p E_o}{L_p E} + \frac{AqD_n B n_o B}{L_n B \tanh \left( \frac{w_B}{L_n B} \right)} \]

\[ I_{CS} = \frac{AqD_n B n_o B}{L_n B \tanh \left( \frac{w_B}{L_n B} \right)} + \frac{AqD_p C p_o C}{L_p C} \]

\[ \alpha_F = - \left. \frac{I_C}{I_E} \right|_{V_{BC}=0} \quad \alpha_R = - \left. \frac{I_E}{I_C} \right|_{V_{BE}=0} \]
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Ebers-Moll model

Combining these expressions the Ebers-Moll Equations are

\[ I_E = -I_{ES} \left[ \exp\left(\frac{qV_{BE}}{kT}\right) - 1 \right] + \alpha_{RICS} \left[ \exp\left(\frac{qV_{BC}}{kT}\right) - 1 \right] \]

\[ I_C = \alpha_{FIES} \left[ \exp\left(\frac{qV_{BE}}{kT}\right) - 1 \right] - I_{CS} \left[ \exp\left(\frac{qV_{BC}}{kT}\right) - 1 \right] \]

or, in the matrix form:

\[
\begin{bmatrix}
I_E \\
I_C
\end{bmatrix} = \begin{bmatrix}
-I_{ES} & \alpha_{RICS} \\
\alpha_{FIES} & -I_{CS}
\end{bmatrix} \begin{bmatrix}
\exp(qV_{BE}/kT) - 1 \\
\exp(qV_{BC}/kT) - 1
\end{bmatrix}
\]
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Ebers-Moll model

\[ I_F = I_{ES} \left[ \exp \left( \frac{qV_{BE}}{kT} \right) - 1 \right] \]

\[ I'_R = I_{CS} \left[ \exp \left( \frac{qV_{BC}}{kT} \right) - 1 \right] \]
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Emitter efficiency

\[ \gamma_F = \left. \frac{I_{nE}}{I_{nE} + I_{pE}} \right|_{V_{BC}=0} = \left. \frac{1}{1 + \frac{I_{pE}}{I_{nE}}} \right|_{V_{BC}=0} \]

\[ \gamma_F = \frac{1}{1 + \frac{D_{pE} \rho_{oE} L_{nB}}{D_{nB} n_{oB} L_{pE}} \tanh \left( \frac{w_B}{L_{nB}} \right) } \]

\[ w_B << L_{nB} \]

\[ \gamma_F \approx \frac{1}{1 + \frac{D_{pE} \rho_{oE} L_{nB} w_B}{D_{nB} n_{oB} L_{pE} L_{nB}} } = \frac{1}{1 + \frac{\mu_{pE} \rho_{oE} w_B}{\mu_{nB} n_{oB} L_{pE} L_{nB}} } \]
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Transport factor in the base

\[ \alpha_T = - \left. \frac{I_{nC}}{I_{nE}} \right|_{V_{BC}=0} = \left. \frac{J_{nC}}{J_{nE}} \right|_{V_{BC}=0} \]

\[ \alpha_T = \frac{1}{\cosh\left(\frac{w_B}{L_{nB}}\right)} \]

\[ \alpha_T \approx \frac{1}{1 + \left(\frac{w_B}{L_{nB}}\right)^2} \approx 1 - \frac{(w_B/L_{nB})^2}{2} \]