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BIPOLAR TRANSISTOR

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Annotation
This article is about bipolar transistor. Bipolar transistors and particularly power transistors, have long base-storage times when they are driven into saturation; the base storage limits turn-off time in switching applications. A Baker clamp can prevent the transistor from heavily saturating, which reduces the amount of charge stored in the base and thus improves switching time.

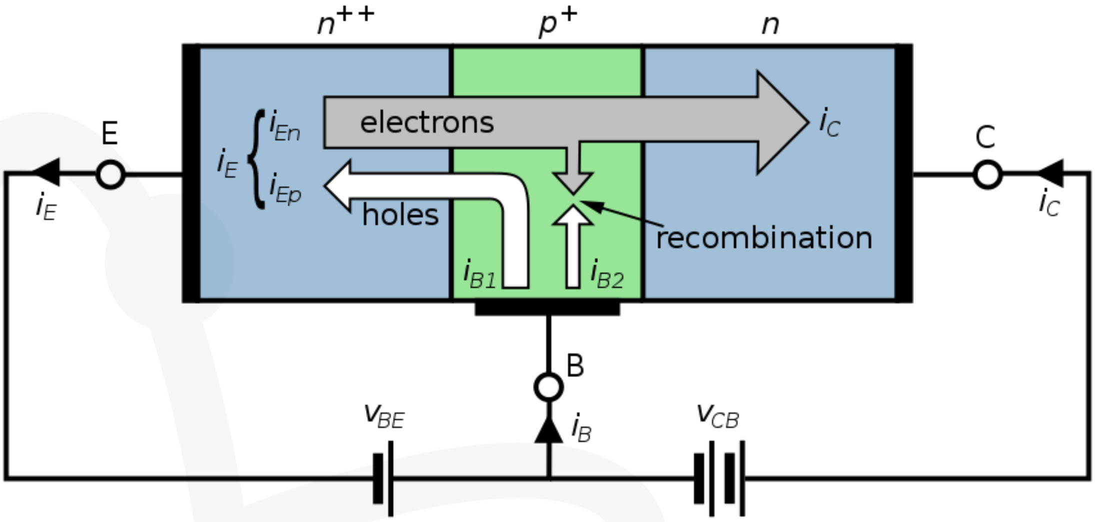
Keywords: bipolar transistor, technique, alternative energy source, mechanics, bipolar junction transistor.

A bipolar junction transistor (BJT) is a type of transistor that uses both electrons and electron holes as charge carriers. In contrast, a unipolar transistor, such as a field-effect transistor, uses only one kind of charge carrier. A bipolar transistor allows a small current injected at one of its terminals to control a much larger current flowing between the terminals, making the device capable of amplification or switching.

BJTs use two junctions between two semiconductor types, n-type and p-type, which are regions in a single crystal of material. The junctions can be made in several different ways, such as changing the doping of the semiconductor material as it is grown, by depositing metal pellets to form alloy junctions, or by such methods as diffusion of n-type and p-type doping substances into the crystal. The superior predictability and performance of junction transistors quickly displaced the original point-contact transistor. Diffused transistors, along with other components, are elements of integrated circuits for analog and digital functions. Hundreds of bipolar junction transistors can be made in one circuit at very low cost.

Bipolar transistor integrated circuits were the main active devices of a generation of mainframe and mini computers, but most computer systems now use integrated circuits relying on field-effect transistors. Bipolar transistors are still used for amplification of signals, switching and in digital circuits. Specialized types are used for high voltage switches, for radio-frequency amplifiers, or for switching high currents.

BJTs exist as PNP and NPN types, based on the doping types of the three main terminal regions. An NPN transistor comprises two semiconductor junctions that share a thin p-doped region, and a PNP transistor comprises two semiconductor junctions that share a thin n-doped region. N-type means doped with impurities (such as phosphorus or arsenic) that provide mobile electrons, while P-type means doped with impurities (such as boron) that provide holes that readily accept electrons.



NPN BJT with forward-biased B–E junction and reverse-biased B–C junction

Charge flow in a BJT is due to diffusion of charge carriers across a junction between two regions of different charge carrier concentration. The regions of a BJT are called emitter, base and collector. A discrete transistor has three leads for connection to these regions. Typically, the emitter region is heavily doped compared to the other two layers, and the collector is doped more lightly than the base (collector doping is typically ten times lighter than base doping). By design, most of the BJT collector current is due to the flow of charge carriers (electrons or holes) injected from a heavily doped emitter into the base where they are minority carriers that diffuse toward the collector and so BJTs are classified as minority-carrier devices.

In typical operation, the base–emitter junction is forward biased, which means that the p-doped side of the junction is at a more positive potential than the n-doped side and the base–collector junction is reverse-biased. When forward bias is applied to the base–emitter junction, the equilibrium between the thermally generated carriers and the repelling electric field of the n-doped emitter depletion region is disturbed. This allows thermally excited electrons (in an NPN; holes in a PNP) to inject from the emitter into the base region. These electrons diffuse through the base from the region of high concentration near the emitter toward the region of low concentration near the collector. The electrons in the base are called minority carriers because the base is doped p-type, which makes holes the majority carrier in the base. In a PNP device, analogous behaviour occurs, but with holes as the dominant current carriers.

To minimize the fraction of carriers that recombine before reaching the collector–base junction, the transistor's base region must be thin enough that carriers can diffuse across it in much less time than the semiconductor's minority-carrier lifetime. Having a lightly doped base ensures recombination rates are low. In particular, the thickness of the base must be much less than the diffusion length of the carriers. The collector–base junction is reverse-biased and so negligible carrier injection occurs from the collector to the base, but carriers that are injected into the base from the emitter and diffuse to reach the collector–base depletion region, are swept into the collector by the electric field in the depletion region. The thin shared base and asymmetric collector–emitter doping are what differentiates a bipolar transistor from two separate diodes connected in series.

Voltage, Current and Charge Control

The collector–emitter current can be viewed as being controlled by the base–emitter current (current control), or by the base–emitter voltage (voltage control). These views are related by the current–voltage relation of the base–emitter junction, which is the usual exponential current–voltage curve of a p–n junction (diode).

The explanation for collector current is the concentration gradient of minority carriers in the base region. Due to low-level injection (in which there are much fewer excess carriers than normal majority carriers) the ambipolar transport rates (in which the excess majority and minority carriers flow at the same rate) is in effect determined by the excess minority carriers.

Detailed transistor models of transistor action, such as the Gummel–Poon model, account for the distribution of this charge explicitly to explain transistor behaviour more exactly. The charge-control view easily handles phototransistors, where minority carriers in the base region are created by the absorption of photons and handles the dynamics of turn-off, or recovery time, which depends on charge in the base region recombining. However, because base charge is not a signal that is visible at the terminals, the current- and voltage-control views are generally used in circuit design and analysis.

In analog circuit design, the current-control view is sometimes used because it is approximately linear. That is, the collector current is approximately times the base current. Some basic circuits can be designed by assuming that the base–emitter voltage is approximately constant and that collector current is β times the base current. However, to accurately and reliably design production BJT circuits, the voltage-control (for example, Ebers–Moll) model is required. The voltage-control model requires an exponential function to be taken into account, but when it is linearized such that the transistor can be modeled as a transconductance, as in the Ebers–Moll model, design for circuits such as differential amplifiers again becomes a mostly linear problem, so the voltage-control view is often preferred. For translinear circuits, in which the exponential I–V curve is key to the operation, the transistors are usually modeled as voltage-controlled current sources whose transconductance is proportional to their collector current. In general, transistor-level circuit analysis is performed using SPICE or a comparable analog-circuit simulator, so mathematical model complexity is usually not of much concern to the designer, but a simplified view of the characteristics allows designs to be created following a logical process.

Bipolar transistors and particularly power transistors, have long base-storage times when they are driven into saturation; the base storage limits turn-off time in switching applications. A Baker clamp can prevent the transistor from heavily saturating, which reduces the amount of charge stored in the base and thus improves switching time.

Transistor Characteristics: Alpha (α) and Beta (β)

The proportion of carriers able to cross the base and reach the collector is a measure of the BJT efficiency. The heavy doping of the emitter region and light doping of the base region causes many more electrons to be injected from the emitter into the base than holes to be injected from the base into the emitter. A thin and lightly-doped base region means that most of the minority carriers that are injected into the base will diffuse to the collector and not recombine.

The common-emitter current gain is represented by β_F or the h-parameter h_{FE}; it is approximately the ratio of the DC collector current to the DC base current in forward-active region. It is typically greater than 50 for small-signal transistors, but can be smaller in transistors designed for high-power applications. Both injection efficiency and recombination in the base reduce the BJT gain.

Another useful characteristic is the common-base current gain, α_F. The common-base current gain is approximately the gain of current from emitter to collector in the forward-active region. This ratio usually has a value close to unity; between 0.980 and 0.998. It is less than unity due to recombination of charge carriers as they cross the base region.

Alpha and beta are related by the following identities:

$$\alpha_F = \frac{I_C}{I_E}, \qquad \beta_F = \frac{I_C}{I_B},$$

$$\alpha_F = \frac{\beta_F}{1+\beta_F} \iff \beta_F = \frac{\alpha_F}{1-\alpha_F}.$$

Beta is a convenient figure of merit to describe the performance of a bipolar transistor, but is not a fundamental physical property of the device. Bipolar transistors can be considered voltage-controlled devices (fundamentally the collector current is controlled by the base–emitter voltage; the base current could be considered a defect and is controlled by the characteristics of the base–emitter junction and recombination in the base). In many designs beta is assumed high enough so that base current has a negligible effect on the circuit. In some circuits (generally switching circuits), sufficient base current is supplied so that even the lowest beta value a particular device may have will still allow the required collector current to flow.

A BJT consists of three differently doped semiconductor regions: the emitter region, the base region and the collector region. These regions are, respectively, p type, n type and p type in a PNP transistor, and n type, p type and n type in an NPN transistor. Each semiconductor region is connected to a terminal, appropriately labeled: emitter (E), base (B) and collector (C).

The base is physically located between the emitter and the collector and is made from lightly doped, high-resistivity material. The collector surrounds the emitter region, making it almost impossible for the electrons injected into the base region to escape without being collected, thus making the resulting value of α very close to unity and so, giving the transistor a large β. A cross-section view of a BJT indicates that the collector–base junction has a much larger area than the emitter–base junction.

The bipolar junction transistor, unlike other transistors, is usually not a symmetrical device. This means that interchanging the collector and the emitter makes the transistor leave the forward active mode and start to operate in reverse mode. Because the transistor's internal structure is usually optimized for forward-mode operation, interchanging the collector and the emitter makes the values of α and β in reverse operation much smaller than those in forward operation; often the α of the reverse mode is lower than 0.5. The lack of symmetry is primarily due to the doping ratios of the emitter and the collector. The emitter is heavily doped, while the collector is lightly doped, allowing a large reverse bias voltage to be applied before the collector–base junction breaks down. The collector–base junction is reverse biased in normal operation. The reason the emitter is heavily doped is to increase the emitter injection efficiency: the ratio of carriers injected by the emitter to those injected by the base. For high current gain, most of the carriers injected into the emitter–base junction must come from the emitter.

The low-performance "lateral" bipolar transistors sometimes used in CMOS processes are sometimes designed symmetrically, that is, with no difference between forward and backward operation.

Small changes in the voltage applied across the base–emitter terminals cause the current between the emitter and the collector to change significantly. This effect can be used to amplify the input voltage or current. BJTs can be thought of as voltage-controlled current sources, but are more simply characterized as current-controlled current sources, or current amplifiers, due to the low impedance at the base.

Early transistors were made from germanium but most modern BJTs are made from silicon. A significant minority are also now made from gallium arsenide, especially for very high speed applications (see HBT, below).

The heterojunction bipolar transistor (HBT) is an improvement of the BJT that can handle signals of very high frequencies up to several hundred GHz. It is common in modern ultrafast circuits, mostly RF systems.

Symbol for NPN bipolar transistor with current flow direction.

Two commonly used HBTs are silicon–germanium and aluminum gallium arsenide, though a wide variety of semiconductors may be used for the HBT structure. HBT structures are usually grown by epitaxy techniques like MOCVD and MBE.

Bipolar transistors have four distinct regions of operation, defined by BJT junction biases.

Forward-Active (or simply active)

The base–emitter junction is forward biased and the base–collector junction is reverse biased. Most bipolar transistors are designed to afford the greatest common-emitter current gain, β_F, in forward-active mode. If this is the case, the collector–emitter current is approximately proportional to the base current, but many times larger, for small base current variations.

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Reverse-Active (or inverse-active or inverted)

By reversing the biasing conditions of the forward-active region, a bipolar transistor goes into reverse-active mode. In this mode, the emitter and collector regions switch roles. Because most BJTs are designed to maximize current gain in forward-active mode, the β_F in inverted mode is several times smaller (2–3 times for the ordinary germanium transistor). This transistor mode is seldom used, usually being considered only for failsafe conditions and some types of bipolar logic. The reverse bias breakdown voltage to the base may be an order of magnitude lower in this region.

Saturation

With both junctions forward biased, a BJT is in saturation mode and facilitates high current conduction from the emitter to the collector (or the other direction in the case of NPN, with negatively charged carriers flowing from emitter to collector). This mode corresponds to a logical "on", or a closed switch.

Cut-off

In cut-off, biasing conditions opposite of saturation (both junctions reverse biased) are present. There is very little current, which corresponds to a logical "off", or an open switch.

Input and output characteristics for a common-base silicon transistor amplifier.

The modes of operation can be described in terms of the applied voltages (this description applies to NPN transistors; polarities are reversed for PNP transistors):

Forward-Active

Base higher than emitter, collector higher than base (in this mode the collector current is proportional to base current by).

Saturation

Base higher than emitter, but collector is not higher than base.

Cut-off

Base lower than emitter, but collector is higher than base. It means the transistor is not letting conventional current go through from collector to emitter.

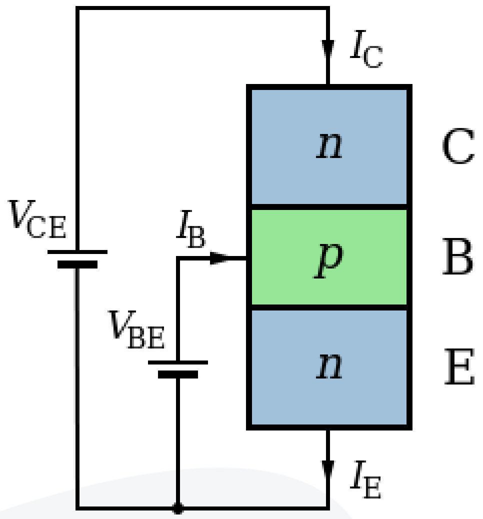
Reverse-Active

Base lower than emitter, collector lower than base: reverse conventional current goes through transistor.

In terms of junction biasing: (reverse biased base–collector junction means $V_{bc} < 0$ for NPN, opposite for PNP)

Although these regions are well defined for sufficiently large applied voltage, they overlap somewhat for small (less than a few hundred millivolts) biases. For example, in the typical grounded-emitter configuration of an NPN BJT used as a pulldown switch in digital logic, the "off" state never involves a reverse-biased junction because the base voltage never goes below ground; nevertheless the forward bias is close enough to zero that essentially no current flows, so this end of the forward active region can be regarded as the cutoff region.

Active-Mode Transistors in Circuits



Structure and use of NPN transistor. Arrow according to schematic

The diagram shows a schematic representation of an NPN transistor connected to two voltage sources. (The same description applies to a PNP transistor with reversed directions of current flow and applied voltage.) This applied voltage causes the lower P–N junction to become forward biased, allowing a flow of electrons from the emitter into the base. In active mode, the electric field existing between base and collector (caused by V_{CE}) will cause the majority of these electrons to cross the upper P–N junction into the collector to form the collector current I_C. The remainder of the electrons recombine with holes, the majority carriers in the base, making a current through the base connection to form the base current, I_B. As shown in the diagram, the emitter current, I_E, is the total transistor current, which is the sum of the other terminal currents, (i.e., $I_E = I_B + I_C$).

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In the diagram, the arrows representing current point in the direction of conventional current – the flow of electrons is in the opposite direction of the arrows because electrons carry negative electric charge. In active mode, the ratio of the collector current to the base current is called the DC current gain. This gain is usually 100 or more, but robust circuit designs do not depend on the exact value (for example see op-amp). The value of this gain for DC signals is referred to as and the value of this gain for small signals is referred to as. That is, when a small change in the currents occurs and sufficient time has passed for the new condition to reach a steady state is the ratio of the change in collector current to the change in base current.

The emitter current is related to exponentially. At room temperature, an increase in by approximately 60 mV increases the emitter current by a factor of 10. Because the base current is approximately proportional to the collector and emitter currents, they vary in the same way.

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