

13.4 BIPOLAR JUNCTION TRANSISTORS

Transistors are silicon switches that enable a weak signal to control a much larger current flow, which is the process of amplification: magnifying the amplitude of a signal. *Bipolar junction transistors* (BJTs) are a basic type of transistor and are formed by two back-to-back pn junctions. Figure 13.11 shows the general BJT structures and their associated symbolic representations. The BJT consists of three layers, or regions, of silicon in either of two configurations: NPN and PNP. The middle region is called the *base*, and the two outer regions are separately referred to as the *collector* and *emitter*. As will soon be shown, the base-emitter junction is what enables control of a potentially large current flow between the collector and emitter with a very small base-emitter current. A BJT's construction is more than simply placing two diodes back to back. The base region is extremely thin to enable conduction between the collector and emitter, and the collector and emitter are sized differently according to the fabrication process.

Currents in an NPN transistor flow from the base to the emitter and from the collector to the emitter. The relationship between these currents is defined by a proportionality constant called beta (β , also known as h_{FE}): $I_C = \beta I_B$. Beta is specific to each type of transistor and is characterized by the manufacturer in data sheets. Typical values for beta are from 100 to less than 1000. The beta current relationship provides a quick view of how a small base current can control a much larger collector current. A higher beta indicates greater potential for signal amplification. Because the base-emitter junction is essentially a diode, it must be sufficiently forward biased for the transistor to conduct current ($V_{BE} = 0.7$ V under typical conditions). A PNP transistor functions similarly, although the polarities of currents and voltages are reversed.

When a transistor circuit is designed, care must be taken not to overdrive the base-emitter junction. Like any other diode, it presents very low impedance beyond its forward voltage. Without some type of current limiting, the transistor will overheat and become damaged. Transistors are biased using resistors placed at two or three of its terminals to establish suitable operating voltages. Figure 13.12 shows a common NPN configuration at DC with a current limiting resistor, R_B , at the base and a voltage-dropping resistor, R_C , at the collector. The emitter is grounded, establishing the base voltage, V_B , at 0.7 V. R_B sets the current flowing into the base and thereby controls the collector voltage, V_C . As R_B increases, V_C increases, because less current is pulled through the collector, reducing the voltage drop across R_C . In this example, the base current, I_B , is $(5\text{ V} - V_B) / R_B = 0.43$ mA. Assuming a beta of 100, the collector current, I_C , is 43 mA, and $V_C = 5\text{ V} - I_C R_C = 2.85$ V.

The transistor is limited in how much current it can drive by both its physical characteristics and the manner in which it is biased. Physically speaking, a transistor will have a specified maximum power dissipation beyond which it will overheat and eventually become damaged. In this circuit, the transistor's power dissipation is $V_{CE}I_C + V_{BE}I_B$, although the dominant term is between the collector and emitter, where the great majority of the current flow exists. Using this small simplification, the transistor is dissipating approximately $2.85\text{ V} \times 43\text{ mA} = 123$ mW.

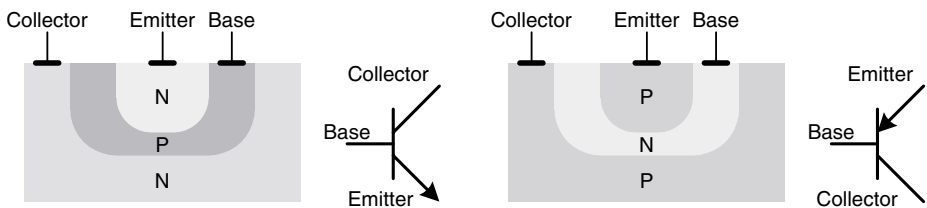


FIGURE 13.11 NPN and PNP BJT structures and graphical representations.

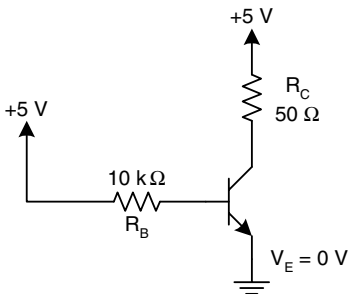


FIGURE 13.12 NPN DC topology.

Assuming that a transistor is not operated beyond its physical limitations, the bias configuration places an upper limit on how much current flows into the collector. A BJT has three modes of operation: *cutoff*, *active*, and *saturation*. In cutoff, the transistor is not conducting, because the base-emitter junction is either reverse biased or insufficiently forward biased. The collector is at its maximum voltage, and the base-collector junction is reverse biased, because no current is flowing to create a voltage drop through R_C or its equivalent. When the base-emitter junction is forward biased, the transistor conducts current and V_C begins to drop. The transistor is in active mode. As long as the base-collector junction remains reverse biased, increasing base current will cause a corresponding increase in collector current, and the transistor remains in active mode. If I_B is increased to the point at which the base-collector junction is forward biased (increased I_C causes V_C to approach V_E), the transistor enters saturation and no longer can draw more current through the collector. Saturation does not damage the transistor, but it results in a nonlinear relationship between I_B and I_C , nullifying the effect of beta. If R_C is increased or decreased, saturation occurs at lower or higher I_C , respectively. Amplifier circuits must avoid saturation to function properly because of the resulting nonlinearity. When used in a purely digital context, however, transistors can be driven from cutoff to saturation as long as the power dissipation specifications are obeyed.

13.5 DIGITAL AMPLIFICATION WITH THE BJT

With a basic knowledge of BJT operation, an NPN transistor can be already be applied in a useful digital application: driving a high-current LED array with a relatively weak output pin from a logic IC. Typical digital output pins have relatively low current drive capabilities, because they are designed primarily to interface with other logic gates that have low input current requirements. CMOS logic ICs tend to exhibit symmetrical drive currents in both logic 1 and logic 0. A CMOS output may be rated for anywhere from several milliamps to tens of milliamps. Bipolar logic ICs tend to exhibit relatively low drive current at logic 1, often less than one milliamp, and higher currents of several milliamps at logic 0. The use of bipolar logic is widespread, and it is often advantageous to take advantage of the greater drive capability of the logic-0 state. Figure 13.13 shows a logic output connected directly to an LED with each of the two possible polarities. The active-low configuration turns the LED on when the output is logic 0, and the active-high turns the LED on when the output is logic 1.

If neither the logic-1 nor logic-0 current capabilities are sufficient for the load, a simple transistor circuit can solve the problem. A typical 74LS logic family output pin is specified to source 0.4 mA at 2.7 V when driving a logic 1. Assuming a minimum beta of 100, an NPN transistor can be used to