Transistor Characteristic Curves

A fundamental property of a transistor and how it works is pointed out in the following **Figure**, where a transistor is correctly biased by two power supplies.

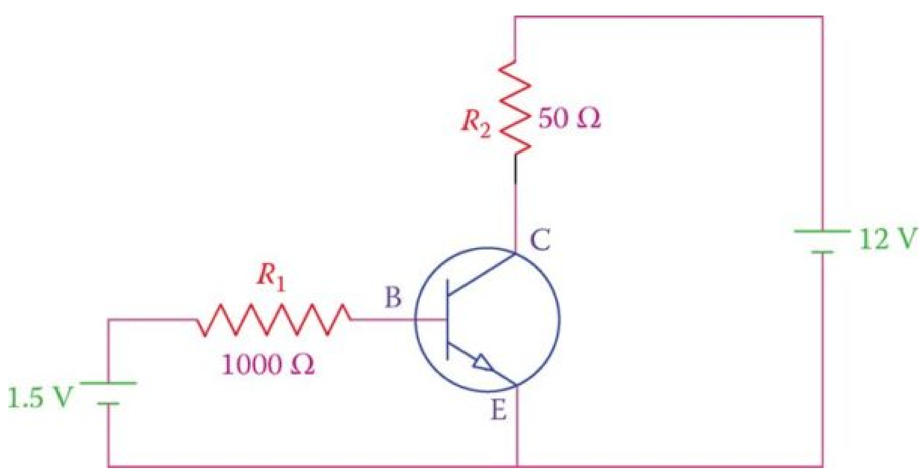


Figure: Transistor Working with Two Power Supplies

Figure 1 shows a simple circuit of a transistor, in which the 1.5 V battery and the resistance R_B determine the base current I_B, and the 24 V battery together with R_C define the collector current I_C. We are interested in determining the variation of the collector current I_C. This current can be varied either by changing the base current I_B or the collector-emitter voltage V_{CE} (the voltage between the collector C and the emitter E). The base current can be varied by the variable resistor R_B.

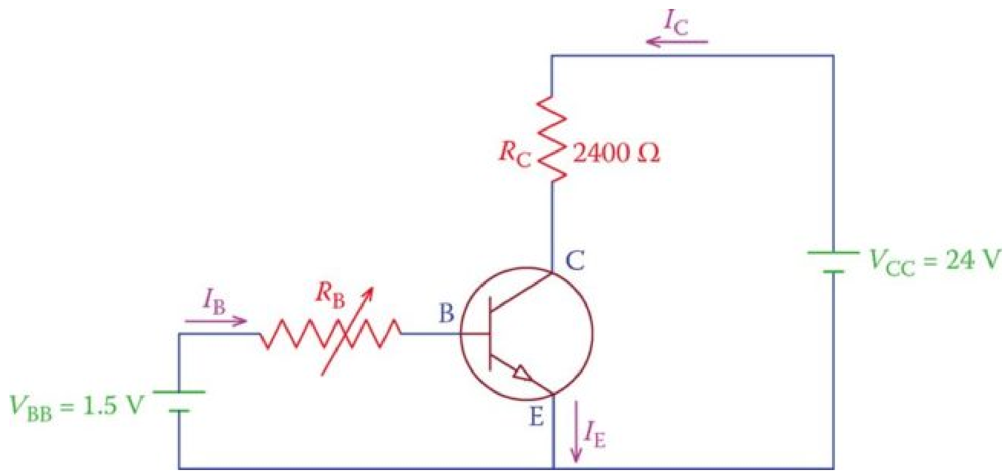


Figure 1 Simple circuit for a transistor operation.

> *The characteristic curves of a transistor provide the relationship between collector-emitter voltage and collector current for different values of the base current. Because there are two parameters that affect I_C, a set of individual curves shown together denote various operating conditions.*

A typical curve is shown in **Figure 2a,** and a set of these curves are depicted in **Figure 2b**. Each individual curve depicts the variation of I_C versus the value of collector-emitter voltage (V_{CE}) for a fixed value of base current I_B.

When **I_B is zero**, a transistor is cut off, and it does not conduct no matter how much voltage is applied to the collector; any collector current is due to leaks, is very small, and is negligible. In both Figure 2a and b, the curve corresponding to I_B = 0 is exaggerated for clarity.

> *The area under the curve corresponding to I_B = 0, shaded in **Figure 2a,** represents the region where a transistor is cut off and is not conducting.*

Saturation Region

For each **nonzero value of I_B**, the collector current starts from zero when the collector-emitter voltage is zero. A transistor starts conducting and the collector current increases rapidly when V_{CE} > 0. The area around this abrupt change in I_C also shaded in **Figure 2a,** corresponds to when a **transistor is in saturation**.

Saturation implies that the collector current has reached its maximum value for that collector-emitter voltage and cannot increase further by increasing the base current I_B. For example, consider point M corresponding to $V_{CE} = V_M$ in **Figure 2b.** For this point, I_C has reached its maximum and cannot be increased by increasing I_B. In contrast, an increase in I_B can move point N to N′, both corresponding to a collector-emitter voltage V_N.

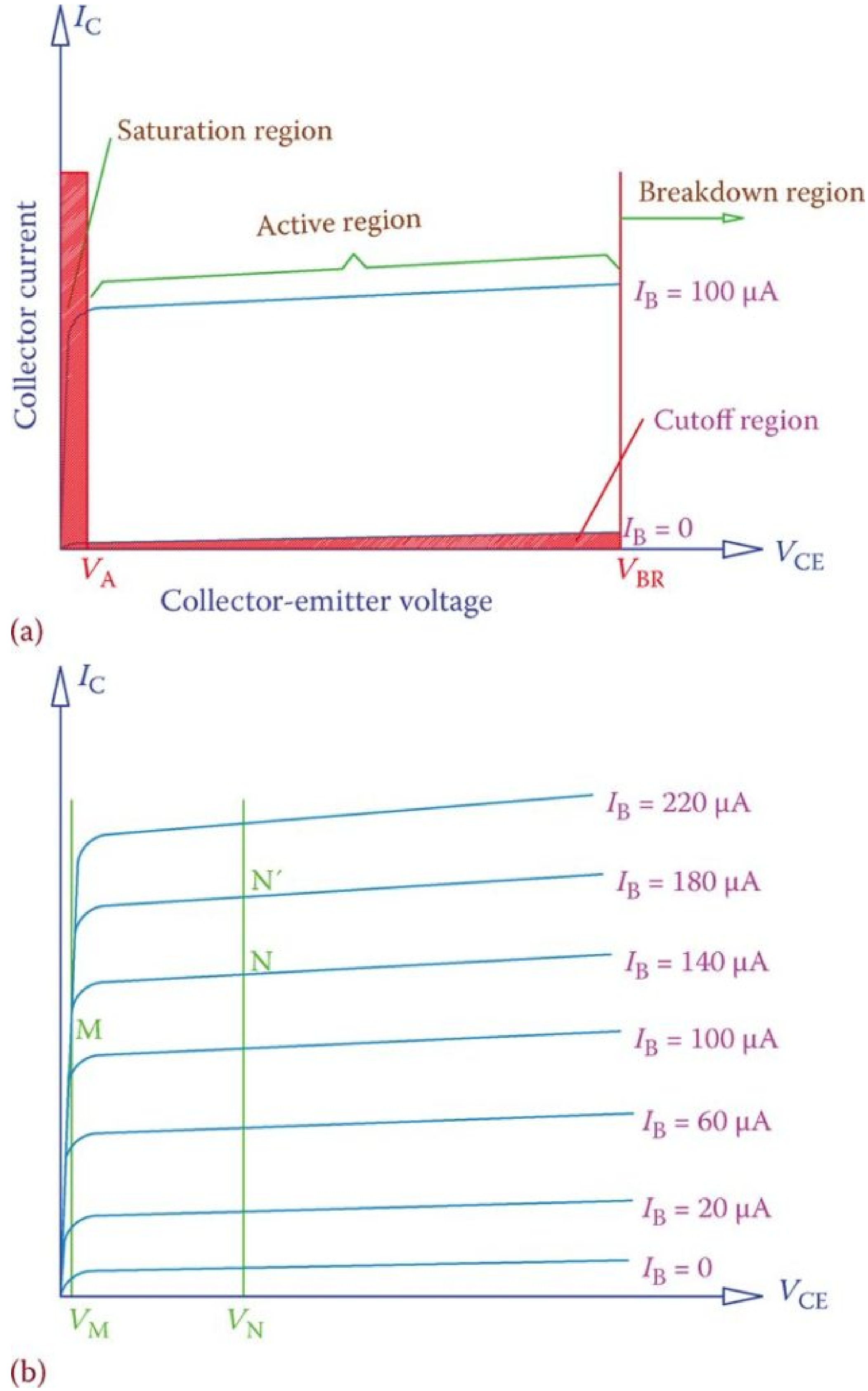


Figure 2 Collector current versus collector voltage characteristic curve of a transistor. (a) For one value of base current. (b) For multiple values of base current.

Saturation (in a transistor): The state of a transistor at which the collector current has reached its maximum value for the present collector-emitter voltage, and cannot increase further by only increasing the base current I_B.

The meaning of transistor saturation is better demonstrated in **Figure 3,** in which the scale of the horizontal axis is augmented so that the line segments with sharp slopes can be better displayed.

Two characteristic curves, corresponding to two base currents I_{B1} and I_{B2} are shown. Suppose that the collector-emitter voltage is 2 V. On both curves the corresponding point is A. This implies that if the base current is increased to I_{B2}, but the V_{CE} is still 2 V, the collector current does not change. The collector current increases only if the V_{CE} increases, for instance, to 4 V, for which the operating point moves from A to B.

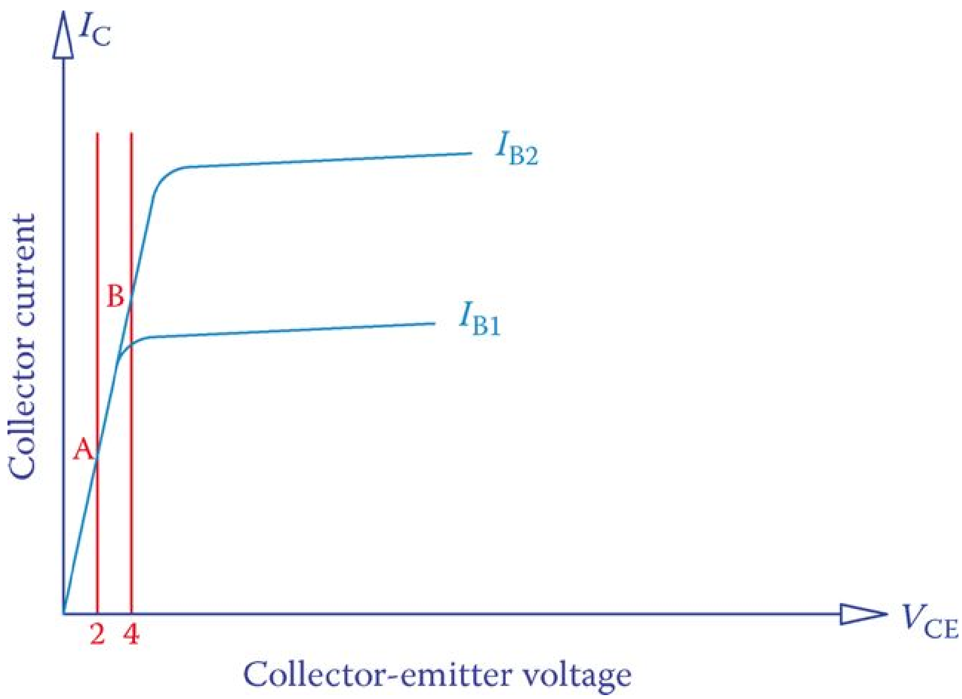


Figure 3 Typical set of characteristic curves for a transistor.

Active Region

When saturated, a transistor cannot operate as expected. In normal operation, transistors function in the active region, the area that the characteristic curve is a segment of an almost horizontal straight line. In this region increasing collector-emitter voltage has little effect on the collector current. **In other words**, the transistor exhibits a large resistance in this region, so that increasing voltage has little effect on the current through it. This resistance is variable because it depends on the value of I_B (for each value of I_B the ratio V_{CE}/I_C is different).

> ***Active region:*** *An area in the characteristic curve of a transistor, in terms of collector-emitter voltage and collector current values that the transistor can function. If any of these values falls outside of its range a transistor falls in the saturation region or cutoff region and cannot function (see **Figure 2a**).*

The active region is between the two voltages denoted by V_A and V_{BR} in Figure 2a. If V_{CE} surpasses the breakdown voltage V_{BR}, the transistor gets damaged, and if $V_{CE} < V_A$, the transistor is in a saturation state.

> ***Breakdown voltage:*** *Voltage at which a semiconductor device changes behavior or gets damaged.*

The operating point of a transistor is a point on these curves, corresponding to a given I_B and a given value for V_{CE}. A transistor, nevertheless, cannot work at all the possible points that can be found on the characteristic curves. This is because of the physical limitations of a transistor in handling a collector current without getting overheated and damaged. The limiting power boundary is shown in **Figure 4** by the dashed curve for a typical transistor.

It is possible to run the transistor in all the points to the left of the dashed curve, but not on the region on the right side of this curve. In this region, either I_C is high or V_{CE} is high, resulting in relative high-power consumption in a transistor, which converts to heat.

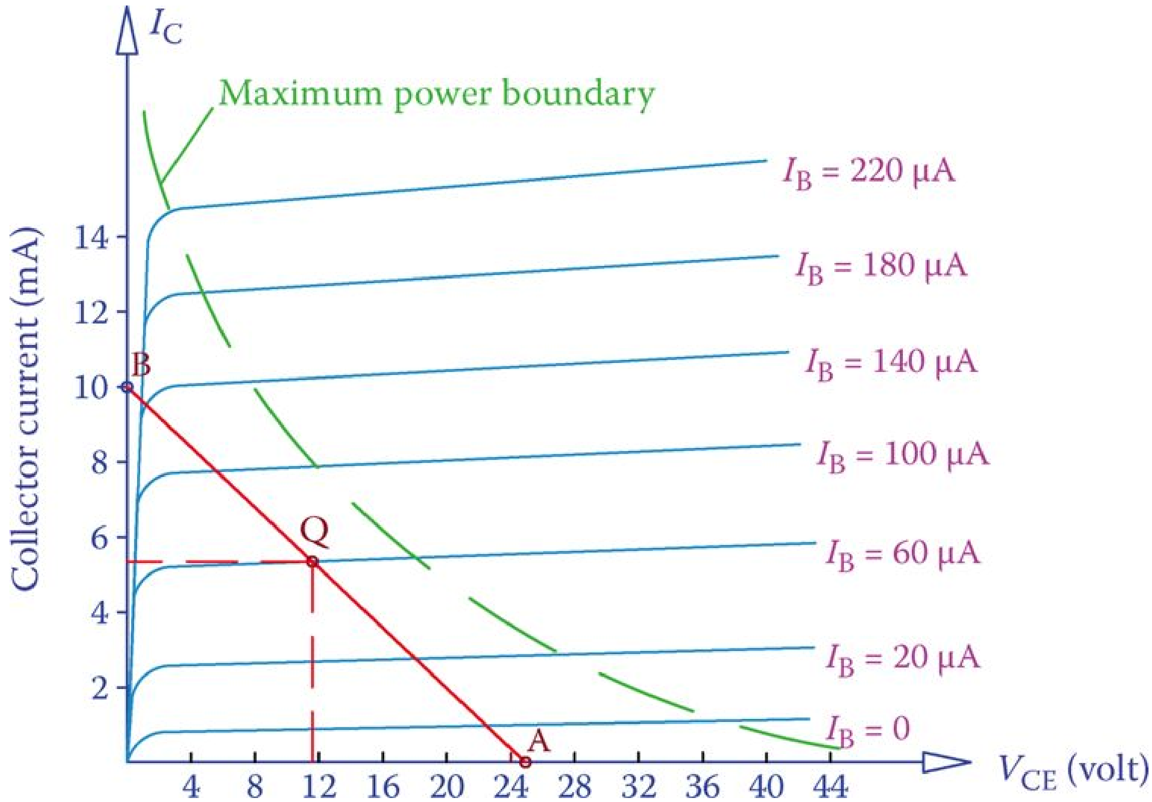


Figure 4 Operating point and boundary curve for the maximum power capacity of a transistor.

The operating point for a transistor (represented by Q in **Figure 4**), under the operating conditions governed by the supply voltage V_{CC} and the base voltage V_{BB} (see **Figure 1**) and the resistances R_B and R_C, is at the intersection of lines corresponding to V_{CE} and the base current.

For a constant set of values for V_{CC}, V_{BB}, and R_C if R_B is varied the value of I_B, and consequently I_C and V_{CE}, change. Each pair of I_C and V_{CE} defines an operating point denoted by Q. When as a result of varying R_B, while the parameters V_{CC}, V_{BB}, and R_C are kept constant, the values of the collector-emitter voltage V_{CE} and collector current I_C vary, this point Q moves on a straight line AB, as shown in **Figure 4.**

V_{CE} is obtained from the supply voltage V_{CC} minus the voltage drop in R_C (and any other resistor in the collector-emitter loop connected to V_{CC}).

In the cutoff state, the current through R_C is zero and no voltage is dropped in R_C (and any other resistor in series with R_C in the same loop). Consequently, all the applied voltage (V_{CC}) appears at the collector. This defines point A of the line, where V_{CE} is maximum.

Also, if a transistor is conducting, but there is no internal resistance between C and E, this defines the maximum current that the collector can have (point B of the line). This maximum current can be found by dividing V_{CC} by all the resistors in the loop (only R_C in **Figure 1**). Thus, for a given supply voltage V_{CC}, the collector current can vary between zero (at point A) and a maximum value (at point B), as the line AB shows.

The intersection of the line AB with one of the transistor characteristic curves defines the operating point Q. The line AB is called the load line. The load line, thus, represents all the possible locations of point Q for a transistor in a given circuit with constant V_{CC} and resistance(s) in the collector-emitter circuit.

> ***Load line (in a transistor):*** *Line showing the operating points of a transistor on a transistor characteristic curve, based on the supply voltage and the resistors in the transistor circuit. This line is between the points corresponding to the maximum collector voltage and maximum collector current.*

Example 1

For the transistor shown in Figure 1, whose characteristic curves are shown in **Figure 4**, if the base current is 60 µA, find the collector current and the value of ß.

Solution

The maximum current through the collector is defined by dividing the supply voltage (24 V) by the resistor RC. Thus, point B end of the load line on the current (vertical) axis is at

$$\frac{24}{2400} = 10mA$$

The other end of the load line (point A) is on the horizontal axis at 24 V. This line is the same as shown in **Figure 4** and intersects the curve corresponding to 60 µA base current at point Q (as shown).

Dropping a perpendicular from Q to the vertical axis gives the current in the collector. On the basis of the figure, this current is 5.5 mA.

The value for ß can be found from dividing collector current by the base current.

$$\frac{5.5mA}{60\mu A} = \frac{5500\mu A}{60\mu A} \approx 92$$

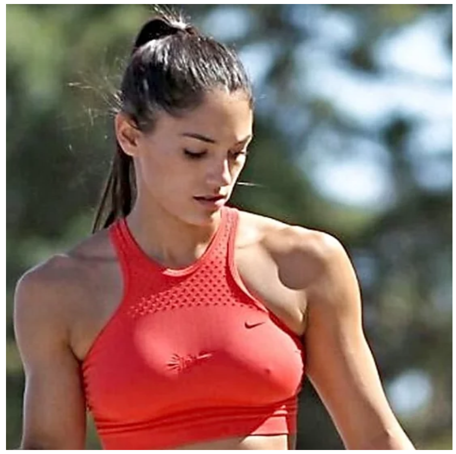
Example 2

If in Example 1 the supply voltage changes to 30 V and RC is 2200 Ω (other parameters remaining unchanged), how much are IC and VCE?

Solution

A new load line needs to be drawn on the same graph of Figure 4. The intersection of this line with the line corresponding to I_B = 60 μA defines the values of I_C and V_{CE}.

Point A for this new line is at V_{CE} = 30 V, thus between 28 and 32 (not shown), and point B is at I_B = 30 ÷ 2200 = > 13.6 mA. If you draw this line you will find its intersection with 60 μA base current, which corresponds to I_C = 5.6 mA and V_{CE} = 17.4 V.



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