14. Bipolar Transistor (PNP, NPN)

The transistor is a three-layer semiconductor device consisting of either two n- and one p-type layers of material or two p- and one n-type layers of material. The former is called an npn transistor, while the latter is called a pnp transistor. Both are shown in Fig14.1 and Fig 14.2 with the proper dc biasing which is necessary to establish the proper region of operation for ac amplification.

The emitter layer is heavily doped, the base lightly doped, and the collector only lightly doped. The outer layers have widths much greater than the sandwiched p- or n-type material. For the transistors shown in Fig. 2 the ratio of the total width to that of the center layer is 0.150/0.001 =150:1. The doping of the sandwiched layer is also considerably less than that of the outer layers (typically, 101 or less). This lower doping level decreases the conductivity (increases the resistance) of this material by limiting the number of "free" carriers. The abbreviation BJT, from bipolar junction transistor, is often applied to this three terminal device. The term bipolar reflects the fact that holes and electrons participate in the injection process into the oppositely polarized material.

If only one carrier is employed (electron or hole), it is considered a unipolar device.

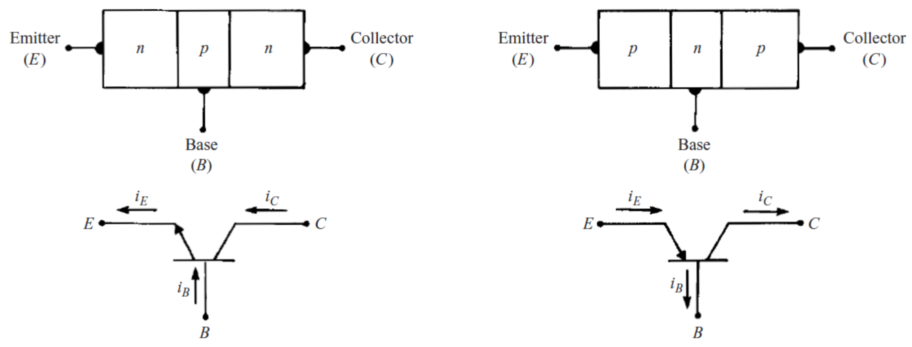


Fig 14.1

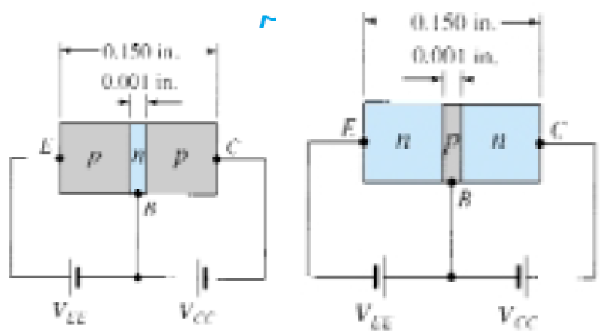


Fig 14.2

The transistor has two junctions: one between the emitter and the base, and another between the collector and the base. Because of this, a transistor is like two back to back diodes. The lower diode is called the emitter-base diode, or simply the emitter diode. The upper diode is called the collector-base diode, or the collector diode.

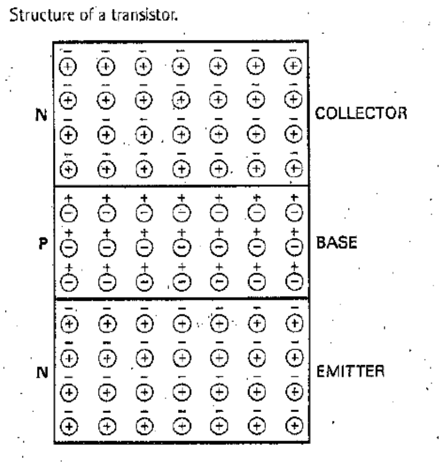


Fig 14.3

Free electrons in the n region will diffuse across the junctions and recombine with the holes in the p region.The result is two depletion layers, as shown in the Fig 14.4 .

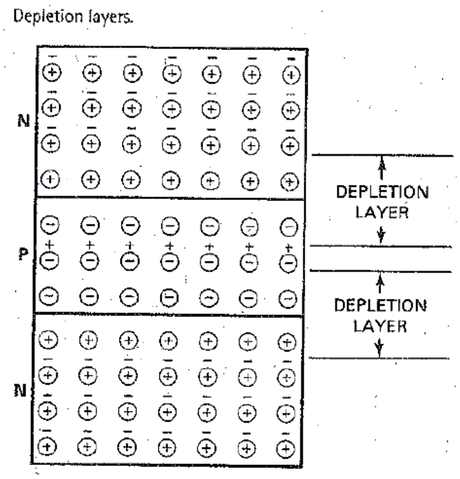
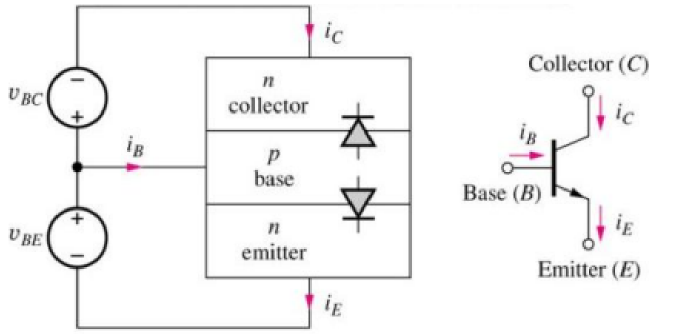
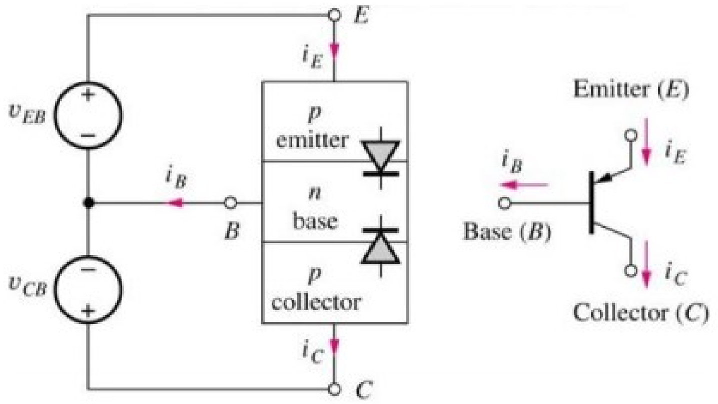


Fig 14.4

For each of these depletion layers, the barrier potential is approximately 0.7 V at 25˚C for a silicon transistor(0.3 V at 25˚C for a germanium transistor).

Transport model of NPN and PNP transistor





Transistor Operation

The basic operation of the transistor is described using the pnp transistor of Fig 14.5. The operation of the npn transistor is exactly the same if the roles played by the electron and hole are interchanged. In Fig 14.5. the pnp transistor has been redrawn without the base-to-collector bias. The depletion region has been reduced in width due to the applied bias, resulting in a heavy flow of majority carriers from the p- to the n-type material.

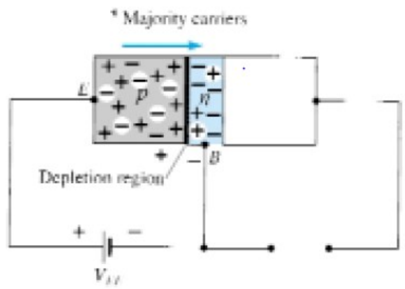
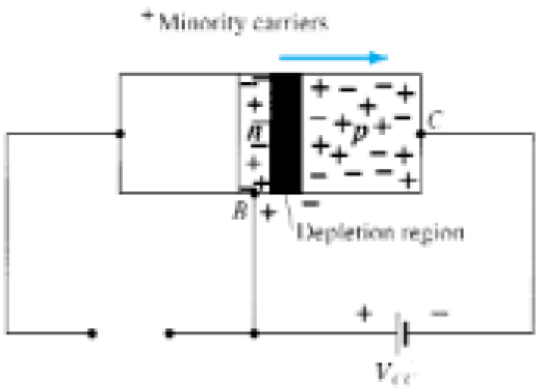


Fig 14.5 Forward-biased junction of a *pnp* transistor.

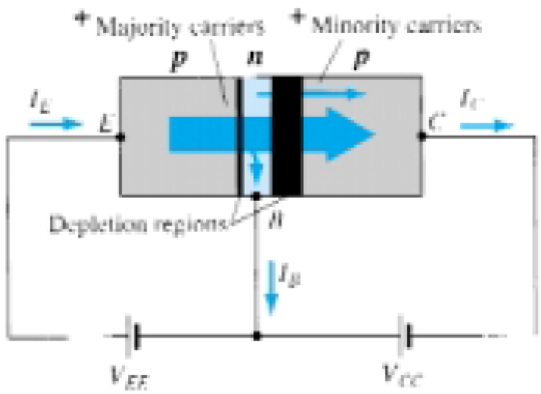
Let us now remove the base-to-emitter bias of the pnp transistor of Fig 14.2a as shown in Fig. 14.6a.The flow of majority carriers is zero, resulting in only a minority-carrier flow, as indicated in Fig 14.6a. In summary, therefore: One p-n junction of a transistor is reverse biased, while the other is forward biased.

In Fig 14.6b both biasing potentials have been applied to a pnp transistor, with the resulting majority- and minority-carrier flow indicated. Note in Fig 14.6b the widths of the depletion regions, indicating clearly which junction is forward-biased and which is reverse-biased. As indicated in Fig 14.6b, a large number of majority carriers will diffuse across the forward-biased p-n junction into the n-type material. The question then is whether these carriers will contribute directly to the base current I_B or pass directly into the p-type material. Since the sandwiched n-type material is very thin and has a low conductivity, a very small number of these carriers will take this path of high resistance to the base terminal. The magnitude of the base current is typically on the order of microamperes as compared to milliamperes for the emitter and collector currents. The larger number of these majority carriers will diffuse across the reverse-biased junction into the p-type material connected to the collector terminal as indicated in Fig 14.6b. The reason for the relative ease with which the majority carriers can cross the reverse-biased junction is easily understood if we consider that for the reverse-biased diode the injected majority carriers will appear as minority carriers in the n-type material. In other words, there has been an injection of minority carriers into the *n*-type base region material. Combining this with the fact that all the minority carriers in the depletion region will cross the reverse-biased junction of a diode accounts for the flow indicated in Fig 14.6 b.



Reverse-biased junction of a *pnp* transistor.

Fig 14.6a



Majority and minority carrier flow of a *pnp* transistor.

Fig 14.6b

15. Transistor Current

Applying Kirchhoff's current law to the transistor of Fig 14.6 b as if it were a single node, we obtain

$$I_E = I_C + I_B$$

and find that the emitter current is the sum of the collector and base currents.
Since the base current is so small, the collector current approximately equals the emitter current

$$I_C \sim I_E$$

Emitter is the source of electrons , it has the largest current. Since most of the emitter electrons flow to the collector , the collector current is almost as large as the emitter current. The base current is very small by comparison, often less than 1 percent of the collector current.

The **dc alpha (α_{dc})** is defined as the dc collector current divided by the dc emitter current.

$$\alpha_{dc} = I_C/I_E$$

If $I_C = I_E$ $\alpha_{dc} < 1$. In low power transistor $\alpha_{dc} > 0.99$, In high power transistor $\alpha_{dc} > 0.95$.

The **dc beta (β_{dc})** of a transistor is defined as the ratio of the dc collector current to the dc base current.

$$\beta_{dc} = I_C / I_B$$

The dc beta is also known as the **current gain** because a small base current controls a much large collector current.

In low power transistor β_{dc} 100-300, In high power transistor β_{dc} 20-100.

Example Problems

1. A transistor has a collector current of 10mA and a base current of 40μA.What is the current gain of the transistor?

   $\beta_{dc} = 10mA/40\mu A = 250$.

2. A transistor has a current gain of 175. If the base current is 0.1mA, what is the collector current?

   $I_C = 175(0.1mA) = 17.5$ mA.

3. A transistor has a collector current of 2 mA. If the current gain is 135.What is the base current?

   $I_B = 2$ mA/135 = 14.3 μA.

16. CE- Configuration

There are three useful ways to connect a transistor; they are Common Emitter (CE) common Base (CB) and common Collector (CC).

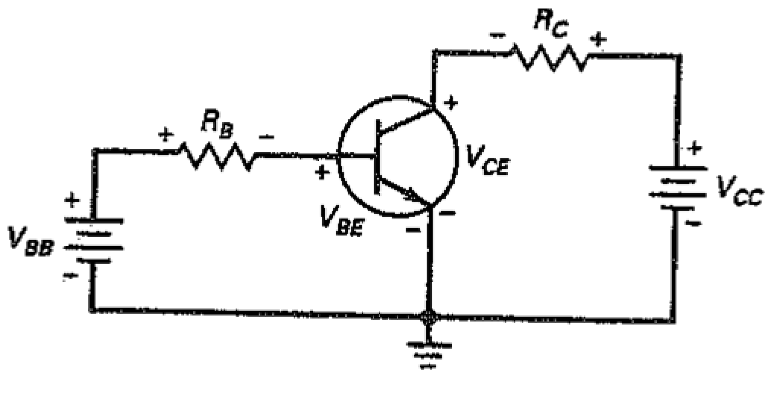


Fig 16.1 Circuit diagram

As can be seen in the Fig16.1 the common or the ground side of each voltage source is connected to the ground, hence it is called Common Emitter (CE) configuration.

The source V_{BB} forward biases the Base – Emitter Junction, R_B acts as the current limiting resistor. So by changing V_{BB} or R_B we can change the base current. If the base current changes it means that the number of electrons supplied by the emitter changes which in turn changes the number of electrons reaching the collector and thus the collector current also changes. In other word, Base current controls the Collector current (very important).

Applying Ohm's Law in the left (Base loop) of Fig 16.1,

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

The V_{CC} supply reverse biases the collector junction which is very important because only when you give a positive voltage to the collector of an n-p-n transistor, it will attract most of the free electrons injected into the base.Applying Kirchoff's voltage law to the collector loop

$$V_{CE} = V_{CC} - I_C R_C$$

Base Curve

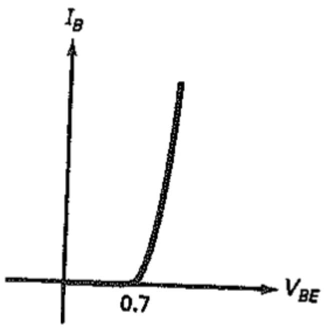


Fig 16.2 Input characteristics

Since the base emitter junction is like a forward biased p-n junction diode the I_B Versus V_{BE} graph looks just like an I-V characteristics of an ordinary forward biased diode.

Collector Curves

As already mentioned current flowing through the collector loop depends not only on V_{CC} but also on I_B. Suppose we fix V_{BB} such that $I_B = 10\mu A$. Then on plotting I_C vs V_{CE} we get a graph as shown in Fig 16.3.

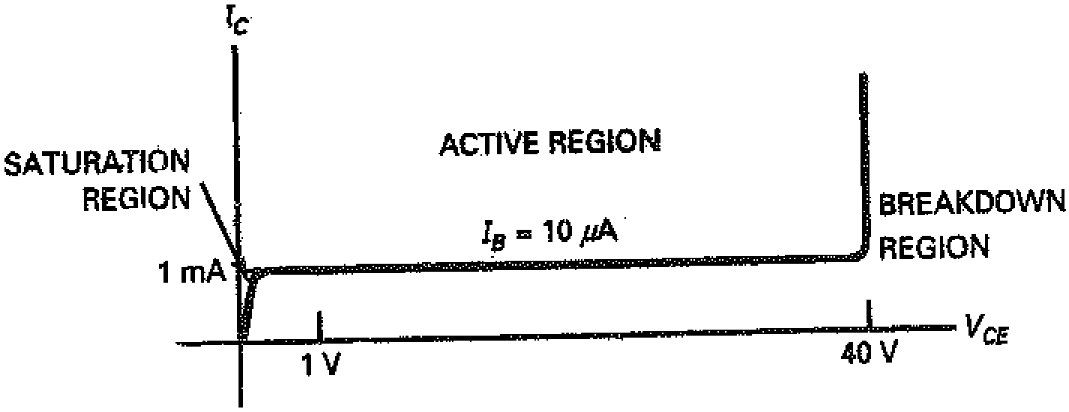


Fig 16.3 output characteristics for I_B=10μA

Regions of Operation

There are three different regions of operation of the transistor, First consider the region where V_{CE} is between 1V and 40 V. This represents the normal operation of a transistor. In this region the emitter diode is forward biased, and the collector diode is reverse biased. Furthermore, the collector is gathering almost all the electrons that the emitter has sent into the base. This is why changes in the collector voltage have no effect on the collector current. This region is called active region. Collector current is constant at this region.Another region of operation is the breakdown region. The transistor should never operate in this region because it will be destroyed.

Third, there is the early rising part of the curve, where V_{CE} is between 0V and a few tenths of a volt. This region is called saturation region. In this region, the collector diode has insufficient positive voltage to collect all the free electrons injected into the base.

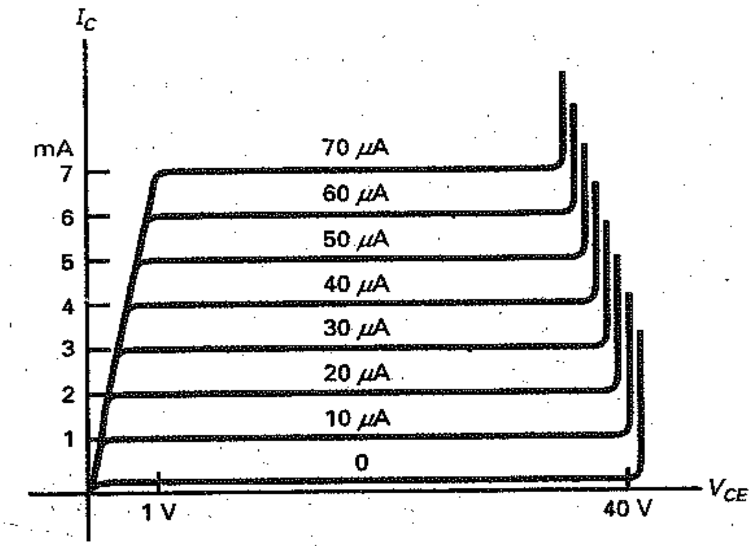


Fig 16.4 Set of collector curves

There is a fourth possible region of operation for transistors, i.e. when base current is Zero there is still a small collector current. This region is called cut-off region. The cut-off current exists because of the reverse minority-carrier current and surface leakage current I_{CEO}. It is small enough to be neglected.

Current gain in CE configuration is given by: output current/ input current

$\beta = I_C/I_B$

17.1 Common Base

The common-base terminology is derived from the fact that the base is common to both the input and output sides of the configuration.

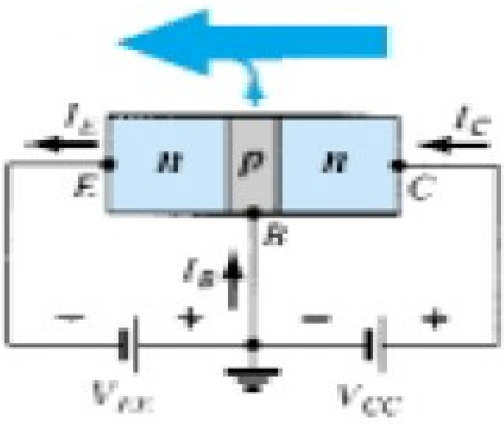


Fig 17.1.1 Circuit diagram

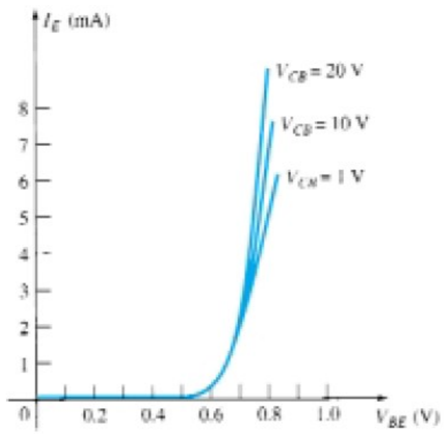


Fig 17.1.2 input characteristics

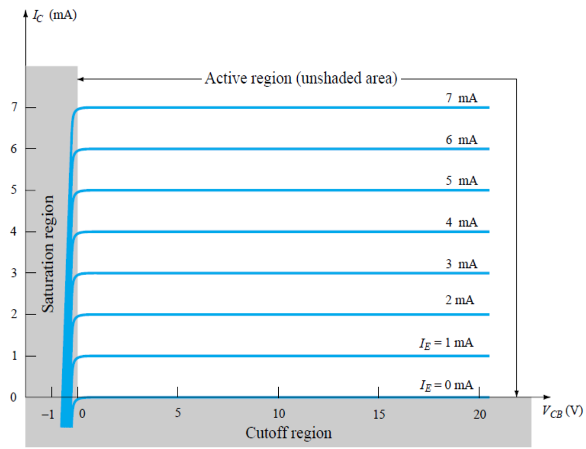


Fig 17.1.3 output characteristics

From the characteristic curves it can be seen that

$$\boxed{I_C \cong I_E}$$

In the active region the collector-base junction is reverse-biased, while the base-emitter junction is forward-biased. At the lower end of the active region the emitter current (I_E) is zero, the collector current is simply that due to the reverse saturation current I_{CBO}, as indicated in Fig 17.1.3.

In the saturation region the collector-base and base-emitter junctions are forward-biased.
In the cutoff region the collector-base and base-emitter junctions of a transistor are both reverse-biased.

Here current gain is given by:

$$\boxed{\alpha = I_C/I_E}$$

$$I_E = I_C + I_B$$

$$I_C/\alpha = I_C + I_C/\beta$$

Dividing both sides by I_C we get

$$1/\alpha = 1 + 1/\beta$$

Or

$$\boxed{\alpha = \frac{\beta}{\beta + 1}}$$

$$\boxed{\beta = \frac{\alpha}{1-\alpha}}$$

Also,

$$\boxed{I_C = \beta I_B}$$

$$I_E = I_C + I_B$$

$$= \beta I_B + I_B$$

$$\boxed{I_E = (\beta + 1) I_B}$$

19. Transistor as a Switch

For the transistor to function as an amplifier, biasing voltages are applied such that it always operates within the active region that is the linear part of the output characteristics curves is used. However, both bipolar transistors can be made to operate as “ON/OFF” type solid state switches by biasing the transistors base differently to that of a signal amplifier. BJT switches can be used for controlling high power devices such as motors, solenoids or lamps, but they can also be used in digital electronics and logic gate circuits. For transistor to act as a switch it is driven it back and forth between its “fully-OFF” (cut-off) and “fully-ON” (saturation) regions.

For example consider the circuit in Fig 19.1.

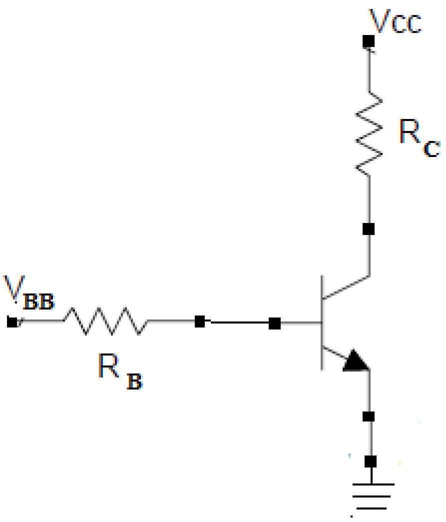


Fig 19.1 A transistor in common emitter configuration

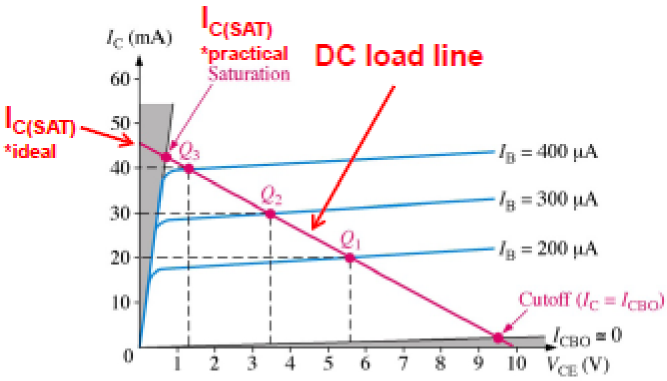


Fig19.2

Example Problems

1. Consider the circuit in Fig 19.1. Given V_{CC} = +5 V; R_B = 50 KΩ; R_C = 0.7 KΩ; β = 125. Find the base current that drives the transitor to saturation.

To begin, we write down the KVL equation.

$I_C = (V_{CC} - V_{CE})/(R_C)$

We find the maximum value of the collector current under saturation and the corresponding base current.

$I_{CESAT} = V_{CC}/R_C = 5/(0.7\ K) = 7.1$ mA

$I_B = I_{CESAT}/\beta = 56.8\ \mu A$

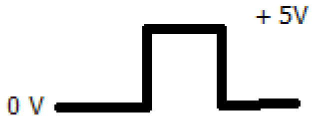
For the saturation, the condition is

$I_B > I_{CESAT}/\beta$

That is $I_B > 56.8\ \mu A$

If the base current is increased beyond 56.8 microampere then the transistor will be driven into saturation.

2.Suppose a voltage V_{BB} as shown in Figure is applied to the base of the transistor in Fig 19.1 , what would happen?



When V_{BB} is +5 V,

$I_B = (V_{BB} - 0.7)/R_B = 86\ \mu A$. This is greater that $56.8\ \mu A$. Thus the transistor saturates.

Thus $V_{CE} = 0$; Transistor is ON.

When V_{BB} is 0 V,

$I_B = (V_{BB} - 0.7)/R_B = 0$ A. This is less than $56.8\ \mu A$. Thus the transistor is in cutoff.

Thus $V_{CE} = V_{CC}$; Transistor is OFF.