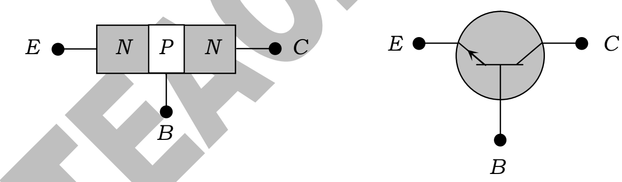
SEMICONDUCTOR PHYSICS-2

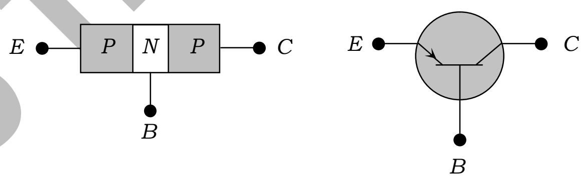
[Transistor, constructional characteristics, biasing of transistors, transistor configuration, transistor as an amplifier, transistor as a switch, transistor as an oscillator]

Transistor
It is an electronic device whose fundamental action is transfer of resistor/resistance. Transistor in general is known as bipolar junction transistor (BJT). It is a current operated device.

Constructional characteristics:-
It consists of three main regions
(i) **Emitter (*E*):** It provides majority charge carriers by which current flows in the transistor. Therefore the emitter semiconductor is heavily doped and is of moderate size.
(ii) **Base (*B*):** The based region is lightly doped and thin.
(iii) **Collector (*C*):** The size of collector region is larger than the two other regions and is moderately doped. It collects a major portion of the majority charge carriers supplied by the emitter.
Junction transistor are of two types :
(i) ***NPN* transistor**: It is formed by sandwiching a thin layer of *P*-type semiconductor between two *N*-type semiconductors
In *NPN* transistor electrons are majority charge carriers and flow from emitter to base.



(ii) ***PNP* transistor**: It is formed by sandwiching a thin layer of *N*-type semiconductor between two *P*-type semiconductor
In *PNP* transistor holes are majority charge carriers and flow from emitter to base.



In the symbols of both NPN and PNP transistor, arrow indicates the direction of conventional current.

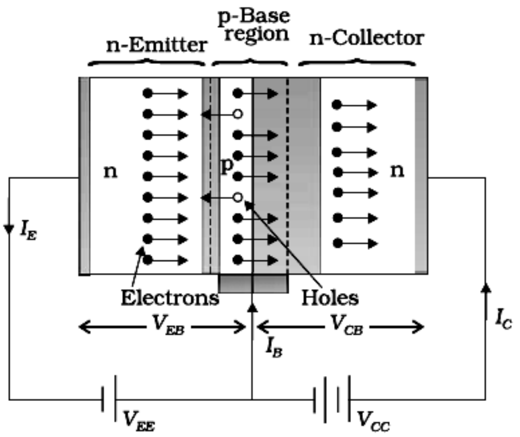
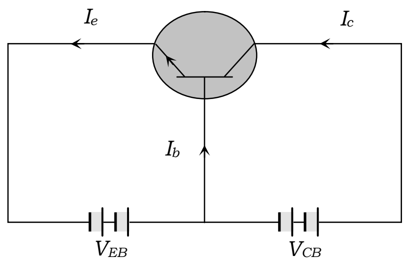
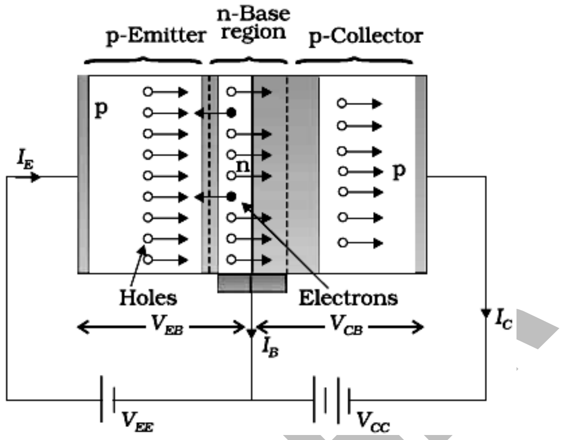
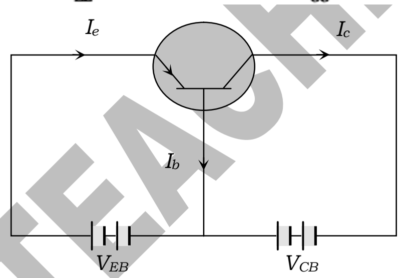
Working of Transistor
(1) There are four possible ways of biasing the two *P-N* junctions (emitter junction and collector junction) of transistor.
(i) Active mode: Also known as linear mode operation.
(ii) Saturation mode: Maximum collector current flows and transistor acts as a closed switch from collector to emitter terminals.
(iii) Cut-off mode: Denotes operation like an open switch where only leakage current flows.
(iv) Inverse mode: The emitter and collector are inter changed.

Different modes of operation of a transistor

Operating mode	Emitter base bias	Collector base bias
Active	Forward	Reverse
Saturation	forward	Forward
Cut off	Reverse	Reverse
Inverse	Reverse	Forward

(2) A transistor is mostly used in the active region of operation *i.e.* emitter base junction is forward biased and collector base junction is reverse biased.
(3) From the operation of junction transistor it is found that when the current in emitter circuit changes, there is corresponding change in collector current.
(4) In each state of the transistor there is an input port and an output port. In general each electrical quantity (*V* or *I*) obtained at the output is controlled by the input.

Circuit diagram of *PNP*/ *NPN* transistor

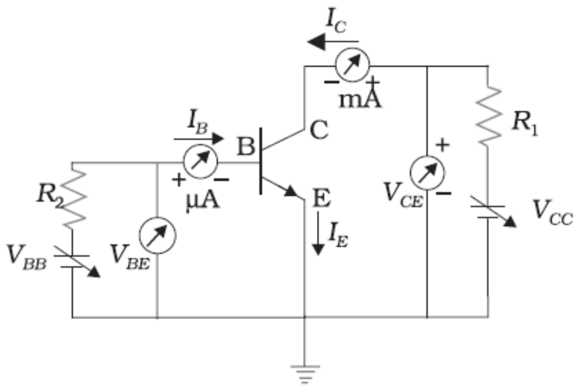
***NPN* – transistor**	***PNP* – transistor**
 	 
5% emitter electron combine with the holes in the base region resulting in small base current. Remaining 95% electrons enter the collector region.	5% emitter holes combine with the electrons in the base region resulting in small base current. Remaining 95% holes enter the collector region.
$I_e > I_c$, and $I_e = I_b + I_c$	$I_e > I_c$, and $I_e = I_b + I_c$

Transistor Configurations

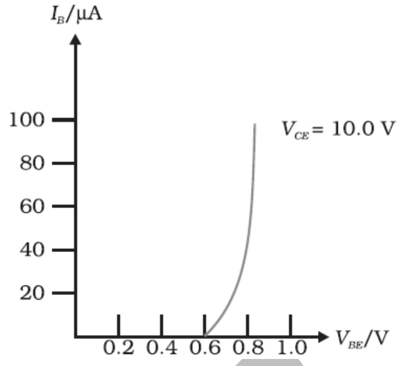
A transistor can be connected in a circuit in the following three different configurations. Common base (CB), Common emitter (CE) and Common collector (CC) configuration.

(1) **CE configurations :** [The transistor is most widely used in the CE configuration and we shall restrict our discussion to only this configuration. Since more commonly used transistors are n-p-n Si transistors, we shall confine our discussion to such transistors only. With p-n-p transistors the polarities of the external power supplies are to be inverted.]

(i) **Input Characteristics:-**

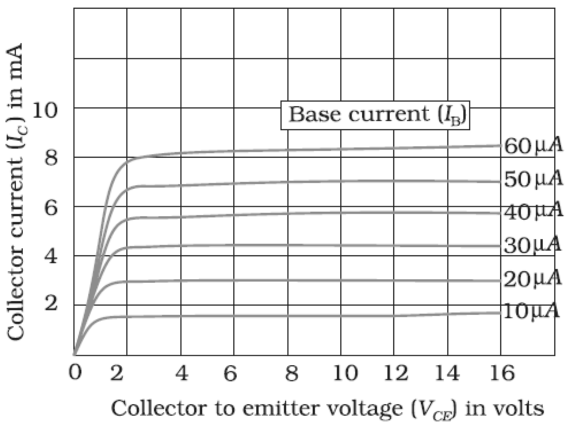


When a transistor is used in CE configuration, the input is between the base and the emitter and the output is between the collector and the emitter. The variation of the base current I_B with the base-emitter voltage V_{BE} is called the input characteristic. To study the input characteristics of the transistor in CE configuration, a curve is plotted between the base current I_B against the base-emitter voltage V_{BE}. The collector-emitter voltage V_{CE} is kept fixed while studying the dependence of I_B on V_{BE}. We are interested to obtain the input characteristic when the transistor is in active state. So the collector-emitter voltage V_{CE} is kept large enough to make the base collector junction reverse biased. Since $V_{CE} = V_{CB} + V_{BE}$ and for Si transistor V_{BE} is 0.6 to 0.7 V, V_{CE} must be sufficiently larger than 0.7 V. Since the transistor is operated as an amplifier over large range of V_{CE}, the reverse bias across the base collector junction is high most of the time. Therefore, the input characteristics may be obtained for V_{CE} somewhere in the range of 3 V to 20 V. Since *the increase in V_{CE} appears as increase in V_{CB}, its effect on I_B is negligible***.** As a consequence, input characteristics for various values of V_{CE} will give almost identical curves. Hence, *it is enough to determine only one input characteristics.* The input characteristics of a transistor is as shown in Fig.



(ii) **Output Characteristics:-**

The output characteristic is obtained by observing the variation of I_C as V_{CE} is varied keeping I_B constant. It is obvious that if V_{BE} is increased by a small amount, both hole current from the emitter region and the electron current from the base region will increase. As a consequence both I_B and I_C will increase proportionately. This shows that when I_B increases I_C also increases. The plot of I_C versus V_{CE} for different fixed values of I_B gives one output characteristic. So there will be different output characteristics corresponding to different values of I_B as shown in Fig.



(iii) Input resistance (r_i): This is defined as the ratio of change in base emitter voltage (ΔV_{BE}) to the resulting change in base current (ΔI_B) at constant collector-emitter voltage (V_{CE}). This is dynamic (ac resistance) and as can be seen from the input characteristic, its value varies with
the operating current in the transistor:

$$r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}}$$

The value of r_i can be anything from a few hundreds to a few thousand ohms.

(iv) Output resistance (r_o): This is defined as the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at a constant base current I_B.

$$r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B}$$

The output characteristics show that initially for very small values of V_{CE}, I_C increases almost linearly. This happens because the base-collector junction is not reverse biased and the transistor is not in active state. In fact, the transistor is in the saturation state and the current is controlled by the supply voltage V_{CC} (=V_{CE}) in this part of the characteristic. When V_{CE} is more than that required to reverse bias the base-collector junction, I_C increases very little with V_{CE}. The reciprocal of the slope of the linear part of the output characteristic gives the values of r_o. The output resistance of the transistor is mainly controlled by the bias of the base collector junction. The high magnitude of the output resistance (of the order of 100 kΩ) is due to the reverse-biased state of this diode. This also explains why the resistance at the initial part of the characteristic, when the transistor is in saturation state, is very low.

(v) Current amplification factor (β): This is defined as the ratio of the change in collector current to the change in base current at a constant collector-emitter voltage (V_{CE}) when the transistor is in active state.

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

This is also known as *small signal current gain* and its value is very large.

If we simply find the ratio of I_C and I_B we get what is called dc β of the transistor. Hence,

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

Since I_C increases with I_B almost linearly and $I_C = 0$ when $I_B = 0$, the values of both β_{dc} and β_{ac} are nearly equal. So, for most calculations β_{dc} can be used. Both β_{ac} and β_{dc} vary with V_{CE} and I_B (or I_C) slightly.

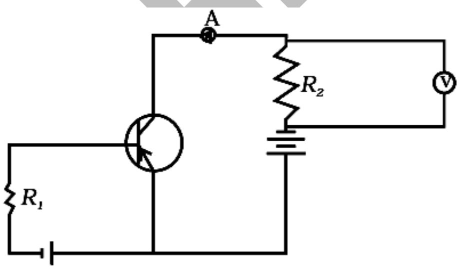
Understanding Concept:-

1. From the output characteristics shown in Fig. above, calculate the values of β_{ac} and β_{dc} of the transistor when V_{CE} is 10 V and I_C = 4.0 mA.

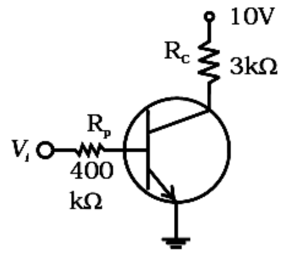
2. For transistor action, which of the following statements are correct:
(a) Base, emitter and collector regions should have similar size and doping concentrations.
(b) The base region must be very thin and lightly doped.
(c) The emitter junction is forward biased and collector junction is reverse biased.
(d) Both the emitter junction as well as the collector junction are forward biased.

3. In a npn transistor circuit, the collector current is 10mA. If 95 per cent of the electrons emitted reach the collector, which of the following statements are true?
(a) The emitter current will be 8 mA.
(b) The emitter current will be 10.53 mA.
(c) The base current will be 0.53 mA.
(d) The base current will be 2 mA.

4. If the resistance R_1 is increased (Fig.), how will the readings of the ammeter and voltmeter change?

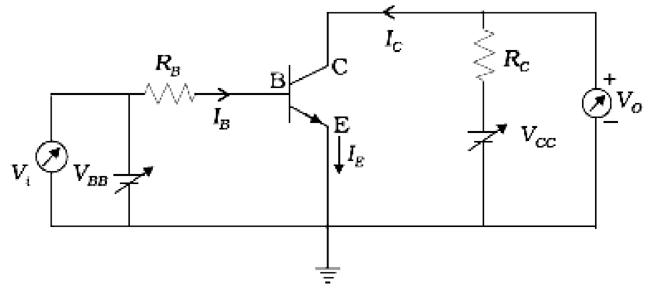


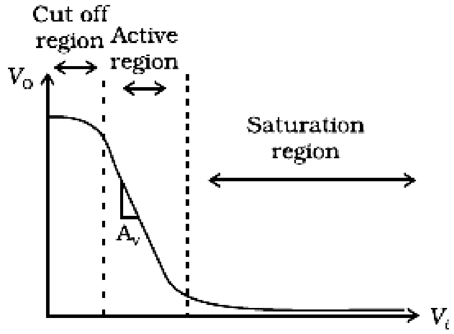
5. In the circuit shown in Fig., when the input voltage of the base resistance is 10V, V_{be} is zero and V_{ce} is also zero. Find the values of I_b, I_c and β.



Transistor as a device

(i) Transistor as a switch





Applying Kirchhoff's voltage rule to the input and output sides of this circuit, we get

$V_{BB} = I_BR= + V_{BE}$ --------------(1)

and

$V_{CE} = V_{CC} – I_CR_C$. ------------(2)

We shall treat V_{BB} as the dc input voltage V_i and V_{CE} as the dc output voltage V_O. So, we have

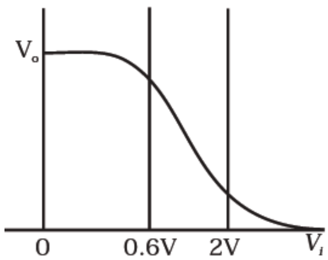
$V_i = I_BR_B + V_{BE}$

and

$V_o = V_{CC} – I_CR_C$.

[*Taking the case of Si transistor, as long as input V_i is less than 0.6 V, the transistor will be in cut off state and current I_C will be zero.*
Hence $V_o = V_{CC}$
When V_i becomes greater than 0.6 V the transistor is in active state with some current I_C in the output path and the output V_o decrease as the term I_CR_C increases. With increase of V_i, I_C increases almost linearly and so V_o decreases linearly till its value becomes less than about 1.0 V.
Beyond this, the change becomes non linear and transistor goes into saturation state. With further increase in Vi the output voltage is found to decrease further towards zero though it may never become zero.
*According to the plot of V_o vs V_i curve, [also called the **transfer characteristics** of the base-biased transistor, we see that between cut off state and active state and also between active state and saturation state there are regions of non-linearity showing that the transition from cutoff state to active state and from active state to saturation state are not sharply defined.*]

As long as V_i is low and unable to forward-bias the transistor, V_o is high (at V_{CC}). If V_i is high enough to drive the transistor into saturation, then V_o is low, very near to zero. When the transistor is not conducting it is said to be switched off and when it is driven into saturation it is said to be switched on. Hence we can define low and high states as below and above certain voltage levels corresponding to cutoff and saturation of the transistor, then we can say that a **low input switches** the transistor **off** and a **high input switches** it **on**.
Alternatively, we can say that a low input to the transistor gives a high output and a high input gives a low output.
The switching circuits are designed in such a way that the transistor does not remain in active state. {C.T.M.}
Understanding Concept:-
1. In Fig. (above), the V_{BB} supply can be varied from 0V to 5.0 V. The Si transistor has β_{dc} = 250 and R_B = 100 KΩ, R_C = 1 KΩ, V_{CC} = 5.0V. Assume that when the transistor is saturated, V_{CE} = 0V and V_{BE} = 0.8V. Calculate (a) the minimum base current, for which the transistor will reach saturation. Hence, (b) determine V_1 when the transistor is 'switched on'. (c) find the ranges of V_1 for which the transistor is 'switched off' and 'switched on'.
2. Figure shows the transfer characteristics of a base biased CE transistor. Which of the following statements are true?
(a) At V_i = 0.4V, transistor is in active state.
(b) At V_i = 1V, it can be used as an amplifier.
(c) At V_i = 0.5V, it can be used as a switch turned off.
(d) At V_i = 2.5V, it can be used as a switch turned on.

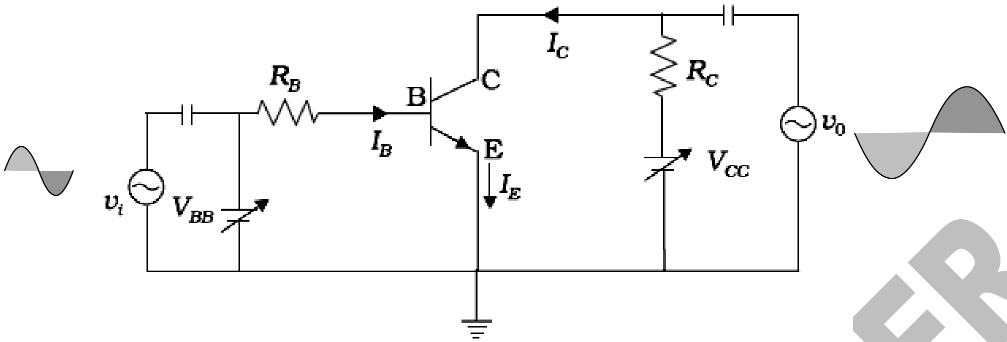


Transistor as an Amplifier

A device which increases the amplitude of the input signal is called amplifier.

(i). The transistor can be used as an amplifier in the following three configuration

(a) CB amplifier (b) CE amplifier **(in Syllabus)** (c) CC amplifier



[To operate the transistor as an amplifier it is necessary to fix its operating point somewhere in the middle of its active region. If we fix the value of V_{BB} corresponding to a point in the middle of the linear part of the transfer curve then the dc base current I_B would be constant and corresponding collector current I_C will also be constant. The dc voltage $V_{CE} = V_{CC} - I_C R_C$ would also remain constant. The operating values of V_{CE} and I_B determine the operating point, of the amplifier.

If a small sinusoidal voltage with amplitude v_s is superposed on the dc base bias by connecting the source of that signal in series with the V_{BB} supply, then the base current will have sinusoidal variations superimposed on the value of I_B. As a consequence the collector current also will have sinusoidal variations superimposed on the value of I_C, producing in turn corresponding change in the value of V_O. We can measure the ac variations across the input and output terminals by blocking the dc voltages by large capacitors.

Working:- Suppose we superimpose an ac input signal v_i (to be amplified) on the bias V_{BB} (dc) as shown in Fig. The output is taken between the collector and the ground.

Let $v_i = 0$. Then applying Kirchhoff's law to the output loop, we get

$V_{cc} = V_{CE} + I_C R_C$ ------------(1)

Likewise, the input loop gives

$V_{BB} = V_{BE} + I_B R_B$ ----------(2)

When v_i is not zero, we get

$V_{BE} + v_i = V_{BE} + I_B R_B + \Delta I_B (R_B + r_i)$

The change in V_{BE} can be related to the input resistance r_i and the change in I_B. Hence

$v_i = \Delta I_B (R_B + r_i) = r\, \Delta I_B$

Now the change in I_C due to a change in I_B causes a change in V_{CE} and the voltage drop across the resistor R_C because V_{CC} is fixed. Therefore

$\Delta V_{CC} = \Delta V_{CE} + R_C \Delta I_C = 0$

or $\Delta V_{CE} = -R_C \Delta I_C = v_o$

where the change in V_{CE} is the output voltage v_0.

Hence, the voltage gain of the amplifier is

$A_V = \frac{v_o}{v_i} = \frac{\Delta V_{CE}}{r\,\Delta I_B} = \frac{-R_C\,\Delta I_C}{r\,\Delta I_B} = -\beta_{ac}\frac{R_C}{r}$; where β_{ac} is defines as the a.c current gain of the amplifier.

The negative sign represents that output voltage is opposite with phase with the input voltage.

Similarly, the power gain A_P can be expressed as the product of the current gain and voltage gain. Mathematically

$A_P = \beta_{ac} \times A_v$

Since β_{ac} and A_v are greater than 1, we get ac power gain. However it should be realized that transistor is not a power generating device. The energy for the higher ac power at the output is supplied by the battery.

* Trans conductance (g_m): The ratio of the change in collector current to the change in emitter base voltage is called trans conductance. *i.e.* $g_m = \frac{\Delta I_c}{\Delta V_{EB}}$. Also $g_m = \frac{A_V}{R_C}$; R_c = Load resistance

Understanding Concept:-

1. For a CE transistor amplifier, the audio signal voltage across the collector resistance of 2.0 KΩ is 2.0 V. Suppose the current amplification factor of the transistor is 100, What should be the value of R_B in series with V_{BB} supply of 2.0 V if the dc base current has to be 10 times the signal current. Also calculate the dc drop across the collector resistance. (Refer to Fig. above for amplifier).

2. For a transistor amplifier, the voltage gain

(a) remains constant for all frequencies.

(b) is high at high and low frequencies and constant in the middle frequency range.

(c) is low at high and low frequencies and constant at mid frequencies.

(d) None of the above.

3. For a CE-transistor amplifier, the audio signal voltage across the collected resistance of 2 kΩ is 2 V. Suppose the current amplification factor of the transistor is 100, find the input signal voltage and base current, if the base resistance is 1 kΩ.

4. Two amplifiers are connected one after the other in series (cascaded). The first amplifier has a voltage gain of 10 and the second has a voltage gain of 20. If the input signal is 0.01 volt, calculate the output ac signal.

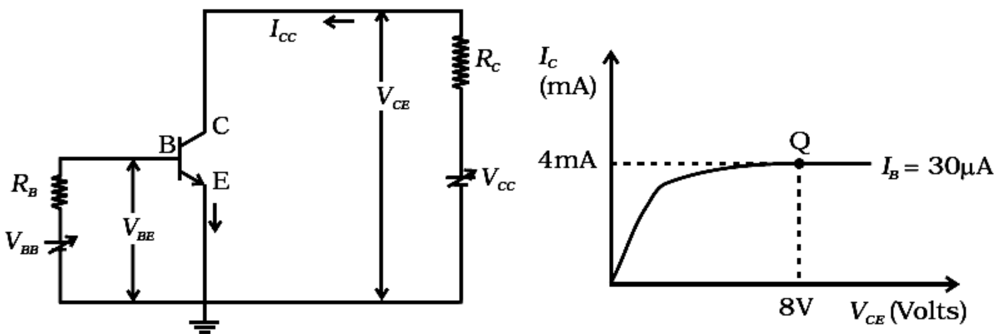
5. The amplifiers X, Y and Z are connected in series. If the voltage gains of X, Y and Z are 10, 20 and 30, respectively and the input signal is 1 mV peak value, then what is the output signal
voltage (peak value)

(i) if dc supply voltage is 10V?

(ii) if dc supply voltage is 5V?

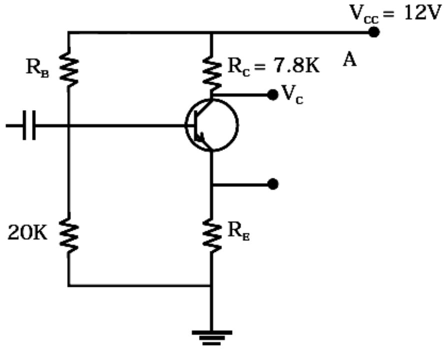
6. In a CE transistor amplifier there is a current and voltage gain associated with the circuit. In other words there is a power gain. Considering power a measure of energy, does the circuit violate conservation of energy?

7. Consider the circuit arrangement shown in Fig. for studying input and output characteristics of npn transistor in CE configuration.

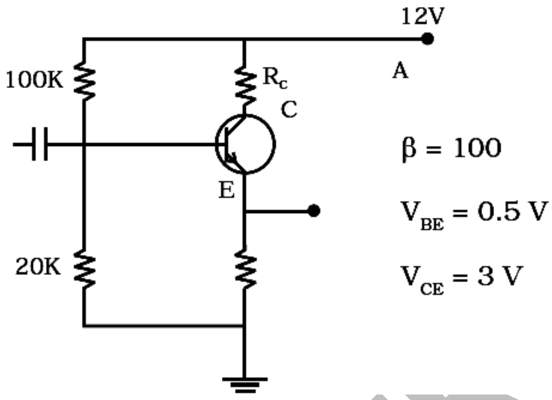


Select the values of R_B and R_C for a transistor whose V_{BE} = 0.7 V, so that the transistor is operating at point Q as shown in the characteristics shown in Fig. Given that the input impedance of the transistor is very small and V_{CC} = V_{BB} = 16 V, also find the voltage gain and power gain of circuit making appropriate assumptions.

8. For the transistor circuit shown in Fig., evaluate V_E, R_B, R_E given I_C = 1 mA, V_{CE} = 3V, V_{BE}= 0.5 V and V_{CC} = 12 V, β = 100.



9. In the circuit shown in Fig., find the value of RC.



10. When npn transistor is used as an amplifier: **[AIEEE-2004]**
(1) electrons move from base to collector
(2) holes move from emitter to base
(3) electrons move from collector to base
(4) holes move from base to emitter

Transistor as an Oscillator

(1) It is defined as a circuit which generates an *ac* output signal without any externally applied input signal.

Audio frequency oscillators generates signals of frequencies ranging from a few *Hz* to 20 *kHz* and radio frequency oscillators have a range from few *kHz* to *MHz*.

(2) In an oscillator the frequency, waveform, and magnitude of *ac* power generated is controlled by circuit itself.

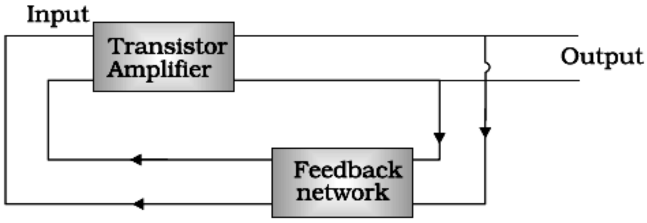
(3) An oscillator may be considered as amplifier which provides it's own input signal.

(4) The essential of a transistor oscillator are

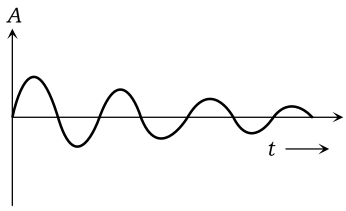
(i) **Tank circuit:** Parallel combination of *L* and *C*. This network resonates at a frequency $\nu_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$.

(ii) **Amplifier:** It receives *dc* power from the battery and converts into *ac* power. The amplifier increases the strength of oscillations.

(iii) **Feed back circuit:** A portion of the output power is returned back (feedback) to the input in phase with the starting power (this process is termed positive feedback)

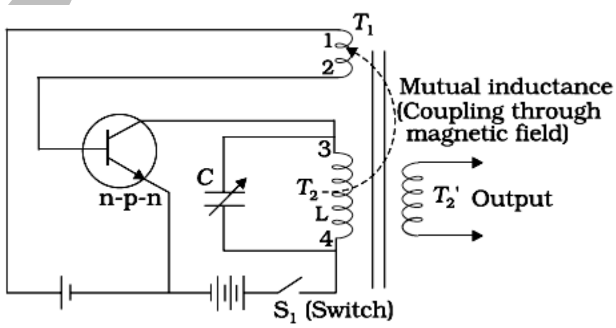


[NOTE:-Need for positive feedback: The oscillations are damped due to the presence of some inherent electrical resistance in the circuit. Consequently, the amplitude of oscillations decreases rapidly and the oscillations ultimately stop. Such oscillations are of little practical importance. In order to obtain oscillations of constant amplitude, we make an arrangement for regenerative or positive feedback from the output circuit to the input circuit so that the losses in the circuit can be compensated.**]**

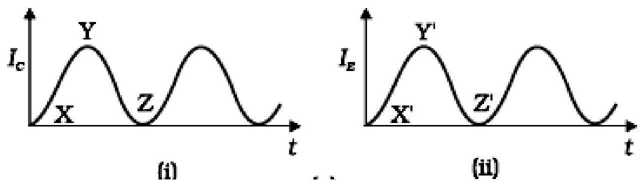


Working:-

Suppose switch S_1 is put on to apply proper bias for the first time. Obviously, a surge of collector current flows in the transistor. This current flows through the coil T_2 where terminals are numbered 3 and 4 [Fig.]. This current does not reach full amplitude instantaneously but increases from X to Y, as shown in Fig.(i). The inductive coupling between coil T_2 and coil T_1 now causes a current to flow in the emitter circuit (note that this actually is the feedback from input to output). As a result of this positive feedback, this current (in T_1; emitter current) also increases from X' to Y' Fig.(ii). The current in T_2 (collector current) connected in the collector circuit acquires the value Y when the transistor becomes saturated. This means that maximum collector current is flowing and can increase no further. Since there is no further change in collector current, the magnetic field around T_2 ceases to grow. As soon as the field becomes static, there will be no further feedback from T_2 to T_1. Without continued feedback, the emitter current begins to fall. Consequently, collector current decreases from Y towards Z [Fig.(i)]. However, a decrease of collector current causes the magnetic field to decay around the coil T_2. Thus, T_1 is now seeing a decaying field in T_2 (opposite from what it saw when the field was growing at the initial start operation). This causes a further decrease in the emitter current till it reaches Z' when the transistor is cut-off. This means that both I_E and I_C cease to flow. Therefore, the transistor has reverted back to its original state (when the power was first switched on). The whole process now repeats itself. That is, the transistor is driven to saturation, then to cut-off, and then back to



Note that the coils T_2 and T_1 are wound on the same core and hence are inductively coupled through their mutual inductance.



saturation. The time for change from saturation to cut-off and back is determined by the constants of the tank circuit or tuned circuit (inductance L of coil T_2 and C connected in parallel to it). The resonance frequency (ν) of this tuned circuit determines the frequency at which the oscillator will oscillate.

$$\nu = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

In the circuit as shown, the tank or tuned circuit is connected in the collector side. Hence, it is known as tuned collector oscillator. If the tuned circuit is on the base side, it will be known as tuned base oscillator. There are many other types of tank circuits (say RC) or feedback circuits giving different types of oscillators like Colpit's oscillator, Hartley oscillator, RC-oscillator.