विघ्न विचारत भीरु जन, नहीं आरम्भे काम, विपति देख छोड़े तुरंत मध्यम मन कर श्याम।
पुरुष सिंह संकल्प कर, सहते विपति अनेक, 'बना' न छोड़े ध्येय को, रघुबर राखे टेक।।

रचितः मानव धर्म प्रणेता
सद्गुरु श्री रणछोड़दासजी महाराज

STUDY PACKAGE

This is TYPE 1 Package please wait for Type 2

Subject : PHYSICS

Topic : SEMI CONDUCTORS ELECTRONICS

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Index

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Electronics

The study of matter in the solid state and its physical properties has contributed a lot to modern living–particularly, the science of electronics.

Solids may be crystalline or amorphous –crystalline solids have long-range order in their structure while amorphous solids do not have such order. Here we will deal with crystalline solids only.

Crystalline solids & their electronic properties

A crystalline solid is built around a lattice, the regular, repeating mathematical points extending throughout space. The forces responsible for the regular arrangement of atoms in a lattice are similar to those in molecular bonds – covalent and ionic. A third type crystalline bond is a metallic bond: one or more of the outermost electrons in each atom become detached from the parent atom and are free to move throughout the crystal. These electrons are known as "free electrons", and are responsible for the conduction of electricity by metals.

Band structure of solids

As isolated atoms are brought together to form a solid, interactions occur between neighbouring atoms. The attractive and repulsive forces between atoms find a proper balance when the proper inter-atomic spacing is reached. As this process occurs, there are important changes in the electronic energy levels and these changes lead to the varied electrical properties of solids.

An electron moving within a crystal lattice is subjected to a periodic potential due to the ionic cores present in the regular arrangement of the lattice. This is very different from the potential feld by an electron within a hydrogen atom. The energy levels (or the single atom: they are distributed in a band like structure, with gaps in between. The highest energy band wave functions are highly delocalized: an electron in one of these bands tends to be free enough to move over the entire body of the crystal. This band is known as a conduction band. The wave function belonging to lower bands are not so highly localised, they are localised to within a few neighbouring atoms of the lattice. The electrons in these bands are responsible for the formation of inter-atomic bonds: the band is referred to as the valence band and the electrons, valence electrons.'

Energy bands, that are lower in energy than the valence band, have progressively decreasing widths and have properties similar to atomic levels. Their wave functions a localized to a single atom and they are, therefore, tightly bound.

Metals, insulators and semiconductors

The energy gap between the lowest level of the conduction band and the highest level of the valence band is known as the band gap (E_g). The band gap (E_g) and the nature of the filling of the energy levels (according to the Pauli Exclusion principle) are cheifly respeonsible for the electrical properties of solids.

When there exists a large number of electrons within the conduction band as a result of the filling process, this leads to conduction. Another reason for the existence of electrons within the conduction band is the thermal excitation of electrons from the valence band.

The probability of electronic at a temperature T(in Kelvin) varies as the factor $e^{-Eg/2kT}$, where E_0 is the band gap and k is Boltzmann's constant. Thus materials having very small gaps ($E_0 \leq 1$ meV) behave as conductors, while those having large band gaps ($E_g < 5$ eV) behave as insulators at ordinary temperatures. Materials (like crystalline Si, Ge) having band gaps Eg–1eV behave as semiconductors at ordinary temperatures.

As the temperature is raised in a semiconductor, electrons from the valence band pick up thermal excitation from atomic motion within the lattice and this leads to a transition to the conduction band, if sufficient energy is transferred to the electron.

For each electron that transits to the conduction band, a valency is left within the valence band. This vacancy, referred to as a hole, helps in conduction as well. When an external electric field is applied to a semiconductor sample, the electrons within the conduction band experience a force proportional to the electric field.

$F = q_e E$, where q_e is the electronic charge.

The acceleration of the electron is,

$a = \frac{q_e E}{m}$, m being the effective mass of the electron in the conduction band.

Due to collisions between the electron and and ionic cores within the lattice, this motion leads to an effective uniform drift velocity for electrons within the electric field.

The electron accelerates for a time τ, the collision time, before it loses its energy to the lattice in a collision. In this model (the Drude–Lorenz model), the average drift velocity of the electron is

$$v_d = a\tau = \frac{q_e E}{m_e} E$$

If there are n_e electrons per unit volume, the current density j is given by

$$j = n_e q_e v_d = \frac{n_e q_e^2 \tau}{m_e} E$$

$\equiv \sigma E$ (by definition), Further, $v_d = \frac{q_e \tau}{m_e} E = \mu_e E$ (by definition)

where μ_e is the 'mobility' of the electron in the conduction band.

Conduction occurs also in the valence band. Here, the electrons 'hop' from one vacancy ("hole") to another in the electric field E, causing an electric current. This current may be thought of as due to the motion of "hole" within the valence band, the "holes" imagined to possess a positive charge equal in magnitude to that on an electron.

This accounts for the fact that the "holes" move in an opposite direction to electrons within the valence band.

The net current density within the semiconductor is given by:

$$j = \left(\frac{n_e q_e^2 \tau_e}{m_e} + \frac{n_n q_e^2 \tau_n}{m_n} \right) E$$

$$= q_e(n_e \mu_e + n_n \mu_n)E$$

where n_h and μ_h are the concentration of holes and hole mobility, respectively, within the valence band.

$$\therefore\ \sigma = q_e(n_e \mu_e + n_h \mu_h)$$

Illustration 1: Germanium has a band gap of 0.67 eV. Calculate the value of the quantity $e^{-Eg/kT}$, which is related to the probability of a transition of an electron from the valence band to the conduction band, for two temperatures at 27^0C and 127^0C.

Sol: The band gap of Ge = 0.67 eV

At T = 300 K (or 273 + 27)

$$k_BT = \frac{1}{11600} \times 300$$

≈ 0.026 eV & at T = 400 K (127^0C)

$k_BT \approx 0.0345$ eV

$e^{-Eg/kT} = 6.4 \times 10^{-12}$ at 27^0C

and 3.7×10^{-9} at 127^0C

Intrinsic and Extrinsic Semiconductors

For intrinsic semiconductors, the concentration of electrons within the conduction band (n_e) equals that of holes within the valence band (n_h)

Intrinsic semiconductors are usually those which do not have any impurities within them. At absolute zero (T = 0), these semiconductors do not have any electorns in the conduction band or holes within the valence band examples are pure crystalline Si, Ge, Ga, As, In Sb, etc.

Extrinsic semiconduction occurs due to the introduction of excess holes or, electrons into a semiconductor (Si for example). This is done by introducing microscopic quantities of Group V elements (P, As) as impurities into the Si – lattice. These impurities are added in very small concentrations so that they do not change the Si-lattice. Being pentavalent, there exists an excess electron (in addition to the four, which form bonds) in P_0. An energy level P (or As) lies just below the conduction band of Si.

The excess electron (in this donor level) of P is immediately transferred to the conduction band of Si: this results in an increase in the concentration of conduction electrons – n_e. However, this also results in a reduction in the number of holes, such that,

$$n_e n_h = n_1^2$$

This type of Si with excess electrons is known as n-type Si.

Addition of small quantities of acceptor type impurities (trivalent group III elements like B) leads to an empty 'acceptor' level just above the filled valence band. This leads to electrons getting transferred from the valence band into this acceptor level, and thus, the introduction of holes into the valence band.

The relation $n_e n_h = n_1^2$, also holds good here.

The concentration of electrons in the conduction band gets correspondingly reduced. Such semiconductors are known as p-type semiconductors.

Illustration 2: A semiconductor has an electron concentration of 0.45×10^{12}/ m^3 and a hole concentration of 5×10^{20} / m^3. Find its conductivity. ($\mu_e = 0.135$ m^2/V-S, $\mu_h = 0.048$ m^2/V-S).

Sol: The conductivity, $\sigma = e(n_e\mu_e + n_h\mu_h)$

$= 1.6 \times 10^{-19}$ (o.45 $\times 10^{22} \times 0.135 + 5 \times 10^{20} \times 0.048$)

$= 3.84\ \Omega^{-1}$-m^{-1}.

Exercise 1: A silicon sample is made into a p-type semiconductor by doping, on an average on Indium atom per 5×10^7 silicon atoms. If number density of atoms in the silicon sample is 5×10^{28} atoms/m^3 then find the number density of Indium atoms in silicon per cm^3.

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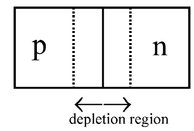
p-n Junction

When a p-type semiconductor is joined to an n-type semiconductor (both Si, Ge) the device is known as a p-n junction.

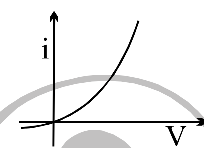


The excess elelctrons in n-type Si diffuse into the p-type Si and fill up the holes in the adjacent p-region. A small region adjoining the junction is, therefore devoid of electrons and holes therefore has very high resistivity. This region is known as the depletion region.

On the application of a forward electric field (p to positive & n to negative) the width of the depletion region is reduced and concequently, a current flows across the junction easily.

When the p end is connected to a negative electrode an the n end to the positive electrode of a circuit the depletion region widens and the resistance increases tremendously due to the withdrawals of charge carries. Thus the p-n junction, almost, does not conduct in the reverse direction. Therefore, a p-n junction acts like a diode (or a rectifier).

The current vs. Voltage relation for a diode is $i = I_s\left(e^{q_eV/kT} - 1\right)$



Where V is the forward p.d. applied across the diode and I_s is the reverse saturation current, q_e is the electronic charge (in magnitude); k, the Boltzmann constant and T, the absolute temperature.

The forward current becomes significant only after $V \geq 0.7$ V (for si-diodes), in practice, and this is known as the knee voltage. The reverse saturation current (I_s) also depends on temperature, through this dependence is rather weak. I_s is of the order of a few μA to a few mA depending on the diode.

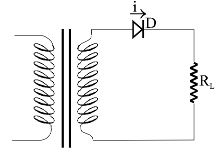
Illustration 3 : At a temperature of 300 K, a p-n juction has a saturation current of 0.6 mA. Find the current when the voltage across the diode is 1 mV, 100 mV and -1 V.

Solution: At a temperature of 300 K, the p-n junction has a saturation current $I_S = 0.6 \times 10^{-3}$A
The current voltage relation for the diode is
$i = i_S\,(e^{qV/kBT} - 1)$
k_BT (at 300k) ≈ 0.026 eV
For V = 1 mV, i = 23 μA, V = 100 mV, i = 27.5 mA and V = -1V, i = -0.6 mA

Rectifiers

(i) Half wave rectifier

A half-wave rectifier circuit consists of a diode D and the load resistance R_L in series, as shown in the adjacent diagram.



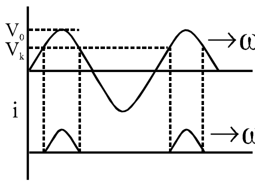
If V_k is the knee-voltage of the diode (≈ 0.7 V for si diode) and I is the current flowing during forward bais: $iR_L + V_R = V_0 \sin\omega t$, Where the RHS represents the emf applied to the circuit.

$$\therefore i = \frac{V_0 \sin\omega t - V_R}{R_L} \text{ and } i > 0$$

The diode is in forward bias, when $\sin\omega t \geq \frac{V_R}{V_0}$

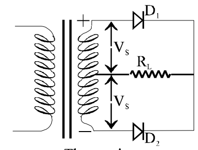
or, $\sin^{-1}(V_k/V_0) \leq \omega t \leq \pi - \sin^{-1}(V_k/V_0)$ dueing the 1st half cycle.

The current i flowing in the circuit.



(ii) Full wave rectifier

A full wave rectifier circuit is shown in the adjacent diagram. It consists of two diodes D_1 and D_2 connected to a load resistance R_L. An ac–voltage $V_s = V_0\sin\omega t$ is applied across the circuit as shown. The current through R_L is just a in the case of the half-wave rectifier except that it flows during both the half-cycles.



The maximum reverse

The current through the load resistance is not a smooth dc. The maximum reverse voltage across a diode is twice the peak forward voltage.

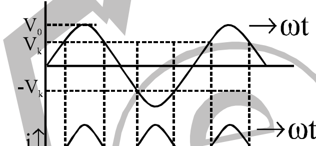
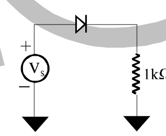
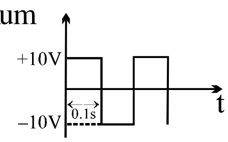


Illustration 4: A p-n juction forms part of a rectifier circuit. A voltage waveform as shown in figure is applied to the circuit. If the diode is ideal except for a drop of 0.7 V in the forward biased condition,

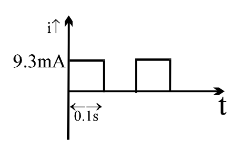


(a) Plot the current through the resistor as as function of time. What is the maximum current?

(b) Calculate the average heat lost in the resistance over a single cycle.



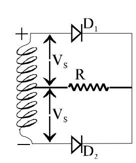
Solution: (a) In forward bias, the potential drop across the diode is 0.7 V, and the rest of the p.d. is dropped across the resistance R ($=1k\Omega$)



The current (maximum) $= \frac{10-0.7}{1000} = 9.3$ mA

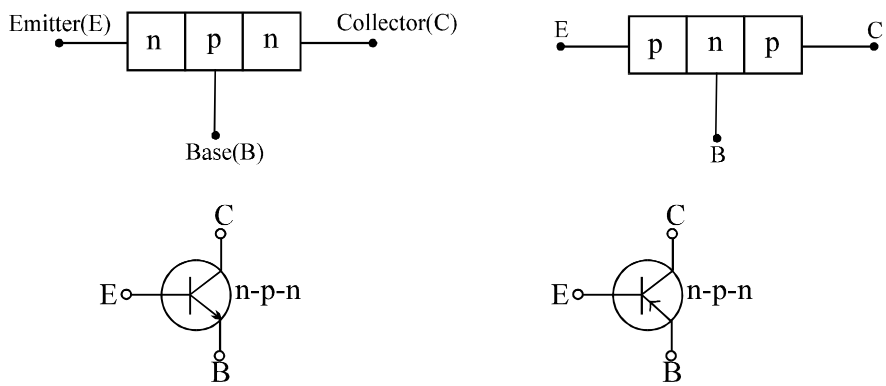
(b) The average heat lost in the resistance over a single cycle is
$i^2R\Delta t = (9.3 \times 10^{-3})^2 \times 10^3 \times 10^{-1}$ J
$= 8.65 \times 10^{-3}$ J

Exercise 2: In the full-wave rectifier circuit, the diodes D_1, D_2 are ideal and identical. The emf $V_s = 100\sin(100\,\pi t)$ volt is applied as shown (t is in sec). Calculate the voltage across the diode D_1 as a function of time.



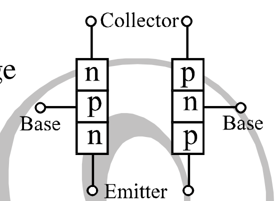
Transistor

Transistors are semiconductor devices capable of power amplification. A transistor consists of a thin central layer of one type of semiconductor sandwicthed between two relatively thick pieces of the other type. Also known as the bipolar function transistor (BJT), it can be of two types, vix., pnp or npn. The npn transistor consists of a very thin piece of p-type material sandwiched between two pieces of n-type, while the pnp transistor has a central piece of n-type. The pieces at either side are called the emitter and the collector respectively while the central part is known as the base. The base is lightly doped compared with the emitter and the collector, and is only about 3-5 μm thick.

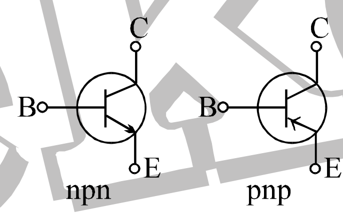


(i) Biasing of a transistor

A transistor can operate in any one of the three states, depending on the voltage across its junctions. These are the active state, the cut off state and the saturation state.



State	Junction	
	Emitter Base	Base collector
Active	FB	RB
Cut off	RB	RB
Saturation	FB	FB



Where FB – Forward biased, RB – Reversed biased.

The active state is the basic mode of operation. It is utilized in most amplifiers and oscillators. The cut-off and saturation states are typical of transistors operation in the switching mode. Basically, in any application using a transistor, two circuits are formed. One is the input and the other is the output circuit.

Operation of an npn transistor:

An increase in the forward input voltage V_{BE} (across the emitter-base junction) brings about a fall in the height of the potential barrier at the emitter junction and an increase in the current flowing across that junction, i.e. in the emitter current I_E. The electrons that make up this current are injected from the emitter into the base and diffuse through the base into the collector region, thereby boosting the collector current. Since the collector junction is reverse biased, the electrons are swept to the collector. Almost all the electrons emitted from the emitter are collected by the collector. But a small fraction of electrons recombine in the base region, which constitute the base current I_B.

(ii) Working of a transistor

In amplification we bias B.E. junction in forward and C-B junction in reverse. Base emitter junction is forward biased hence electrons are injected by the emitter into base (n-p-n). The thickness of base region in very small, as a result most of the electrons diffusing in to base region cross into the collector base juction. The reverse biased CB junction sweeps off electrons as they are injected into the junction.

By using Kirchhoff's law, we can write, $I_E = I_B + I_C$

Where I_E is emitter current, I_C is collector current, I_B is base current.

Generally we use transistor for amplification in common emitter mode and common base mode. The collector-base, current gain is defined as

$\beta = \frac{I_C}{I_B}$, β is very large (nearly 100) and, the collector – emitter current gain is defined as

$\alpha = \frac{I_C}{I_E}$, α is very close to 1, but less than 1.

The parameters β and α for a transistor are decided by the constriction, the doping profile and other similar manufacturing parameters; not by the baising circuit.

Since $I_E = I_B + I_C$

$$\therefore \frac{I_E}{I_C} = \frac{I_B}{I_C} + 1$$

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

We get $\beta = \frac{\alpha}{1-\alpha}$

In an amplifier a.c. signals are amplified. Therefore,

$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B}$ We get voltage gain $\frac{V_o}{V_i} = \beta . \frac{R_L}{R_{BE}}$

where R_L is load resistance

R_{BE} is input resistance.

Since the current gain is β,

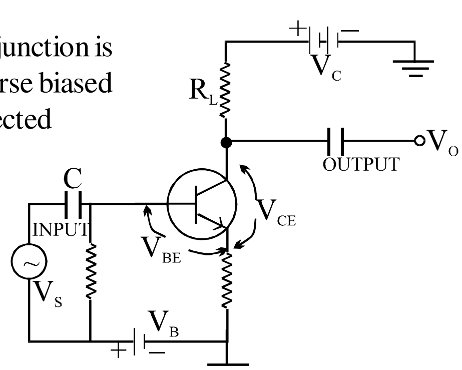
Power gain = voltage gain x current gain

$$= \beta \frac{R_L}{R_{BE}}$$

Thrans conductance is defined as $g_m = \frac{\Delta I_C}{\Delta V_{BE}}$

(iii) Transistor as an Amplifier

In order to use a transistor as an amplifier, the emitter-base junction is forward biased (FB) and the base collector junction is reverse biased (RB). In a common-emitter (CE) amplifier, the load is connected between the collector and the emitter through d.c. supply.



An a.c. input singnal V_S is superimposed on the bias V_{BE}. This changes V_{BE} by an amount $\Delta V_{BE} = V_s$.
The output is taken between the collector and the gournd.
Applying Kirchoff's voltage law on the output loop, if $V_S = 0$.

$$V_C = V_{CE} + I_C R_L$$

Similarly, $V_B = V_{BE}$

when $V_S \neq 0$, then $V_B + V_S = V_{BE} + \Delta V_{BE}$

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

$$V_S = \Delta V_{BE} = r_i \Delta I_B$$

The change in I_B causes a change in I_C. Thus, $\beta_{ac} = \dfrac{\Delta I_C}{\Delta I_B}$ (current gain factor)

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_L because V_C is fixed.

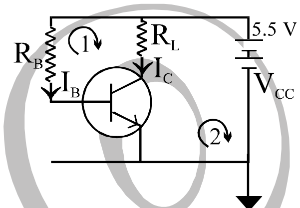
Thus, $\Delta V_C = \Delta V_{CE} + R_L \Delta I_C = 0$

$$v_o = \Delta V_{CE} = -R_L \Delta I_C = -\beta_{ac} R_L \Delta I_B$$

The voltage gain

$$A_V = \frac{v_o}{v_i} = \frac{\Delta V_{CE}}{\Delta V_{BE}} = -\frac{\beta_{ac} R_L}{r_i} = -g_m R_L \quad \text{Where } g_m = \frac{\beta_{ac}}{r_i} = \text{transconductance.}$$

Illustration 5: In the following circuit the base current I_B is 10 μ A and the collector current is 5.2mA. Can this transistor circuit be used as an amplifier? In the circuit $R_B = 5\,\Omega$ and $R_L = 1\,K\Omega$



Solution: We know that for a transistor is CE configuration to be used as an amplifier the BE junction must be forward biased & base collector junction must be reverse biased. In the given question we are required to just check this

loop-1

$I_B R_B - I_C R_L - V_{CB} = 0$

$\Rightarrow V_{CB} = [(5 \times 10^3 \times 10 \times 10^{-6}) - (5.2 \times 10^{-3} \times 10^3)]V$

$\Rightarrow (0.05 - 5.2)V$

$\Rightarrow v_C < v_B$ ......(1)

loop - 2

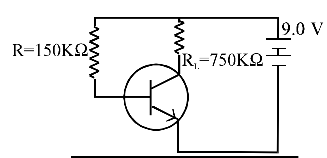
$V_{CE} + I_C R_L - V_C = 0$

$\Rightarrow V_{CE} = (5.5 - 5.2)V = 0.3\ V \Rightarrow V_C > V_E$

as emitter is grounded, $V_C = 0.3V$ ....(2)

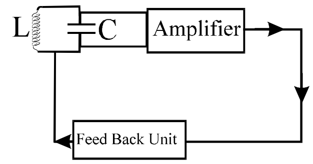
from (1) and (2) $V_B = 5.5\ V \Rightarrow$ BC junction is forward biased & hence the given is transistor would not word as an amplifier

Exercise 3: In the transistor circuit shown in figure direct current gain of the transistor is 80. Assuming $V_{BE} \approx 0$, calculate (a) Base current I_B (b) Potential difference between collectors and emitter terminals.



(iv) Transistor used in an oscillator circuit

The function of an oscillator circuit is to produce an alternating voltage of desired frequency without applying any external input signal. This can be achieved by feeding back a portion of the output voltage of an amplifier to its input terminal as shown in the figure.

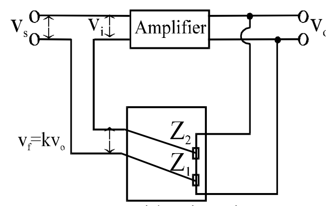


An amplifier and an LC network are the basic part of the circuits. The amplifier is just a transistor used in common emitter mode and the LC network consists of an inductor and a capacitor. The output frequency of an oscillator is the resonating frequency of L-C network which is given as $f_o = \dfrac{1}{2\pi\sqrt{LC}}$

From the figure, $v_i = v_s + v_f$

where $v_f = kv_o = \dfrac{Z_1}{Z_1 + Z_2} v_o$

k is feedback constant which represent the fraction of output voltage which is to be feedback to input. Z_1 and Z_2 works as voltage divider. The voltage across the Z_1 is feedback in the input of oscillator.



Feed back unit

The voltage gain of the amplifier is

$$A_v = \frac{v_o}{v_i}$$

and the overall gain is $A'_v = \dfrac{v_o}{v_s}$

Now, $v_o = A_v v_i = A_v(v_s + v_f)$

or $v_o = A_v\left(\dfrac{v_o}{A'_v} + kv_o\right)$

or $A'_v = \dfrac{A_v}{1 - kA_v}$

By properly adjusting the feed back, it is possible to get $kA_v = 1$ which gives $A'_v = \infty$, or we get an output without applying any input. The oscillator generates an ac signal.

Exercise 4: In a silicon transistor, the base current is changed by 20 μA. This results in a change of 0.02 V is base to emitter voltage and a change of 2 mA in the collector current.

(a) Find the input resistance r_i and β_{ac} of the transistor.

(b) If this transistor is used as an amplifier with the load resistance 5 $k\Omega$. Find the voltage gain of the amplifier.

(v) Analysis of transistor circuit

Input KVL,

$V_{BB} = I_B R_B + V_{BE} + I_E R_E$

usually $R_E = 0$.

Therefore,

$V_{BB} = I_B R_B + V_{BE}$ .....(1)

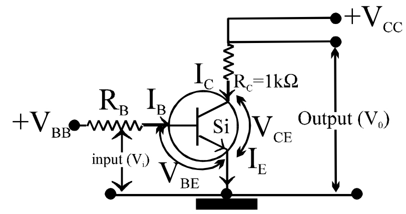
For silicon transistor $V_{BE} = 0.7$ V

Output KVL,

$V_{CC} = I_C R_C + V_{CE} + I_E R_E$

for $R_E = 0$,

$V_{CC} = I_C R_C + V_{CE}$ ....(2)



current relationship, $I_C = \beta I_B$ ....(3)

Where β is d.c. current gain of the transistor.

$I_C = \alpha I_E$ ....(4)

Where α is the a.c. current gaing of the transistor

output voltage, $V_o = I_C R_C$.

input voltage, $V_i = I_B R_B$.

Therefore voltage gain $A_V = \dfrac{V_o}{V_i} = \dfrac{I_C R_C}{I_B R_B} = \beta \dfrac{R_C}{R_B}$ ......(5)

Exercise 5: In the circuit shown, assume $\beta = 60$ and input resistance $R_{in} = 1000\,\Omega$. Find the voltage gain of the amplifier.