Electrical Engineering

Analog Electronics Including Electronic Devices & Circuits

Comprehensive Theory

with Solved Examples and Practice Questions

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CHAPTER 1

Semiconductor Physics

1.1 Conductor, Semiconductor and Insulator

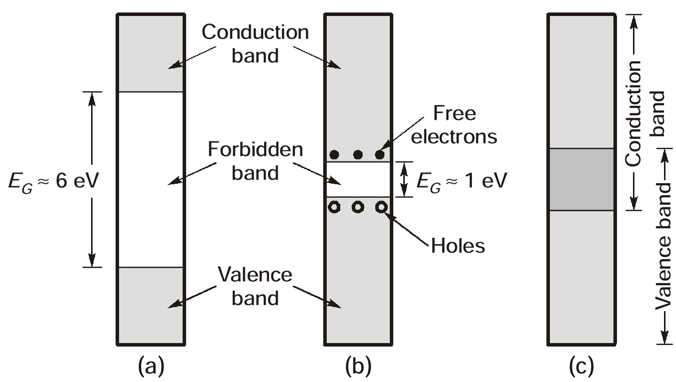


***Figure*-1.1 :** *Simplified energy band diagrams of (a) insulator (b) semiconductor (c) conductor*

1.1.1 Insulators

- An insulating material has an energy band diagram as shown in Fig. 1.1 (a).
- It has a very wide forbidden-energy gap ($\simeq$ 6 eV) separating the filled valence band from the vacant conduction band. Because of this, it is practically impossible for an electron in the valence band to jump the gap, reach the conduction band.
- At room temperature, an insulator does not conduct. However it may conduct if its temperature is very high or if a high voltage is applied across it. This is termed as the **breakdown of the insulator.**
- **Example:** diamond.

1.1.2 Semiconductors

- A semiconductor has an energy-band gap as shown in Fig. 1.1 (b).
- At 0°K semiconductor materials have the same structure as insulators except the difference in the size of the band gap E_G, which is much smaller in semiconductors ($E_G \simeq 1$ eV) than in insulators.
- The relatively small band gaps of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amount of thermal or optical energy.
- The difference between semiconductors and insulators is that the conductivity of semiconductors can increase greatly by thermal or optical energy.
- **Example:** Ge and Si.

1.1.3 Metals

- There is no forbidden energy gap between the valence and conduction bands. The two bands actually overlap as shown in Fig. 1.1 (c).
- Without supplying any additional energy such as heat or light, a metal already contains a large number of free electrons and that is why it works as a good conductor.
- **Example:** Al, Cu etc.

Remember

Conduction band electrons can move along sea of atoms present in the specimen under consideration while the valence band electrons (restrained electrons) are bound to parent atom. These conduction band electrons are known as ***free electrons***.

NOTE

Since the band-gap energy of a crystal is a function of interatomic spacing, it is not surprising that E_G depends somewhat on temperature. It has been determined experimentally that E_G for silicon decrease with temperature at the rate of 3.60×10^{-4} eV/°K.

Hence, for silicon, $E_G(T) = 1.21 - 3.60 \times 10^{-4}\ T$

and at room temperature (300°K), $E_G = 1.1$ eV

Similarly, for germanium, $E_G(T) = 0.785 - 2.23 \times 10^{-4}\ T$

and at room temperature, $E_G = 0.72$ eV

1.1.4 Semiconductor Materials: Ge, Si and GaAs

Semiconductors: A semiconductor has an energy-band gap as shown in Figure 1.1 (b). At 0°K semiconductor materials have the same structure as insulators except the difference in the size of the band gap E_G, which is much smaller in semiconductors ($E_G \simeq 1\ eV$) than in insulators.

The relatively small band gaps of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amount of thermal or optical energy. The difference between semiconductors and insulators is that the conductivity of semiconductors can increase greatly by thermal or optical energy.

Example: Ge and Si

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.

Single crystal and compound crystal semiconductor are two classifications of semiconductor depending upon number of constitutional elements. Examples of single crystal semiconductors are germanium (Ge) and silicon (Si) whereas compound semiconductors are gallium arsenide (GaAs), cadmium sulphide (CdS), gallium nitride (GaN) and gallium arsenide phosphide (GaAsP) etc.

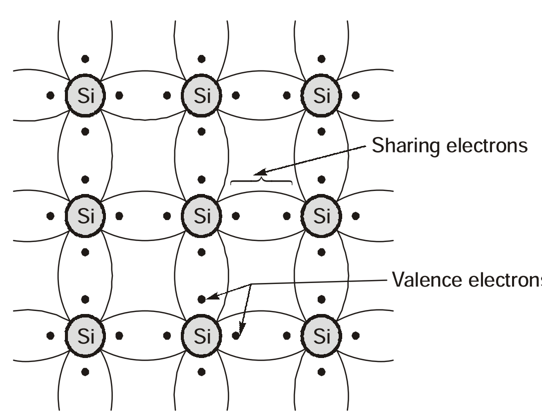


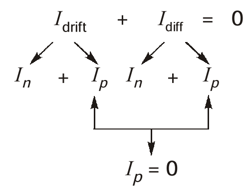
Figure*-1.2 : *Covalent bonding of the silicon atom

Intrinsic Materials and Covalent Bonding

Semiconductor in its purest form (without any impurity) is known as **intrinsic semiconductor**.

1.8 Potential Variation in a Open Circuit Semiconductor Bar

As, $J = 0$



or, $$J_{P\text{drift}} + J_{P\text{ diffusion}} = 0$$

$$pq\mu_p E - qD_p \frac{dp}{dx} = 0$$

$$E = \left(\frac{D_p}{\mu_p}\right) \cdot \frac{1}{P} \cdot \frac{d_p}{dx} = -\frac{dv}{dx} = V_T \cdot \frac{1}{P} \cdot \frac{dP}{dx}$$

$$-\int_{V_1}^{V_2} dv = V_T \int_{P_1}^{P_2} \frac{1}{P} . dp$$

$$V_2 - V_1 = V_T(-\ln p)_{P_1}^{P_2}$$

$$\boxed{V_{21} = V_T \ln\left(\frac{P_1}{P_2}\right)}$$

$$\boxed{P_1 = P_2 e^{\frac{V_{21}}{V_T}}} \quad \text{or} \quad \boxed{P_2 = P_1 e^{-\frac{V_{21}}{V_T}}}$$

Student's Assignments

Q.1 A semiconductor is irradiated with light such that carriers are uniformly generated throughout its volume. The semiconductor is n-type with $N_D = 10^{19}/\text{cm}^3$. If the excess electron concentration in the steady state is $\Delta n = 10^{15}/\text{cm}^3$ and if $\tau_p = 10$ μsec. (minority carries life time) the generation rate due to irradiation

(a) is 10^{20} e-h pairs/cm^3/s

(b) is 10^{24} e-h pairs/cm^3/s

(c) is 10^{10} e-h pairs/cm^3/s

(d) cannot be determined, the given data is insufficient

Q.2 In a p-type Si simple the hole concentration is $2.25 \times 10^{15}/\text{cm}^3$. The intrinsic carrier concentration is $1.5 \times 10^{10}/\text{cm}^3$ the electron concentration is

(a) zero (b) $10^{10}/\text{cm}^3$

(c) $10^5/\text{cm}^3$ (d) $1.5 \times 10^{25}/\text{cm}^3$

Q.3 A Silicon sample A is doped with 10^{18} atoms/cm^3 of Boron. Another sample *B* of identical dimensions is doped with 10^{18} atoms/cm^3 of Phosphorus. The ratio of electron to hole mobility is 3. The ratio of conductivity of the sample *A* to *B* is

(a) 3 (b) 1/3

(b) 2/3 (d) 3/2

Q.4 The concentration of minority carriers in an extrinsic semiconductor under equilibrium is
(a) directly proportional to the doping concentration
(b) inversely proportional to the doping concentration
(c) directly proportional to the intrinsic concentration
(d) inversely proportional to the intrinsic concentration

Q.5 Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the
(a) diffusion current
(b) drift current
(c) recombination current
(d) induced current

Q.6 A heavily doped n-typed semiconductor has the following data:
Hole-electron mobility ratio : 0.4
Doping concentration : 4.2×10^8 atoms/m^3
Intrinsic concentration : 1.5×10^4 atoms/m^3
The ratio of conductance of the n-type semiconductor to that of the intrinsic semiconductor of same material and at the same temperature is given by
(a) 0.00005 (b) 2,000
(c) 10,000 (d) 20,000

Q.7 The electron and hole concentrations in an intrinsic semiconductor are n_i per cm^3 at 300 K. Now, if acceptor impurities are introduced with a concentration of N_A per cm^3 (where $N_A >> n_i$) the electron concentration per cm^3 at 300 K will be
(a) n_i (b) $n_i + N_A$
(c) $N_A - n_i$ (d) $\dfrac{n_i^2}{N_A}$

Q.8 The ratio of the mobility to the diffusion coefficient in a semiconductor has the unit
(a) V^{-1} (b) cm $\times V^{-1}$
(c) $V \times$ cm^{-1} (d) $V \times$ s

Q.9 Drift current in semiconductors depends upon
(a) only the electric field
(b) only the carrier concentration gradient
(c) both the electric field and the carrier concentration
(d) both the electric field and the carrier concentration gradient

ANSWERS

1. (a)	**2.** (c)	**3.** (b)	**4.** (b)	**5.** (a)
6. (d)	**7.** (d)	**8.** (a)	**9.** (c)	

Student's Assignments Explanations

1. (a)
10^{20} e-h pairs/cm$_3$/s
Given that, $\Delta n = 10^{15}$/cm^3

$$\tau_p = 10\ \mu\text{sec} = 10 \times 10^{-6}\ \text{sec.}$$

$$\text{Generation rater} = \frac{\Delta n}{\tau_p} = \frac{10^{15}}{10 \times 10^{-6}}$$

$$= 10^{20}\ \text{e-h pairs/cm}^3\text{/s}$$

2. (c)
By Mass Action Law

$$n \cdot p = n_i^2$$

where,
n = electron concentration
p = hole concentration
n_i = intrinsic carrier concentration
$p = 2.25 \times 10^{15}$/cm^3
$n_i = 1.5 \times 10^{10}$/cm^3

$$n = \frac{n_i^2}{p} = \frac{(1.5 \times 10^{10})^2}{2.25 \times 10^{15}} = \frac{2.25 \times 10^{20}}{2.25 \times 10^{15}}$$

$n = 10^5$/cm^3

3. (b)

$$\sigma_n = nq\mu_n$$

$$\frac{\sigma_p}{\sigma_n} = \frac{\mu_p}{\mu_n} = \frac{1}{3}$$

4. (b)

$$np = n_i^2$$

n_i = constant

For n-type p is minority carrier concentration

$$p = \frac{n_i^2}{n}$$

$$p \propto \frac{1}{n}$$

6. (d)

For n-type semiconductor, $\sigma_n = nq\mu_n$

For intrinsic semiconductor,

$$\sigma_i = n_i q(\mu_n + \mu_p)$$

$$\frac{\sigma_n}{\sigma_i} = \frac{n\mu_n}{n_i(\mu_n + \mu_p)}$$

$$= \frac{4.2 \times 10^8 \times \mu_n}{1.5 \times 10^4 \times \mu_n\left(1 + \frac{\mu_p}{\mu_n}\right)}$$

$$= \frac{4.2 \times 10^8}{1.5 \times 10^4 \times 1.4} = 2 \times 10^4$$

7. (d)

By the law of electrical neutrality

$$p + N_D = n + N_A$$

as $N_D = 0$

$N_A >> n_i \cong 0 \quad p = N_A$

using mass action law $np = n_i^2$

So, $$n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A}$$

8. (a)

$$\frac{D}{\mu} = V_T$$

$$\Rightarrow \quad \frac{\mu}{D} = \frac{1}{V_T} \Rightarrow \text{units : } V^{-1}$$

9. (c)

$$J = n\,e\,v_d$$

Put, $v_d = \mu E$

$\therefore$ $J = n\,e\,\mu E$

Hence, $I = n\,e\,\mu\,EA$

So, I depends upon carrier concentration and electric field.

■■■■

CHAPTER 12

Operational Amplifier

12.1 Introduction

Linear integrated circuits are being used in a number of electronic applications such as in fields like audio and radio communication, medical electronics, instrumentation control, etc. An important linear IC is operational amplifier which will be discussed in this chapter.

The operational amplifier (commonly referred to as op-amp) is a multi-terminal device which internally is quite complex. Fortunately, for the ordinary user, it is not necessary to know about the op-amp's internal make-up. The manufacturers have done their job so well that op-amp's performance can be completely described by its terminal characteristics and those of external components that are connected to it. However, the electronics of op-amp is described where various stages of op-amp are discussed.

12.2 Block Diagram Representation of A Typical Op-Amp

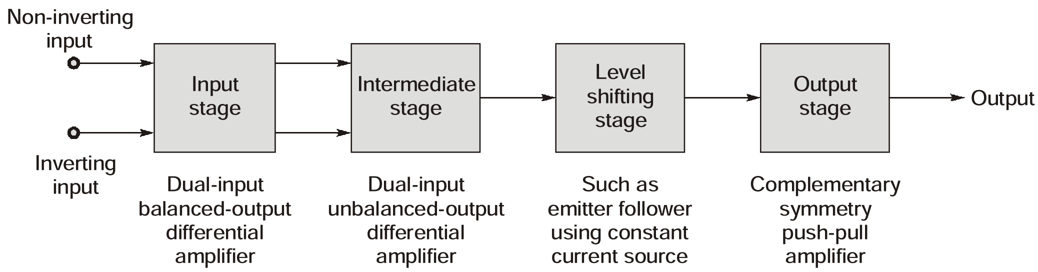


Figure-12.1 : *Block diagram of a typical op-amp*

- An operational-amplifier is a direct-coupled high gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output.
- The input stage is the dual-input, balanced-output differential amplifier. This stage generally provides most of the voltage gain and also establishes the input resistance of the op-amp.
- The intermediate stage is usually another differential amplifier, which is driven by the output of the first stage. In most amplifiers the intermediate stage is dual input, unbalanced (single-ended) output.
- As direct coupling is used, so the DC voltage at the output of the intermediate stage is well above ground potential. Therefore, generally, the level translator (shifting) circuit is used after intermediate stage to shift the DC level at the output of intermediate stage downward to zero volts with respect to ground.

- The final stage is usually a push-pull complementary amplifier output stage. The output stage increases the output voltage swing and raises the current supplying capability of the op-amp. A well-designed output stage also provides low output resistance.

NOTE

The operational amplifier is a versatile device that can be used to amplify DC as well as AC input signals and was originally designed for computing such mathematical functions as addition, subtraction, multiplication, and integration. Thus the name ***operational amplifier*** stems from its original use for these mathematical operations.

12.3 Schematic Symbol

Given an op-amp schematic diagram, we can save time by using a schematic symbol for the entire op-amp circuit. Fig. (12.2) shows the most widely used symbol for a circuit with two inputs and one output.

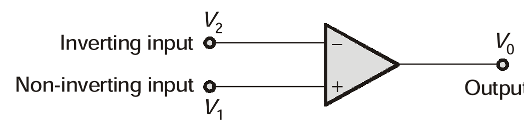


Figure-12.2: *Schematic symbol for the op-amp*

For simplicity, power supply and other pin connections are omitted. Since the input differential stage of the op-amp is designed to be operated in the differential mode, the differential inputs are designated by the (+) and (–) notations. The (+) input is non-inverting input. An AC signal or DC voltage applied to this input produces an inphase (or same polarity) signal at the output. On the otherhand, the (–) input is inverting input because an AC signal or DC voltage applied to this input produces an 180° out-of-phase (or opposite polarity) signal at the output.

In figure

V_1 = Voltage at the non-inverting input (volts)

V_2 = Voltage at the inverting input (volts)

V_0 = Output voltage (volts)

Here $$\boxed{V_o = A(V_1 - V_2)} \qquad ...(12.1)$$

All these voltages are measured with respect to ground.

where, A = Large-signal voltage gain, which is specified on the data sheet for an op-amp.

12.4 Operational Amplifier Characteristics

In an ideal op-amp it is assumed that the op-amp responds equally well to both DC and AC input voltages. However, a practical op-amp does not behave this way. A practical op-amp has some DC voltage at the output even if both the inputs are grounded. The factors responsible for this and the suitable compensating techniques are discussed here.

12.5 DC Characteristics

An ideal op-amp draws no current from the source and its response is also independent of temperature. However, a real op-amp does not work this way. Current is taken from the source into the op-amp inputs. Also the two inputs respond differently to current and voltage due to mismatch in transistors. A real op-amp also shifts its operation with temperature. These non-ideal DC characteristics that add error components to the DC output voltage are:

- Input bias current.
- Input offset current.
- Input offset voltage.
- Thermal drift.

CHAPTER 13

Signal Generators and Waveform Shaping Circuits

13.1 Introduction

There are two distinctly different approaches for the generation of sinusoids, perhaps the most commonly used of the standard waveforms. The first approach employs a ***positive-feedback loop*** consisting of an amplifier and an RC or LC ***frequency-selective network***. The amplitude of the generated sine waves is limited, or set using a non-linear mechanism, implemented either with a separate circuit or using the non-linearities of the amplifying device itself. In spite of this, these circuits, which generate sine waves utilizing resonance phenomenon, are known as ***linear oscillators***.

Circuits that generate square, triangular, pulse (etc.) waveforms called ***non-linear oscillators*** or ***function generators***, employ circuit building blocks known as ***multivibrators***. There are there types of multivibrators: the ***bistable***, the ***astable*** and the ***monostable***. The multivibrator circuits presented in this chapter employ op-amps and are intended for precision analog applications.

13.2 Oscillators

Thus far we have examined op-amps wired as amplifiers. This section will introduce the use of op-amps as oscillators capable of generating a variety of output waveforms. Basically, the function of an oscillator is to generate alternating current or voltage waveforms. More precisely, an oscillator is a circuit that generates a repetitive waveform of fixed amplitude and frequency without any external input signal. Oscillators are used in radio, television, computers and communications. Although there are different types of oscillators, they all work on the same basic principle.

13.2.1 Basic Principles for Oscillation

An oscillator is a type of feedback amplifier in which part of the output is fedback to the input via a feedback circuit. If the signal feedback is of proper magnitude and phase, the circuit produces alternating currents or voltages. To visualize the requirements of an oscillator, consider the block diagram of Figure (13.1). This diagram looks identical to that of the feedback amplifiers. However, here the input voltage is zero (v_{in} = 0). Also the feedback is positive because most oscillators use positive feedback.

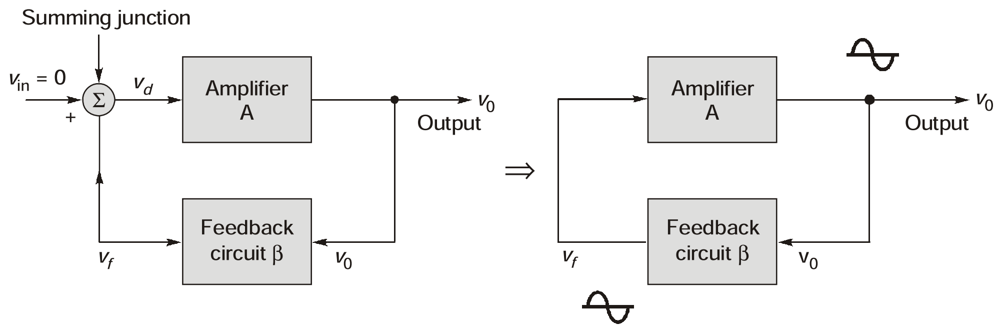


***Figure-13.1 :** Oscillator block diagram*

In the block diagram of Fig. (13.1),

$$v_d = v_f + v_{in}$$
$$v_0 = A\,v_d$$
$$v_f = \beta v_0$$

using these relationships, the following equation is obtained:

$$\frac{v_0}{v_{in}} = \frac{A}{1-A\beta}$$

However, $v_{in} = 0$ and $v_0 \neq 0$ implies that,

$$A\beta = 1 \qquad \text{...(13.1)}$$

Expressed in polar form

$$\boxed{A\beta = 1\angle 0^\circ \text{ or } 360^\circ} \qquad \text{...(13.2)}$$

Equation (13.2) gives two requirements for oscillation:

- the magnitude of the loop gain Aβ must be at least 1, and
- the total phase shift of the loop gain Aβ must be equal to 0° or 360°.

The condition given by equation (13.2) is known as ***Barkhausen criterion.***

In figure (13.1) if the amplifier causes a phase shift of 180°, the feedback circuit must provide an additional phase shift of 180° so that the total phase shift around the loop is 360°. The type of waveform generated by an oscillator depends on the components in the circuit hence may be sinusoidal, square or triangular. In addition the frequency of oscillation is determined by the components in the feedback circuit.

13.2.2 Oscillator Types

Because of their widespred use, many different type of oscillators are available. These oscillator types are summarized in table.

Types of components used	Frequency of oscillation	Types of waveform generated
RC oscillator	Audio frequency (AF)	Sinusoidal
LC oscillator	Radio frequency (RF)	Square wave
Crystal oscillator		Triangular wave
		Sawtooth wave, etc.

Note: In every practical oscillator the loop gain is slightly larger than unity, and the amplitude of the oscillations is limited by the onset of non-linearity.

13.3 The Phase-Shift Oscillator

We select the so called ***phase-shift oscillator*** [Fig. (13.2)] as a first example because it exemplifies very simply the principles set forth above. Here an FET amplifier of conventional design is followed by three cascaded arrangements of a capacitor C and a resistor R, the output of the last RC combination being returned to the gate. If the loading of the phase-shift network on the amplifier can be neglected, the amplifier shifts by 180° the phase of any voltage which appears on the gate, and the network of resistors and capacitors shifts the phase by an additional amount. At some frequency the phase-shift introduced by the RC network will be precisely 180° and at this frequency the total phase-shift from the gate around the circuit and back to the gate will be exactly zero. This particular frequency will be the one at which the circuit will oscillate, provided that the magnitude of the amplification is sufficiently large.

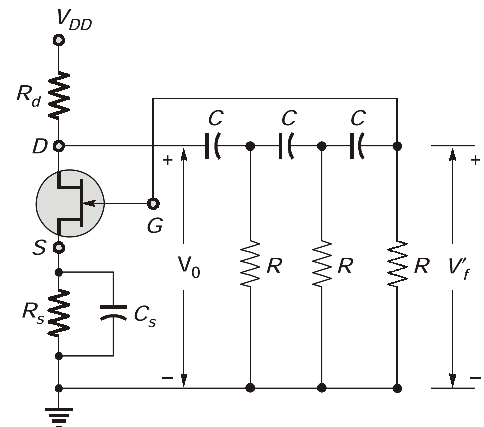


Figure-13.2: *An FET phase-shift oscillator*

The frequency of oscillation for this circuit is given by

$$\boxed{1 = \frac{1}{2\pi RC\sqrt{6}}} \qquad ...(13.3)$$

At that frequency of oscillation, $\beta = +\frac{1}{29}$. In order that $|\beta A|$ shall not be less than unity, it is required that $|A|$ be at least 29. Hence an FET with $\mu < 29$ cannot be made to oscillate in such a circuit.

13.3.1 Phase Shift Oscillator Using BJT

RC phase-shift oscillator using BJT is shown in Fig. (13.3), the output *R* of the feedback network would be shunted by the relatively low input resistance of the transistor.

The frequency of oscillation is given by

$$\boxed{f = \frac{1}{2\pi RC}\cdot\frac{1}{\sqrt{6+4K}}} \qquad ...(13.4)$$

where $K \equiv R_c/R$. The condition for sustaining of oscillation is given by

$$\boxed{h_{fe} > 4K + 23 + \frac{29}{K}} \qquad ...(13.5)$$

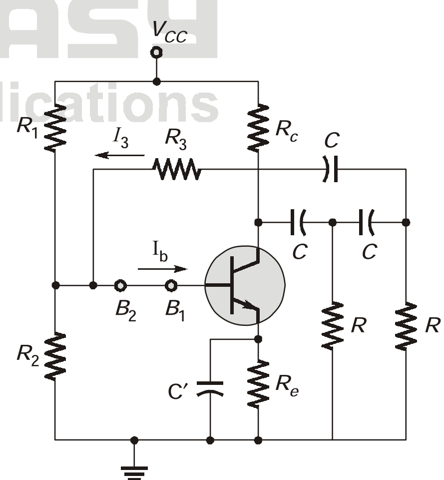


Figure- 13.3 : *(Transistor phase-shift oscillator)*

Remember:

The value of K which gives the minimum h_{fe} turns out to be 2.7 and for this optimum value of R_c/R, we find $h_{fe} = 44.5$.

13.3.2 Phase-Shift Oscillator with Op-Amp

The phase shift oscillator using op-amp is shown in Fig. (13.4).

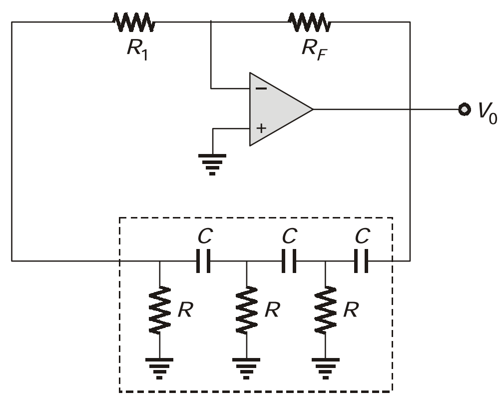


Figure-13.4 : *Phase-shift oscillator using op-amp*

The op-amp is used in the inverting mode; therefore, any signal that appears at the inverting terminal is shifted by 180° at the output. An additional 180° phase shift required for oscillation is provided by the cascaded RC networks. Thus the total phase shift around the loop is 360° (or 0°). At some specific frequency when the phae shift of the cascaded RC networks is exactly 180° and the gain of the amplifier is sufficiently large, the circuit will oscillate at that frequency. This frequency is called the frequency of oscillation f_0 and is given by

$$\boxed{f_o = \frac{1}{2\pi\sqrt{6}RC} = \frac{0.065}{RC}} \quad ...(13.6)$$

At this frequency, the gain A must be at least 29.
That is,

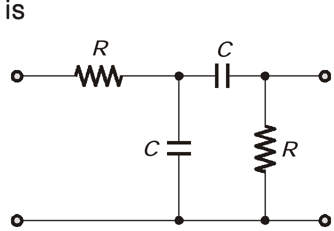
$$\left|\frac{R_F}{R_1}\right| = 29 \quad ...(13.7)$$

or

$$\boxed{R_F = 29\,R_1} \quad ...(13.8)$$

The disadvantage of RC phase-shift oscillator is that the frequency of oscillation can not be altered. In further we will study the oscillators in which frequency can be altered by changing circuit parameters.

Example - 13.1 An FET oscillator uses the given phase shift network as shown below. The minimum gain required for oscillation is



(a) – 29
(b) 1
(c) 3
(d) 29