14

Semiconductor Devices

TOPICS DISCUSSED

- Atomic theory
- P-type and n-type semiconductor material
- P–n junction
- Forward and reverse-biased p–n junction
- Semiconductor diodes
- Zener diode
- Bipolar junction transistors
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- SCR
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- Photovoltaic cells
- Phototransistor
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14.1 INTRODUCTION

The transistor, most commonly used in electronic circuits, was invented in 1948. The first integrated circuit (IC) came in the market in the mid 1960s. Through continuous research and development, very large scale integrated (VLSI) circuits have been brought in use, resulting in gradual miniaturization of electronic circuits and devices. The sizes of calculators, computers, communication satellite, and all such electronic gadgets and systems have become smaller but powerful. It is predicted that nano-technology will further revolutionize the industry in general in the years to come.

Electronics deals with the flow of electrons through vacuum, gas or semiconductors. Electronic devices like diodes, transistors, field effect transistors (FETs), silicon controlled rectifiers (SCRs), optoelectronic devices, and resistors, inductors, capacitors, etc. form circuits of electronic gadgets, equipment, and control systems.

An electronic device consists of integrated circuits which have several diodes, transistors, resistors, capacitors, etc. mounted on a single chip. Electronic components like diodes, transistors, SCRs, etc. are made of semiconductor materials.

As we know, all materials are classified into three categories, namely conductors, semiconductors, and insulators. Gold, silver, copper, aluminium, etc., are conducting materials. Conducting materials have a large number of free electrons in their atomic structure which allow flow of current.

Rubber, ceramic, glass, wood, paper, bakelite, mica, etc. are insulating materials. In these materials no free electrons are available and as such no current should flow through them.

Substances like germanium, silicon, carbon, etc. are called semiconducting materials. Atoms of these materials binds themselves through sharing of electrons in their outermost shell or orbit. Such bonds are called covalent bonds. At absolute zero degree temperature, semiconducting materials behave like insulators as no free electrons are available for conduction. However, with increase of temperature or on application of voltage, some electrons become free electrons by breaking away from their covalent bonds and create a current flow. That is why these materials are called semiconductors. To have a complete understanding of behaviour of semiconducting materials we will first have a quick review of atomic theory.

14.2 REVIEW OF ATOMIC THEORY

An atom of any material consists of a central nucleus around which protons with positive charge and orbiting electrons of equal but opposite charge, an atom is electrically neutral. If, however, an atom loses an electron it will lose some negative charge and will become a positively charged ion. Similarly, if an atom gains an electron it will become a negatively charged ion. Different materials are made up of different types of atoms. However, their electrons and protons are identical. An electron from one atom can replace an electron of any other atom of different material.

Electrons orbit in different shells around the nucleus. Each shell contains a definite number of electrons. For example, the total number of electrons in first, second, and third shells are 2, 8, and 18, respectively. The number of electrons in the outermost shell of the atom determine the electrical property of the material. The number of electrons present in the outermost shell are called *valence electrons*. The outermost shell of an atom may be completely filled or partially filled. The outermost orbit must have eight electrons. If the outermost orbit has less than eight electrons, we call them vacancies or holes (i.e., empty spaces).

Let us consider atoms of two semiconducting materials, silicon and germanium. Silicon has 14 electrons orbiting in three orbits and they are distributed as 2, 8, 4. The nucleus has 14 protons which are positively charged. Thus, the atom is electrically neutral. Germanium has 32 electrons orbiting in four shells as 2, 8, 18, 4. The nucleus has 32 protons, and hence the atom is electrically neutral. Two-dimensional representations of silicon and germanium atom has been shown in Fig. 14.1. Both silicon and germanium have four valence electrons and four holes in their outermost orbits. The closer an electron is to the nucleus, the stronger is the binding force between the electrons and the protons in the nucleus. Electrons in the outermost orbit are comparatively loosely bound with the nucleus. This means, a small amount of energy will be required to take out an electron from the outermost orbit. When an electron leaves its orbit, it becomes a free electron.

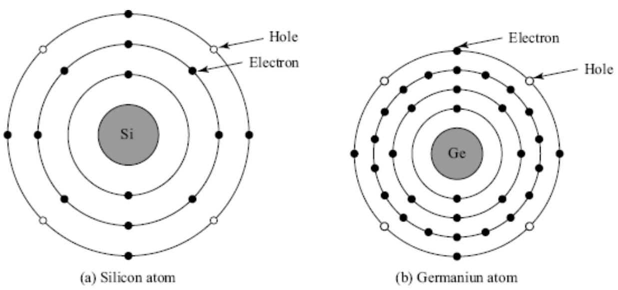


Figure 14.1 Atomic structure of silicon and germanium atom (outermost orbit in both the cases has four electrons leaving four unfilled spaces or vacancies, called holes)

14.3 BINDING FORCES BETWEEN ATOMS IN SEMICONDUCTOR MATERIALS

A semiconductor atom having four valence electrons and four holes require four more electrons so as to make the outermost orbit completely filled (total number must be eight). The atoms in a crystal are bouring atoms to satisfy the need to have eight electrons on the valence shell in an atom is called *covalent bonding*. Because of covalent bonding, i.e., bonding through sharing of electrons, it is seen that the valence shells of all the electrons are full, i.e., all of them have eight electrons in their outermost orbit. At absolute zero temperature there will be no free electrons in the crystal. However, although the electrons are bound to their atoms due to covalent bonding, a rise in temperature breaks some of the covalent bonding and make some electrons free. A semiconductor material, silicon or germanium where the electrons are bound to their respective atoms and are not free to conduct electric current, are called *intrinsic*, or *pure semiconductors*. When the temperature of the crystal is raised, external energy in the form of heat gets applied to the semiconductor material. This heat energy enables the valence electrons to acquire sufficient energy to break away from the atoms and become free electrons. When an electron leaves to become free, it leaves a vacant space called a hole. For every free electron there will be a corresponding hole produced, which is called an electron–hole pair. A large number of such electron–hole pairs are formed due to rise in temperature of the semiconductor. When electrons become free they get attracted and fall into a hole created by another electron. This merging of free electrons and holes is called recombination. The time of creation of a free electron and its falling into a hole is very quick and the time taken is of the order of nanoseconds. Thus, pure silicon or germanium is not of much use in electronics except for the manufacturing of heat- or light-sensitive resistance.

The conductivity of semiconductor materials can be increased by adding some amount of another material having either three or five valence electrons. Adding such materials with the pure semiconductor material is called *doping*. The material formed by doping is called extrinsic semiconductors.

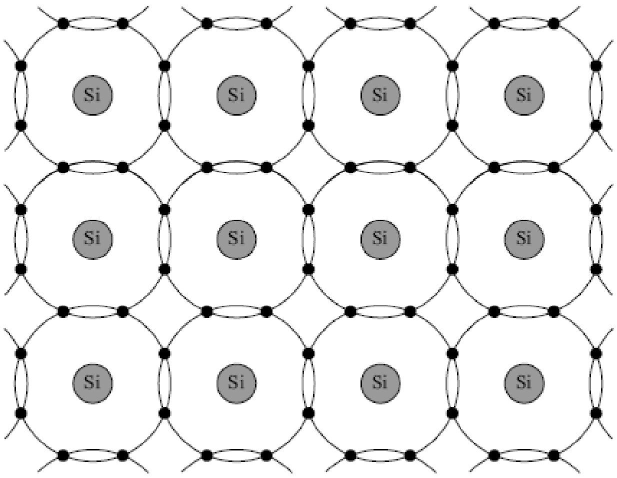


Figure 14.2 Covalent bonding of silicon atoms by sharing of valence electrons, for ease of understanding only the outermost orbit of each silicon atom has been shown. The inner two orbits have been omitted.

that is added to a pure semiconductor is also referred to as impurity material. Depending upon whether a pentavalent or trivalent doping material is added, extrinsic semiconductors are respectively called n-type semiconductor or p-type semiconductors. These two types of materials when joined together form, a p–n junction which is the basis of working of all the electronic devices. The students are advised to understand the mechanism of working of a p–n junction so as to understand the functioning of all electronic devices and circuits.

14.4.1 N-Type Semiconductor Material

N-Type semiconductor is formed by doping a pure silicon or germanium crystal with a material having five valence electrons. Antimony, arsenic, and phosphorous are pentavalent materials as can be read from the periodic table. If arsenic in very small quantity is added to a silicon crystal, four out of five valence electrons will form covalent bonds with silicon atoms with one electron left free. Thus, for each arsenic atom there will be one free electron. Although the percentage of arsenic added is very small, the number of atoms being very large, a huge amount of free electrons will be available in the n-type semiconductor. These electrons being free (not taking part in any covalent bonding) are loosely bound to their parent atom and are free to conduct electricity. Fig. 14.3 shows impurity atoms of antimony having five valence electrons forming covalent bonds with germanium having four valence electrons. There is one extra electron for each impurity atom added. This extra electron is not a part of any covalent bond and is called free electron. This free electron has been shown out of the orbit.

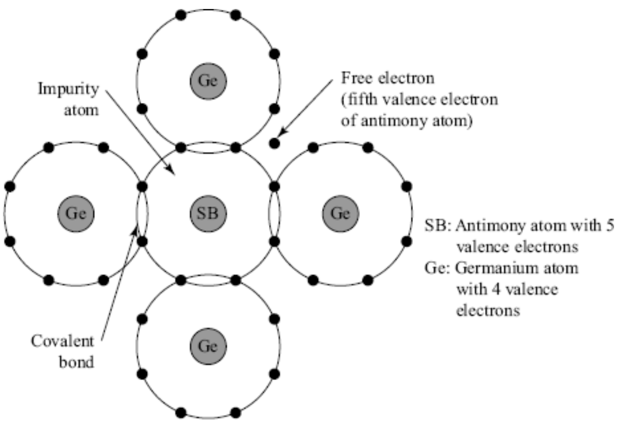


Figure 14.3 Covalent bonding in an n-type extrinsic semiconductor

It is noticed that each antimony atom is making covalent bonds with four neighbouring germanium atoms. Each bond has one electron belonging to germanium atom and one electron belonging to antimony atom. Each antimony atom will make four covalent bonds with four germanium atoms. By sharing of electrons in the covalent bonds all the atoms will satisfy their need to have all the eight posifree electrons is equal to the total number of protons in the nuclei of the atoms.

The added impurity material has infact donated one free electron per atom to the extrinsic semiconductor, and hence are called *donor atoms*. Donor atoms create free electrons which form the majority charge carrier (responsible for current flow) in an n-type material.

Temperature rise above absolute zero also creates free electrons and holes due to breaking of covalent bonds, thus increasing the total number of free electrons. However, a certain amount of holes are also formed.

When electrons leave their positions creating holes, the movement of electrons gets associated with the movement of holes. The holes therefore form charge carriers, and since they are in minority, they are called minority charge carriers in the n-type semiconductor.

Thus, in an n-type semiconductor the majority charge carriers are the electrons and the minority charge carriers are thermally generated holes.

14.4.2 P-Type Semiconductor Material

P-Type material is formed when silicon or germanium crystal is doped with (added with) a small percentage of trivalent impurity material like boron, gallium or indium. When covalent bonds are formed between boron having three valence electrons with silicon having four valence electrons, there will be shortage of one electron in the covalent bonds. This is represented by an empty space in the covalent bonds and is called a hole as shown in Fig. 14.4. There will be one hole corresponding to each of the impurity atoms taking part in forming covalent bonds. This makes seven out of eight positions filled.

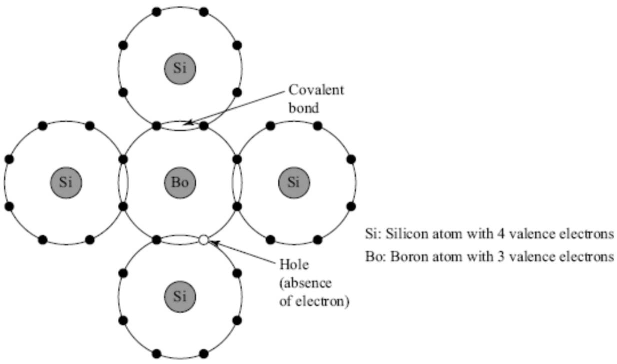


Figure 14.4 P-type semiconductor material

One position is left vacant which we call a hole. Similar to n-type material, p-type material is also electrically neutral. The total number of electrons in the orbits is equal to the total number of protons in the nucleus of the atoms. Although the amount of impurity materure is raised there will be creation of free electrons and holes. These thermally generated electrons will be the minority charge carriers because of their being small in numbers.

14.4.3 The p–n Junction

A p-type semiconductor can be represented by holes as the majority charge carriers. The trivalent impurities that produce a p-type semiconductor are called acceptor impurities because the holes are ready to accept any free electrons. A free electron coming from elsewhere occupying a hole in a p-type material will create negative ions on the p-side because the atom will gain one more electron. This way, the number of electrons with negative charge will be one more than the number of protons with positive charge on the nucleus. Thus a p-type semiconductor will have negative acceptor ions and holes as majority carrier.

An n-type semiconductor can be represented by donor impurities because they give one free electrons to the semiconductor crystal and become positive ions. p-type and n-type semiconductor materials have been shown side by side in Fig. 14.5 (a). In the p-type material small circles represent the holes as the majority carriers. In the n-type material the black dots represent the free electrons as the majority charge carriers. Electrons are negative charge carriers while holes are positive charge carriers.

It may be noted that when an electron moves out of an atom, the atom becomes a positively charged ion which is immobile, i.e., unable to move. Similarly, addition of an electron in a hole makes an atom a negatively charged immobile ion. The minority carriers produced due to thermal effect have not been shown in Fig. 14.5. When a p-type semiconductor is joined with an n-type semiconductor, as shown in Fig. 14.5 (b), through a special technique, a junction called p–n junction is formed. We will examine what happens to the electrons and holes at a p–n junction.

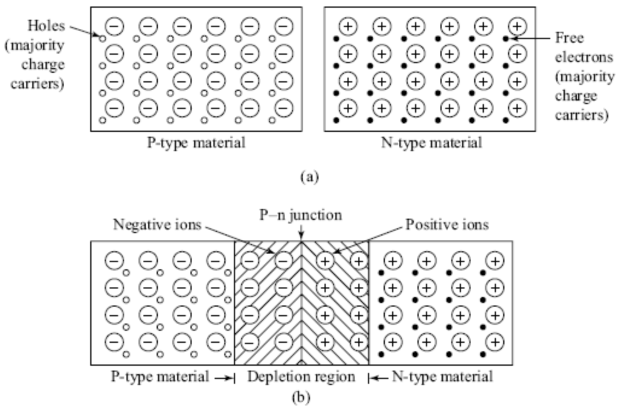


Figure 14.5 (a) P-type and n-type materials represented side by side; (b) formation of p–n junction

the n-side of the junction. The electrons crossing over the junction will occupy the holes in the p-type material making the atoms negatively charged immobile ions. The atoms accepting the negative charge become negatively charged ions which were earlier neutral atoms. Thus, looking at Fig. 14.5 (b) we see that on one side of the junction there is an accumulation of negative ions and on the other side there is accumulation of positive ions. Negative ions created on the p-side close to the junction will acquire a negative voltage and the positive ions created on the n-side close to the junction will acquire a positive voltage. The negative voltage on the p-side will repel further diffusion of electrons from the n-side. The positive voltage on the n-side will repel diffusion of holes from the p-side. When a p–n junction is made there is an initial diffusion of electrons and holes which creates a *barrier voltage* at the junction, which stops any further diffusion of charge carriers. This initial diffusion of charge carriers at the junction, and the development resultant barrier voltage take place when a p–n junction is formed during the manufacturing process. The barrier voltage depends upon the amount of doping, charge carriers, and the junction temperature. For germanium the barrier voltage is 0.3 V and for silicon the barrier voltage is 0.7 V at room temperature (25°C). The shaded portion on both sides of the p–n junction is having only immobile ions of opposite polarities which creates a potential difference, i.e., barrier voltage. This portion is devoid of any electron or hole, i.e., any charge carriers. This region is depleted of any charge carrier, and hence is called the *depletion region*. It may be noted that the thickness of the depletion region in Fig. 14.5 (b) has been shown expanded. In fact, this layer is very thin, of the order of micrometer.

The p-side of the depletion region acceptor impurity atoms that have lost their holes associated with them by accepting electrons have become negatively charged ions. Similarly the n-side of the depletion region consists of donor atoms (pentavalent atoms) that have lost their associated free electrons and have become positive ions. As shown in Fig. 14.5 (b), the depletion layer is equally divided on both sides of the p–n junction. This is because both the p-type and the n-type materials have been equally doped. Equal percentage of doping materials have been added on both sides. If the doping is different, the width of the depletion region on the two sides will be different. Application of some voltage across the p–n junction is called biasing. Depending on the polarity of biasing the width of the depletion layer will change.

14.4.4 Biasing of p–n Junction

Biasing of a p–n junction means application of some external voltage across the two sides of the p–n junction. When the p-side is connected to the positive terminal of a battery and the n-side is connected to the negative terminal, the p–n junction is said to be a *forward-biased* junction. If the positive terminal of the battery is connected to the n-side and the negative terminal on the p-side, the p–n junction is said to be a *reverse-biased* junction.

(a) A forward-biased p–n junction

In Fig. 14.6 (a) is shown the p-side connected to the positive terminal of a battery and the n-side connected to the negative terminal. The holes on the p-side are positively charged and the electrons on the n-voltage is gradually increased, the depletion region and barrier potential will disappear as shown in Fig. 14.6 (b).

The resistance R in the circuit is connected to limit the current flowing in the circuit. Fig. 14.6 (a) shows the p–n junction before the forward voltage is applied. As in Fig. 14.6 (b), when the switch S is closed, the forward voltage gets applied. When the voltage is gradually increased from zero voltage to 0.3 V, for the germanium semiconductor the barrier voltage is overcome. When the barrier voltage is overcome, the depletion layer disappears. Electrons from the n-side are attracted by the positive terminal A of the p-side and the holes from the p-side get attracted by the negative terminal B of the n-side.

Electrons are the negatively charged particles and the holes are assumed to be positively charged particles. As soon as the potential barrier is overcome at 0.3 V for germanium and at 0.7 V for silicon, the majority charge carriers start moving across the p–n junction establishing a forward current, I_F to flow as shown in Fig. 14.6 (c). The forward voltage, V versus forward current, I_F characteristics for germanium and silicon have been shown. With increase of forward voltage beyond 0.3 V or 0.7 V for germanium and silicon, respectively, the forward current increases as shown. Thus, in forward-biased p–n junction, the potential barrier is neutralized allowing current flow.

(b) A reverse-biased p–n junction

In reverse biasing, the battery connection is reversed, i.e., the negative terminal of the battery is connected to the p-side and the positive terminal is connected to the n-side of the p–n junction as shown in Fig. 14.7. Electrons from the n-side are attracted to the positive terminal of the battery and the holes from the p-side get attracted to the negative terminal of the battery.

Since the holes of the p-side are attracted by the negative terminal and the electrons of the n-side are attracted by the positive terminal of the battery, the depletion layer gets widened as the applied voltage is gradually increased. The barrier voltage also gets gradually increased and as such the possibility of the majority charge carriers crossing the barrier is reduced to zero. Due to minority charge carriers a negligibly small current of the order of micro amperes will flow as shown in Fig. 14.7 (b). A reverse-biased, p–n junction, therefore, offers very high resistance to current flow. The number of minority charge carriers are small and a very small reverse voltage is required to pull all the minority charge carriers by the two terminals of the applied voltage across the junction. Any further increase in reverse voltage does not increase the negligible small reverse current produced. Hence, this very small amount of reverse current is also referred to as *reverse saturation current*.

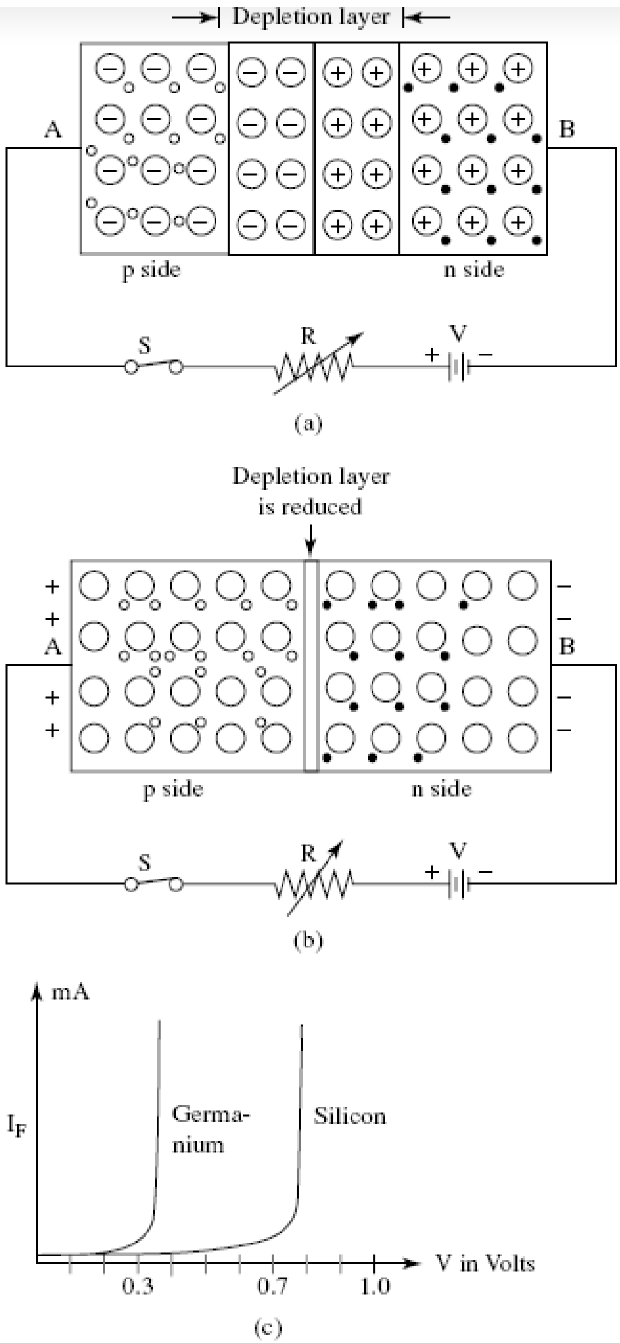


Figure 14.6 Forward biasing of a p–n junction. (a) Before switch S is; (b) switch S is closed and forward voltage gradually increased; (c) forward characteristics of the p–n junction

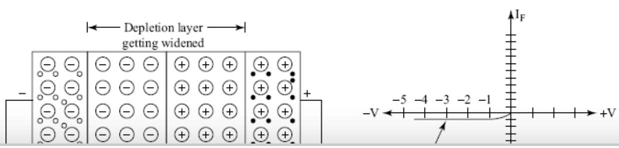


Figure 14.7 (a) Reverse biasing of a p–n junction; (b) reverse V–I characteristics

To sum up, on biasing of a p–n junction we can make the following statements:

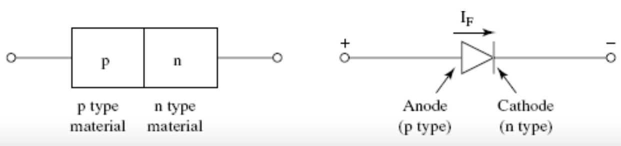
1. A p–n junction is forward biased if its p-side is connected to the positive terminal of the supply and n-side is connected to the negative terminal of the supply.
2. The depletion layer width gets narrowed down on application of forward voltage.
3. The majority charge carriers current is established in a forward-biased p–n junction.
4. Barrier potential for germanium is 0.3 V and for silicon is 0.7 V at room temperature. These are the voltage drops across the p–n junction when current flows.
5. When p-side is connected to the negative terminal and n-side is connected to the positive terminal of the supply, the p–n junction is said to be reverse biased.
6. The width of the depletion layer, and hence the barrier potential increases when the junction is reverse biased.
7. A minutely small current flows through a reverse-biased p–n junction due to the minority charge carriers.
8. A forward-biased p–n junction offers very small resistance to current flow while a reverse-biased p–n junction offers very high resistance to current flow.

14.5 SEMICONDUCTOR DIODES

A semiconductor diode is simply a p–n junction which offers very low resistance when forward biased and very high resistance when reverse biased. Diodes are available in different current ratings. Low-current-rated diodes are used in switching circuits as the diode works like a switch allowing current to flow in one direction. A p–n junction with connecting leads on both sides form a p–n junction diode as shown in Fig. 14.8 (a). The symbolic representation of a p–n junction diode has been shown in Fig. 14.8 (b).

The p-side is connected to the positive terminal for forward bias and is called anode. The n-side is connected to the negative terminal for forward bias and is called cathode.

A very high forward current or a very high reverse voltage can destroy a diode. That is why the manufacturer, data sheet is to be consulted to note the maximum permissible forward current and maximum permissible reverse voltage. High-current power diodes are available these days which allow large forward current and considerable amount of reverse voltage.



14.5.1 Volt–ampere Characteristic of a Diode

When a p–n junction diode is connected to a source of supply in such a way that it is forward biased, the relationship between the voltage applied and current flowing will give us a forward V–I characteristic. The connection diagram for finding the V–I characteristic has been shown in Fig. 14.9. When the applied voltage is gradually increased, at a small value of forward voltage the forward current is negligible small. At a voltage near 0.3 V, the current suddenly increases. This voltage at which the forward current starts increasing is called the cut-in voltage of the diode. The voltage drop across the diode while it is conducting remains almost constant. For the germanium semiconductor diode, the forward voltage drop is 0.3 V and for the silicon diode, the forward voltage drop is 0.7 V.

For determining the reverse characteristic, the supply connection has to be reversed. Under the reverse-biased condition, the junction resistance is very high and ideally no current should flow. But due to minority charge carriers, a negligibly small current of the order of microamperes will flow. This current is also called leakage current of the diode. It gets saturated to its initial value of a few microamperes or even less than that. Increase of negative biasing, i.e., increase of negative voltage across the diode does not increase this reverse current. However, if the reverse voltage is increased to a large value, at one stage, the p–n junction will break down with a sudden rise in reverse current. The reverse voltage at which the diode breaks down and a large reverse current starts flowing is called the breakdown voltage. At this reverse breakdown voltage, current continues to increase.

14.5.2 An Ideal Diode

An ideal diode will conduct in one direction and oppose any current flow in the other direction. An ideal diode will have zero forward resistance and infinite reverse resistance. An ideal diode is difficult to realize. If certain assumptions are made, we may realize a near ideal diode. For example, we may ignore the reverse current I_R and assume that forward voltage drop, V_F as constant at 0.3 V for germanium and 0.7 V for silicon (for an ideal diode, $I_R = 0$ and $V_F = 0$). The V–I characteristic for a diode which is near real is shown in Fig. 14.10 (a). The equivalent circuit is shown in Fig. 14.10 (b). The biased diode is assumed to have a constant forward voltage drop, V_F and no series resistance. In the equivalent circuit of a practical diode a voltage source V_F (equal to 0.3 V for the germanium diode and 0.7 V for the silicon diode) has been shown in series with an ideal diode so as to represent voltage drop across an ideal divode equal to zero. An example will clarify this concept.

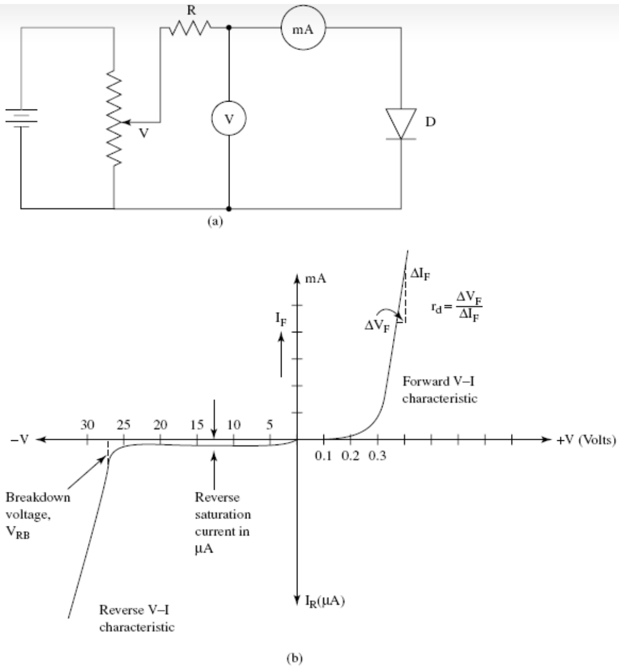


Figure 14.9 (a) Circuit diagram; (b) V–I characteristic

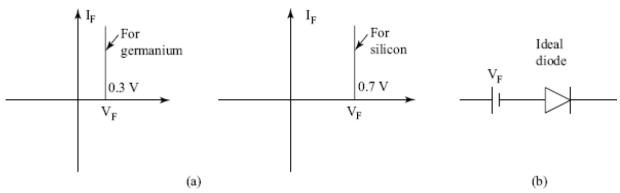
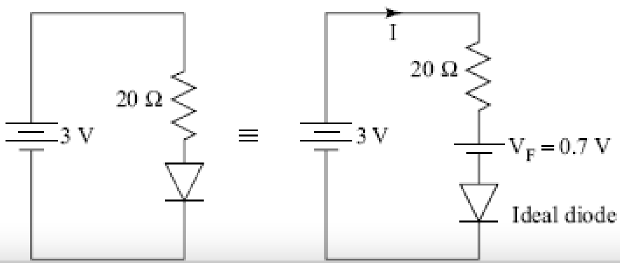


Figure 14.10 (a) Approximate V–I characteristics; (b) equivalent circuit

Example 14.1 A silicon diode is connected across a 3 V supply with a series resistance of 20 Ω. Neglecting diode resistance, calculate the diode current.

Solution:



A silicon diode has V_F = 0.7 V. The diode equivalent circuit has been shown. Applying Kirchhoff's voltage law,

+ 3 V – 20 I – 0.7 V = 0

or,

20 I = 3 – 0.7 = 2.3 V

$I = \frac{2.3}{20}$ = 0.115 A

14.5.3 Diode Parameters and Diode Ratings

A diode is specified in terms of certain parameters. These are as follows:

1. Forward Voltage drop, V_F
2. Reverse Breakdown Voltage, V_{RB}
3. Reverse saturation current, I_R
4. Dynamic resistance, r_d
5. Maximum forward current, I_{FM}

The dynamic resistance, r_d is calculated from the slope of the forward V–I characteristic as shown in Fig. 14.9 (b)

$$r_d = \frac{\Delta V_F}{\Delta I_F} \Omega$$

The values of these parameters are normally provided by the manufacturers in their specification sheet.

Diodes are available in low-, medium-, and high-current ratings. Diodes of low-current ratings are used in electronic switching circuits, i.e., they work as switches. Their forward current ranges from a few mA to a maximum of 100 mA. The safe reverse bias that can be applied is around 75 V. The reverse saturation current is very small, usually less than a micro-ampere.

Medium current diodes have a maximum current rating of 400 mA and reverse voltage of about 200 V.

High-current diodes are also called *power diodes*. They are rated for high current and high reverse voltage ratings. Metal heat sinks are used for dissipation of heat produced in a diode when it is conducting.

In addition to their use in switching circuits, diodes are used in rectifier circuits for half-wave and full-wave rectification.

14.6 ZENER DIODE

We have known that when a diode is reverse based, only a minutely small current called saturature current flows (ideally no current should flow). If the reverse voltage is increased continuously, the is limited to the current-carrying capacity of the diode, it can be operated under reverse breakdown condition. The V–I characteristic of the diode under the reverse-biased condition can be made dropping down almost vertically by proper doping of the semiconductor material. A diode with a very sharp breakdown voltage is called a *zener diode*. Diodes designed to operate under the reverse breakdown condition, maintain a fairly constant voltage over a wide range of current levels. When the reverse voltage is reduced below the breakdown voltage, the current level returns to the very low saturation current level.

There are two ways that breakdown of a zener diode may occur. One is called *zener breakdown* and the other is called *avalanche breakdown*. If the depletion layer of a diode is narrow and we apply a reverse voltage, the voltage per unit of width of the depletion layer becomes high. This establishes a strong electric field intensity which causes electrons to break away from their parent atoms. Thus, a depletion layer which was insulating in nature, becomes a conducting path. This kind of breakdown due to the creation of a strong electric field intensity, i.e., V/μm is called zener breakdown.

If the width of the depletion layer is wide for a zener breakdown, a sufficient reverse voltage may provide the free electrons (minority carriers causing saturation current) to gain sufficient energy to knockout electrons from the atoms of the semiconductor in the depletion region. This is called ionization by collision. The breakdown occurring this way is called avalanche breakdown.

Zener breakdown occurs at a voltage less than 5 V and avalanche breakdown voltage is higher than 5 V. The symbol, the circuit, and the V–I characteristic of a zener diode are shown in Fig. 14.12. The forward V–I characteristic of a zener diode is the same as an ordinary diode.

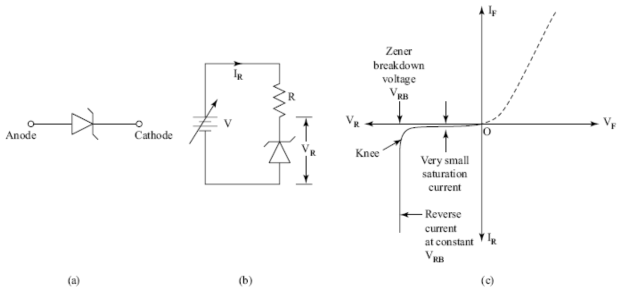


Figure 14.12 (a) Symbol of a zener diode; (b) zener diode circuit; (c) V–I characteristic

As shown in Fig. 14.12 (b), a zener diode is operating under the reverse-biased condition. A resistance, R is connected to limit the current beyond the normal current-carrying capacity. A constant voltage, V_R will be available across the zener diode, even if the input voltage changes. Manufacturers specify the zener breakdown voltage and the maximum zener current. Type of zener diodes are

It is the dynamic resistance of the zener diode somewhat below the knee point on the reverse V–I characteristic. It is similar to the dynamic resistance of a forward-biased diode. Zener resistance, R_Z is given by

$$R_z = \frac{\Delta V_z}{\Delta I_z}$$

The value of RZ is to be small so that it will indicate a steep curve where due to a small change in voltage, DVZ a large change in current, DIZ takes place. The value of zener resistance varies with the current. It decreases with increase in current.

An application of zener diode as a voltage regulator or stabilizer, and often used as reference voltage in electronic circuits has been shown in Fig. 14.13. How the zener diode helps in maintaining a constant voltage when the load current changes and when the input voltage changes can be understood from the following two applications.

14.6.1 Zener Diode As Voltage Regulator

A voltage regulator maintains nearly constant voltage output across the load over a wide range of variation of load current. A zener diode voltage regulator circuit has been shown in Fig. 14.13.

The task of a voltage regulator is to maintain a nearly constant output voltage as the load current varies over a wide range. The zener diode used in the circuit is shown in Fig. 14.13 maintains a constant voltage across the load terminals A and B. The function of the zener diode is to maintain the output voltage more or less constant even if the load current changes. This is accomplished by operating the zener diode in the breakdown region when voltage across it changes only very slightly over a wide variation of zener current. The zener breakdown voltage has to be lower than the applied voltage, V.

14.6.2 Zener Diode As a Reference Voltage

In many applications it becomes desirable that a constant voltage is maintained between two points in a circuit and use this voltage as a reference voltage to which voltage of another point or circuit is to be compared. The difference between reference voltage and compared voltage is first amplified and then used to perform some control operations. A zener diode will maintain a constant voltage across its terminals even if there is a change in the supply voltage, V in the circuit as shown in Fig. 14.13.

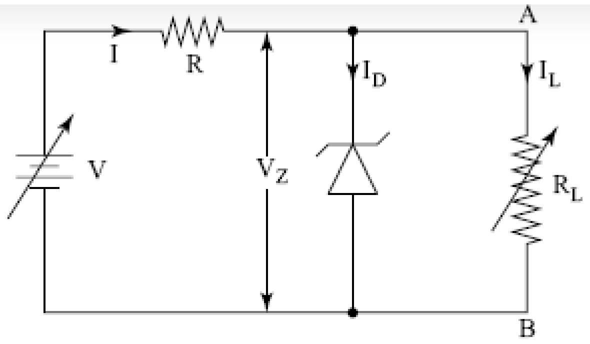


Figure 14.13 Zener diode used in voltage regulator circuit

14.7 BIPOLAR JUNCTION TRANSISTORS

Transistors are used in almost all electronic circuits. The ability to amplify electrical signals accounts for their wide use. The word transistor is the short form of the word “transfer resistor”. The signal amplification in a transistor is achieved by transfering the signal from a region of low resistance to a region of high resistance. The concept of transfer of resistance, when viewed this way, has given the name transistor.

A bipolar junction transistor has three layers of semiconductor material. These layers are arranged either in an n–p–n sequence or in a p–n–p sequence. In an n–p–n transistor, a p-type semiconductor material is sandwiched between two n-type materials. In a p–n–p transistor, an n-type semiconductor material is sandwiched between two p-type materials.

A transistor, in general, has two p–n junctions connected back to back as shown in Fig. 14.14. As shown in the figure, the central layer is called the *base*, one of the outer layers is called the *emitter*, and the other is called the *collector*.

The basic principle of transistor operation is that a small current in the base region can control a much larger current flow through the transistor, i.e., from the emitter to the collector. A transistor can be used as current amplification or a voltage amplification device. Since a transistor combines two junction diodes, it works on the basis of p–n junction theory as has already been explained.

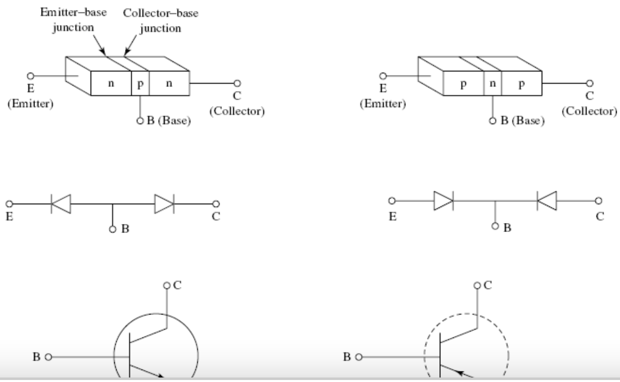


Figure 14.14 (a) Block representation, two-diode transistor analogy, and symbol of a n–p–n transistor; (b) block representation, two-diode transistor analogy, and symbol of a p–n–p transistor

The symbolic representation of a transistor has also been shown. The symbol for an n–p–n or a p–n–p transistor is the same except for the direction of the arrow head. The arrow head has to be shown from p terminal to n terminal between the emitter and the base. The emitter of a transistor is heavily doped. The base is lightly doped while the collector is less heavily doped than the emitter.

14.7.1 Working of a n–p–n Transistor

For a transistor to work, it has to be biased by applying external voltage supply with proper polarity. For operation in the active region, a transistor's emitter–base junction must be forward biased while the collector base region reverse biased as shown in Fig. 14.15 (a) and (b).

The forward bias of the EB junction reduces the width of the depletion region and the barrier voltage gets reduced.

The reverse bias of the CB junction increases the width of the depletion region and the barrier voltage gets increased.

Since the EB junction is forward biased, electrons form the majority charge carriers and would flow from the emitter to the base region. Since the base is lightly doped, there will be a smaller number of holes present there. Only a small percentage of electrons from the emitter will recombine with holes in the base region. Only around two per cent of the electrons from the emitter recombine with the holes that are present in base region. The reverse bias of the CB junction causes expansion of the depletion layer. The width of the base region is thinner than the collector region. Therefore, the depletion region will penetrate deep into the base region. The electrons from the emitter region will arrive near the CB depletion region. Due to large CB bias voltage, electrons will be pulled across the CB junction by the positive terminal of the collector. The collector thus collects the 98 per cent of the electrons emitted by the emitter.

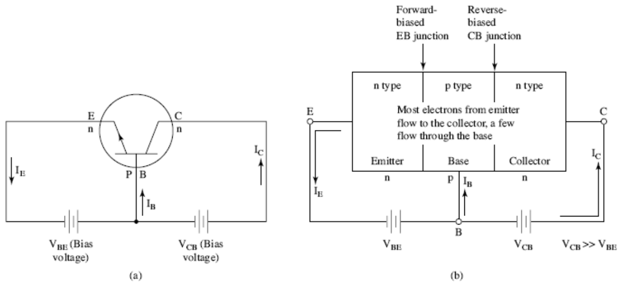


Figure 14.15 (a) Biasing of a n–p–n transistor for normal operation; (b) operation of a n–p–n transistor

emitter and collector current levels can be controlled by the base–emitter bias voltage. Note that the conventional direction of current flow i.e., the directions of emitter current, I_E, base current, I_B and collector current, I_C have been shown opposite to the direction of flow of charge carriers.

Note that for a silicon transistor, substantial current will start flowing only when the bias voltage V_{BE} is about 0.7 V and for the germanium transistor V_{BE} is 0.3 V. Beyond this voltage, a small variation of V_{BE} will control I_E and I_C, and V_{BE} has to supply only a small I_B.

To sum up, the following statements can be made for the operation of a n–p–n transistor:

1. The outer layers of n–p–n transistors are called emitter and collector, respectively, the central layer is called the base.
2. The base–emitter junction, EB is forward biased and the collector–base junction is reverse biased, and V_{CB} is higher than V_{BE}.
3. The base section is made very thin and is lightly doped so that majority of the charge carriers (electrons in n–p–n transistor) can move from the emitter to the collector.
4. Most charge carriers flow from emitter to collector and only a small percentage flow through the base material.
5. Variation of base–emitter voltage changes base, emitter, and collector currents.

14.7.2 Working of a p–n–p Transistor

The p–n–p transistors work the same way as n–p–n transistors except that in p–n–p transistors the majority charge carriers are holes. The biasing is same as that of a n–p–n transistor. The emitter-base junction is forward biased and the collector–base junction is reverse biased as shown in Fig. 14.16.

The majority charge carriers from the emitter are the holes. As the base is thin and lightly doped only a small percentage of holes emanating from the emitter recombine with electrons in the base region. The rest of the holes, which are nearly 98 per cent, cross the base–collector barrier potential, because they are attracted by the negative terminal of the base–collector bias voltage.

Thus, holes are emitted from the p-type emitter across the forward-biased emitter–base junction and only a few of them find electrons in the base region to recombine with. Most of the holes get attracted to the collector side by the reverse-biased collector–base junction.

By varying the forward bias voltage at the base–emitter junction, we can control the large emitter and collector current through small variations of base current.

Both n–p–n and p–n–p type of transistors are called bipolar junction transistors, or simply BJTs because the charge carriers for both types of transistors are electrons, and holes, although for n–p–n transistors the majority charge carriers are electrons and for p–n–p transistors the majority charge carriers are the holes.

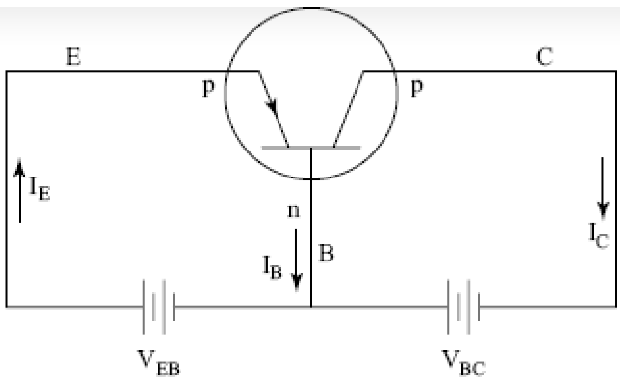


Figure 14.16 P–n–p transistor

When both junctions of a transistor are reverse biased, the transistor is said to be cut off and operating in the cut-off region.

The ratio of the collector current to the emitter current of a transistor is called α_{dc} which is greater than 0.95. We can express

$$I_E = I_C + I_B \quad \text{(i)}$$

and $$IC = \alpha_{dc} I_E \text{ neglecting the reverse saturation current} \quad \text{(ii)}$$

Therefore, $$I_B = (1 - \alpha_{dc}) I_E \quad \text{(iii)}$$

where α_{dc} is the emitter to collector current gain.

The value of alpha dc (α_{dc}) is normally 0.95 to 0.99. As the collector–base junction is reverse biased, a small reverse saturation current flows across the junction due to minority charge carriers which are very small in number, and can be neglected.

From eqs. (i) and (ii)

$$I_C = \alpha_{dc} I_E = \alpha_{dc}(I_C + I_B)$$

or, $$I_C(1 - \alpha_{dc}) = \alpha_{dc} I_B$$

or, $$I_C = \frac{\alpha_{dc}}{1 - \alpha_{dc}} I_B \quad \text{(iv)}$$

or, $$I_c = \beta_{dc} I_B \quad \text{(v)}$$

where $$\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

Beta dc (β_{dc}) is called the base to collector current gain. This is the ratio of I_C and I_B. The value of β_{dc} varies from 25 to over 200.

Example 14.2 An n–p–n transistor has been shown provided with biasing voltage V_{BE} and V_{CB}. Calculate the values of I_C and I_E if α_{dc} is 0.96 and I_B is 80 μA. Also calculate the value of β_{dc}.

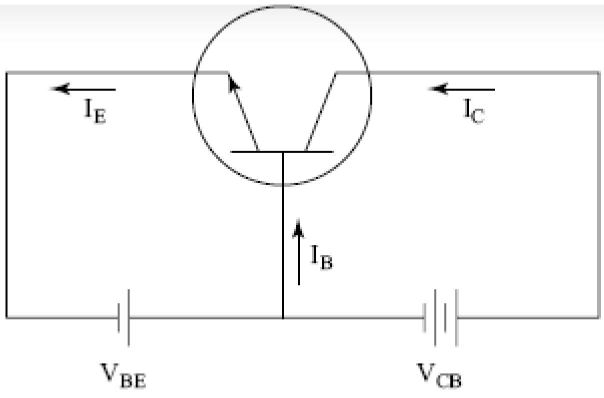


Figure 14.17 Relates to example 14.2

Solution:

Given $\alpha_{dc} = 0.96$, $I_B = 80 \times 10^{6}$ A

$$\beta_{dc} = \frac{\alpha_{dc}}{1-\alpha_{dc}} = \frac{0.96}{1-0.96} = \frac{0.96}{.04} = 24$$

$$I_C = \frac{\alpha_{dc}}{1-\alpha_{dc}} I_B = \frac{0.96}{1-0.96} \times 80 \times 10^{-6}$$

$$= 1.92 \text{ mA}$$

Again,

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

or,

$$I_E = \frac{I_C}{\alpha_{dc}} = \frac{1.92}{0.96} \text{mA} = 2 \text{ mA}$$

14.7.3 Transistor Configurations

A transistor has three terminals. For the connection of input and configurations, namely (i) common-base configuration; (ii) common-emitter configuration; and (iii) common-collector configuration.

These three types of connections can be made for both n–p–n and p–n–p transistors.

Each type of configuration has its advantages and disadvantages. These configurations have been illustrated in Fig. 14.18. The common emitter configuration is widely used because of its very high voltage and power gain. Discussions will therefore be restricted to the common emitter configuration of a transistor. The characteristics of a transistor in the common emitter configuration is discussed as follows.

Common-emitter transistor characteristics

The circuit diagram for determining the common-emitter transistor characteristics has been shown in Fig. 14.19. In this p–n–p transistor, input voltage is applied between the base and the emitter terminals. The output is taken from the collector and the emitter terminals as has been shown. The emitter terminal is common to both input and output. That is why this connection is called the common-emitter configuration.

The input characteristic is drawn between V_{BE} and I_B. To draw the input characteristic, the voltage between the collector and the emitter, i.e., V_{CE} is kept constant at a value. By changing V_{BE} through V_{BB}, current I_B is recorded for atleast, say five readings. A plot of I_B against V_{BE} when made shows that the characteristic is similar to the characteristic of a forward-biased p–n junction. The value of I_B is very small, is of the order of several microamperes only.

The output characteristics are drawn between I_C and V_{CE} keeping I_B constant at different values. For each value of I_B, V_{CE} is adjusted in steps and the values of I_C are recorded. The values of I_C are plotted against V_{CE} for each value of I_B as shown in Fig. 14.20. Fig. 14.20 (a) shows the input characteristic and Fig. 14.20 (b) shows the output characteristics.

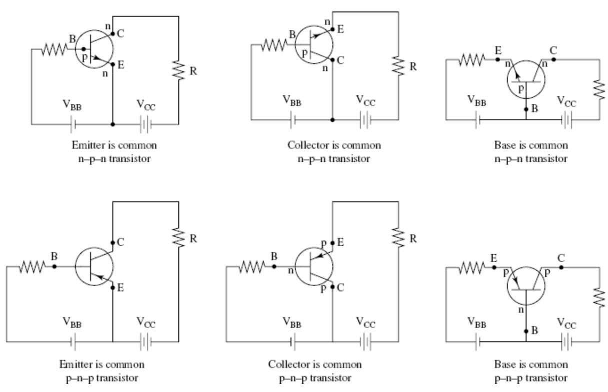


Figure 14.18 Common-emitter, common-collector, and common-base configurations of n–p–n and p–n–p transistors

and emitter current. The *current gain* from the base to the collector can be stated as

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

Thus, the transistor can be used as a current-amplication device.

The *voltage gain*, A_V of the transistor is defined as the ratio of output voltage to input voltage.

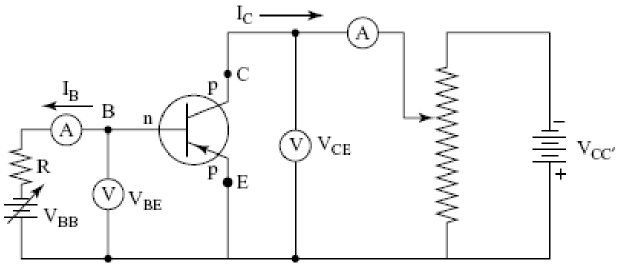


Figure 14.19 Circuit diagram for determining the common-emitter transistor characteristics

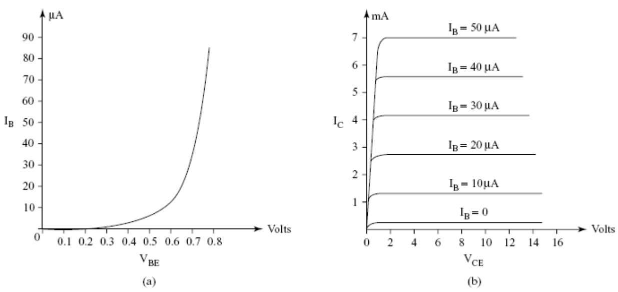


Figure 14.20 (a) Common-emitter input characteristics; (b) common-emitter output characteristics

14.7.4 Transistor As an Amplifier

In Fig. 14.21 is shown a simple transistor amplifier circuit using an n–p–n transistor connected in the common-emitter configuration. The ac signal which is to be amplified is connected to the base circuit as shown. The output is taken across a resistance, R_L in the collector circuit. The base circuit dc voltage, V_{BB} is such that the base will always remain positive irrespective of the magnitude of the input ac signal. The voltage, V_{BE} is the summation of dc voltage V_{BB} and the ac input signal, V_i. The dc voltage, V_{BB} is the bias voltage.

the base current I_B will flow, which is the sum of the dc base current and the ac current. It can be observed that I_B is always positive.

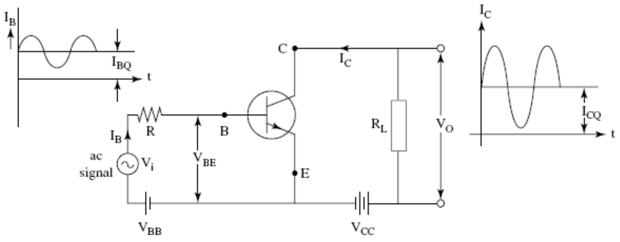


Figure 14.21 Transistor as an amplifier

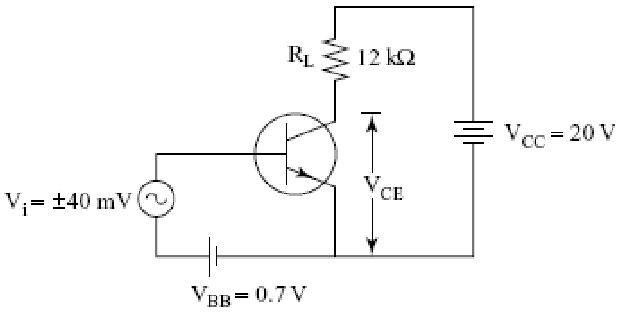


Figure 14.22 Transistor amplifier circuit

During the positive half cycle of the input signal, the dc and ac voltages are added up and as such the base current is highly positive. During the negative half cycle, ac voltage is subtracted from the dc voltage. The net voltage is low but positive. The base current now will be positive but low.

Because of the large variation in the base current there will be a large variation in the collector current, which will flow through the load resistance. An amplified output voltage is thus available across the load. The amplified collector ac current is superimposed on the dc current, I_{CQ} which will flow through the collector when the ac input signal is not applied. It is the current when the base current is I_{BQ}.

Example 14.3 In an n–p–n transistor in the common emitter configuration, an ac input signal of ± 40 mV is applied as shown in Fig. 14.22. The dc current gain, β_{dc} and ac current gain β_{ac} are given as 80 and 100, respectively. Calculate the voltage amplification, A_V of the amplifier. The I_B versus V_{BE} characteristic is such that for V_B = 0.7 V, I_B = 12 μA and for V_i = ± 40 mV, I_b = ±4 μA. Also calculate the dc collector voltage.

Solution:

The collector voltage V_{CE} is calculated as

$V_{CE} = V_{CC} – I_C R_L$

$= 20 – 0.96 \times 10^{-3} \times 12 \times 10^{3}$

$= 20 – 11.52$

$= 8.48$ V

AC base current, $I_b = \pm 4\ \mu A$ for $V_i = \pm 40$ mV

$I_C = \beta_{ac} I_b = 100 \times (\pm 4\ \mu A) = \pm 400\ \mu A$

AC output voltage across load resistance, V_0 is calculated as

$V_0 = I_C R_L = \pm 400 \times 10^{-6} \times 12 \times 10^{3} = \pm 4.8$ V

AC voltage amplification factor, A_V is calculated as

$$A_v = \frac{v_0}{v_i} = \frac{\pm 4.8\ \text{V}}{\pm 40\ \text{mV}} = \frac{\pm 4.8}{\pm 40 \times 10^{-3}} = 60$$

14.7.5 Transistor As a Switch

A BJT can be used as an amplifier and also as a switch. A switch either closes a circuit or opens a circuit. There are two states for a switch, i.e., either there is no current flow (cut off) or the switch is closed, i.e., current flows through it with the minimum of resistance offered.

These two conditions can be created by applying a pulse wave input to the base of the BJT. In the case of an amplifier we had applied a bias voltage plus an ac signal that had to be amplified to the base circuit. In the case of switching operation, a pulse voltage of appropriate level has to be applied as shown in Fig. 14.23 (a) and (b).

The base voltage level is either at zero level or at an appropriate positive level. When the input voltage, V_i is at zero level, the base current is zero and there is no collector current, i.e., $I_C = 0$ as shown is Fig. 14.23 (a).

The transistor is cut off and works like an open switch.

From Fig. 14

V_{CE} = Supply voltage – voltage drop across R_2

$V_{CE} = V_{CC} – I_C R_2$

When the base-emitter voltage is at zero level, the transistor is not working, and hence, $I_C = 0$. Therefore,

$V_{CE} = V_{CC}$

When V_i is at positive level, base current, I_B will flow. If the BJT is to be used as a switching device, the level of I_B is made high enough so that the transistor is saturated. At saturated state the level of I_C will

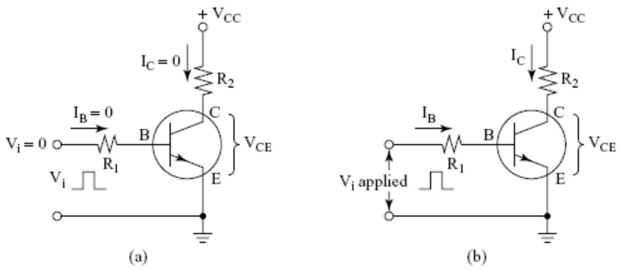


Figure 14.23 (a) Off state of a BJT; (b) on state of a BJT

Example 14.4 What minimum input voltage level is required to switch a BJT into saturation (on state) when V_{CC} = 10 V, R_1 = 16 kΩ, R_2 = 6.2 kΩ and β_{dc} = 20 in an n–p–n CE configuration BJT.

Solution:

$V_{CC} = I_C R_2 + V_{CE}$

for $V_{CE} = 0$

$$I_C = \frac{V_{CC}}{R_2} = \frac{10}{6.2\times10^3} = 1.612 \text{ mA}$$

$= 1612\ \mu A$

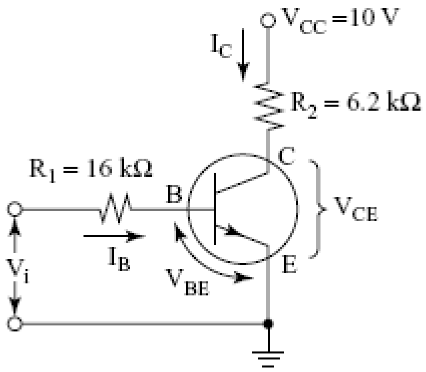


Figure 14.24

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

or, $$I_B = \frac{I_C}{\beta_{dc}} = \frac{1612}{20} = 80.6\ \mu A$$

Taking $V_{BE} = 0.7$ V, $$V_i - I_B R_1 = V_{BE}$$

Field effect transistors (FETs), like BJTs are used in amplifier and switching circuits. FETs are of two types, namely, junction field effect transistor (JFET) and metal oxide semiconductor field effect transistor (MOSFET). Unlike a BJT, FET is a voltage operated device having virtually no requirement of any input current. The two types of FET are described below.

14.8.1 Junction Field Effect Transistors

A JFET has been shown in the form of a block diagram in Fig. 14.25 along with its symbol. A JFET is made of an n-type semiconductor material called channel, sandwiched between two p-type materials. The two p-type materials are connected togather to form a gate.

The two ends of the central n-type material, i.e., the channel has two end terminals. One terminal of the channel is called *drain* and the other terminal is called *source*. The gate material is highly doped as compared to the channel. The principle of operation of a JFET is explained as follows.

With the gate terminal open, when a positive voltage is applied to the drain with respect to the source, a drain current, I_D will flow. Now, if a gate-source voltage, V_{GS} is applied with the gate having connected to the negative terminal, the gate-channel p–n junctions will be reverse biased. Since the gate material is heavily doped, due to the negative bias voltage, the depletion region will expand and penetrate into the channel from both sides. If the voltage, V_{GS} is increased, the penetration of the depletion region will be so high that it will stop the flow of current, I_D through the channel. Thus, by varying the voltage, V_{GS}, the depletion region at the gate-channel region can be varied. This will result in the passage for current I_D at the gate region narrowed down, causing high resistance to the current flow. This way the drain to source current can be varied. If the voltage V_{GS} is increased more, the depletion region from both sides will expand and close the passage of current, I_D, and hence the device will come to non-conducting or cut-off state. The two gate-channel p–n junctions are kept reverse biased, and the gate current is normally very low.

Now, assume that an ac signal is applied to the gate circuit. The signal will be superimposed on the negative dc bias voltage. Since the gate is negatively biased, in the negative half cycle of the ac signal, the negative bias voltage of the gate will increase. During the positive half cycle the negative bias of the gate will be reduced. When the signal goes negative of the depletion layer of the reverse-biased p–n Junction will widen, causing a reduction of I_D. When the signal becomes positive, the effective negative bias of the gate will decrease, the depletion region will reduce, channel widens, channel resistance decreases, and hence I_D increases. This way, by varying the reverse bias of the gate, the drain current is controlled.

Here the channel has been made of an n-type semiconductor material. That is why the device is called n-channel JFET. If the channel is made of p-type material, the device will be called p-channel JFET.

The reverse bias voltage produces an electric field which changes the depletion region at the gate-channel junction. The effect of the carriers when the channel is made of an n-type material. For a p-type channel, the charge carriers will be only the holes.

For a p-channel JFET, the channel is made of a p-type material sandwiched between two n-type materials. The battery connection is reversed, i.e., the drain is connected to the negative terminal of the battery and the source is connected to the positive terminal. The drain current flows from the source to the drain. The gate channel junctions are reverse biased. The relationship between drain current, I_D and voltage across the device, V_{DS} when external gate-source bias, V_{GS} is applied is shown in Fig. 14.27.

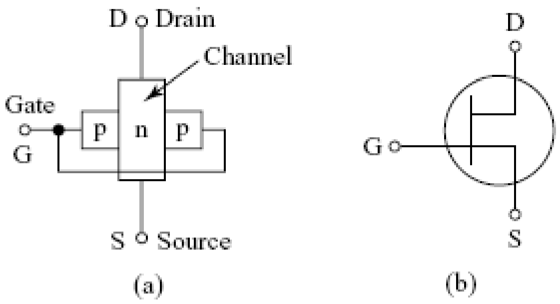


Figure 14.25 (a) Construction of a JFET; (b) symbol of a JFET

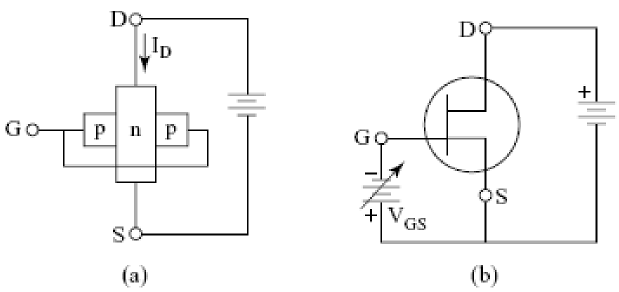


Figure 14.26 (a) A JFET with no gate-source bias voltage; (b) variable gate-source voltage applied to a JFET

In Fig. 14.27 (b) is shown the I_D versus V_{GS} characteristic. This characteristic shows how the drain current, I_D is controlled by the negative gate voltage V_{GS}. As shown in Fig. 14.27 (b), at –4V the drain current stops flowing and the device is at cut-off state. At no voltage at the gate, i.e., when V_{GS} is zero, the drain current, I_D is maximum. This characteristic is also called the *transfer characteristic*.

The variation of I_D with variation of V_{GS} at a constant V_{DS} is called the forward transfer admittance, Y_{fs}, of the FET. Its value indicates how the drain current, I_D is controlled by the gate-source voltage, V_{GS}.

$$Y_{fs} = \frac{\Delta I_D}{\Delta V_{GS}} \text{ at constant } V_{DS}$$

14.8.2 FET Applications

FETs, like BJTs are used for voltage amplification and in switching circuits. Fig. 14.28 shows an FET voltage amplifier circuit. The gate–source junctions are reverse biased. The drain-source terminals are provided with dc voltage supply with the positive terminal connected to the drain. An ac signal voltage is connected in series with the gate circuit. R_1 is a resistance connected in the drain circuit of the FET. An input ac voltage, vi will produce an output voltage change across the device, i.e., VD. The ratio of the output voltage to the input voltage is called voltage amplification of the circuit, A_v.

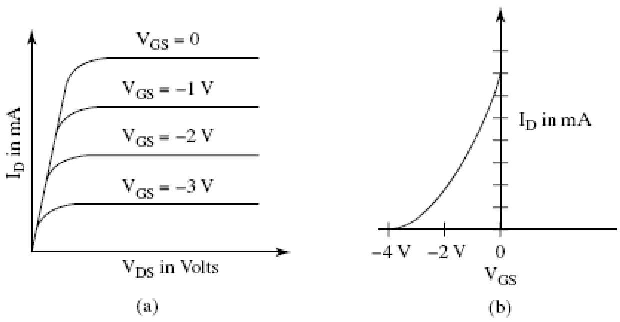


Figure 14.27 (a) I_D versus V_{DS} characteristics for variable V_{GS} of a JFET; (b) I_D versus V_{GS} characteristics (also called transfer characteristic) for a JFET

Example 14.5 In an FET voltage amplifier circuit as shown in Fig. 14.28, an input voltage of ± 50 mV is applied. Calculate the voltage gain of the amplifier. The following are given:

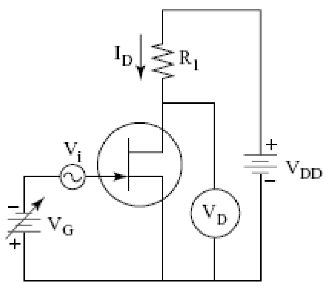


Figure 14.28 A voltage amplifier circuit using an FET

Solution:

We have to calculate the output voltage change for an input of ± 50 mV.

The dc level of the drain voltage is

$V_D = V_{DD} – I_D × R_1 = 18 – 2.5 × 10^{-3} × 5 × 10^{3}$
$= 7.5$ V

When the positive half cycle of the ac input is flowing, $V_i = +50$ mV. For this current,

$ΔI_D = Y_{fs} × v_i = 5000 × 10^{-6} × 50 × 10^{-3}$
$= 0.25$ mA

The new drain voltage is

$V_D = V_{DD} – (I_D + DI_D) R_1$
$= 18 – (2.5 + 0.25) × 10^{-3} × 5 × 10^{-3}$
$= 6.25$ V

Thus, V_D has changed from $V_D = 7.5$ V to $V_D = 6.25$ V. The change of V_D is equal to –1.25 V For the negative half cycle of input cycle, the change of V_D can be calculated as +1.25 V. Thus, we see that for an input voltage variation of ± 50 mV with VG adjusted for ID = 2.5 mA, the output voltage change obtained is ± 1.25 V. The voltage amplification of the circuit, A_v is

$$A_v = \frac{1.25}{50 \times 10^{-3}} = 25$$

Thus, the input voltage is amplified 25 times.

14.9 MOSFET

MOSFET is one of the most widely used devices incorporated in integrated circuits (IC). It is a three-terminal device, the three-terminals are drain, source, and the gate. A MOSFET is also known as insulated gate field effect transistor (IGFET) as the gate of the MOSFET is insulated from the channel between the drain and the source. A MOSFET is commercially more important than JFET because the MOS devices are suitable for very large-scale integration. MOSFET can be *n-channel*-type or *p-channel*-type channel formed between the source and the Drain. MOSFET, either n-channel or p-channel type can further be categorized into enhancement MOSFET or depletion MOSFET.

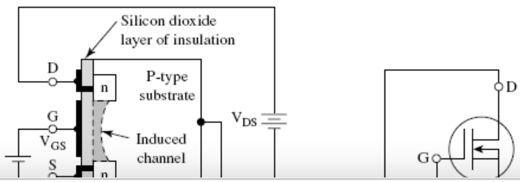


Figure 14.29 EMOSFET constructional details

14.9.1 The Enhancement MOSFET (EMOSFET)

The constructional details of an EMOSFET has been shown in Fig. 14.29. In an n-channel EMOSFET two blocks of heavily doped n-type material have been diffused into a p-type substrate or a base (a substrate is a surface or material on which a device is made or developed/grown). The terminals for external connection have been brought out. The whole of the surface has been coated with a layer of silicon dioxide. A thin metal plate has been placed on the surface of the silicon dioxide layer wherefrom the gate terminal connection has been taken. In fact, the metal plate itself will function as the gate of the MOSFET. The substrate is a high resistive material.

It may be noted that no continuous channel exists between the source and the drain. The two n-blocks forming the drain and the source, makes two p–n junctions with the p-type substrate. When a positive voltage, V_{DS} is applied between the drain and the source terminals, the p–n junction close to the drain is reverse biased while the other junction close to the source is forward biased. Since one of the p–n junctions is reverse biased between terminals D and S, only a negligible small current will flow between the drain and the source due to the minority charge carriers. Virtually no continuous channel exists between the drain and the source with the result that virtually no current flows between the drain and the source without any gate voltage applied. In the symbolic representation, the broken line represents this condition. When a positive voltage, V_{GS} is applied on the gate, the gate voltage will induce a channel by pulling the minority charge carriers of the p-type substrate towards the gate. If the gate voltage is increased more and more, negatively charged minority carriers, i.e., the electrons in this case, from the p-type substrate will get collected in the region between the drain and the source as shown in Fig. 14.29 (a). These electrons cannot cross the SiO_2 layer, and hence constitute an n-type-induced channel between the drain and the source. A minimum or threshold gate voltage, V_{GST} is required before drain current will flow. The magnitude of the current between the drain and the source will depend on the gate potential. Thus, the magnitude of drain current can be controlled by changing the gate voltage. The conductivity of the channel is enhanced due to the gate voltage. With no gate voltage, the device is non-conducting, i.e., off. When the device is to be switched on, a gate voltage higher than the threshold voltage has to be applied. This type of MOSFET is therefore suitable for switching operations.

14.9.2 The Depletion MOSFET

As shown in Fig. 14.30, the region between the drain and the source on the top surface of the p-type substrate is called the channel. The channel is produced by diffusing an n-type impurity material between the drain and source terminals before the insulating SiO_2 layer is deposited. When a positive voltage V_{DS} is applied between the drain and the source, a drain current I_D flows with no gate voltage applied, i.e., when $V_{GS} = 0$. It is to be noticed that a capacitor exists between the metal plate of the gate and the channel having the SiO_2 layer as the dielectric between the two plates. When a negdecrease. The depletion of the majority charge carriers justifies its name as depletion MOSFET. The drain current will get reduced if V_{GS} is made more negative.

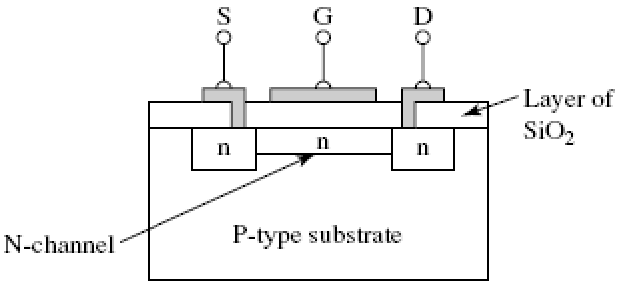


Figure 14.30 An n-channel depletion MOSFET

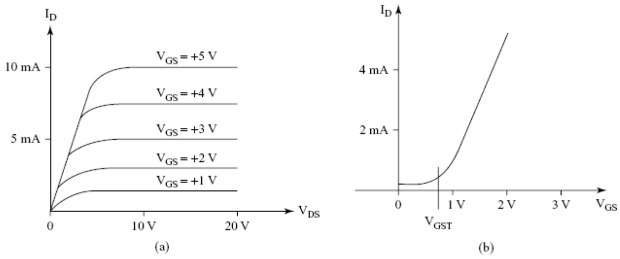


Figure 14.31 (a) Typical drain characteristic of an EMOSFET; (b) transfer characteristic

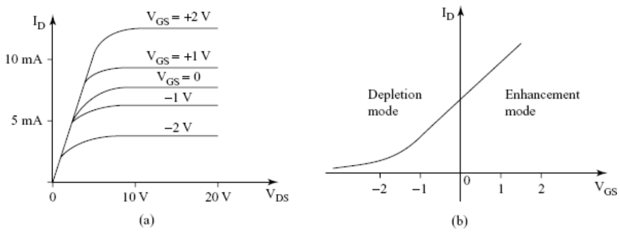


Figure 14.32 (a) Drain characteristic of DEMOSFET; (b) transfer characteristics

A depletion MOSFET can also be made to operate in enhancement mode by applying a positive gate voltage. When a positive voltage is applied to the gate due to capacitor action, negative charges will get induced in the channel thereby increasing its conductivity. As a result drain current will increase.

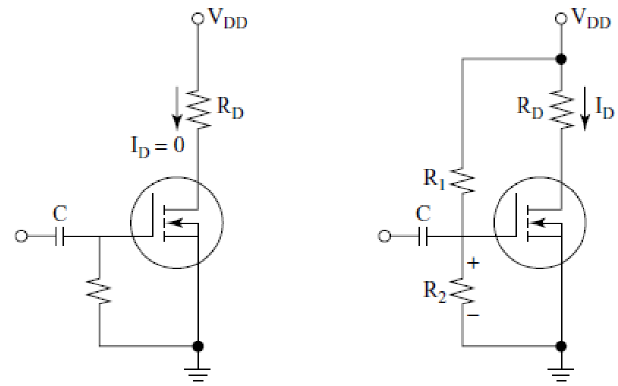
to source voltage, i.e., V_{GS}. The forward transfer characteristic which is the relation between I_D and V_{GS} has also been shown.

Figure 14.32 shows the drain characteristics for a depletion-type MOSFET, or DEMOSFET and its transfer characteristic. In the transfer characteristic the two modes of operation of the MOSFET for negative and positive gate voltage, respectively have been shown.

The basic difference between JFET and a MOSFET is that a MOSFET has very high input resistance of the order of 10^{10} Ω or so. MOSFETs should be handled very carefully because the very thin layer of SiO_2 is susceptible to high voltages and can be easily punctured.

14.9.4 Applications of MOSFET

Like JFETs, MOSFETs are also used in a wide range of applications. In fact we may use either JFET or MOSFET in most of the applications interchangeably. But the MOSFETs require very careful handling. MOSFETs are used in switching circuits, as phase shift oscillator, as an amplifier, etc. Fig. 14.33 shows a capacitor-coupled MOSFET switching circuit. As shown in Fig. 14.33 (a), no gate voltage is applied to the device i.e., V_{GS} = 0. The device is off. A positive gate voltage higher than the threshold voltage is required to turn the device on.



(a) $V_{GS} = 0$, Circuit is off

(b) Positive V_{GS} applied, circuit is on

Figure 14.33 MOSFET switching circuit

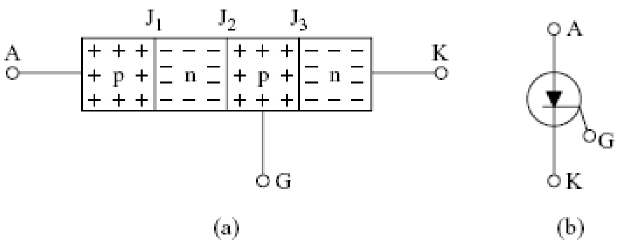


Figure 14.34 (a) Four layer three junction diagramatic representa-

Through the voltage divider R_1 and R_2 as in Fig. 14.33 (b) a positive voltage when applied, the circuit is switched on. The device can be set to be on for a desired level of drain current, by determining the V_{GS} from the transfer characteristic provided by the manufacturer. To make sure that the device gets switched off, the V_{GS} must be brought below the minimum threshold voltage, i.e., V_{GST}.

14.10 SILICON-CONTROLLED RECTIFIER

A silicon controlled rectifier (SCR) is a four-layer three-junction device. Thyristor is the general name given to a family of such semiconductor devices having four layers and three junctions. After semiconductor diodes and transistors, thyristors were introduced in a big way in almost all control applications in industry.

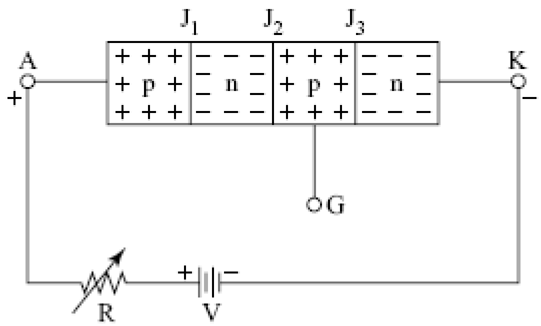
A SCR shown in Fig. 14.34 has four alternate layers of p, n, p, and n. It has three terminals, viz A (anode), K (cathode), and G (gate). The three p–n junctions are J_1, J_2, and J_3.

The majority charge carriers in the p-type material are the holes and in the n-type material are the electrons, respectively. Electrons are negatively charged while the holes are positively charged. The gate terminal is connected to the p-layer near the cathode. The gate is provided with positive supply to trigger the SCR. Now, let us see what happens when the SCR is biased as in Fig. 14.35.

14.10.1 Characteristics of SCR

The anode is connected to the positive terminal of the battery while the cathode is connected to the negative terminal. Junctions J_1 and J_3 are forward biased while junction J_3 is reverse biased.

Junction J_3 will have an expanded depletion layer because of its reverse biasing. As such no current will flow from anode to cathode except a very minute amount of leakage current also called reverse saturation current. The SCR under the forward-biased condition will not conduct. However, if we keep on increasing the voltage between the terminals A and K, a stage comes when the depletion layer at junction, J_2 will breakdown due to a large voltage gradient across the depletion layer. This phenomenon is called *avalanche breakdown*, the other two junctions, J_1 and J_3 being forward biased, there will be free movement of charge carriers resulting in a large current flow through the device. The SCR is said to be in conducting state.



For the reverse biasing, the cathode is made positive with respect to the anode by connecting the negative terminal of the dc source to the anode and the positive terminal to the cathode. Junctions J_1 and J_3 are reverse biased and junction J_2 is forward biased. No current, except some negligible leakage current will flow. However, when the reverse voltage is gradually increased, the width of the depletion layers at junctions J_1 and J_3 will become thin and a breakdown voltage will be reached when free charge carriers will be flowing through the device resulting in a large current flow in the reverse direction. The V–I characteristic of an SCR is shown in Fig. 14.36. At a forward voltage of $V_{AK} = V_{BOF}$, the SCR starts conducting. The voltage across the device falls to a low value and a large amount of current starts flowing. This current is controlled by an external resistance placed in the circuit. The voltage at which the SCR starts conducting is called its triggering voltage. By gate control, it is possible to reduce this triggering voltage.

In Fig. 14.36 it is seen that the application of gate current I_{g1} reduces the voltage at which the device starts conducting. A further increase in gate current to I_{g2}, V_{AK} required to make the device conducting is again reduced. This process is called gate control process.

Under the reverse-biased condition, the device is in blocking state because two of its junctions are reverse biased and a large barrier potential is built up across the junctions. But upon increasing the reverse voltage to V_{BDR}, there is a breakdown of junctions. The device starts conducting in the opposite direction and a large reverse current starts flowing. The reverse current is so large that it will damage the SCR. That is why an SCR is not operated in the reverse conduction mode.

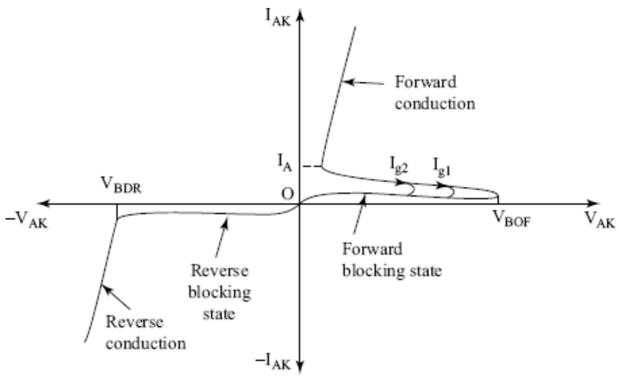
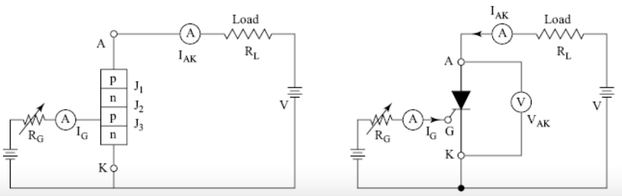


Figure 14.36 V–I characteristic of an SCR



An SCR can be operated with and without gate control as explained above. With gate control the forward bias voltage required gets reduced. Operation of an SCR with gate control has been shown in Fig. 14.37. The gate is biased with a positive voltage. The gate current, I_G is controlled by adjusting the resistance R_G. At certain voltage V_{AK} and gate current I_G the junction J_2 will break down and the SCR will start conducting. Current will flow through the load. The conduction will continue on any value of load. However, the conduction current I_{AK} should not fall below a certain value when the depletion layer will start building up due to reduced number of charge carriers. This minimum value of current required to hold the conduction of the device is called the *holding current*, I_H of the SCR. It is the minimum value of current below which the SCR stops conducting and returns to the off state.

The SCR is turned on, i.e., brought to the conduction state at a lower voltage by applying a gate current. As we increase the gate current the SCR will be turned on at lower values of V_{AK}.

The gate current can turn on the SCR but once turned on, the gate loses its control.

The SCR will continue to conduct even when the gate current is reduced to zero. This means that there must be some method of switching off the SCR. The method of switching off (turning off) of the SCR is called *commutation*. The SCR can be turned off if the current flowing through it, i.e., I_{AK} is reduced to a value lower than the holding current, I_H. The SCR can also be commutated (switched off) by applying a reverse voltage across the SCR by means of a commutating circuit. Inductors and capacitors are used in the commutating circuits which facilitate the development of a reverse voltage across the SCR for its commutation. The method of turning on an SCR is called triggering and the method of switching off or turning off an SCR is called its commutation.

14.10.2 Two-transistor Analogy of an SCR

An SCR can be considered made up of one p–n–p and one n–p–n transistor sandwiched together as shown in Fig. 14.38 (a). Two-transistor-equivalent circuit has been shown in Fig. 14.38 (b). T_1 and T_2 are the two equivalent transistors of the SCR. The gate current, I_G acts as the base current for transistor, T_2.

As shown in Fig. 14.38 (b) the anode is made positive with respect to the cathode and a gate current, I_G is supplied. This gate current acts as the base current of transistor, T_2. This transistor gets turned on. The emitter current of T_2 now becomes the base current of transistor, T_1. Transistor T_2 now gets turned on. The collector current of T_1 adds to the base current of transistor T_2. This way current multiplication takes place. Even if the gate current is removed, the device will not get turned off as long as the current flow does not come down to the level below the holding current.

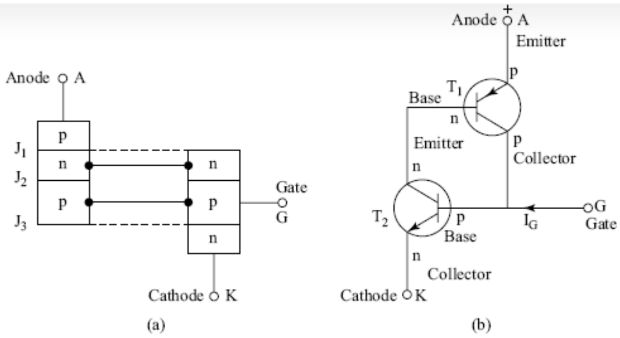


Figure 14.38 Two-transistor analogy of an SCR. (a) Block diagram; (b) equivalent circuit

14.10.3 Applications of SCR

SCR is a members of the thyristor family. DIAC (bidirectional diode thyristor), TRIAC (bidirectional triode thyristor), etc. are some of the other members. An SCR is often referred to as a thyristor. Thyristors find wide applications in the field of industrial electronics and control. They are extensively used as controlled rectifiers, as inverters, converters, cycloconverters, in ac and dc motor control circuits, dc circuit breakers, in electronic control of heating and welding circuits, etc. We will discuss the use of SCR as a controlled rectifier.

Single-phase half-wave-controlled rectifier

We have known earlier that a diode can be used as a half-wave rectifier. The circuit for a half-wave rectifier is shown again in Fig. 14.39 with the input and output voltage wave. When the input terminal A is positive, current flows through the diode and the load. When terminal B is negative the diode is reverse biased and no current flows through it and the load. The output voltage wave shape is half-wave rectified voltage wave whose average value is $\frac{V_m}{\pi}$, where V_m is the maximum value of the input voltage wave.

In a controlled rectifier, instead of a diode we will use an SCR as shown in Fig. 14.40 (a). We have just seen that a diode allows current flow for the whole of the positive half cycles. In case of an SCR control, if the SCR gate is provided with sufficient bias voltage, the SCR will be on all the time, provided the anode to cathode voltage is positive. We will get a half-wave rectified output across the load as we get in the case of a diode circuit. If a gate current can be provided at an instant of time, say t_1 as shown in Fig. 14.40 (b), the SCR will be turned on at that instant and current will flow. Current will flow for the period starting from t_1, at an angle α to π. This is called the conduction time as has been shown by the shaded portion of voltage wave in Fig. 14.40 (b). In the negative half cycle, the SCR will be reverse biased and no current will flow as is in the case of a diode circuit also. In the second positive half cycle again, the gate will be provided with a gate current so as to turn on the SCR with a delay angle of α; the SCR will conduct for the period of time shown by shading on the voltage wave. The average value of the output controlled half-wave rectifier. The angle α is called the firing angle of the SCR. The conduction angle is (π – α). Triggering circuits are designed for the gate circuit to switch the SCR on. The gate current can be made to flow at any time of the input voltage wave, and hence we can get a variable output voltage.

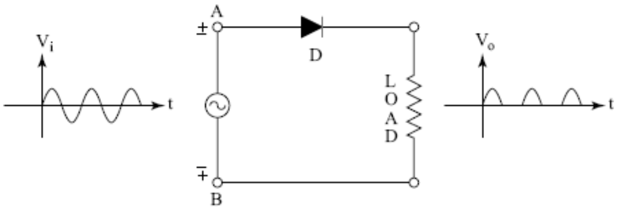


Figure 14.39 Half-wave diode rectifier

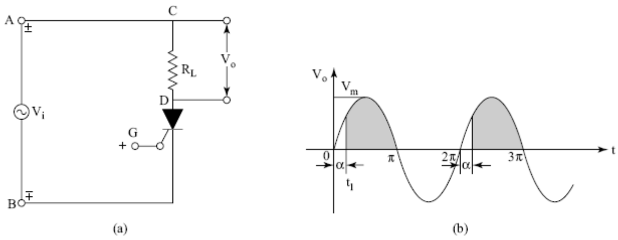
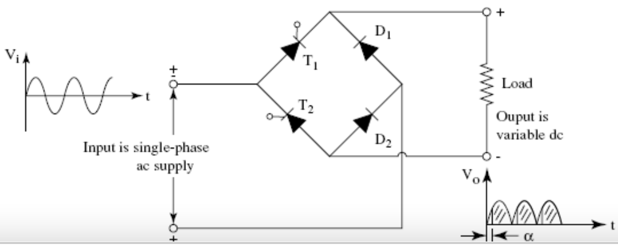


Figure 14.40 (a) Half-wave-controlled rectifier circuit; (b) output voltage wave shape

Similar to a full-wave rectifier using diodes, we can have a full-wave-controlled rectifier using more number of SCRs.

Single-phase full-wave-controlled bridge

For conversion of single-phase ac supply to a variable dc output across a load, we can use an SCR bridge circuit using two SCRs and two diodes as shown in Fig. 14.41. In the positive half cycle of the input ac supply, SCR T_1 and diode D_1 will be conducting. In the negative half cycle of the input voltage, diode D_1 and SCR T_2 will be conducting. The firing angle of both the SCRs are controlled so that the average output voltage is variable dc.



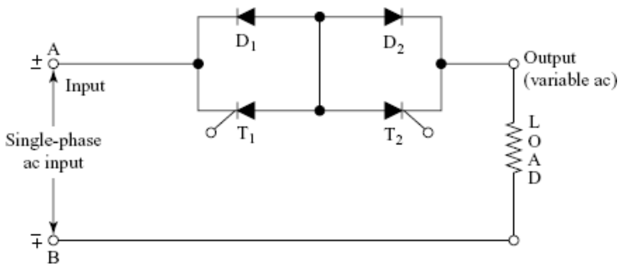


Figure 14.42 Static switching circuit using SCRs and diodes

If we used four diodes in the bridge circuit, the output voltage would have been a full-wave-rectified dc. By using two SCRs T_1 and T_2 we are able to vary the magnitude of the average output voltage by changing the firing angle α of the two SCRs. The output voltage is variable dc because the angle α can be changed by changing the time at which the gate current will be made available to the two SCRs. With this variable dc we can control the speed of a dc motor, for example. In Fig. 14.41, the gate control circuit for the SCRs have not been shown.

Static switching circuit using SCR-diode combinations

From a fixed ac voltage, a variable ac output voltage can be made available using SCR–diode combinations as shown in Fig. 14.42.

In the positive half cycle of the input voltage when terminal A is positive, SCR T_1 and diode D_2 will conduct. The conduction angle is decided by the time at which the SCR, T_1 will be triggered. In the negative half cycle, terminal B is positive, and hence SCR T_2 and diode D_1 will conduct. The time of triggering of the gate of SCR, T_2 will decide the conduction angle in the negative half cycle. By changing the firing angle of the SCRs, a variable ac voltage will be available across the load, and hence load current will change.

14.11 DIAC

Like an SCR, DIAC is also a member of the thyristor family. A DIAC is a bidirectional diode which conducts in both directions whereas a diode conducts in one direction. Unlike an ordinary diode, a DIAC conducts only when the applied voltage reaches the breakover voltage. DIAC is a two-terminal device without a gate terminal. When the applied voltage between its two terminals, which are termed A_1 and A_2, is raised to the breakover voltage, the DIAC starts conducting. The symbolic representation and V–I characteristics of a DIAC have been shown in Fig. 14.43. Terminal A_1 is called anode 1 and terminal A_2 is called anode 2.

14.12 TRIAC

A TRIAC combines in itself two SCRs connected in anti-parallel or inverse-parallel with one gate terminal as has been shown in Fig.14.44 (a). The four layers n_1 p_2 n_3 p_3 form one SCR and the other four layers p_1 n_2 p_2 n_4 form the other SCR. Layer p_2 is common to

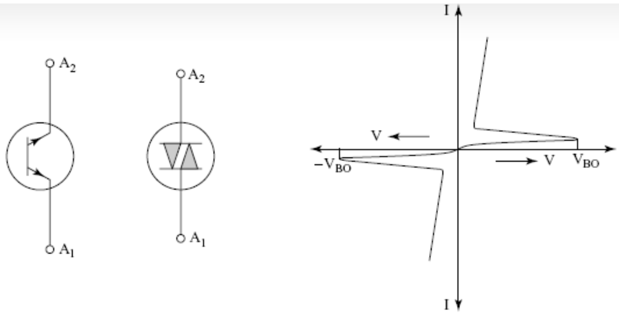


Figure 14.43 Symbols of DIAC and its V–I characteristics

Terminal MT_2 is positive and terminal MT_1 is negative in the first quadrant as shown in the V–I characteristics. The V–I characteristics are just like an SCR. When the polarities of its terminals are changed, the TRIAC conducts in the opposite direction and the V–I characteristics are shown in the third quadrant. The TRIAC when starts conducting in any direction, a heavy current will flow which has to be controlled by some external resistance. The TRIAC's time of triggering, and hence its conduction time is controlled by a common gate. By applying a proper signal, the firing angle of the TRIAC can be changed, and hence a variable voltage can be made available across the load. The TRIAC is the most widely used thyristors in control circuits. TRIACS have replaced SCRs in many applications because of their bidirectional characteristics.

A TRIAC can be triggered by applying a voltage to its gate terminal. When terminal MT_2 is positive with respect to MT_1, a positive gate voltage is to be applied to make the TRIAC conducting. When terminal MT_1 is positive with respect to MT_2, a negative gate voltage will make the TRIAC start conducting.

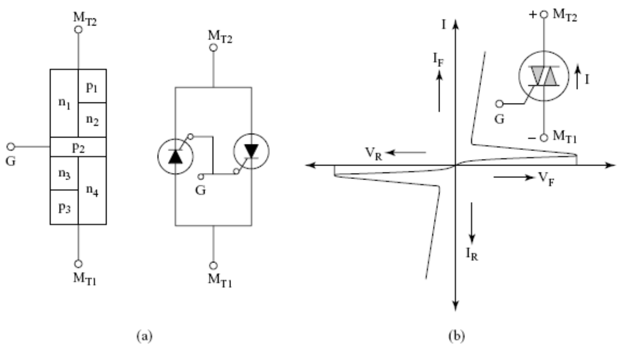


Figure 14.44 (a) Construction and symbol of TRIAC; (b) V–I characteristics of a TRIAC

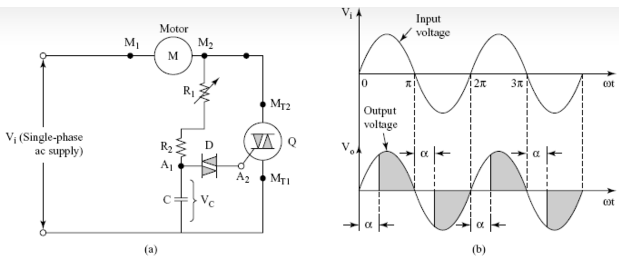


Figure 14.45 (a) Phase control circuit using a TRIAC; (b) input and output voltage waveforms

TRIAC phase-control circuit

The circuit for control of ac voltage using a TRIAC has been shown in Fig. 14.45 (a). From a fixed input ac voltage, a variable ac voltage can be made available across the load. The triac will control the voltage in either direction, and as such, control is achieved on both positive and negative half cycles of the input voltage.

A TRIAC control circuit for the speed control of a single-phase induction motor has been shown in Fig. 14.45. A DIAC has been used to provide the gate voltage for triggering the TRIAC. These days a DIAC–TRIAC combination is available in the market. The input and variable output voltage wave forms have been shown in Fig. 14.45 (b). Let us consider the time when the TRIAC is off and the input voltage has been applied. During the positive half cycle of the input voltage, the capacitor is charged as current will flow through R_1, R_2, and C. When the voltage across the capacitor, VC becomes equal to the sum of the DIAC switching voltage and the gate triggering voltage of the TRIAC, the DIAC, D conducts and passes a gate current to trigger the TRIAC, Q. Now the capacitor will start discharging. The capacitor will continue to discharge until the capacitor current falls below the holding current level of D. The TRIAC will get switched off (commutated) at the end of the positive half cycle of the input voltage. The same process of the capacitor being charged in the negative half cycle of the supply will take place and help make the TRIAC getting switched on through the DIAC supplying gate voltage. The firing angle, a of the TRIAC can be controlled by adjusting the value of the variable resistance R_1. The time constant of the R–C circuit (R_1 + R_2 and C) get altered when R_1 is changed, and hence the rate of charge of C changes.

14.13 OPTOELECTRONIC DEVICES

Photo-electronic devices are made of semiconductor material whose conduction is affected by the amount of light falling on them. They also produce light; their resistance change with light falling on them. Some photo-electronic devices emit light and modify light. For example, Light emitting diodes (LEDs) produce light. Liquid crystal displays (LCDs) modify light. Both LEDs and LCDs are used for electronic display of numerals and alphabets. Light is converted into electricity by solar cells. Resistance of certain material is affected by the amount of light falling on them. They are called light dependent resistors (LDRs). Widely used optoelectronic devices are discussed in this section.

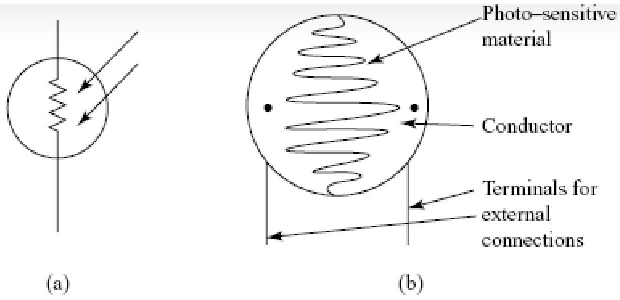


Figure 14.46 (a) Symbol of an LDR; (b) constructional details of an LDR

14.13.1 Light-dependent Resistor

An LDR is a semiconductor device whose resistance varies with the amount of light falling on it. Light energy falling on its surface provides sufficient energy to the valence electrons to break away from their atoms. Thus, these charge carriers, i.e., free electrons and holes make the material more conductive. A material becoming more conductive means its resistance is getting reduced. That is why these resistors are also called photoresistors, i.e., light-dependent resistors.

Cadmium sulfide and cadmium selenide are used in making LDRs. The material in the form of a long strip is arranged in a zigzag form on a base. A glass or plastic cover is provided for protection. The symbol and the constructional arrangement of an LDR have been shown in Fig. 14.46.

The response time of these photo-sensitive material is quite small, of the order of few milliseconds. The variation of resistance with falling light on these materials is quite high. For example, in the absence of light, i.e., in darkness, the resistance could be 100 kΩ, while in bright sunlight while the resistance may change to 10 to 20 kΩ.

The principle of operation of a street light circuit using an LDR has been illustrated in Fig. 14.47. In sunlight, the streat lights should be off. Under dark conditions, the lights should automatically get switched on. A 12 V battery supply is connected to the relay coil which has an LDR resistance connected in series as shown in Fig. 14.47. During night darkness the LDR resistance is very high, and hence a very small amount of current will flow through the relay coil. During night, or during darkness, and even during cloudy days, the lights L_1, L_2, L_3 should be on as they get 230 V supply through the normally closed contact of the relay. Current through the relay coil is very low because the LDR resistance during darkness is very high. The armature (the movable part of the relay) of the relay will stay at the position shown. When during day time light falls on the LDR which may be placed in a convenient position, its resistance will decrease, and hence current through the relay will increase. At a particular value of current, the armature will be attracted and pulled towards the fixed part of the relay against the spring pressure. Then the relay contact, 'a' will open. The lights will not get any supply, and hence will be off. When darkness comes, the LDR resistance will increase, current through the relay will decrease, the

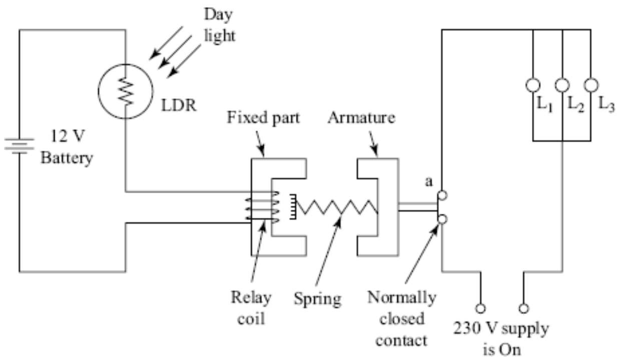


Figure 14.47 Lights controlled by relay-operated LDR circuit

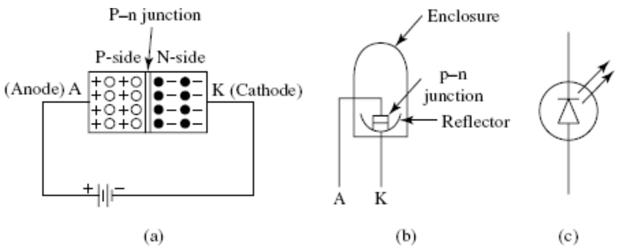


Figure 14.48 (a) LED junction; (b) constructional details of an LED; (c) symbol of LED

A number of such interesting automatic control circuits can be made using LDR, DIAC, TRIAC, and SCRs. Students may refer to any standard book on industrial electronics and control to study such control circuits and try to fabricate some of them as a part of their project work.

14.13.2 Light-emitting Diodes

We have known that when a p–n junction is forward biased, the electrons from the n-side cross over to the p-side to recombine with the holes on the p-side.

The free electrons have higher energy than the holes. When a negatively charged electron from the n-side enters the p-side and recombines with a positively charged hole, some amount of energy is emitted in the form of heat and light. Similarly, a hole from the p-side has a tendency to cross the junction and recombine with an electron on the n-side. Each recombination causes radiation of energy in the form of heat and light. If the semiconductor material is translucent, it will emit light. LEDs are made from special semiconductor materials such as arsenide phosphide or gallium phosphide.

The intensity of light energy emitted from an LED will depend upon the forward voltage applied. The applied voltage is low, of the order circuits, diagrams, photographs, etc. can be arranged with the help of an array of LEDs.

A simple on/off display using an LED is shown in Fig. 14.49. When the supply is on, the LED will get supply and will be forward biased. A resistance R is connected in series to limit the current through the LED. T is a step-down transformer. Thus, the LED will show on/off status of supply.

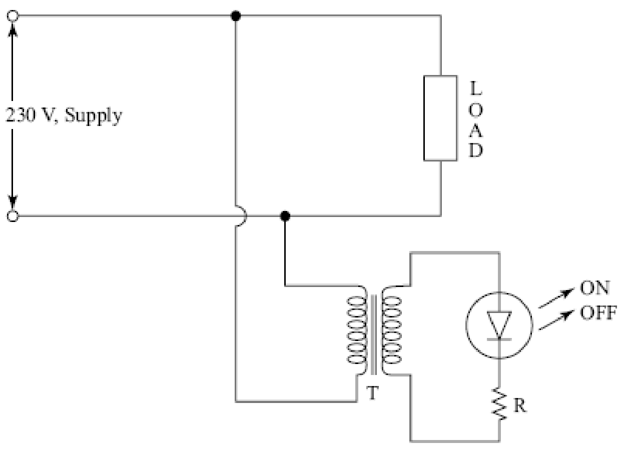


Figure 14.49 An LED used in on/off display of power supply

There are a number of advantages of LEDs to be used in display devices. They are compact, are illuminated very quickly, light intensity in them can be controlled by varying the applied voltage, are available in different colours, are quite simple, and are cheap.

14.13.3 Seven Segment Displays

A seven segment display board using seven LEDs is most widely used in display devices in the field of electronics and instrumentation.

Some LED displays, you might have noticed in control panels, calculators, mobile phones, electronic digital instruments, digital watch, etc. the LEDs are very minute structures. Often plastic light pipes are used to enlarge the lighted area as shown in Fig. 14.50. Display of digits ranging from 1000 to 1999 can be made on the display board by illuminating the segments in a particular order.

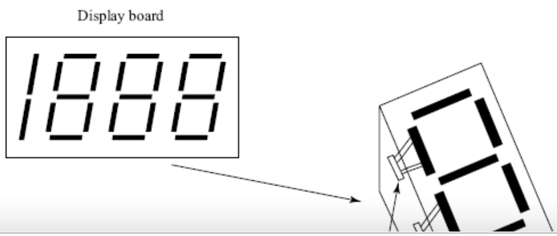


Figure 14.50 Numerical display boards using seven segments illuminated by LEDs

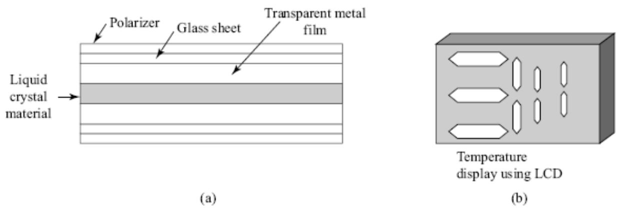


Figure 14.51 (a) Cross-section of a liquid crystal cell; (b) LCD

14.13.4 Liquid Crystal Displays

LCDs use liquid crystal cells which has a very thin liquid crystal material placed between two glass sheets. On the inner side of the glass sheets a transparent metal film is deposited as shown in Fig. 14.51 (a).

On the surface of the two glass sheets, polarizing optical filters are placed. The liquid crystal material twists the light passing through the polarizing filters and the cell looks semi-transparent. When the cell is energized with electrical signal, the liquid crystal molecules orient in a definite crystal pattern and no twisting of liquid occurs and the cell appears dark. Liquid crystal cell can also be made to appear bright when the background is dark. Seven segment displays of numerical numbers, alphabets, and others are often made from liquid crystal displays (LCDs). Due to the orientation of the molecules of the liquid crystal, a digit or an alphabet can be shown bright against a dark background as shown in Fig. 14.51 (b).

14.13.5 Photodiodes

When a p–n junction is reverse biased, only a very small current called the leakage current or saturation current flows. This very small amount of current is due to the thermally generated holes and electrons which defuse across the p–n junction as minority charge carriers (electrons and holes are called charge carriers). If the junction temperature increases, more and more charge carriers are generated and the reverse current is increased. Thus, increase in junction temperature increases the reverse current.

Similarly, when light falls on the p–n junction, due to the incident light energy, electron–hole pairs are generated and the electrons and holes freely move across the junction increasing the reverse current. The magnitude of reverse current will depend on the intensity of light falling on the p–n junction. Thus, by changing the illumination level, current flowing through the device can be varied as shown in Fig. 14.52. Diodes which are designed to be light (i.e., photo) sensitive are called photodiodes. Photodiodes operate under the reverse-biased condition and are designed to be light sensitive. There is minority charge carrier current flow when the p–n junction is illuminated.

The resistance of the device at a different illumination level will be different. A photodiode can work like an LDR when the light falling on its junction is varied. Thus, a photodiode can work as a photo-conductive device like an LDR.

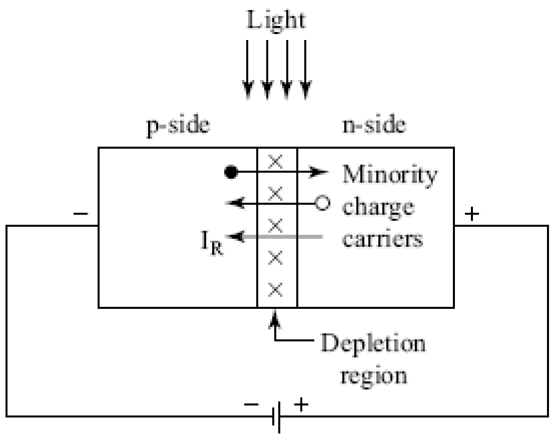


Figure 14.52 Photodiode with reverse-bias (only a very small reverse current flows across the junction due to minority carriers)

14.13.6 Photovoltaic Cells or Solar Cells

A photovoltaic cell or a solar cell is a photodiode with no reverse bias voltage applied across it. Even when the reverse bias voltage across a photodiode is removed, the minority charge carriers continue to cross the junction when light continues to fall on the p–n junction. Reverse current will continue to flow through the circuit with the bias voltage removed but the circuit kept closed as shown in Fig. 14.53 (a) and (b).

Electrons from the p-side (minority charge carriers) will flow to the n-side and return to the p-terminal through the n-terminal of the device. This way the device will work as a voltage source, i.e., a small voltage cell as shown in Fig. 14.53 (c). p-Side is the positive terminal and n-side is the negative terminal as has been shown. Thus, a junction-illuminated photodiode is a photovoltaic cell

A solar cell is essentially a photodiode. A large number of photodiodes are connected in series and parallel fixed on a panel so as to get considerable voltage and current output. This way sun's energy (solar energy) is converted into electrical energy. Much research is being conducted to increase the energy conversion efficiency and to reduce the cost of manufacturing of solar cells and solar panels.

14.13.7 Phototransistors

A phototransistor is similar to a bipolar junction transistor, generally an n–p–n type with a bias voltage applied between the collector and the emitter with the base terminal kept open. No supply is given to the base. The transistor action is achieved by the light energy falling on its base–emitter junction. Thus, instead of base current, light energy provides the input to the base.

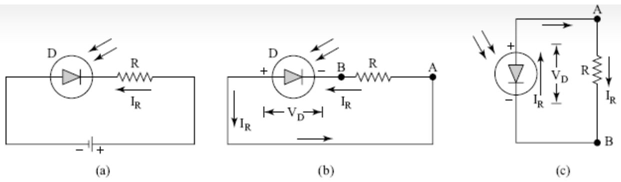


Figure 14.53 (a) Photodiode with reverse bias; (b) an illuminated photodiode without any bias voltage; (c) photovoltaic cell

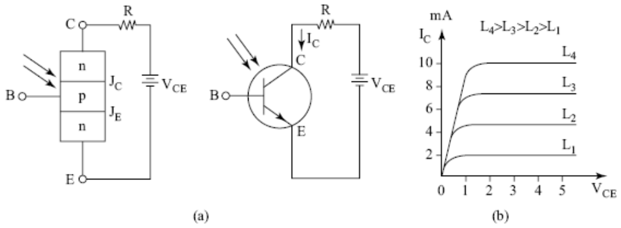


Figure 14.54 (a) Phototransistor working

An n–p–n type BJT with the base terminal open has been shown in Fig. 14.54. The collector base junction, J_C is reverse biased while the base–emitter junction, J_E is forward biased. The collector–base junction is constructed like a photodiode. In the absence of light falling on the junction, only a small amount of reverse saturation current, also called leakage current, will flow through the device. This current of very low value is due to the minority charge carriers flowing at room temperature. When light energy falls on the C–B junction, additional charge carriers are created to add to the reverse saturation current. Thus, light energy increases the base current. The reverse saturation current can be increased by increasing the illumination level of the collector–base junction. This will increase the collector current, I_C. Collector current will increase when the illumination level of the C–B junction is raised. The V–I characteristic is drawn between V_{CE} and I_C at different illumination levels, L_1, L_2, L_3, L_4, etc., as shown in Fig. 14.54 (b). For an equal level of illumination, a phototransistor provides more output current than a photodiode. A biased phototransistor starts working as soon as light falls on the collector–base junction. An amplified current starts flowing through the device, and consequently the output current increases. The main difference between a phototransistor and a photodiode is in the current gain. A phototransistor is packaged in a metal case with a lens filled on the top. Plastic-encapsulated phototransistors are also available. Phototransistors can be used in electronic control circuits like illumination control, emergency lighting system, relays etc.

A simple phototransistor circuit has been shown in Fig. 14.55. An SCR is being triggered with the help of a phototransistor. When the illumination level is high, the phototransistor will allow sufficient current to flow through it and resistance R_1. Resistance R_2 and R_3 are chosen so that when the phototransistor is on, very little current chosen that, voltage across the gate, V_G, will trigger the SCR, and the SCR will start conducting. When the SCR is conducting, current will flow through the load, which could be a lighting load.

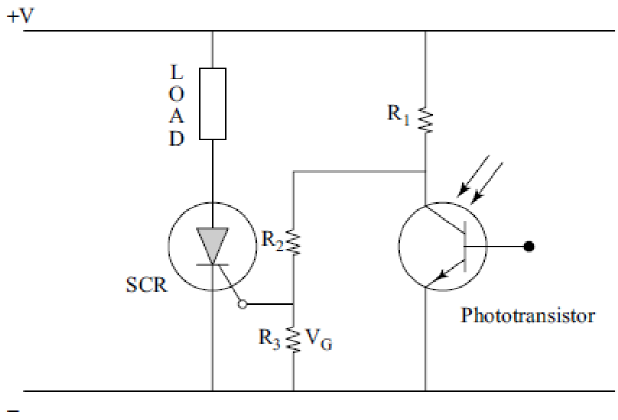


Figure 14.55 A phototransistor trigging an SCR on low illumination level

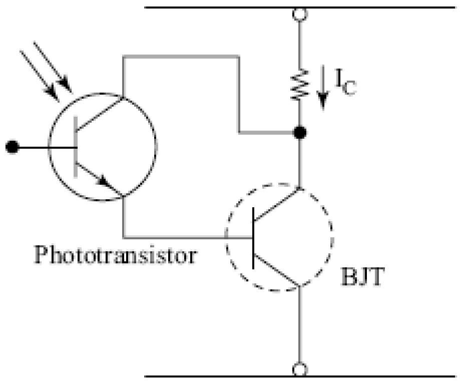


Figure 14.56 Photo-darlington transistor

14.13.8 Photo-darlington

A phototransistor can be connected with another transistor to produce higher output. The arrangement as shown in Fig. 14.56 is called a photo-darlington. Photo-darlington is a phototransistor connected in darlington with another bipolar junction transistor. With this arrangement, the output current obtained will be higher than what could be obtained in a phototransistor or a photodiode. The sensitivity of the device to illumination is high but the switching time is somewhat more here as two transistors are getting involved.

14.13.9 Optocouplers

An optocoupler is a combination of two light-activated devices, viz a phototransistor and an LED. These two are placed together in one

The coupling between the LED and the phototransistor is optical, i.e., through the emitted light. The two circuits are electrically isolated. The voltage level of the two circuits may be made different. Thus, from a low voltage side, control can be made of the high-voltage side. Fig. 14.57 (b) shows an optocoupler contained in a transparent insulating base material. This base material will allow light emitted by the LED to be transmitted to the base of the phototransistor. However, the two, i.e., the LED and the phototransistor are electrically isolated.

An optocoupler can be operated as an electronic switch. A pulse of current through the LED may cause the transistor to be switched on which is otherwise off. An optocoupler can be made as a combination of (i) an LED and a photo-darlington; (ii) a LED and any other device that can be activated by light.

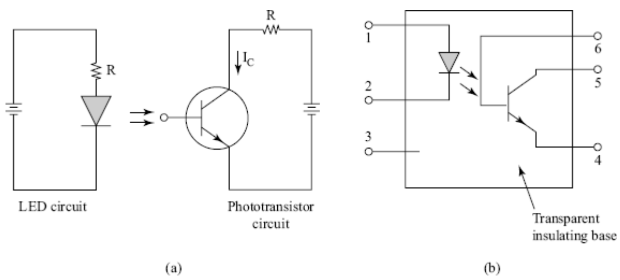


Figure 14.57 (a) Optocoupler circuit, an LED is driving a phototransistor; (b) optocoupler package with terminals

14.14 REVIEW QUESTIONS

A. Short Answer Type Questions

1. Distinguish between an intrinsic and extrinsic semiconductor material. What is a p-type material and an n-type material?
2. Explain how a p–n junction can be used to work as a diode.
3. What is the significance of 'barrier potential' in a p–n junction?
4. A reverse-biased p–n junction has a wide depletion region. Explain.
5. What do you mean by forward biasing and reverse biasing of a p–n junction?
6. Sketch the typical voltage/current characteristics for a forward-biased and reverse-biased p–n junction. Briefly mention the salient points.
7. What is an ideal diode? Draw its characteristic.
8. How is a zener diode different from a conventional diode?
9. Show how a zener diode can be used as a voltage regulator.
10. What are the diode parameters?
11. Show two applications of zener diodes.
12. Explain the operation of a zener diode under forward- and reverse-biased conditions.
13. Explain clearly the difference between acceptor-type and donor-type impurities and state what types of charge

silicon and insert an impurity of arsenic in silicon.

16. What are p-type and n-type semiconductors? Draw and explain the V–I characteristic of a p–n junction diode.
17. Explain for a semiconductor diode the following terms: peak inverse voltage; forward and reverse biasing; potential barrier; depletion layer and reverse saturation current.
18. Explain covalent bonding of semiconductor materials.
19. Distinguish between intrinsic and extrinsic semiconductor. What is doping? Give one example.
20. Show how n-type and p-type semiconductor materials can be formed.
21. Explain the formation of depletion region in a p–n junction. What is barrier voltage?
22. Explain biasing of a p–n junction and draw forward characteristic of the p–n junction.
23. Draw the reverse V–I characteristic of a p–n junction. What is reverse saturation current?
24. Draw and explain the complete volt-ampere characteristic of a p–n junction diode. What is an ideal diode?
25. Mention the specification parameters of a diode.
26. What is a zener diode? How is it different from a p–n junction diode?
27. Explain the construction and working principle of a bipolar junction transistor.
28. Explain the working principle of an n–p–n transistor.
29. Explain the working principle of a p–n–p transistor.
30. Show the three types of transistor configurations.
31. Draw and explain the common–emitter transistor characteristics.
32. Explain with the help of a circuit the working of a transistor as an amplifier.
33. Show how a transistor can be used as a static switch.
34. What is a field effect transistor? How is an FET different from a BJT?
35. Explain the construction and working of a junction field effect transistor.
36. Draw and explain the characteristic of a JFET.
37. What do you mean by transfer characteristic of a JFET?
38. Draw and explain a single voltage amplification circuit using a field effect transistor.
39. Explain the constructional details and the working principle of a MOSFET.
40. Draw and explain a MOSFET switching circuit.
41. Explain the working principle of a silicon control rectifier.
42. Draw the forward and reverse characteristics of an SCR.
43. Explain the operation of an SCR with gate control.
44. Show two transistor analogy of an SCR.
45. Draw and explain a single-phase half-wave-controlled rectifier.
46. Draw and explain a single-phase full-wave- controlled bridge rectifier.
47. Draw and explain a static switching circuit using two diodes and two SCRs.
48. What is a DIAC? Draw its V–I characteristics.
49. Explain how a TRIAC is different than a DIAC.
50. Explain the construction and V–I characteristic of a TRIAC.
51. Draw and explain a phase control circuit using a Triac.

55. Write a brief explanation of the following devices: (i) seven segment displays; (ii) light emitting diodes; (iii) light-dependent resistor, and (iv) liquid crystal displays.
56. What is a photovoltaic cell. How is a solar battery constructed?
57. Explain the difference between a phototransistor and a BJT. Explain its working.
58. Give one practical application of a phototransistor.
59. Write short explanations of the following:

    (i) phototransistor; (ii) photo-darlington; (iii) optocoupler, and (iv) solar cell.

60. Explain the formation of the depletion region in an unbiased p–n junction.
61. What are the barrier potentials of silicon diodes and germanium diodes?
62. Explain how a depletion-type MOSFET can work either in an enhancement mode or in a depletion mode.
63. Name two major differences between a JFET and a MOSFET.

B. Multiple Choice Questions

1. Which of the following is a semiconductor material?
    1. Ceramic
    2. Silicon
    3. Cadmium
    4. Rhodium.
2. Which of the following statements is correct?
    1. Germanium valence electrons will need a smaller amount of additional energy to escape from the atom than silicon valence electrons
    2. Valence electrons of silicon are in the fourth shell while those of germanium are in the third shell
    3. Silicon is more widely used semiconductor material than germanium
    4. Germanium produces less number of electron hole pairs than silicon.
3. Which of the following is not shown in the energy band diagram?
    1. Permeable energy band
    2. Conduction band
    3. Valence band
    4. Forbidden gap.
4. Which of the following statements is not true?
    1. Semiconductors have negative temperature coefficient of resistance
    2. Insulators have positive temperature coefficient of resistance
    3. Insulators have negative temperature coefficient of resistance
    4. Conductors have positive temperature coefficient of resistance.
5. Which of the following statements is not true?
    1. In both silicon and germanium atoms there are four valence electrons
    2. Intrinsic semiconductors behave like conductors at low temperatures

6. Which of the following statements is not true?
    1. An *n*-type material is formed by adding a small amount of pentavalent impurity to the pure silicon
    2. Examples of pentavalent materials are antimony, arsenic, and phosphorous
    3. An *n*-type material, inspite of the presence of a large number of free electrons is still electrically neutral
    4. In an *n*-type material holes are the majority carriers and electrons are the minority carriers.
7. The width of the depletion layer of a *p*–*n* junction will increase when
    1. the *p*–*n* junction is forward biased
    2. the *p*–*n* junction is reverse biased
    3. the *p*–*n* junction is forward biased with a voltage which is higher than the normal rating
    4. the *p*–*n* junction is kept unbiased for a long time.
8. In the reverse-biased state of a diode current flowing, which is called reverse saturation current is due to
    1. majority carriers
    2. minority carriers
    3. increase in reverse voltage applied externally
    4. both majority and minority carriers.
9. Silicon diode is more popular than germanium diode because
    1. reverse saturation current of silicon is higher than that of germanium
    2. reverse saturation current of silicon is much lower than that of germanium
    3. temperature effect on reverse saturation current of silicon diode is very high
    4. break down voltage of germanium is higher than that of silicon.
10. Which of the following statements is not true for a zener diode?
    1. A forward-biased zener diode behaves identical to a forward-biased diode
    2. Zener diode under the reverse-biased condition is used as a voltage regulator
    3. Zener diode under the forward-biased condition is used as a voltage regulator
    4. The operation of a reverse-biased zener diode is different than that of a reverse-biased diode.
11. Which of the following statements is not true about the rectified sinusoidal wave?
    1. The ripple factor of a full-wave rectifier is 0.48
    2. The ripple factor of a half-wave rectifier is 1.21
    3. The ripple factor of an ideal rectified wave should be zero
    4. The ripple factor of an ideal rectified wave should be unity.
12. Which of the following is not true for a bridge rectifier?
    1. A centre-tapped input side transformer is required
    2. Bridge rectifiers offer full-wave rectification
    3. At a given time only one pair of diodes are conducting
    4. Ripple factor of a bridge rectifier is 0.48.
13. Conduction in a bipolar transistor takes place due to

14. Which one of the following is not a region of operation of a transistor?
    1. Cut-off region
    2. Active region
    3. Saturation region
    4. Cut-in region.
15. Which one of the following is not the configuration of a transistor?
    1. Common–collector configuration
    2. Common–emitter configuration
    3. Common–base configuration
    4. Maximum current gain configuration.
16. Transistor can be used as an amplifier when it is operated
    1. in the saturation region
    2. in the cut-off region
    3. in the active region
    4. in both saturation and cut-off regions.
17. Which of the following is not true for a properly biased transistor?
    1. Can work as a current amplifier
    2. Can work as a voltage amplifier
    3. Can work as a switch
    4. Can work as a rectifier.
18. MOSFET stands for
    1. metal oxide silicon field effect transistor
    2. metal oxide semiconductor field excited transistor
    3. metal oxide semiconductor field effect transistor
    4. metal oxide silicon field excited transistor.
19. Which of the following does not belong to the thyristor family?
    1. DIAC
    2. TRIAC
    3. SCR
    4. SCS.
20. We turn off a conducting SCR by
    1. reducing the anode current below the holding current
    2. decreasing the voltage applied across the SCR
    3. removing the gate terminal connection
    4. applying a negative gate voltage.
21. Which of the following is not an opto-electronic device?
    1. Light-emitting diode
    2. Liquid crystal display
    3. Photovoltaic cell
    4. Silicon-controlled rectifier.

Answers to Multiple Choice Questions

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

14. (d)
15. (d)
16. (c)
17. (d)
18. (c)
19. (a)
20. (a)
21. (d)