O. N. Pandey

Electronics Engineering

Second Edition

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JSS Academy of Technical Education
Noida, India

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Dedicated to my Parents
Smt. Kalavati Devi
and
Shri. Deo Murti Pandey
Who have given so much to me

Preface to Second Edition

I am very thankful to the students and faculty members who have made it one of the most popular books. There has been a need to add one more chapter on Personal Simulation Program with Integrated Circuit Emphasis (PSPICE); therefore, one chapter on PSPICE has been included in this edition. PSPICE is quite vast topic as such it is treated in its basic and simplified manner. Needless to say that all the errors found and reported have been corrected. Six more latest university question papers have been added for the benefit of the students.

I appreciate and thank the students and faculty members for giving their encouraging feedbacks. I am also thankful to Dr. T. N. Nagabhushan, Principal of JSS Academy of Technical Education, Noida, for all the encouragements given during the second edition period.

Noida, India Dr. O. N. Pandey

Preface to First Edition

Development in Electronics Engineering are taking place today at an awesome place. Therefore, it has become essential to understand the fundamentals of Electronics. This book presents fundamentals of electronics.

The book has been written after going through a large number of references. The objective has been to present the matter in simple, straight forward and easy form without losing any important information and detail. Appendices have been added to cover electronic symbols, abbreviations, diagrammatic symbols, various parameter units, conversion factors, periodic table of elements, conduction properties round copper conductor data, standard resistors and capacitors, electronic formulae, equivalent circuits and characteristics. Glossary of electronic terms has been added for quick understanding of electronic terms. Two examination papers with solutions have also been added.

I am very thankful to Dr. Narendra Kumar and Prof. Dinesh Chandra of JSS Academy of Technical Education, Noida for encouragement leading to such technical contribution.

I appreciate the cooperation and help extended by my wife Mrs. Ranjana Pandey, Son Nishith Pandey, relatives and friends. I also appreciate the efforts and help extended by Mrs. Shilpi Gadi, Mrs. Amita Rana, Ms. Paro Bajpai, Mr. Rahul Gupta and others.

Noida, India — Dr. O. N. Pandey

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About the Author

O. N. Pandey was a Professor and Head of the instrumentation and control engineering department at the JSS Academy of Technical Education, Noida. He retired in the year 2017. He obtained his B.Tech., M.E. and Ph.D. degrees from IIT Kanpur and the University of Roorkee (presently known as IIT Roorkee. Dr. Pandey received a UNIDO fellowship and specialization in the field of instrumentation, control, and industrial automation in the USA. He presented several technical papers and also participated in various national and international conferences. Dr. Pandey served as a senior technical officer in CMTI-Bangalore for 12 years. He has been responsible for the development of technologies related to the automation of manufacturing industries.

Chapter 1
Basics of Electronics

1.1 Introduction

Electron mechanics is known as electronics. Electronics puts electrons to work using the science and technology of the electron motion. The advancement of electronics has been very fast. Electronics has given tremendous growth in computer science, communication, control, instrumentation, information technology. Although electronic devices such as computer, cellular phone or television are well-known, but inside of these devices are a mystery. Electronics engineering is the knowledge related with functioning of electronic devices.

Development of electronics started with vacuum diode in 1897 and vacuum triode in 1906. Semiconductor electronics started with the invention of transistor in 1948 and this replaced tube-based electronics. The electronic components developed are diode, transistor, field effect transistor (FET).

Integrated circuits (ICs) were developed in 1958. ICs are basically an entire electronic circuit on a single semiconductor chip. A single chip has all active and passive components and their interconnections integrated during manufacturing process. ICs drastically reduced the size, weight and cost of the electronic devices.

The design and fabrication of high density ICs is known as microelectronics. The small-scale integration (SSI) have components less than 100, medium-scale integration (MSI) have 100 to 1000 components, large-scale integration have 1000 to 10,000 components and very large-scale integration (VLSI) have more than 10,000 components. New IC concepts resulted in new computer architecture which is based on speed, power consumption and component density. Thus, digital integrated circuits came into existence leading to transistor–transistor logic (TTL), emitter-coupled logic ECL, *etc*. The latest electronic component fabrication uses complementary metal–oxide semiconductor (CMOS) technology.

The memories based on electronics are random access memories (RAMs) which are capable of both storing and retrieving data. RAMs store about 100 bits of information. 1600-bit, 64,000-bit and 288,000-bit RAMs have been developed

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using metal–oxide semiconductor (MOS) technology. More than a billion-bit RAM chips are available now. Further, read-only memories (ROMs), programmable ROMs (PROMs), erasable PROMs (EPROMs) are also available. Microprocessor (MP) development led to the "computer on a chip." Other developments due to MOS technology are charge-coupled device (CCD) which are being used in camera manufacturing, image processing and communication. Analog integrated circuits developed are operational amplifier (op-amp), digital-to-analog (D/A), analog-to-digital (A/D) converters, analog multiplexer and active filters.

Electronics engineering developments are taking place today at an awesome pace; therefore, it has become essential to understand the fundamentals of electronics.

1.2 Electronic Charge and Current

The smallest particle of any material is a molecule and subdivision of molecules are atoms. An atom consists of electrons, protons and neutrons. Electrons have negative charge, protons have positive charge and neutrons have no charge at all. An atom is electrically neutral, as the number of its electrons is equal to number of protons. Bonding together has some loosely bound electrons, *i.e.*, free electrons, silver, copper, aluminum and zinc materials have free electrons; therefore, it is easy to make them move. Such materials are known as **conductors**. There are materials like glass, mica and porcelain which have closely bound atoms and movement of electrons from atoms is very difficult. Such materials are non-metallic and are known as **insulators**.

An **electric current** is the movement of electrons along a definite path in a conductor. It is defined as:

Current, $i(t) = \frac{dq}{dt}$

where $i(t)$ = instantaneous current in amperes.

q = electric charge in coulombs.

t = time in seconds.

1.3 Electronic Circuit Components

Electronic circuit components are of two types: active and passive. Active **components** are semiconductor devices such as diodes, transistors, SCRs and FETs. **e components** are resistors, inductors and capacitors. The active components shall be discussed in subsequent chapters, but passive components need to be discussed here itself.

1.3.1 Resistors

Resistance is a property of a conductor which opposes the flow of an electric current, and it is denoted by R.

$$R = \rho \frac{l}{a} \text{ ohm or } \Omega$$

where l = length of the conductor in meter.
a = area of cross section in meter^2
r = specific resistance or resistivity of the material in ohm-meter.

Conductance, $G = \frac{1}{R}$ mho or Ω.

Most common resistors are molded-carbon composition type. These are available in wattage ratings $\frac{1}{4}W, \frac{1}{2}W$ and 1 W with values from few ohms to 22 MΩ. It has 5–20% tolerance. There are some resistors which are known as metal film resistors which have accuracy of ±1%. These are also known as precision type. All these resistors are of very small size wherein printing of the ratings not feasible. Hence, color coding done is as per Fig. 1.1.

The color codes are given in three bands with fourth band for tolerance. The color coding is given in Table 1.1.

The above color coding can be memorized as follows: all capital letters stand for colors.

B B ROY went to Great Britain and brought a Very Good Wife.

Suppose first, second, third and fourth colors are yellow, violet, orange and silver, respectively. What is the resistance value? The resistance value is given by:

Resistance value,

$$R = 47 \times 10^3\ \Omega \pm 10\%$$

or

$$R = 4.7\ \text{k}\Omega \pm 10\%$$

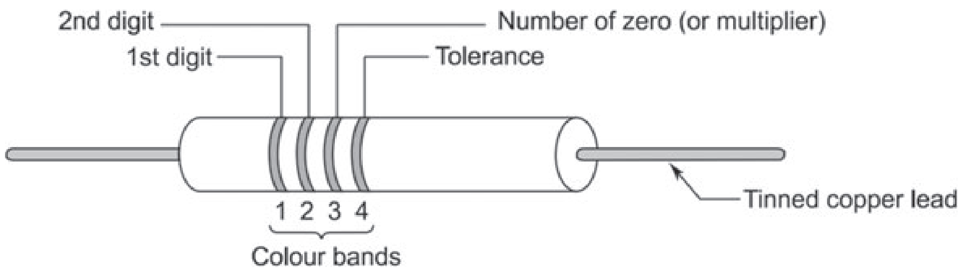


Fig. 1.1 Color coding for resistor values

Table 1.1 Color coding of resistors

S. No.	Color	Digit	Multiplier	Tolerance	S. No.	Color	Digit	Multiplier	Tolerance
01	Black	0	10^0	–	8	Violet	7	10^7	–
1	Brown	1	10^1	–	9	Gray	8	10^8	–
2	Red	2	10^2	–	10	White	9	10^9	–
3	Orange	3	10^3	–	11	Cold	–	–	±5%
4	Yellow	4	10^4	–	12	Silver	–	–	±10%
5	Green	5	10^5	–	13	No-color	–	–	205%
6	Blue	6	10^6	–					

The above were fixed resistors, but there are variable resistors in the form of Rheostats and Potentiometers. The resistors discussed so far have positive temperature coefficients, i.e., resistance value increases if the surrounding temperature increases. But, there are resistors which have negative temperature coefficients, i.e., resistance value decreases if the surrounding temperature increases. Such type of resistors are known as thermistors. These are made of semiconductor such as germanium (Ge) or silicon (Si). Other resistor types are light-dependent resistor (LDR) and voltage-dependent resistor (VDR). LDR resistance value depends on the intensity of light falling on it; therefore, it is also known as photoresistive cell or photoresistor. LDR is made of cadmium sulfide (CDS) or cadmium selenide (CdSe). VDR is based on junction field effect transistor (JFET) which has three terminals, namely drain (D), source (S) and gate (G). The resistance between drain and source terminals is dependent on the gate voltage.

1.3.2 Inductors

Inductors store energy in the form of magnetic field. It has a winding of a conducting wire over a core which can be made of iron or just air itself. The current flowing through the coil establishes a magnetic field through the core. Inductor field reacts so as to oppose any change in current. The unit of inheritance is henry (H).

There are various types of inductors based on usage such as filter chokes which smoothens pulsating current produced by a rectifier. Audio-frequency chokes provide high impedance audio frequencies, *i.e.*, between 60 Hz to 5 KHz. Variable inductors are used in turning circuits for radio frequencies.

1.3.3 Capacitors

A **capacitor** stores energy in the form of electric field. A capacitor consists of two conducting plates separated by an insulating material called **dielectric**. Capacitors can be of fixed value or variable value. The unit of capacitance is Farad (*F*). A capacitor opposes any change in the potential difference or voltage applied across its terminals.

There are mica capacitors which can be used up to 500 V and are available in the range from 5 to 10,000 pF. There are ceramic capacitors which can be used in the range of 3–6000 V. The capacitance value ranges from 3 pF to 3 μF.

Such capacitors can be used in ac as well as dc circuits. Another type in paper capacitor which can be used from 100 V to several thousand volts. The capacitance values range from 0.0005 μF to several mF. Such capacitors can be used for both ac and dc circuits. Electrolytic capacitors are also available which can be used from 1 V to 500 V or more. The values may range from 1 μF to several thousand μF.

These are marked with positive and negative terminals as such used mostly for dc circuits. Variable capacitors are also available wherein dielectric is air-gap and its variation leads to variation in the capacitance value.

1.4 Voltage and Current Relationships

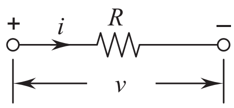
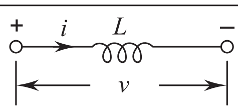
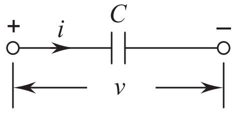
The relationships between potential difference across passive elements and the current through them are given here in Table 1.2

Resistor dissipates energy in the form of heat, inductor stores energy in the form of magnetic field and capacitor stores energy in the form of electric field. The voltage and current in the case of resistors are in phase, whereas in the case of inductors, current lags voltage, and in the case of capacitors, current leads the voltage.

Heat produced by resistors, $H = I^2Rt$ Joules

where I = rms value of current in amperes (A)

Table 1.2 Relationships between voltages and currents

S. No.	*Passive Element*	*Relationship*	*Symbolic Circuits*
1.	Resistor (R)	$v = iR$	
2.	Inductor	$v = L\dfrac{di}{dt}$	
3.	Capacitor	$i = C\dfrac{dv}{dt}$	

R = resistance in ohms (Ω)
t = time in seconds (s)
Energy stored in Inductor, $E = \frac{1}{2} LI^2$ Joules
where L = inductance in Farads (F)
Energy stored in capacitor, $E = \frac{1}{2} CV^2$Joules
where V = voltage across the capacitor in volts (V).
C = capacitance in Farads (F). Conversion of Joule and Calorie:

$$1 \text{ calorie} = 4.18 \text{ J}.$$

1.5 Work, Power and Energy

$\text{Workdone} = \text{Force} \times \text{distance}$
$W = F \times d$ J.
where$W$ = work done in Joules (J)
F = force applied in Newtons (N)
d = distance moved in meters (M)

$$\text{Power} = \text{Rate of work done in Joules/second or watts (W)}.$$

or

$$P = \frac{\mathrm{d}W}{\mathrm{d}t}$$

$$W = VQ \text{ Joules}$$

where
V = voltage in volts (V)
Q = electric charge in columbs (C)

$$\text{Power} = \frac{\text{Energy}}{\text{time}} = \frac{W}{t} = \frac{VQ}{t} \text{ watts}$$

Current, $I = \frac{Q}{t}$ Amperes.

$\therefore$ Power, $P = VI = I^2R = \frac{V^2}{R}$ watts.
Important conversions are:
1 hp (British) = 746 watts
1 hp (Metric) = 735.5 watts

Kinetic energy $= \frac{1}{2} mv^2$

where m = mass of the material

$$v = \text{velocity of the mass}$$

$$\text{Gravitational potential energy} = mgh$$

where m = mass of the material
g = gravitational acceleration, i.e., 9.81 m/s^2
h = height by which mass is lifted.

$$\text{Electric - energy} = \text{power} \times \text{time}$$

or

$$W = VIt = I^2Rt = \frac{V^2}{R}t$$

Electrical energy conversions are:

$$1 \text{ unit} = 1 \text{ kWh} = \frac{\text{Watts} \times \text{hour}}{1000}$$

$$1 \text{ kWh} = 3.6 \times 10^6 \text{ J} = 3.6 \text{ MJ}.$$

1.6 Si Units

The **SI units** are as per international system of units which are commonly used. The basic SI units are given in Table 1.3.

Temperature in Kelvin $= 273 +$ temperature $^\circ$C and the unit change in both units are 1 K and 1 °C respectively.

Complete revolution $= 2\pi$ radians or 360°
$\therefore 2\pi$ radians $= 360^\circ$.
The various prefixes used in units are given in Table 1.4.
Some derived SI units are given in Table 1.5.

Table 1.3 Basic SI units

S. No	Parameter	SI unit	Symbol
1.	Length	meter	m
2.	Mass	kilogram	kg
3.	Time	second	s
4.	Electric current	ampere	A
5.	Absolute temperature	kelvin	K
6.	Luminous intensity	Candela	Cd
7.	Amount of substance	mole	mol.

Table 1.4 Prefixes used in units

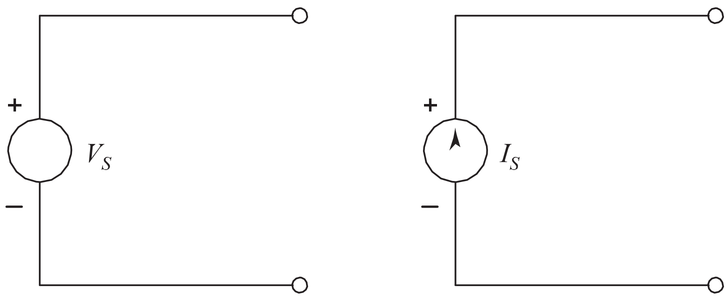
S. No	Prefix	Multiplication factor	Symbol
1.	pico	10^{-12}	*p*
2.	nano	10^{-9}	*n*
3.	micro	10^{-6}	m
4.	milli	10^{-3}	*m*
5.	kilo	10^{3}	*k*
6.	mega	10^{6}	*M*
7.	giga	10^{9}	*G*
8.	tera	10^{12}	*T*

Table 1.5 Derived SI units

S. No	Parameter	S.I. Unit	Symbol
1.	Area	square meter	m^2
2.	Volume	cubic meter	m^3
3.	Linear velocity	meter per second	m/s
4.	Angular velocity	radian per second	rad/s
5.	Linear acceleration	meter/second square	m/s^2
6.	Angular acceleration	radian/second square	rad/s^2
7.	Force	kilogram meter per second square or Newton	kg m/s^2 or N
8.	Weight = mass × gravitational acceleration $g = 9.81$ m/s^2	kilogram force or 9.81 Newtons	kgf or 9.81 N

1.7 Voltage and Current Sources

Voltage sources are power supplies such as batteries, alternators and dynamos. Metadyne generators, photoelectric cells, collector circuits of transistors are **current sources**. All these are known as independent voltage and current sources, respectively. The **ideal voltage and current sources** are shown in Fig. 1.2. Ideal



(*a*) Ideal voltage source (*b*) Ideal current source

Fig. 1.2 Ideal voltage and current source

Fig. 1.3 Realistic voltage and current source

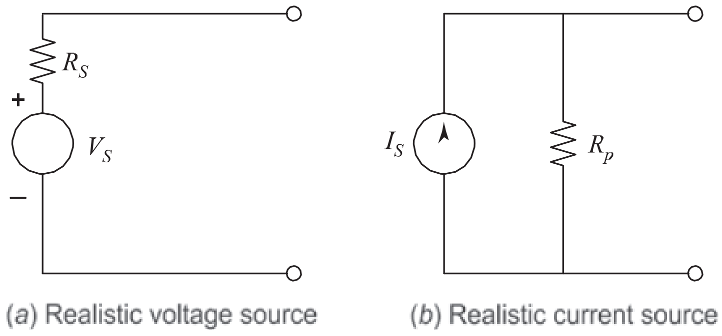
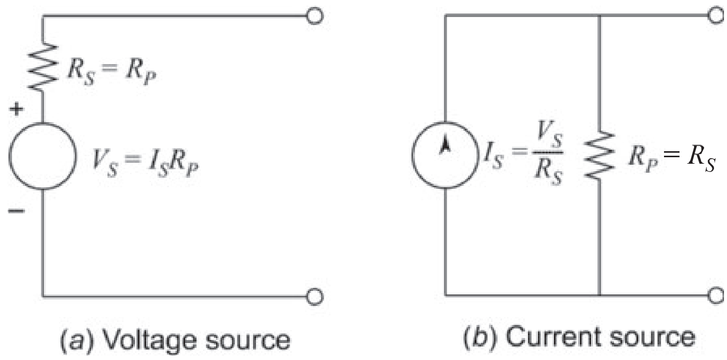


Fig. 1.4 Conversion between voltage and current source



voltage source has zero internal resistance in series, whereas ideal current source has infinite resistance in parallel with the current source.

The realistic voltage source has an internal resistance in series, and realistic current source has a resistance in parallel as shown in Fig. 1.3.

Conversion of voltage source to current source is shown in Fig. 1.4. It can be observed that:

When voltage source is converted into current source, then current source values are:

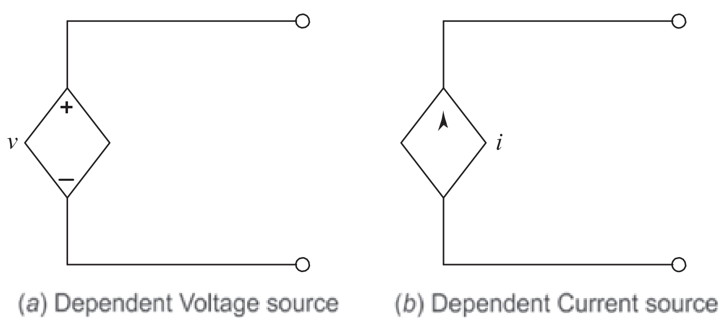
$$I_S = \frac{V_S}{R_s} \text{ and } R_P = R_\xi$$

when current source is converted into voltage source, then voltage source values are:

$$V_s = I_S R_p \text{ and } R_S = R_P$$

when voltage or current source values are dependent on voltage or current values of a branch, then the voltage or current source are known as dependent voltage and current source as shown in Fig. 1.5.

Fig. 1.5 Dependent voltage and current source



1.8 Semiconductor Materials

A material is made up of one or more elements and an element is a substance composed entirely of atoms. The atoms of different elements differ in their structures; therefore, different elements have different characteristics.

An atom is comprised of a relatively massive core or nucleus carrying a positive charge, around which electrons move in orbits at distances which are great compared with the size of the nucleus. The electron mass is 9.11×10^{-31} kg and electron charge is -1.602×10^{-19} Coulomb = $-e$. The nucleus of every atom except that of hydrogen consists of protons and neutrons. Each proton carries a positive charge, e equal in magnitude to that of an electron and its mass is

1.673×10^{-27} kg i.e., 1836 times that of electron. A neutron has no charge and its mass is almost same as that of a proton.

Hydrogen atom has the simplest structure as shown in Fig. 1.6. It consists of only a nucleus of one proton and one electron which revolves in an orbit, of 10^{-10} m diameter around proton. Atomic number of hydrogen is 1. Fig. 1.7 shows atomic structure of silicon (Si). Silicon's atomic number is 14. The electrons are arranged in orbits or shells. First orbit can have maximum of two electrons. The second orbit can have maximum of eight electrons. The third orbit can have maximum of eighteen electrons. The fourth orbit can have maximum thirty-two electrons. The uppermost orbit in an atom cannot have more than eight electrons.

The number of electrons present in the uppermost orbit is known as **valence electrons**. Silicon has four valence electrons. Fig. 1.8 shows a germanium (Ge) atom structure which has four valence electrons.

Atoms that have four valence electrons are known as tetravalent, and those with three are known as trivalent. Atoms with five valence electrons are known as pentavalent. The term valance indicates that the ionization potential required to remove any one of these electrons from atomic structure is significantly lower than that required for any other electron in the structure.

Energy Levels

Within the atomic structure of each and every isolated atom, there are specific **energy levels** associated with each shell and orbiting electron as shown in Fig. 1.9. The farther an electron is from the nucleus, the higher is the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure. Fig. 1.9a shows that in an isolated atom discrete energy levels

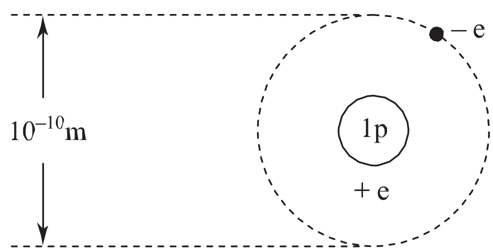


Fig. 1.6 Hydrogen atom

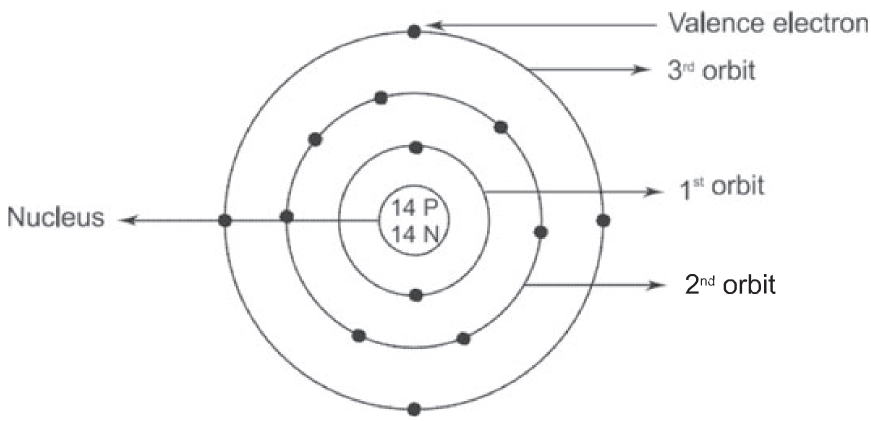
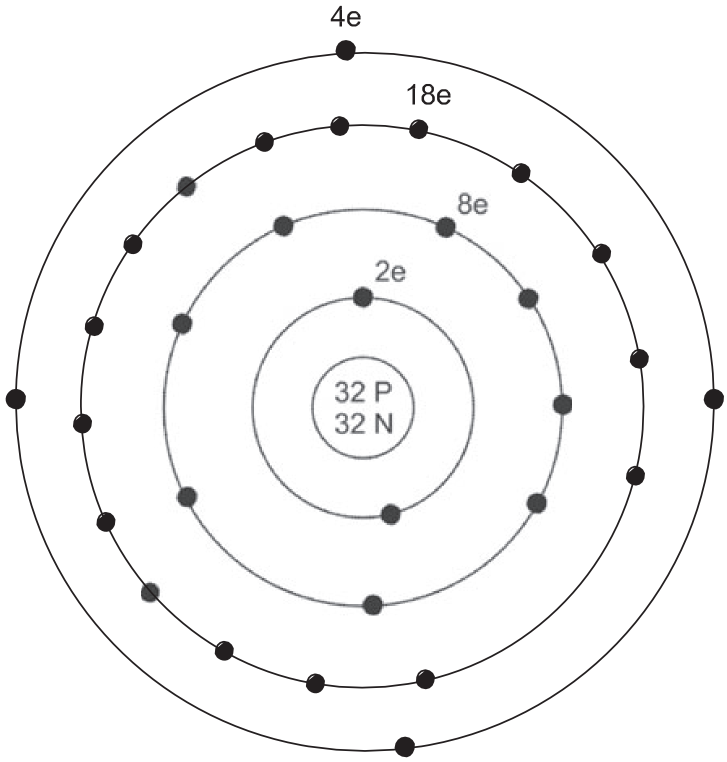


Fig. 1.7 Silicon atom

Fig. 1.8 Germanium atom



can exist. Fig. 1.9b shows a conductor wherein energy levels overlap, hence, electrons are free to move. Fig. 1.9c shows an insulator wherein the electrons require very high energy to bring them to conduction level. Fig. 1.9d shows insulators wherein a minimum energy level is associated with electrons in the conduction band and a maximum energy level of electrons bound to the valence shell of the atom. Between the two is an energy that the electron in valence band must overcome to become free carrier. This energy gap is different for Ge, Si and GaAs. Ge has the smallest gap and GaAs the largest gap. In short, an electron in the valence band of silicon must absorb more energy than one in the valence band of germanium to become a free carrier. Similarly, an electron in the valence band of

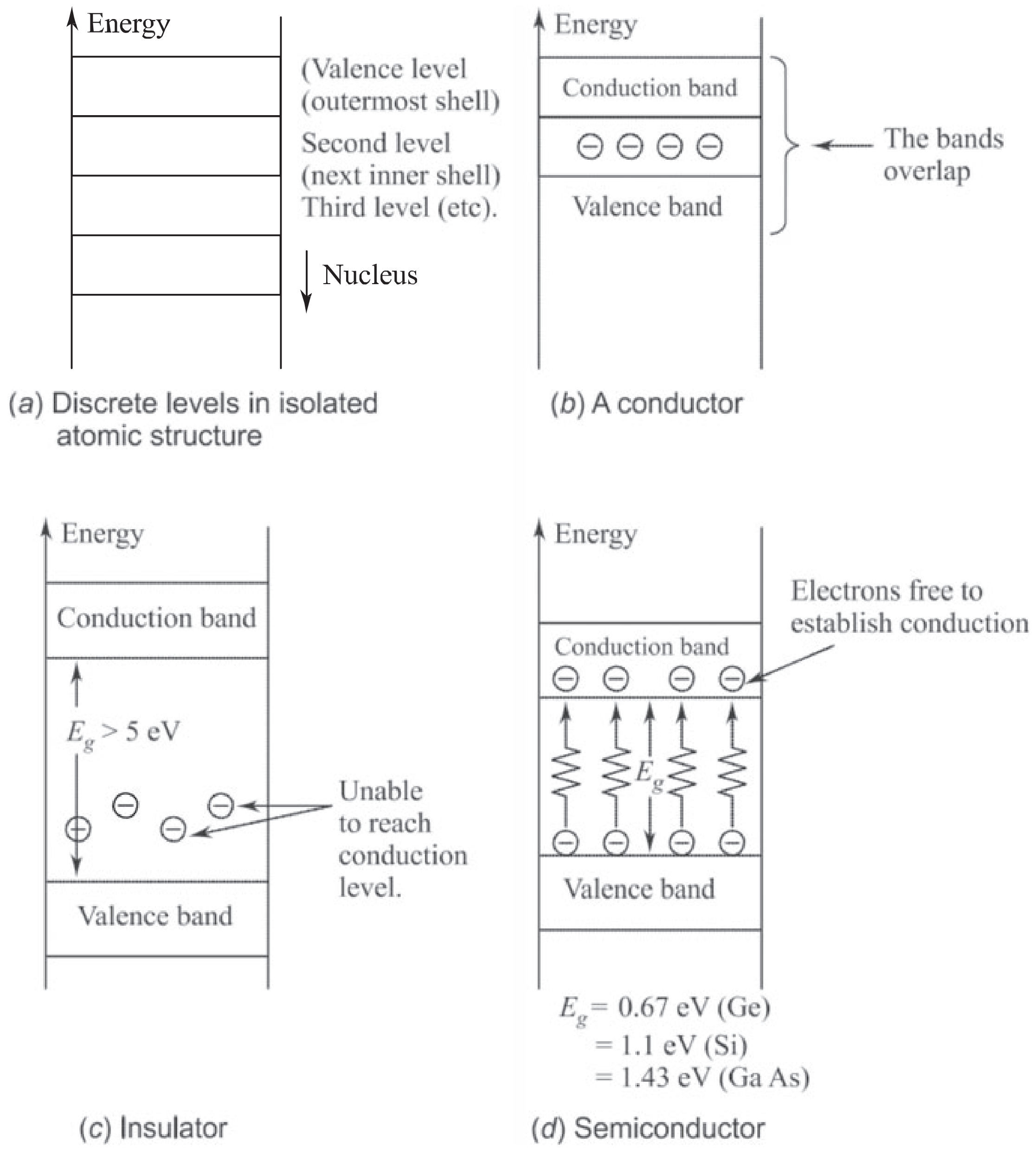


Fig. 1.9 Energy levels

gallium arsenide must gain more energy than one in silicon or germanium to enter the conduction band.

Thus, we can see that semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator. A semiconductor is an element with a valence of four, i.e., an isolated atom of the material has four electrons in its outer or valance orbit. The number of electrons in the valence orbit is the key to electrical conductivity. Conductors have one valence electron and insulators have eight valence electrons. The valance electrons get themselves detached from the nucleus on the application of small electric field. These free electrons constituting the flow of current are called conduction electrons.

There are two types of semiconductors. One is pure type, known as intrinsic type and other is impure type, known as extrinsic type. The conductivity of intrinsic semiconductor is poor at room temperature. Therefore, it is not used in electronic devices. Intrinsic semiconductors properties can be varied by adding impurities, and their conduction properly can be varied by varying temperature.

1.8.1 Intrinsic Semiconductors

In **intrinsic semiconductors** even at room temperature, some of the valance electrons may acquire enough energy to cross over to conduction band from valence band, thereby becoming free electrons. As the electrons leave the valance band, it creates a vacant space in it. This is known as **"hole**." Thermal energy produces free electrons and holes in pairs. In Fig. 1.10, a dc voltage is applied which will force the free electrons to move left and the holes to flow right. When the free electrons arrive at left end of the semiconductor crystal, they enter the external wire and flow to the positive battery terminal. On the other hand, the free electrons at the negative battery terminal will flow to the right end of the crystal. At this point, they enter the crystal and recombine with holes that arrive at the right end of the crystal. In this way, a steady flow of free electrons and holes occur inside the semiconductor. The current in a semiconductor is the combined effect of the flow of free electrons in one direction and the flow of holes in the other direction. Free electrons and holes are called carriers as they carry a charge from one place to another.

1.8.2 Extrinsic Semiconductors

Extrinsic semiconductors are created by a process of adding impurities deliberately to an intrinsic semiconductor. The process is known as doping. The added impurity is known as doping agent. When doped with a trivalent impurity, the impurity accepts one electron to achieve stable state. This type of doping agent is

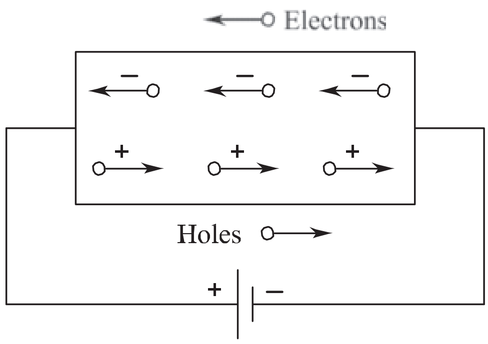


Fig. 1.10 Intrinsic semiconductors

known as an **acceptor**. When doped with a pentavalent impurity, the impurity donates one electron to the conduction band. This type of doping agent is known as **donor**.

There are three semiconductors most frequently used in the construction of electronic devices namely Si (silicon), Ge (germanium) and GaAs (gallium arsenide) Si and Ge are single crystals, whereas GaAs is a compound crystal. Initially, Ge was easily available and refinement, i.e., process of purity was easy. Therefore, Ge was used for first few decades. However, it was found that Ge was very sensitive to changes in temperature. In 1954, the trial of Se was done which was less sensitive to temperature and available in abundance. Therefore, Si became most popular choice. When speed of operation and communication on computers became the basic requirement, GaAs became very handy in 1970s. Thus, GaAs is used as the basic material for new high-speed and very large-scale integrated circuits (VLSI).

1.8.2.1 N-type Semiconductor

A pentavalent (phosphorous) impurity addition to an intrinsic semiconductor (silicon) gives *N*-type semiconductor. Phosphorus has five valance electrons and silicon has four valance therefore; in this case, one free electron is available as shown in Fig. 1.11.

Thus, every phosphorus atom contributes one free electron without creating a hole. Consequently, number of free electrons becomes far greater than the number of holes. Such extrinsic semiconductor is known as *N*-type semiconductor.

1.8.2.2 P-type of Semiconductor

A trivalent (boron, aluminum, etc.) impurity addition to an intrinsic semiconductor (silicon), gives *P*-type semiconductor.

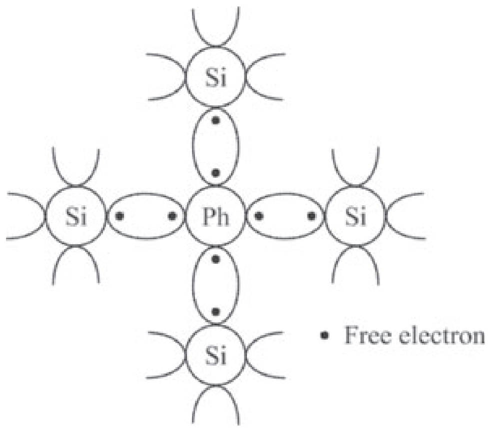


Fig. 1.11 N-type semiconductor, i.e., one free electron without a hole

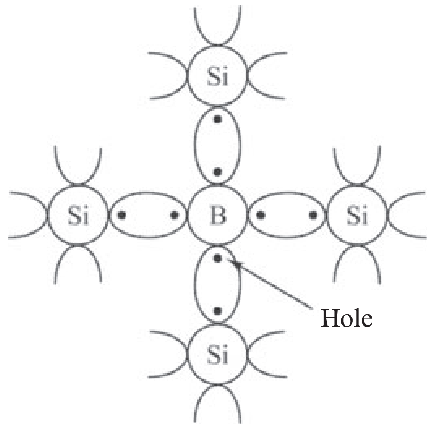


Fig. 1.12 P-type semiconductor, i.e., one hole is available per atom of boron

Boron has three valance electrons and silicon has four valance electrons; therefore, the deficiency of an electron around the boron atom gives rise to a hole, see Fig. 1.12. Thus, every boron atom contributes one hole. Hence, number of holes become far greater than the number of electrons. This results in *P*-type semiconductor.

1.9 P–N Junction and Depletion Layer

1.9.1 P–N Junction

P–N junction is formed by a special fabrication technology. To make a *P–N* junction, the *N*-type and *P*-type semiconductor crystals are cut into thin slices called wafers.

If a wafer of *P*-type semiconductor is joined to a wafer of *N*-type semiconductor in such a manner that the crystal structure remains continuous at the boundary, then a new structure called *P–N* junction is formed.

1.9.2 Depletion Layer

In a *P–N* junction, the *P*-region has holes and negatively charged impurity ions. *N*-region has free electrons and positively charged impurity ions. Electrons and holes are mobile charges whereas the ions are immobile. When a *P–N* junction is formed, the holes in the *P*-region diffuse into *N*-region and the electrons in the *N*-region diffuse into *P*-region. This process is called diffusion which happens for a short time as soon as the *P–N* junction is formed. After a few combinations of holes and electrons, a restraining force is developed which is known as **potential barrier**. This potential barrier prevents further diffusion of holes and electrons. The barrier force development can be easily explained. That is, each recombination of hole and

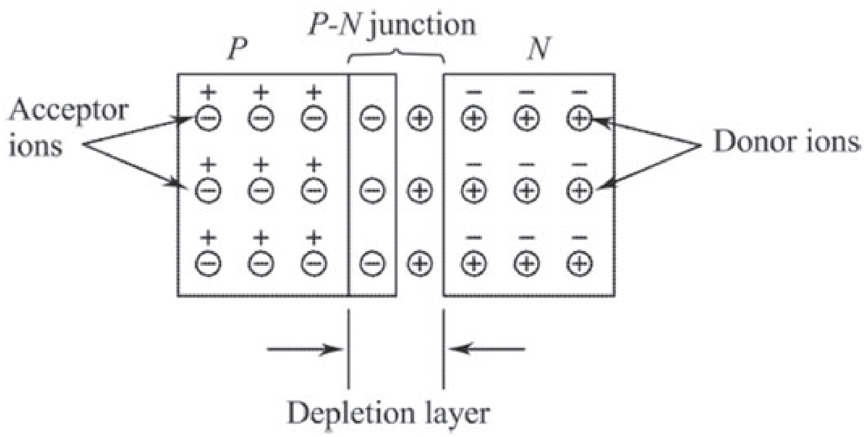


Fig. 1.13 Formation of P–N junction and depletion layer

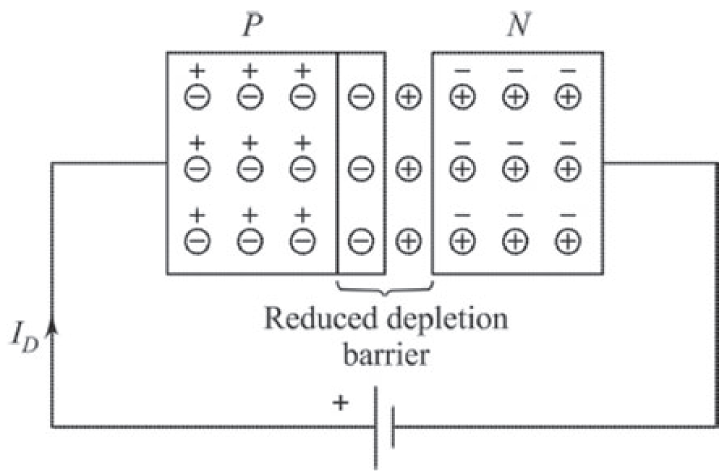
electron eliminates hole and electron. During this process the negative acceptor ions in the *P*-region and positive donor ions in the *N*-region are left uncompensated. The additional holes trying to diffuse into *N*-region and additional electrons trying to diffuse into *P*-region are repelled by these negative and positive charges respectively. The region containing this uncompensated acceptor and donor ions is called **depletion layer**, see Fig. 1.13.

1.9.3 Forward Biasing

When an external voltage is applied to the *P–N* junction in such a direction that it cancels the potential barrier which permits current flow, it is called **forward biasing**.

Figure 1.14 shows forward biasing connections. Positive terminal of battery is connected to *P*-type and negative terminal to *N*-type. The applied forward potential establishes an electric field which acts against the field due to depletion (potential) barrier. Thus, the depletion (potential) barrier is reduced and allows the flow of

Fig. 1.14 Forward biasing reduces, depletion (potential barrier)



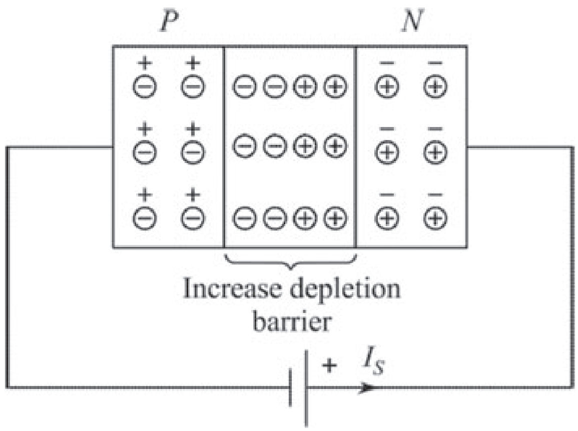


Fig. 1.15 Reverse bias increases depletion barrier (potential barrier)

charged carriers across the barrier. In effect, a small forward voltage is sufficient to make the depletion barrier insignificant. Once the depletion barrier is made insignificant by the forward voltage, junction resistance becomes too small and a high current flows in the circuit.

1.9.4 Reverse Biasing

When the external voltage applied to the *P–N* junction is in such a direction that depletion (potential) barrier is increased, it is called **reverse biasing**.

Figure 1.15 shows reverse biasing connection. Negative terminal of battery is connected to *P*-type and positive terminal to *N*-type. The reverse biasing establishes an electric field which acts in the same direction as the field due to depletion (potential) barrier. Thus, depletion (potential) barrier is increased and prevents the flow of charge carriers across the junction. In effect, a high resistance path is established for the circuit; hence, the current flow is insignificant.

Summary

1. **Semiconductor Devices**: Semiconductor devices are diode, transistor and integrated circuits (ICs), ICs are known as microelectronics. ICs can be small-scale integration (SI), medium-scale integration (MSI), large-scale integration (LSI) and very large-scale integration (VLSI). There are digital as well as analog ICs. Digital logic can be based on transistor–transistor logic (TTL), emitter-coupled logic (ECL), etc. Latest electronic components use complementary metal–oxide semiconductor (CMOS) technology. The semiconductor memories are random access memory (RAM), read-only memory (ROM), programmable ROM (PROM) and erasable PROM (EPROM). Microprocessor (MP) has given bite to "computer on chip." Operational amplifier (op-amp) is an analog IC. Other electronic devices are digital to analog (D/A) converter, analog-to-digital (A/D) converter, analog multiplexers and active filters.

2. **Electronic Circuit Components**: There are two types of electronic circuit components. One type of components are active components such as diodes, transistors, silicon controlled rectifiers (SCRs), field effect transistors (FETs), etc. Other type of components are passive components such as resistors inductors and capacitors.
3. **SI Units**: SI units are as per international system of units. The basic SI units are meter, kilogram, second, ampere, kelvin, candela and mole. Temperature in Kelvin = 273 + temperature in °C.
4. **Voltage and Current Sources**: Voltage source has very small internal resistance and ideal voltage source has zero internal resistance. Current source has very large resistance across it, and ideal current has infinite resistance across it. Voltage and current sources can be converted from one to other or vice-versa for circuit analysis purposes.
5. **Semiconductor Materials**: Number of electrons in uppermost orbit of an atom of a material is known as valence. Conductors have one valance electron, insulators have eight valence electrons and semiconductors have four valence electrons. Each silicon atom in a crystal has its four valence electrons plus four more electrons that are shared by the neighboring atoms.
6. **Intrinsic Semiconductors**: It is a pure semiconductor. When an external voltage is applied to the intrinsic semiconductor, the free electrons flow toward the positive battery terminal and the holes flow toward the negative battery terminal.
7. **Extrinsic Semiconductors**: When an intrinsic semiconductor is doped with pentavalent donor atoms, it has more free electrons than holes. When an intrinsic semiconductor is doped with trivalent acceptor atoms, it has more holes than free electrons.
8. **N-type and P-type semiconductors**: In an N-type semiconductor, the free electrons are the majority carriers, while the holes are the minority carriers. In a P-type semiconductor, the holes are the majority carriers, while the free electrons are the minority carriers.
9. **Forward and Reverse Biasing**: When a battery is connected across the P–N junction, then this process is known as biasing of the P–N junction. In forward biasing of a P–N junction, positive terminal of the battery is connected to the P-side and the negative terminal to the N-side. In reverse biasing, the positive terminal of battery is connected to N-side and negative side is connected to P-side of the P–N junction.
10. **Important Formulae**:

    i .$v = iR$

    ii .$v = L\frac{di}{dt}$

    iii. $i = C\frac{di}{dt}$

    iv. *Heat produced by resistor* = I^2Rt Joules.

v. *Energy stored*
in an inductor = $\frac{1}{R}LI^2$ Joules.
vi. *Energy stored*
in a capacitor = $\frac{1}{2}\mathrm{CV}^2$ Joules .
vii. 1 calorle = 4.18 Joules.
viii. Power $= VI = l^2R = \frac{V^2}{n}$ watts.
ix. 1 hp (Brttish) = 746 watts.
x. 1hp(Metric) = 735.5 watts
xi. 1 unit energy = 1 kWh = 3.6 MJ .

Exercises

1. *What do you understand by electronics? Explain its utility in our daily life.*
2. *Explain latest trends in electronics.*
3. *What do you understand by electric current?*
4. *What are active components? Name three active components.*
5. *What is a resistor? What is the relationship of resistance value with length and of cross section of a conductor?*
6. *Explain color coding of a resistor with an example.*
7. *Explain inductors and capacitors. What are their relationships with current through and voltage across there?*
8. *Explain electrical power, energy and their relationships with current and voltages.*
9. *What is SI unit? Explain basic and derived SI units.*
10. *Write short note on voltage and current sources.*
11. *Explain an atom with a diagram.*
12. *What do you understand by valence of a material? Give valences of conductor, insulator and semiconductor.*
13. *What is an intrinsic semiconductor?*
14. *Explain extrinsic semiconductor.*
15. *What are N-type and P-type semiconductors?*
16. *Explain a P–N junction and depletion layer.*
17. *What do you understand by forward and reverse biasings?*

Chapter 2
Semiconductor Diodes

2.1 Semiconductor Diode

A *P–N* junction is known as **semiconducto diode**. A semiconductor diode is represented by the schematic symbol shown in Fig. 2.1. The arrow indicates the direction of forward bias current flow. It has two terminals.

If the *dc* power supply pushes current in the direction of arrow, it is **foward biased**; if the current is trying to flow opposite to arrow direction, it is **reverse biased**. Figure 2.2 shows forward and reverse-biased circuits.

The general characteristics of a semiconductor diode can be demonstrated through the use of solid-state physics. Shockley's equation represents these characteristics. For the forward and reverse bias regions, the equation is:

$$I_\mathrm{F} = I_\mathrm{S}\left(e^{V_\mathrm{F}/\eta V_\mathrm{T}} - 1\right)$$

where
V_F = applied forward bias voltage across the diode.
I_F = forward bias current through the diode.
I_S = reverse bias saturation current.

η = a factor representing operating conditions, for germanium diode.

η = 1 and for silicon diode η = 2.
V_T = thermal voltage determined by $V_\mathrm{T} = \frac{kT}{q}$.
where
k = Boltzmann's constant = 1.38×10^{-23} J/Kelvin.
T = absolute temperature in kelvins = 273 + temperature in °C.
q = magnitude of electronic charge = 1.6×10^{-19} C.

O. N. Pandey, *Electronics Engineering*,
https://doi.org/10.1007/978-3-030-78995-4_2

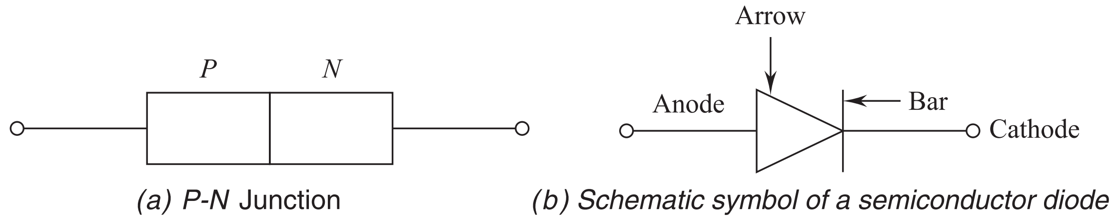


Fig. 2.1 P–N junction and schematic symbol of a diode

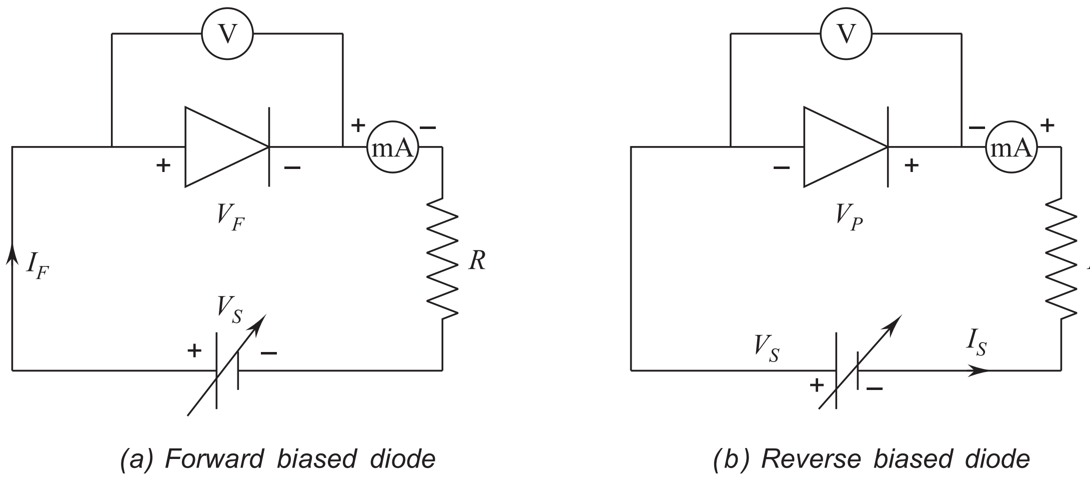


Fig. 2.2 Forward and reverse-biased diodes

At room temperature (T = 300 K), V_T = 26 mV.
Thus, at room temperature, $I_F = I_S\ (e^{40VF\ \eta} - 1)$.

2.2 *V*–I Characteristics

From Eq. (2.1), for forward bias V_F will be positive and current equation is given by:

$$I_F = I_S e^{V_F/\eta V_T} - I_S$$

The first term in the equation is very high as compared to I_S; hence, the forward current is

$$I_F \cong I_S e^{V_F/\eta V_T}$$

The forward bias current for theoretical case is shown in Fig. 2.3 by dotted lines for a silicon diode.

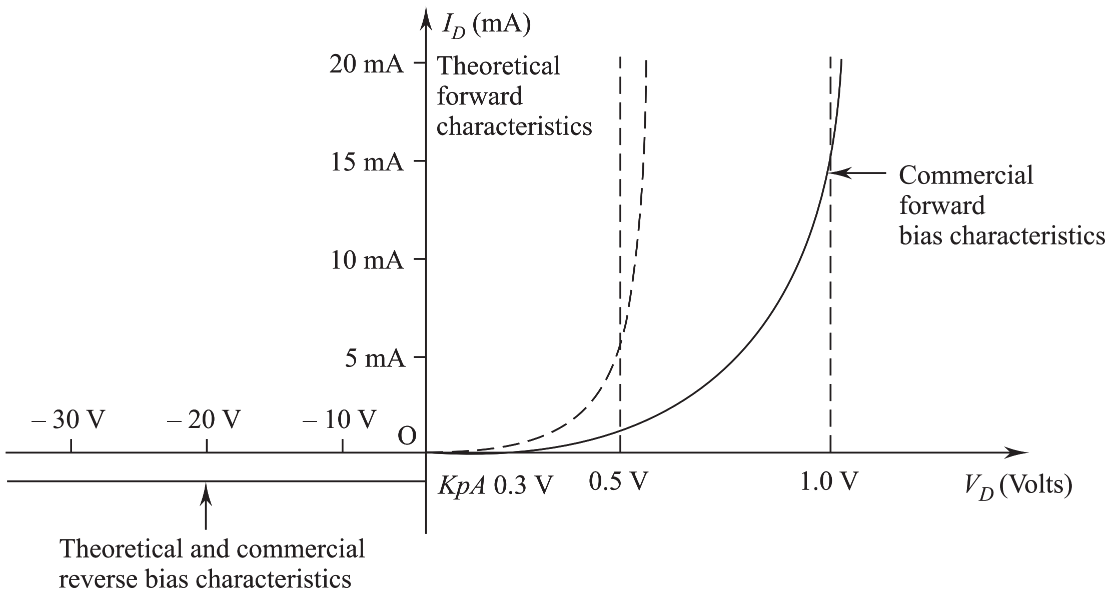


Fig. 2.3 V–I characteristics of ideal and practical diode

For a voltage $V_F = 0$, the equation for current is

$$I_F = I_S(e^0 - 1) = 0.$$

For a negative V_F (reverse bias), the equation for current is

$$I_F = I_s e^{-V_F/\eta V_T} - I_s$$

The first term will be too small as compared to I_{S+}; hence, current becomes

$$I_F \cong -I_S$$

The theoretical characteristics are again shown in Fig. 2.3 by dotted line for $V_D = 0$ and reverse bias. However, commercially available diode forward-bias diode characteristics differ from the theoretical due to internal body resistance and external contact resistance of diode, etc. Thus, commercial forward bias diode characteristics are shown by continuous line in Fig. 2.3. The theoretical and commercial diode current in the reverse bias case is too small, i.e., 10 pA to 1 µA; therefore, characteristics for negative V_D (reverse bias) are almost same.

Example 2.1 The reverse saturation current at room temperature is 0.4 µA when a reverse bias is applied to a Ge diode. What is value of current flowing in the diode, if 0.15 V forward bias is applied at room temperature?

Solution:
Given:

$$I_S = 0.4\,\mu\text{A}$$

Forward bias voltage,

$$V_F = 0.15\,\text{V}$$

∴ The current flowing through the diode under forward bias at room temperature is:

$$I_F = I_S\left(e^{40V_F/\eta} - 1\right)$$

$$h = 1 \text{ for germanium diode}$$

$$\therefore \quad I_F = 0.4 \times 10^{-6}\left(e^{40\times 015} - 1\right)$$

or

$$I_F = 160.87\,\mu\text{A}.$$

2.3 Ge, Si and GaAs Characteristics

The *V–I* characteristics considered so far have been for silicon diodes. The *V–I* characteristics for the three materials are shown in Fig. 2.4. The center of the knee of the curve, i.e., barrier potential, is about 0.3 V for **Ge**, 0.7 V for **Si** and 1.2 V for **GaAs**. It can be seen that best characteristics are for GaAs and next good one is for Si; the Ge is the last one, i.e., least desirable. It is important to note in the reverse bias case, there is a voltage V_Z at which reverse bias current suddenly jumps to very high current. V_Z is known as zero potential. The zero voltages for Ge, Si and GaAs are −50 V, −100 V and −1 kV, respectively.

2.4 Ideal and Practical V–I Characteristics

An ideal diode characteristic should be such that it allows full current to flow in forward bias condition and zero current in reverse bias condition. In other words, an ideal diode will act as a closed switch in forward bias condition, whereas as an open switch in reverse bias condition. Figure 2.5 shows an ideal semiconductor diode in forward bias and reverse bias condition.

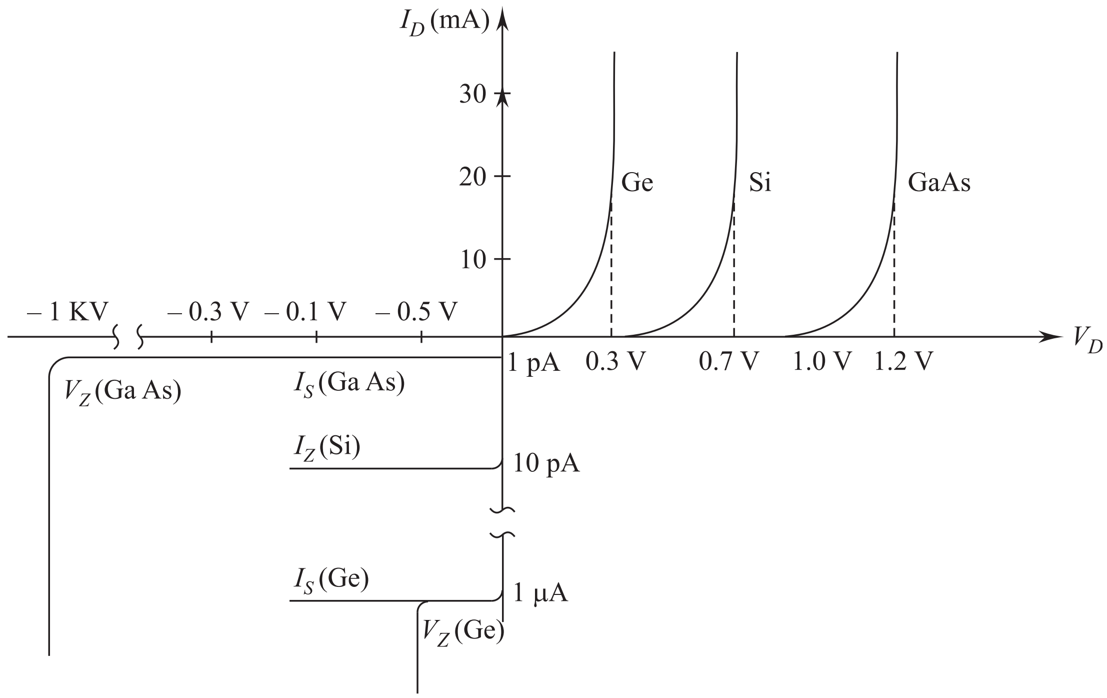


Fig. 2.4 *V–I* characteristics of Ge, Si and GaAs

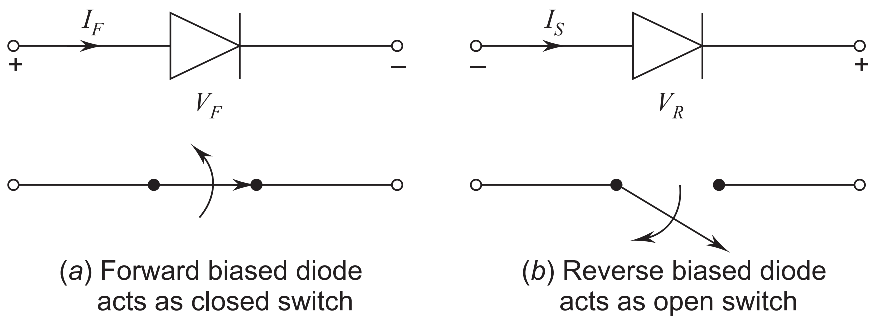


Fig. 2.5 An ideal semiconductor diode

The **ideal semiconductor *V–I* characteristics are** shown in Fig. 2.6. The semiconductor diode has zero resistance in forward bias and infinite resistance in reverse bias condition. **The actual *V–I* characteristics** will be as explained earlier for theoretical or commercial cases.

2.5 Diode Resistance

It is clear by now that a forward-biased diode conducts easily, whereas reverse-biased diode conduction is negligible. In other words, forward resistance of a diode is very small as compared to its reverse resistance.

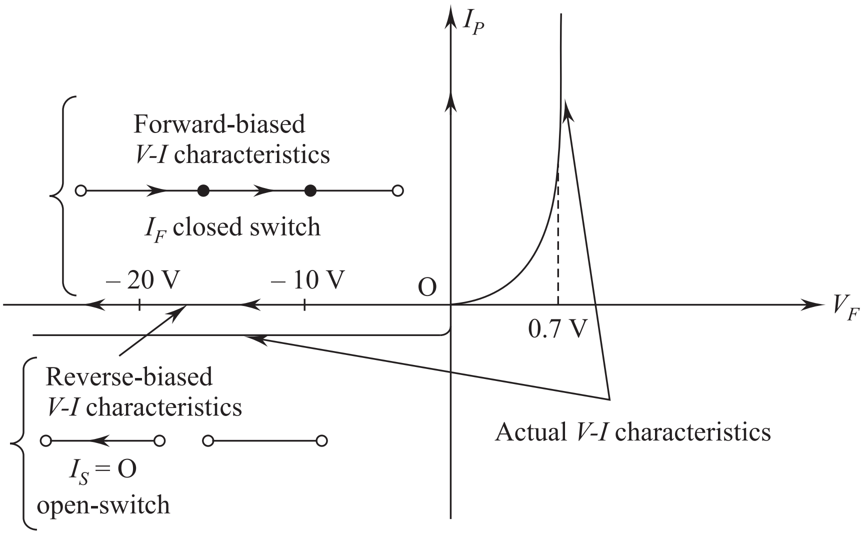


Fig. 2.6 An ideal and actual V–I characteristic of a semiconductor diode

2.5.1 *Forward Resistance*

Forward-biased diode resistance changes with the changing current; thus, it can be *d*c forward resistance or *ac* forward resistance.

2.5.1.1 DC Forward Resistance or Static Resistance (R_F)

In the case of application where direct current flows, the forward diode resistance can be explained by Fig. 2.7. Suppose voltage applied is *OA* and *dc* current *OB* is flowing through the diode, then

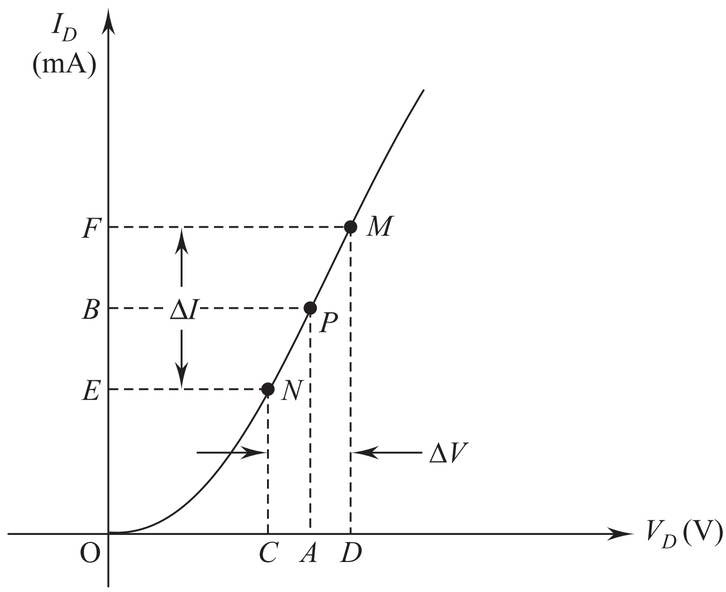


Fig. 2.7 DC forward bias resistance

DC **forward resistance**

$$R_F = \frac{OA}{OB}$$

2.5.1.2 AC Forward Resistance (r_F) or Dynamic Resistance

AC forward resistance is the resistance offered by the diode due to the changing current. Consider Fig. 2.7.

AC **forward resistance**,

$$r_F = \frac{\text{Change in voltage across the diode}}{\text{Corresponding change in current}}$$

or

$$r_F = \frac{OD - OC}{OF - OE} = \frac{CD}{EF} = \frac{\Delta V_F}{\Delta I_F}$$

AC forward resistance is significant as diodes are generally used with *ac* voltages. *AC* forward resistance of diode is very small in the range of 1–25 Ω.

The diode current equation is given by:

$$I_F = I_S\left(e^{V_F/\eta V_T} - 1\right)$$

By differentiating, we get

$$\frac{dI_F}{dV_F} = I_S \times \frac{V_F}{\eta V_T} \times e^{V_F/\eta V_T}$$

or

$$\frac{dV_F}{dI_F} = \frac{\eta V_T}{I_S e^{V_F/\eta V_T}} = \frac{\eta V_T}{I_F + I_S}$$

$$\therefore \quad r_F = \frac{\eta V_T}{I_F + I_S}$$

or

diode resistance,

$$r_F = \frac{\eta V_T}{I_F} \text{ as } I_S \ll I_F$$

Thus, for forward bias, r_F is inversely proportional to I_F. At room temperature, i.e., 27° (300 K), we have:

$$r_F = \frac{1 \times 26\,\text{mV}}{I_F \cdot \text{mA}} \text{ taking } \eta = 1 \text{ (germanium and } V_T = 26\,\text{mV)}$$

Example 2.2 Determine the dynamic resistance of a *P–N* junction diode at forward current of 2 mA. Assume that $\frac{kT}{e} = 2.5\,\text{mV}$.

Solution:
Given: Forward current,

$$I_F = 2\,\text{mA}$$

Voltage equivalent of temperature,

$$V_T = \frac{kT}{e} = 2.5\,\text{mV}$$

We know that:
Dynamic resistance

$$r_F = \frac{\eta V_T}{I_F}$$

$$r_F = \frac{1 \times 2.5\,\text{mV}}{2\,\text{mA}} \text{ taking } \eta = 1$$

or

$$r_F = 1.25\,\Omega.$$

2.5.1.3 Reverse Resistance (R_R)

The resistance of diode due to reverse bias is known as reverse resistance. The reverse resistance is too high, nearly infinite.

Reverse resistance $R_R \simeq 40,000\,R_F$ for germanium.

2.5.2 Transition and Diffusion Capacitance

An electronic circuit is sensitive to frequency. At high frequencies for the diode, stray capacitive effects are considerable. Forward bias condition has the effect of

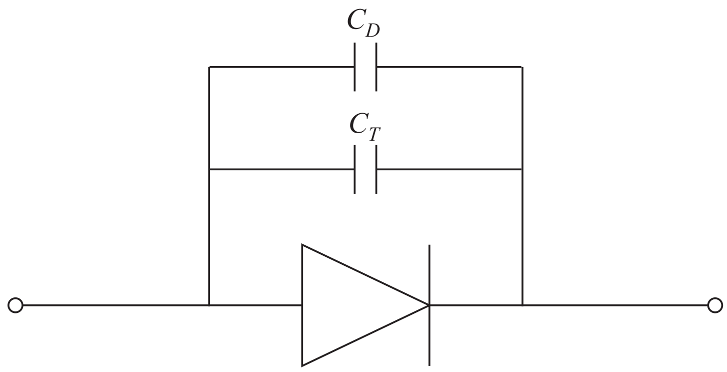


Fig. 2.8 Effect of capacitance on the semiconductor diode

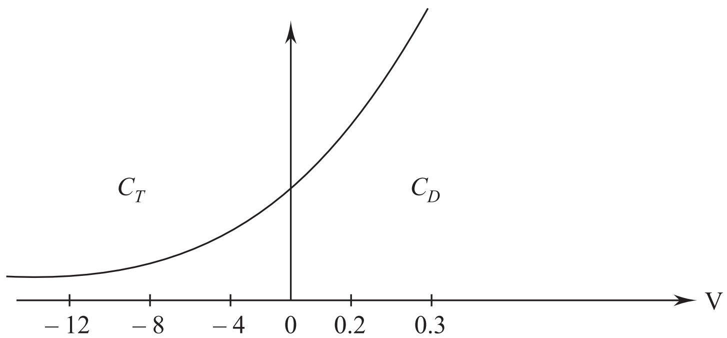
diffusion leading to **diffusion capacitance** (C_T). In reverse bias condition, there is depletion region or **transition capacitance** (C_T). The capacitive effects are represented by capacitors in parallel with the ideal diode, as shown in Fig. 2.8. These are applicable normally in power areas.

The diffusion capacitance is given by the formula:

$$C_D = \frac{I_F}{\eta V_T}$$

where
η = constant (η = 1 for Ge and η = 2 for Si).
V_T = volt equivalent of temperature.
T = mean lifetime of current.
I_F = forward current.
The depletion or transition capacitance is given by formula:

$C_T = \frac{K}{\sqrt{V}}$ where V = applied bias voltage.
The capacitance V_S applied bias voltage plot is given below:

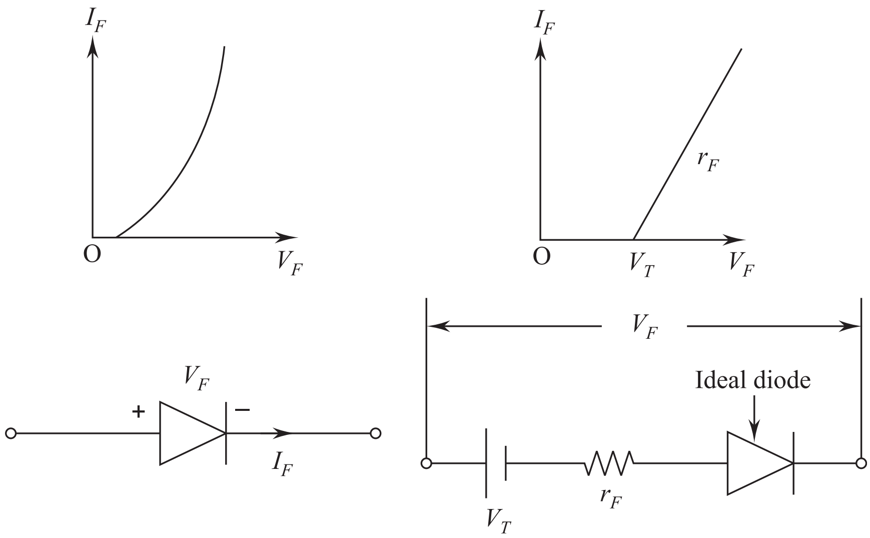


2.5.3 Diode Equivalent Circuit

The diode linear characteristic of forward bias gives:

$$V_F = V_T + I_F r_F$$

The actual and linear characteristics along with **equivalent circuit** are as follows:



$V_T = 0.7$ for Si and 0.3 for Ge.

2.6 Diode Ratings

Data sheets of diode specify several useful parameters, and some of these are explained here.

2.6.1 Repetitive Peak Current (I_{peak})

It is the maximum instantaneous value of repetitive forward bias current.

2.6.2 Average Current (I_{av})

It is an average forward bias current value and is defined by $I_{av} = 0.318\, I_{peak}$.

2.6.3 Peak Inverse Voltage (VR)

It is the absolute peak voltage which must be applied in reverse bias across the diode.

2.6.4 Steady-State Forward Current (I_F)

It is the maximum current which can be passed continuously through the diode.

2.6.5 Peak Forward Surge Current (I_{FS})

It is a current which may flow briefly when a circuit in switch is first switched on. I_{FS} is very much higher than I_{F}.

2.6.6 Static Maximum Voltage Drop (V_{FM})

It is a maximum forward voltage drop for a forward current at the device temperature.

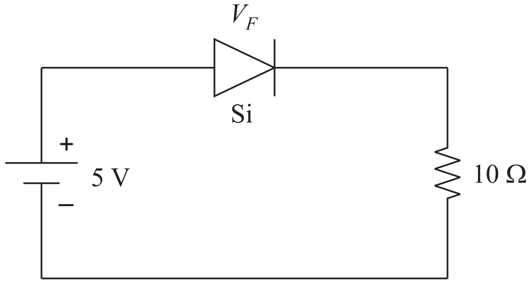
2.6.7 Continuous Power Dissipation (P)

It is the maximum power which can be dissipated continuously in free air.

2.6.8 Reverse Recovery Time (t_{rr})

It is the maximum time for the device to switch from ON to OFF.

Example 2.3 What is the current in the circuit shown below:



Solution: For silicon diode, $V_F = 0.7$ V.
Using KVL in the circuit, we get:

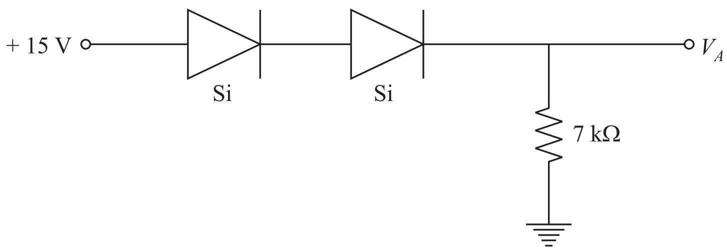
$$5 = V_F + I \times 10$$

or

$$I = \frac{5 - 0.7}{10} = \frac{4.3}{10} = 0.43\,\text{A}$$

Thus, current in the circuit, $I = 0.43$ A.

Example 2.4 Find the voltage V_A and the current in the circuit shown in figure given below:



Solution: For silicon diode,

$$V_F = 0.7\,\text{V}$$

Voltage,

$$V_A = 15 - (0.7 \times 2) = 13.6\,\text{V}$$

and current,

$$I = \frac{13.6}{7 \times 10^3} = 1.942 \times 10^{-3}\,\text{A} \quad \text{or} \quad 1.942\,\text{mA}$$

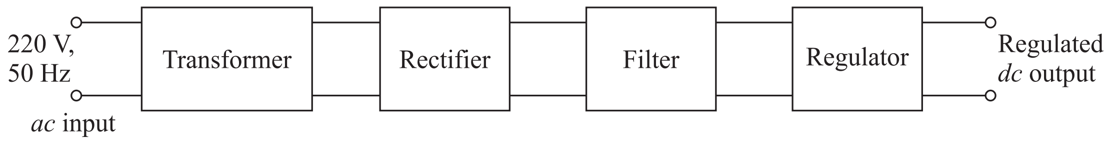


Fig. 2.9 Block diagram of a dc supply

2.7 *P*–N Junction (Diode) as Rectifiers

The electrical power supply to Indian homes and industries is in the form of *ac* voltage. It is 220 V *rms* at 50 Hz for domestic usage. The electronic equipment is operated by *dc* supply. It can be dry cells or **battery eliminator**. A battery eliminator gets *ac* voltage as input and converts it into *dc* supply. Battery eliminator is also known as *dc* power supply. The individual units in a *dc* power supply are input step-down transformer, **rectifier**, filter and regulator. Figure 2.9 shows the block diagram of a *dc* power supply.

2.7.1 Half-Wave Rectifier

A half-wave rectifier is shown in Fig. 2.10. The *ac* supply is input to a step-down transformer. The secondary has a diode which is connected across the load as shown. Suppose secondary voltage is given as:

$$V_{\mathrm{o}} = V_{\mathrm{m}} \sin \omega t$$

Then, half-wave rectifier waveforms will be shown in Fig. 2.11.

The *ac* voltage across the secondary winding of the transformer changes polarity after every half-cycle. During positive half-cycle, the diode is forward biased, and hence, current flows through the load. In other words, during positive half-cycle voltage across the load is also positive half-cycle. During negative half-cycle, the diode is subjected to reverse bias, and hence, negligible current flows through the

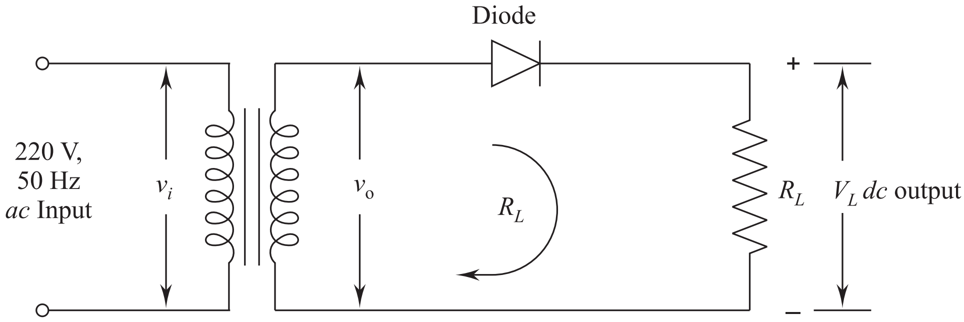


Fig. 2.10 Half-wave rectifier

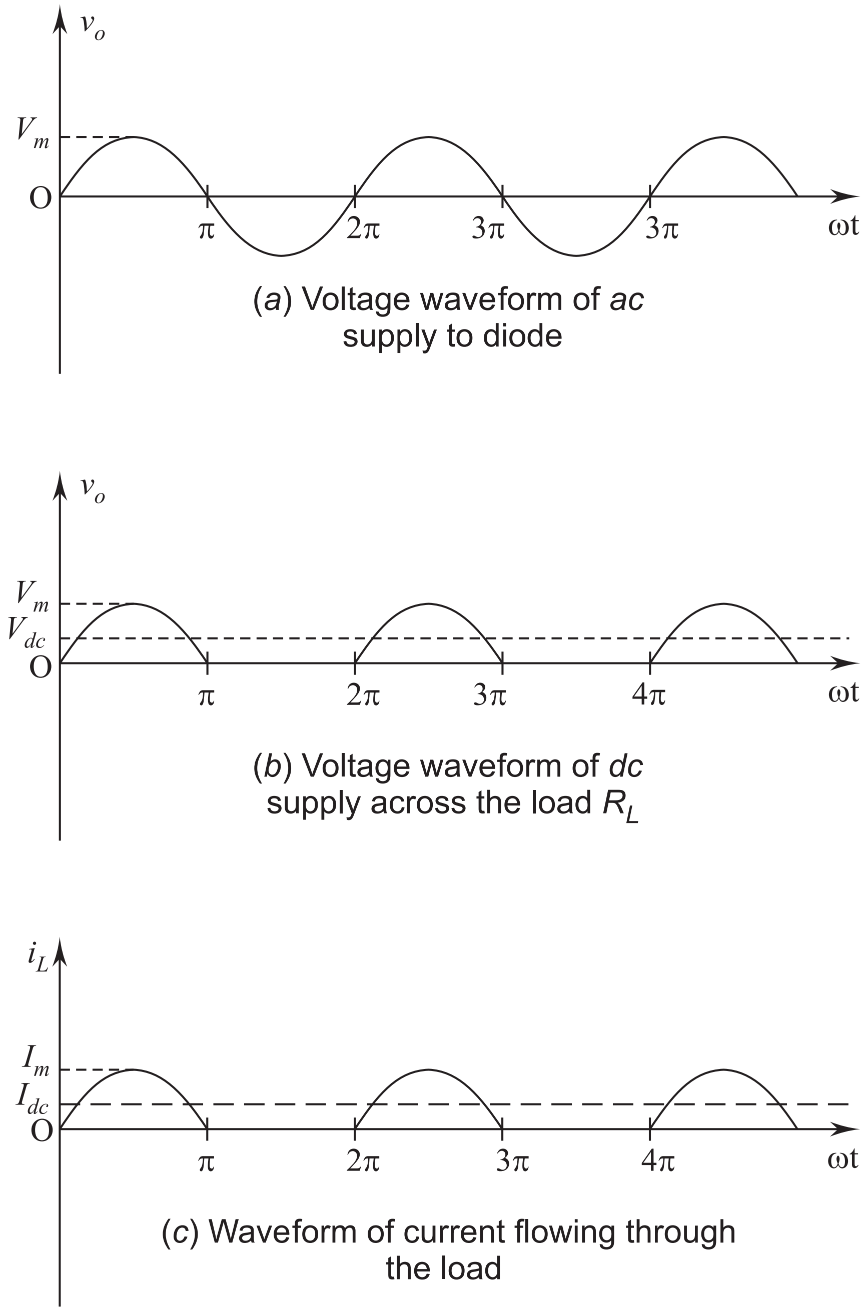


Fig. 2.11 Half-wave rectifier waveforms

load; i.e., there is no voltage across the load. Thus, output across the load is pulsating *dc*.

The current through the load is given by:

$$\begin{aligned} i_L &= I_m \sin \omega t \text{ for } 0 \leq \omega t \leq \pi \\ &= 0 \text{ for } \pi \leq \omega t \leq 2\pi \end{aligned}$$

Peak value of current,

$$I_{\mathrm{m}} = \frac{V_{\mathrm{L}}}{R_{\mathrm{L}}}$$

The average value of load current,

$$I_{\mathrm{av}} = I_{\mathrm{dc}} = \frac{\text{Area of wave for a cycle}}{\text{Duration of a cycle}} = \frac{\text{area}}{\text{base}}$$

We know that:

$$\begin{aligned}
\text{Area} &= \int_0^{2\pi} i_{\mathrm{L}} d(\omega t) \\
&= \int_0^{\pi} I_{\mathrm{m}} \sin \omega t d(\omega t) + \int_{\pi}^{2\pi} 0 d(\omega t) \\
&= I_{\mathrm{m}}[-\cos \omega t]_0^{\pi} + 0 \\
&= I_{\mathrm{m}}[-\cos \pi - (-\cos 0)] \\
&= I_{\mathrm{m}}[1 + 1] = 2I_{\mathrm{m}}
\end{aligned}$$

$$\therefore \quad I_{\mathrm{dc}} = \frac{\text{area}}{\text{base}} = \frac{2I_{\mathrm{m}}}{2\pi}$$

or

$$I_{\mathrm{dc}} = \frac{I_{\mathrm{m}}}{\pi}.$$

The voltage across the load R_{L} is given by:

$$V_{\mathrm{dc}} = I_{\mathrm{dc}} \times R_{\mathrm{L}} = \frac{I_{\mathrm{m}}}{\pi} R_{\mathrm{L}}$$

So far, it was considered that diode forward resistance is zero, but if actual Fresistance r_F is considered, then we get:

$$I_{\mathrm{m}} = \frac{V_{\mathrm{m}}}{(R_{\mathrm{L}} + r_{\mathrm{F}})}$$

$$\therefore \quad V_{dc} = \frac{V_m}{\pi(R_L + r_F)} \times R_L = \frac{V_m}{\pi\left(1 + \frac{r_F}{R_L}\right)}$$

or

$$V_{dc} = \frac{V_m}{\pi} \text{ for } r_F \ll R_L.$$

Rectifier efficiency,

$$\eta = \frac{dc \text{ power output}}{ac \text{ power input}}$$

$$= \frac{\rho_{dc}}{\rho_{ac}} = \frac{(I_m/\pi)^2 \times R_L}{(I_m/2)^2 \times (r_F + R_L)} \text{ as } I_{rms} = \frac{I_m}{2}$$

$$\therefore \quad \eta = \frac{0.406 R_L}{r_F + R_L} = \frac{0.406}{1 + \left(\frac{r_F}{R_L}\right)}$$

or

$$\eta = 0.406 \text{ for } r_F \ll R_L.$$

Thus, in half-wave rectification, a maximum of 0.6% of *ac* power is converted into *dc* power.

Peak Inverse Voltage (PIV) Diode.

The diode is subjected to voltage V_m in the reverse bias situation; therefore, **peak inverse voltage (*PIV*)** in this case is V_m.

Thus, the diode must be able to withstand maximum voltage V_m in the negative half-cycle.

Example 2.5 A half-wave rectifier employs a diode having a forward resistance of 10 Ω. If the input voltage to the rectifier circuit is 12 V(rms), find the dc output voltage at a load 100 mA and PIV.

Solution:

Given: Forward resistance,

$$r_F = 10\,\mathrm{W}$$

Load Current,

$$I_L = 100\,\mathrm{mA}$$

rms value of supply voltage,

$$V_{rms} = 12\,\mathrm{V}$$

Maximum supply voltage,

$$\begin{aligned} V_{SM} &= \sqrt{2}\,V_{rms} \\ &= \sqrt{2} \times 12 = 16.97 \end{aligned}$$

dc output voltage for half-wave rectifier,

$$V_{dc} = \frac{V_{SM}}{\pi} - I_{dc} r_F$$

or

$$V_{dc} = \frac{17}{\pi} - 0.1 \times 10 = 4.4\,\mathrm{V}.$$

$$PIV = V_{SM} = 17\,\mathrm{V}.$$

Example 2.6 A half-wave rectifier uses a diode with an equivalent forward resistance of 0.3 Ω. If the input ac voltage is 10 V(rms) and the load is a resistance of 2.0 Ω, calculate I_{dc} and I_{rms} in the load.

Solution:
Given: Supply voltage, V_{rms} = 10 V, forward resistance,

$$r_F = 0.3\ \Omega \text{ and load resistance } R_L = 20\,\Omega$$

The peak value of supply voltage,

$$V_m = 10\sqrt{2}\,\mathrm{V}$$

The peak value of current,

$$I_m = \frac{V_m}{R_L + r_F} = \frac{10\sqrt{2}}{2 + 0.3} = 6.15\,\mathrm{A}$$

dc output current,

$$I_{dc} = \frac{I_m}{\pi} = \frac{6.15}{\pi} = 1.958\,\text{A}.$$

rms value of output current,

$$I_{rms} = \frac{I_m}{2} = \frac{6.15}{2} = 3.075\,\text{A}.$$

2.7.2 Full-Wave Rectifier

Half-wave rectifier utilizes only one half-cycle of the input wave. **Full-wave rectifier** utilizes both the half-cycles. A unidirectional local current is achieved by inverting alternate half-cycles. Full-wave rectifier can be divided into two categories. One is known as **center tap rectifier** which uses two diodes. The other is known as bridge rectifier which uses four diodes.

2.7.2.1 Center Tap Rectifier

In this case, the secondary winding is center tapped and load along with two diodes is connected as shown in Fig. 2.12a. The secondary winding is divided into two

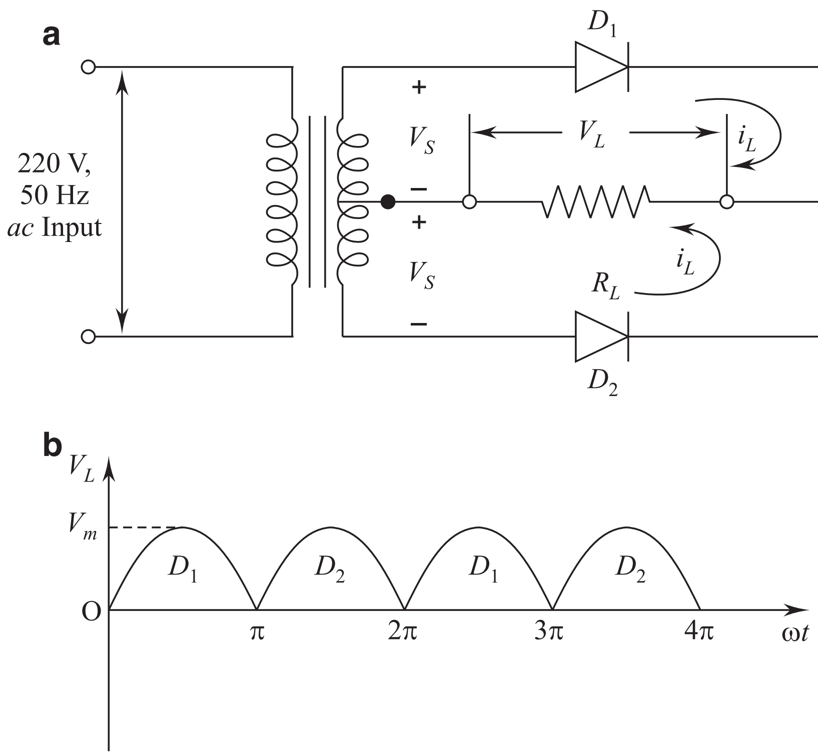


Fig. 2.12 **a** Center-tapped full-wave rectifier and **b** center-tapped full-wave rectifier waveform

equal parts, and a tapping is done and used in circuit as shown. The waveform of *dc* voltage across the load will be shown in Fig. 2.12b. Diode D_I conducts during positive half-cycle, whereas diode D_2 conducts during negative half-cycle.

Thus, load current through load is always in one direction only. Hence, it is full-wave rectified *dc* output.

Peak Inverse Voltage (PIV) of Diode

The voltage V_m is the maximum voltage across half of the secondary winding. When diode D_1 is conducting, resistance of diode is almost zero. Hence, full peak voltage V_m appears across the load resistor R_L. Thus, reverse voltage which appears the diode D_2 summation of voltage across D_2 and that load R_L. Hence, V_m voltage appears across diode D_2; i.e., 2 V_m voltage appears across the non-conducting diodes, D_1 or D_2.

∴ Peak inverse voltage of diode

$$PIV = 2\,V_m$$

Center tapping is difficult, *dc* power output is small as secondary winding is divided, and diodes should have high *PIV*.

2.7.2.2 Bridge Rectifier

It uses four diodes instead of two as shown in Fig. 2.13. But, it does not need a center-tapped transformer.

A simplified circuit diagram of the **bridge rectifier** is shown in Fig. 2.14a. Diodes D_2 and D_4 conduct during positive half-cycle of the supply, whereas diodes D_1 and D_3 are non-conducting as shown in Fig. 2.14b. Hence, current flows through the load resistor R_L and diodes D_2 and D_4. Diodes D_1 and D_3 conduct during negative half-cycle of the supply, whereas diodes D_2 and D_4 are non-conducting as shown in Fig. 2.14c. Thus, current flows in the same direction through the load resistor R_L and diodes D_1 and D_3. Hence, an alternating bidirectional voltage waveform is converted into unidirectional voltage waveform across the load resistor.

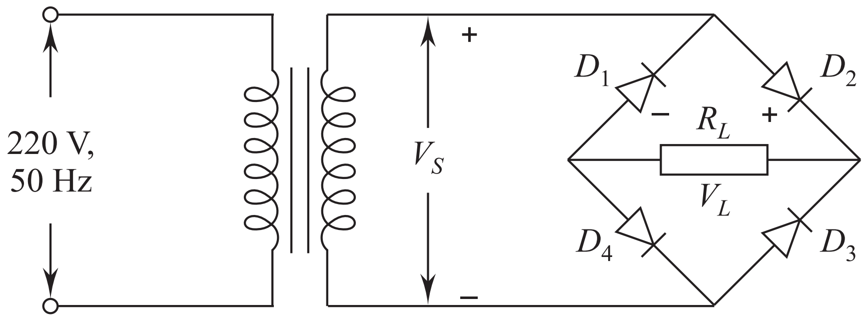
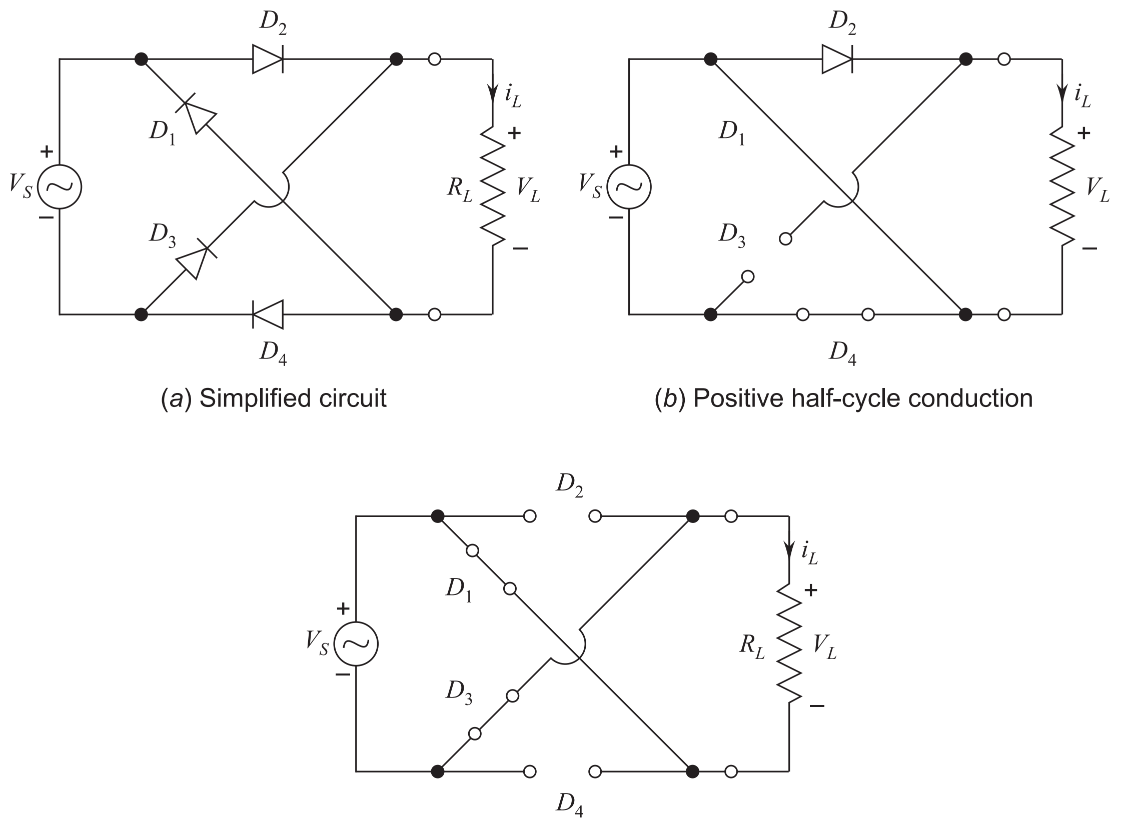


Fig. 2.13 Bridge rectifier



(*a*) Simplified circuit (*b*) Positive half-cycle conduction

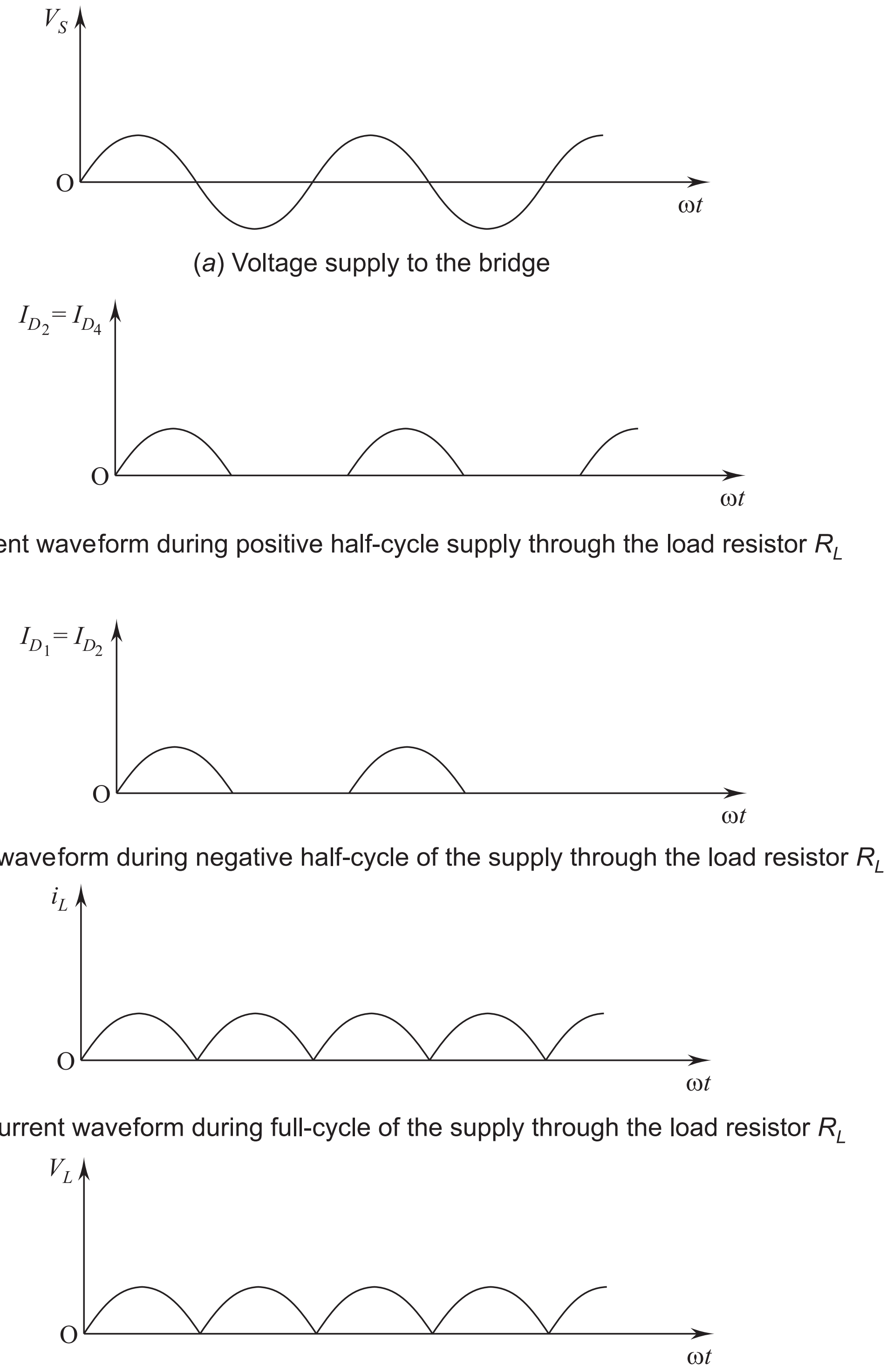
(*c*) Negative half-cycle conduction

Fig. 2.14 Simplified circuit and conduction of bridge rectifier

The waveform of the supply voltage is shown in Fig. 2.15a. The current waveform through the load resistor R_L during positive half-cycle of the supply is shown in Fig. 2.15b. Similarly, the current waveform through the load resistor during negative half-cycle of the supply is shown in Fig. 2.15c. The net current wave during full cycle of the supply through the load resistor R_{L} is shown in Fig. 2.15d. Thus, voltage waveform during full cycle of supply across the load is as shown in Fig. 2.15de, i.e., fully rectified waveform of the supply.

The peak inverse voltage (*PIV*) across each non-conducting diodes in a bridge rectifier is just the peak value of the voltage supply, i.e., V_{m}. Thus, the diodes used for bridge rectifier are cheaper as compared to the ones used for center-tapped rectifiers.

It is important to note that the need for center tapping of supply transformer secondary is eliminated in bridge rectifier. The output is twice that of the center-tapped circuit for the same secondary voltage. For the same *dc* output voltage, *PIV* of bridge rectifier circuit is half that of center-tapped circuit. It requires four diodes, each half-cycle of *ac* input two diodes that conduct are in series, therefore, voltage drop in the internal resistance of the rectifying unit will be twice as great as in the centre-tapped circuit. This is undesirable when the secondary voltage is small.



(*a*) Voltage supply to the bridge

(*b*) Current waveform during positive half-cycle supply through the load resistor R_L

(*c*) Current waveform during negative half-cycle of the supply through the load resistor R_L

(*d*) Net current waveform during full-cycle of the supply through the load resistor R_L

(*e*) Voltage waveform during full-cycle of supply across load resistor R_L

Fig. 2.15 Bridge rectifier waveforms

2.8 Ripple Efficiency and Regulation

A measure of purity of the *dc* output of a rectifier is ripple factor which is defined as follows:

Ripple factor,

$$r = \frac{rms \text{ value of the components of wave}}{\text{average or } dc \text{ value}}$$

Rectification efficiency is defined as:

$$\eta = \frac{dc \text{ power delivered to load}}{ac \text{ input power from transformer secondary}}$$

or

$$\eta = \frac{P_{dc}}{P_{ac}}$$

It may be noted that P_{ac} is the power which would be indicated by a wattmeter connected in the rectifying circuit with its voltage terminates placed across the secondary winding and P_{dc} is the *dc* output power.

The degree of constancy is measured by load voltage regulation defined as:

$$\textbf{Load Regulation} = \frac{\text{No - load average voltage} - \text{Full - load average voltage}}{\text{Full - load average voltage}}$$

2.9 Efficiency of Full-Wave Rectifier

Take $V = V_m \sin \omega t$ as the *ac* voltage given for rectification. R_L and r_F are load resistance and diode resistance, respectively.

Then,

$$P_{dc} = (I_{dc})^2 \times R_L$$

for

$$I_{dc} = \frac{2I_m}{\pi} \quad \text{and} \quad I_m = \frac{V_m}{r_F + R_L}$$

i.e.,

$$P_{dc} = \left(\frac{2I_m}{\pi}\right)^2 \times R_L$$

and

$$P_{ac} = (I_{rs})^2 \times (r_F + R_L)$$

or

$$P_{ac} = \left(\frac{I_m}{\sqrt{2}}\right)^2 \times (r_F + R_L) \text{ as } I_{rms} = \frac{I_m}{\sqrt{2}}$$

Thus,

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(2I_m/\pi)^2 \times R_L}{(I_m/\sqrt{2})^2 \times (r_F + r_L)} = \frac{0.812 R_L}{r_F + R_L}$$

or

$$\eta = \frac{0.812}{1 + \left(\frac{r_F}{R_L}\right)}$$

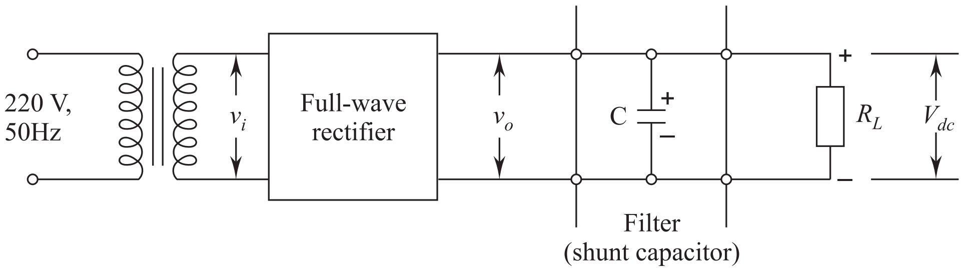
i.e., the efficiency will be maximum if $r_F \ll R_L$.

Hence, maximum efficiency of a full-wave rectifier is 81.2% which is double of half-wave rectifier.

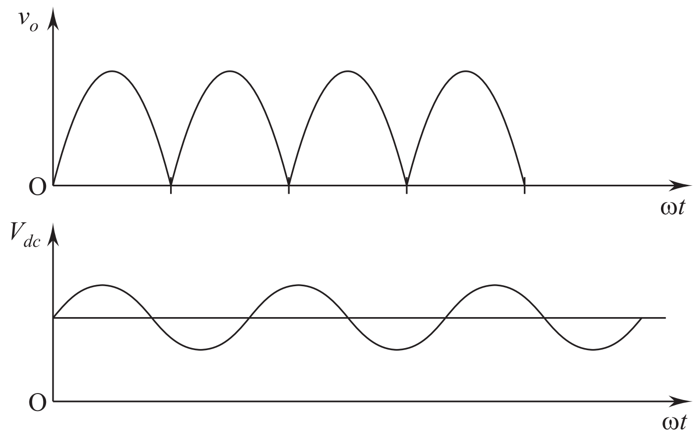
2.10 Filters for Rectifiers

Rectifier output should be similar to a battery output. The rectifier output is pulsating *dc* which can be smoothened out using filter circuits. Figure 2.16 shows schematic of a rectifier with a shunt capacitor filter. Input and output waveforms of the filter are also shown.

There are several types of filters which are in use, but shunt capacitor serving as a filter is most common. As shown in Fig. 2.16a, it is basically just a large value capacitor which is connected across the full-wave rectifier and the load R_L. The pulsating input voltage is applied across the capacitor, and filter output is smoothened. The capacitor changes the conditions under which the diodes conduct as shown in Fig. 2.17. When the rectifier output is increasing, the capacitor charges to peak value voltage V_m. Soon after, the rectifier voltage output tries to fall. As soon as the source voltage becomes slightly less than V_m, the capacitor will try to send current back through the diode. This reverse biases the diode; i.e., it becomes



(*a*) Filter in a rectifier



(*b*) Input and output waveforms of a rectifier filter

Fig. 2.16 Full-wave rectifier with a shunt capacitance filter

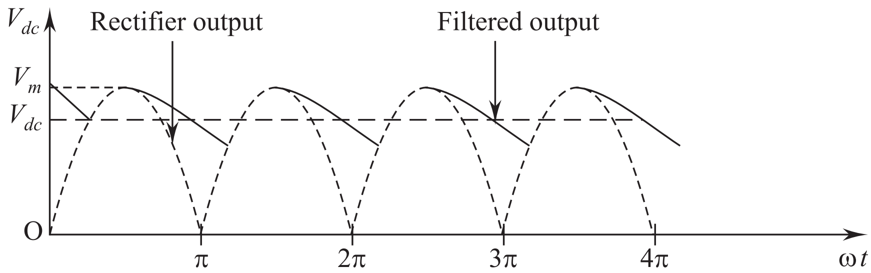
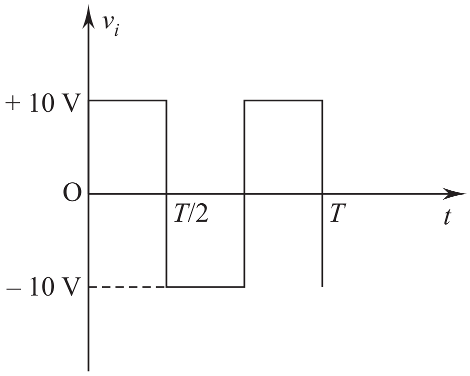
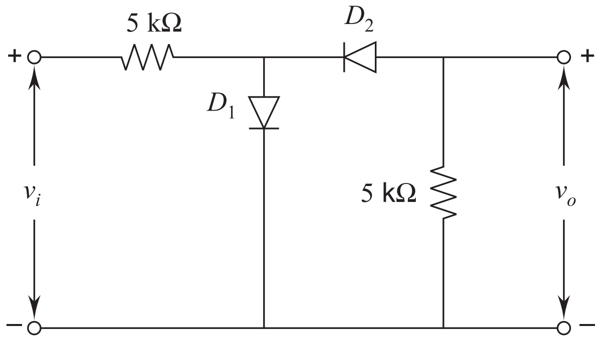


Fig. 2.17 Waveform output of shunt capacitor filter

open circuited. Thus, power source gets separated from the load. The capacitor starts to discharge through the load which prevents the load voltage from falling to zero. This continues to discharge until the source voltage becomes more than the capacitor voltage. This cycle keeps on repeating. The rectifier supplies the charging current through the capacitor branch as well as the load R_L. Thus, current is maintained through the load all the time at almost a constant value.

Example 2.7 Sketch the output voltage v for the circuit given in the following figure. Assume diodes D_1 and D_2 to be ideal diodes.





Solution: During positive half-cycles of input voltage, diode D_1 is forward biased and D_2 is reverse biased. In this case, current flows through only one diode D_1. Thus, output v_o is zero. During negative half-cycles of input voltage, diode D_1 is reverse biased and diode D_2 is forward biased; i.e., current flows through only one diode D_2. The voltage v_o is given by:

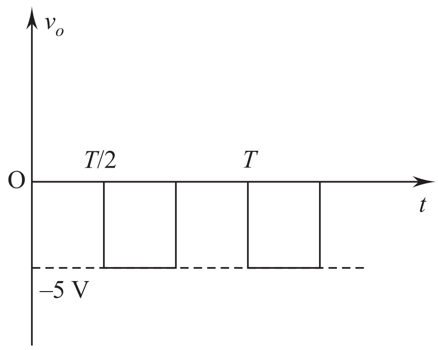
Output voltage,

$$v_o = \frac{v_i \times 5\,k\Omega}{(5\,k\Omega + 5\,k\Omega)}$$

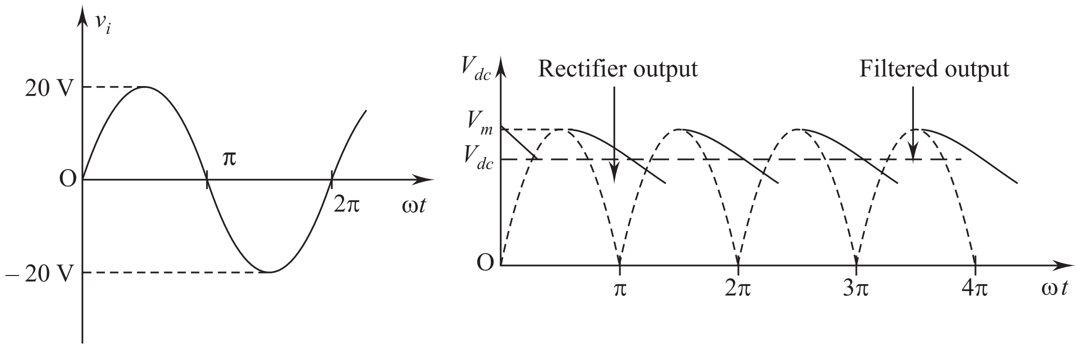
or

$$v_o = \frac{v_i}{2} = 5\,V$$

Thus, the output waveform sketch is as follows:



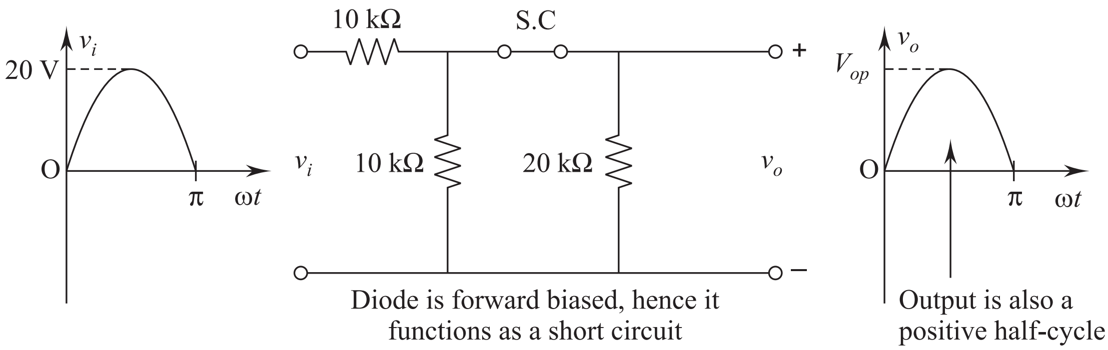
Example 2.8 Sketch the output voltage waveform for the circuit given below. Assume the diode is ideal.



(*a*) (*b*)

Solution:

(a) **For positive half-cycle**: The input waveform circuit behavior and output waveform are as follows:



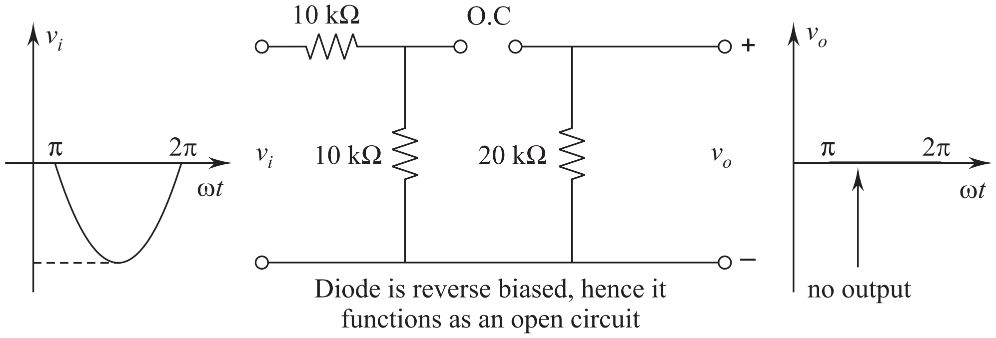
The peak value of output

$$V_{\text{op}} = 20 \times \frac{(101120)}{10 + (101120)} = 20 \times \frac{6.67}{10 + 6.67}$$

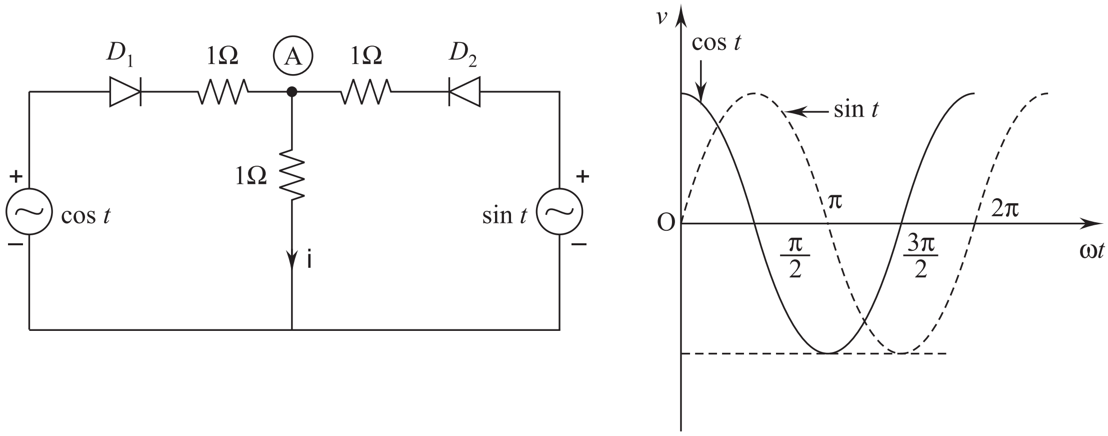
or

$$V_{\text{op}} = 8.0\,\text{volts}.$$

(b) **For negative half-cycle**: The waveforms and circuit are as follows:



Example 2.9 In the given circuit, calculate and sketch the waveform of current, over one period of the input voltage. Assume the diodes to be ideal.



Solution:
Both D_1 and D_2 diodes conduct $0 \leq \omega t \leq \frac{\pi}{2}$, where $\omega = 1$ rad./sec .
If the voltage at node is V, then by applying *KCL,* we get

$$\frac{V_A - \cos t}{1} + \frac{V_A - \sin t}{1} + \frac{V_A}{1} = 0$$

or

$$3V_A = \cos t + \sin t$$

or

$$V_A = \frac{\cos t + \sin t}{3}$$

or

$$i = \frac{V_A}{1} = \frac{\cos t + \sin t}{3} \quad \ldots(i)$$

During $\frac{\pi}{2} \leq \omega t \leq \pi$, only diode D_2 conducts as sin t is in positive half-cycle. Thus,

$$i = \frac{\sin t}{2} \quad \ldots(ii)$$

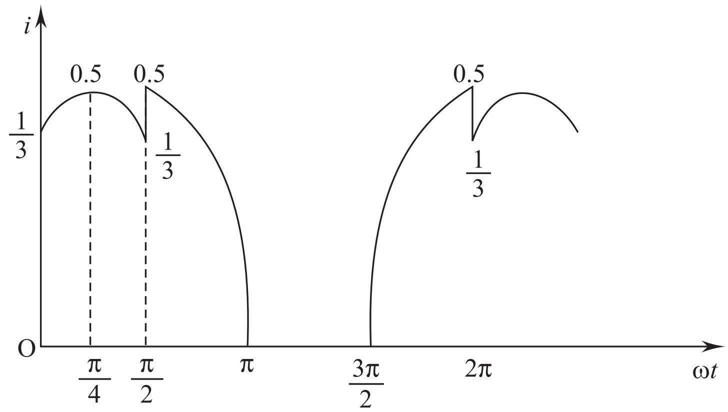
During $\pi \leq \omega t \leq \frac{3\pi}{2}$, none of the diodes conduct.

$$\therefore \qquad i = 0$$

During $\frac{3\pi}{2} \leq \omega t \leq 2\pi$, D_1 conducts and D_2 does not conduct.

$$\therefore \qquad i = \frac{\cos t}{2}.$$

The output waveform is given below:



$$i = \frac{\cos t + \sin t}{3} = \frac{\cos 0 + \sin 0}{3} = \frac{1}{3} \text{ for } \omega t = 0$$
$$= \frac{\cos\frac{\pi}{4} + \sin\frac{\pi}{4}}{3} = \frac{\frac{\sqrt{2}}{2} + \frac{\sqrt{2}}{2}}{3} = \frac{2\sqrt{2}}{2 \times 3} = 0.5 \text{ for } \omega t = \frac{\pi}{4}$$

$$i = \frac{\sin t}{2} = \frac{\sin\frac{\pi}{2}}{2} = \frac{1}{2} = 0.5 \text{ for } \omega t = \frac{\pi}{2} \text{ etc.}$$

Example 2.10 What is the ripple factor having rms value of 2 V on average of 50 V?

Solution: rms value of *ac*,

$$V_{\text{rms}} = 2$$

Average value of voltage output,

$$V_{\text{ac}} = 50\,\text{V}$$

$$\therefore \quad \text{Ripple factor} = \frac{V_{\text{rms}}}{V_{\text{dc}}} = \frac{2}{50} = 0.04$$

Example 2.11 In a power supply, the dc output voltage drops from 44 V with no-load to 42 V at full load. Calculate the percentage of voltage regulation.

Solution:
Given: No-load voltage,

$$V_{\text{NL}} = 44\,\text{V}$$

Full-load voltage, $V_{\text{FL}} = 42\,\text{V}$

$$\begin{aligned} \therefore \quad \%\ \text{Voltage regulation} &= \frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \times 100 = \frac{44 - 42}{42} \times 100 \\ &= \frac{2}{42} \times 100 \\ &= 4.76\,\%. \end{aligned}$$

2.11 Clipping Circuits

Diode **clipping circuits** or clippers separate an input signal at a particular *dc* level and pass the output without distortion, desired upper or lower portion of the original waveform. Clippers are used to eliminate amplitude noise or to fabricate new waveforms from an existing signal. There are two types of clippers—series and parallel.

A simple series clipper is a half-wave rectifier as shown in Fig. 2.18a, wherein input and output waveforms are also shown. It can be seen that the series configuration has the diode in series with load. The orientation of diode decides whether positive or negative region of the applied voltage is “clipped off.” The addition of a *dc* supply to the network has pronounced effect on the clipper output, i.e., can aid or work against the source voltage. The *dc* supply gives biasing effect. Biased series

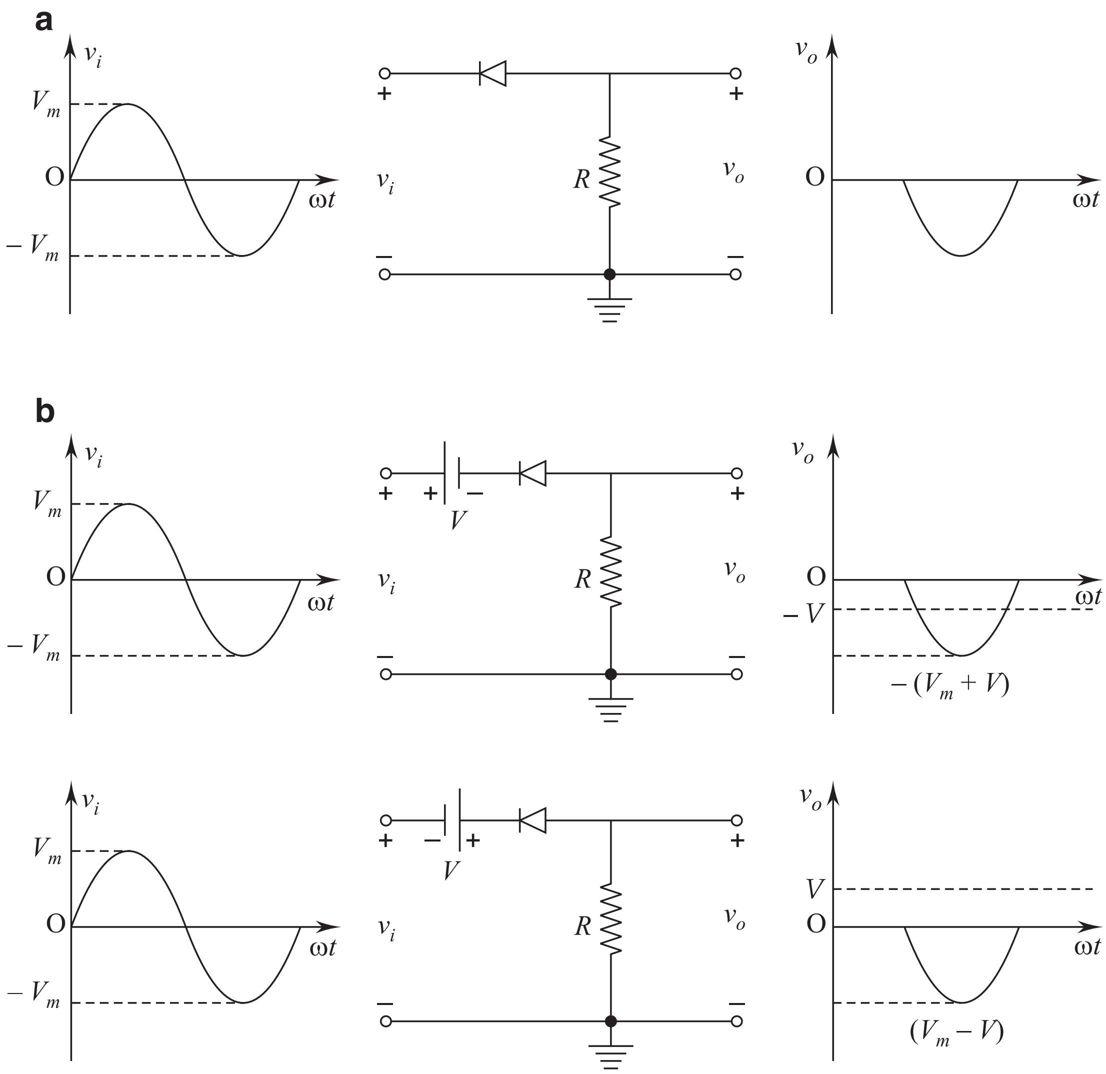


Fig. 2.18 **a** Positive simple series clipper and input/output waveforms and **b** positive biased series clipper and input/output waveforms

clippers with input and output waveforms are shown in Fig. 2.18b. A negative simple series clipper with input/output waveforms is shown in Fig. 2.19a. Negative biased series clippers with input/output waveforms are shown in Fig. 2.19b.

A parallel clipper has the diode in a branch parallel to the load. A positive simple parallel clipper with input/output waveforms is shown in Fig. 2.20a. Positive biased parallel clipper with input/output waveforms is shown in Fig. 2.20b.

A negative simple parallel clipper with input/output waveforms is shown in Fig. 2.21a. Negative biased parallel clippers with input/output waveforms are shown in Fig. 2.21b.