Semiconductor construction

1.1 Atoms

An atom is the smallest particle of an element that retains the characteristics of that element. Each known element has atoms that are different from the atoms of all other elements. This gives each element a unique atomic structure.

According to the classical Bohr model, atoms have a planetary type of structure which consists of a central nucleus surrounded by orbiting electrons. The nucleus consists of positively charged particles called proton & uncharged particles called neutron. Electrons are the basic particles of negative charge. Each type of atom has a certain number of electrons & protons that distinguishes it from the atoms of all other elements. For example, the simplest atom is that of hydrogen. It has one proton & one electron, as shown in figure 1-1(a). The helium atom, shown in figure1-1(b), has two proton & tow neutron in the nucleus orbited by tow electrons.

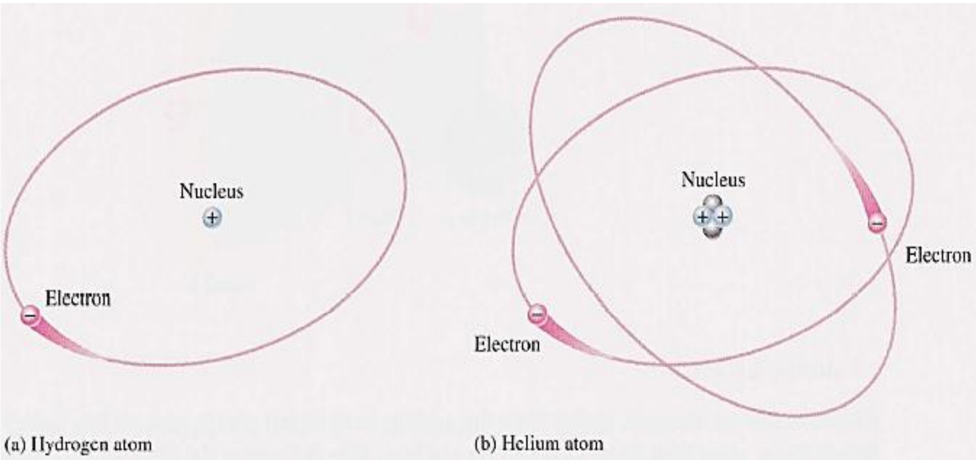


Figure 1-1 Hydrogen & helium atoms

1.2 Electron shells & Orbits

Electrons orbit the nucleus at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant orbits. It is known that discrete values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus.

Each discrete distance (orbit) from the nucleus corresponds to a certain energy level. In an atom, orbits are grouped into energy bands known as shells. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons at permissible energy levels (orbit).

The differences in energy levels within a shell are much smaller than the difference in energy between shells the shells are designated K, L, M, N & so on, with K being closest to the nucleus. This concept is illustrated in figure 1-2.

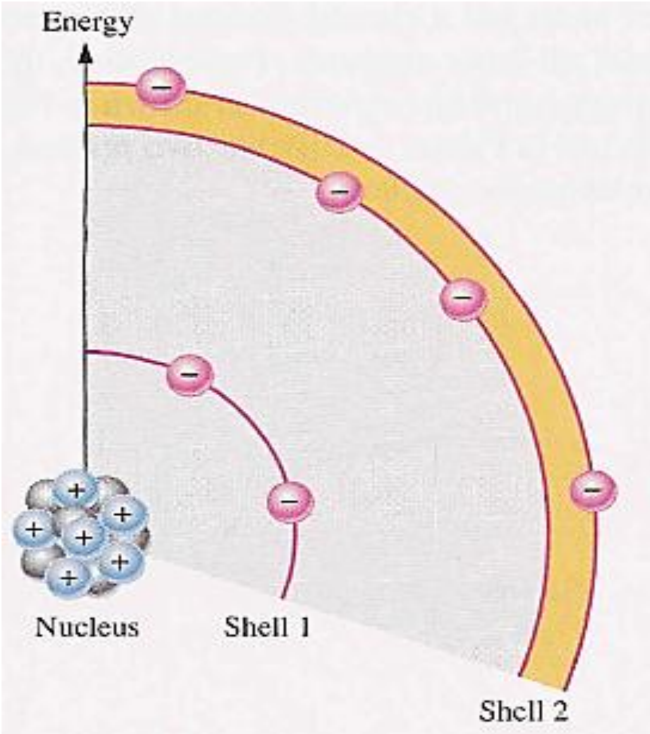


Figure 1-2 Energy levels increase as distance from nucleus increases

1. 3 Valence Electrons

Electrons in orbits farther from the nucleus are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charge nucleus & the negatively charge electron increases with decreasing distance.

Electrons with the highest energy levels exist in the outermost shell of an atom & are relatively loosely bound to the atom. These valence electrons contribute to chemical reactions & bonding within the structure of a material. The valence of an atom is the number of electrons in its outermost shell.

1.4 Ionization

When an atom absorbs energy from a heat source or from light, for example, the energy levels of the electron gains energy , it moves to an orbit farther from the nucleus . Since the valence electrons possess more energy & are more loosely bound to the atom than inner electrons, they can jump to higher orbits more easily when external energy is absorbed.

If a valence electron acquires a sufficient amount of energy, it can be completely removed from the outer shell & the atom's influence. The departure of a valence electron leaves a previously neutral atom with an excess of positive charge (more protons than electrons). The process of losing a valence electron is known as ionization & the resulting positively charged atom is called a positive ion. For example, the chemical symbol for hydrogen is H. When it loses its valence electron & become a positive ion, it is designated H^+. The escaped valence electron is called a free electron.

When a free electron falls into the outer shell of a neutral hydrogen atom, the atom becomes negatively charged (more electrons than protons) and is called a negative ion, designated H^-.

1.5 Silicon & Germanium Atoms

Two types of widely used semiconductor materials are silicon & germanium. Both the silicon & the germanium atoms have four valence electrons. They differ in that silicon has fourteen protons in its nucleus and germanium has 32. Figure 1-3 shows the atomic structure for both materials.

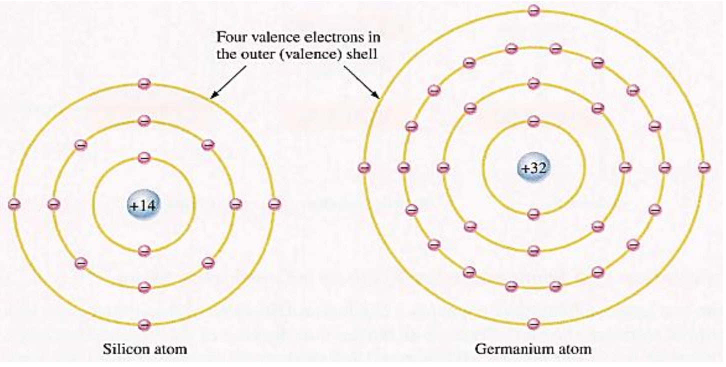


Figure 1-3 Silicon & germanium atoms

1.6 Atomic Bonding

When silicon atoms combine into molecules to form a solid material, they arrange themselves in a fixed pattern called a crystal. The atoms within the crystal structure are held together by covalent bonds, which are created by interaction of the valence electrons of each atom.

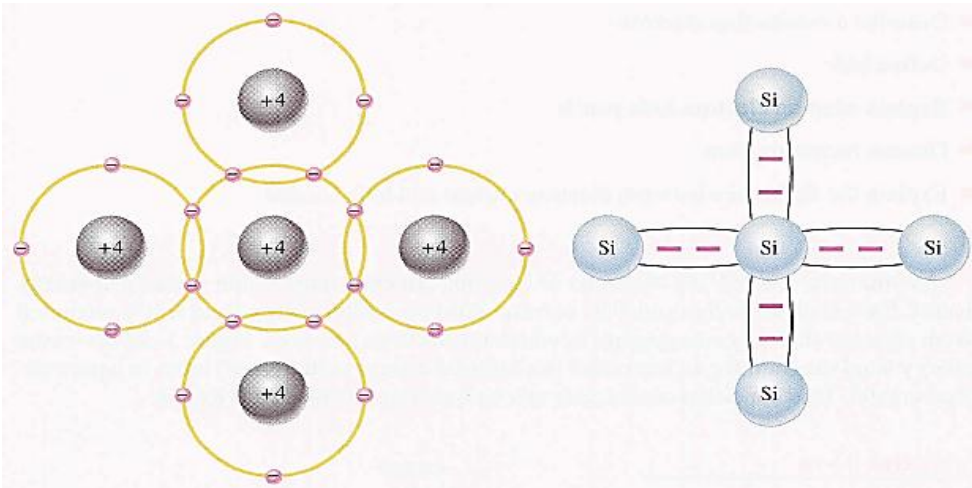


Figure 1-4 Covalent bonds in silicon

Figure 1-4 shows how each silicon atom positions itself with four adjacent atoms. Since an atom can have up to eight electrons in its outer shell, a silicon atom with its four valence electrons shares an electron with each of its four neighbors. This sharing of valence electrons shares produces the covalent bonds that hold the atoms together, because each shared electron is attracted equally by the two adjacent atoms which share it. Covalent bonding of a pure (intrinsic) silicon crystal is shown in figure 1-5. Bonding for germanium is similar because it also has four valence electrons.

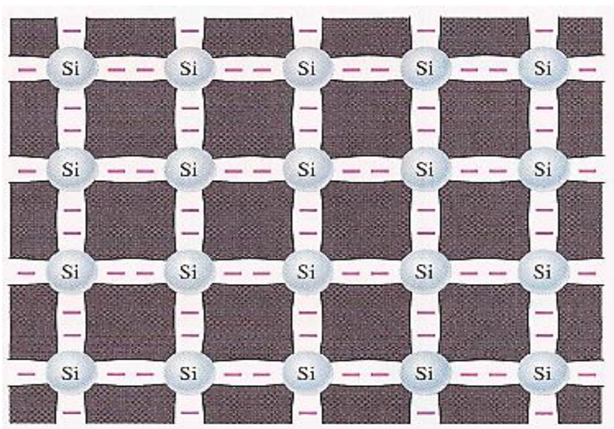
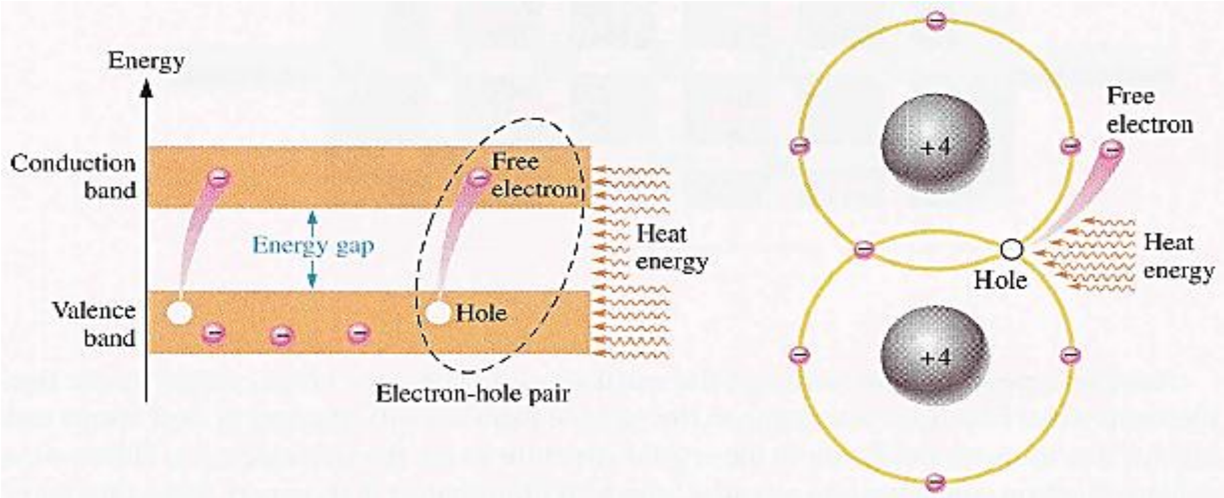


Figure 1-5 Covalent bonds in a pure silicon crystal

1.7 Conduction in Semiconductor Crystals

1.7.1 Conduction Electrons & Holes

A pure silicon crystal at room temperature derives heat (thermal) energy from the surrounding air, causing some valence electrons to gain sufficient energy to jump the gap iron the valence band into the conduction band, becoming free electrons .This is illustrated in the energy diagram of figure 1-6(a) & in the bonding diagram of figure 2-1(b)



(a) energy diagram (b) energy diagram

Figure 1-6 Conduction electrons-holes pair in an excited silicon atom

When an electron jumps to the conduction band, a vacancy is left in the valence band. This vacancy is called a hole. For every electron raised to the conduction band by thermal or light energy, there is one hole left in the valence band, creating what is called an electron-hole pair. Recombination occurs when a conduction band electron loses energy & falls back into a hole in the valence band.

There is also an equal number of holes in the valence band created when these electrons jump into the conduction band. This is illustrated in figure 1-7.

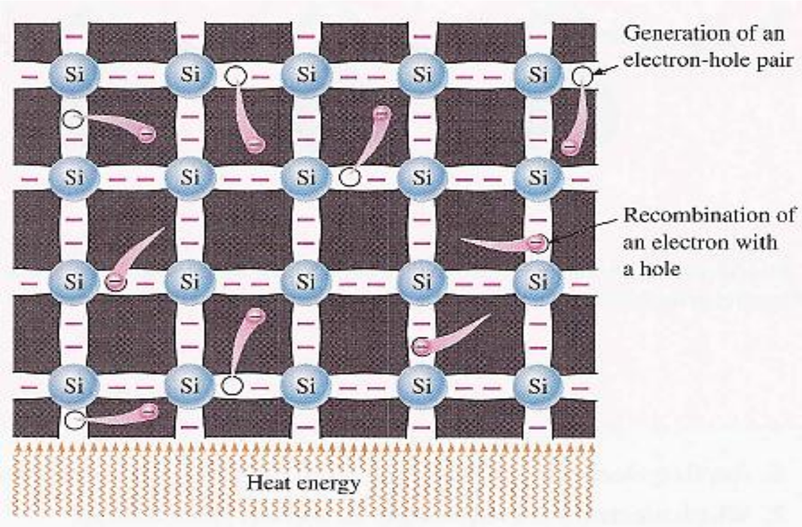


Figure 1-7 Electron-hole pairs in a silicon crystal

1.7.2 Electrons & Holes Current

When a voltage is applied across a piece of silicon, as shown in figure 1-8, the free electron in the conduction band are easily attracted toward the positive end. This movement of free electrons is one type of current in a semiconductor material, called electron current.

Another current mechanism occurs at the valence level, where the holes created by the free electrons exist. However, a valence electron can "fall" into a nearby hole, with little change in its energy level, thus leaving another hole where it came from. Effectively the hole has moved from one place to another in the crystal structure, as illustrated in figure 1-9. This is called hole current.

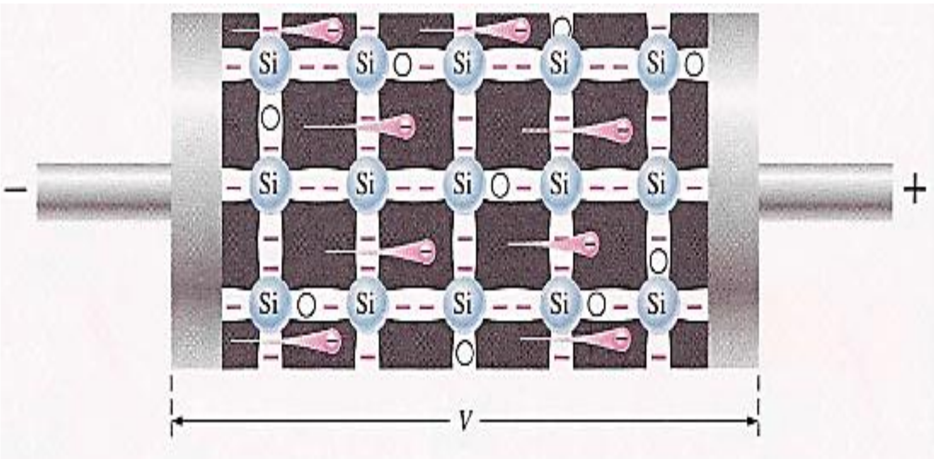


Figure 1-8 Free electron current in silicon

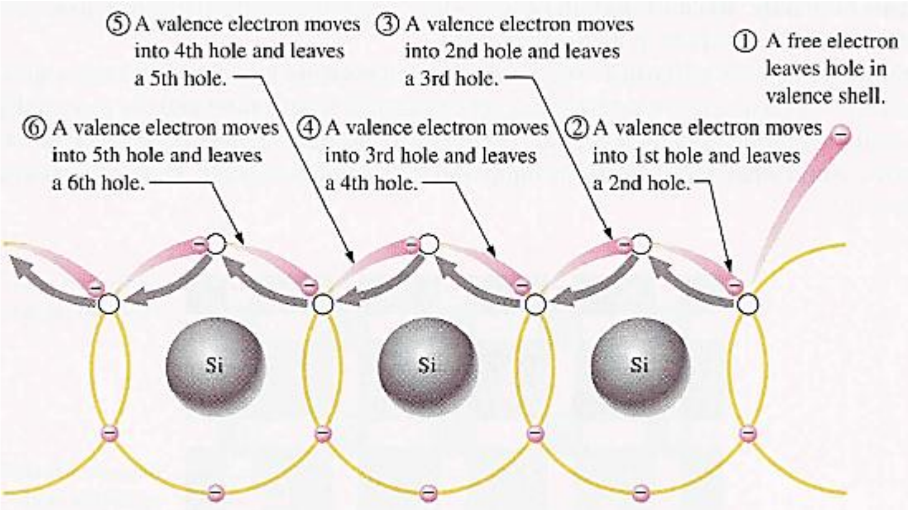


Figure 1-9 Hole current in silicon

1.8 Doping

The resistivity's of silicon & germanium can be drastically reduced and controlled by the addition of impurities to the pure semiconductor material. This process called doping, increases the number of current carriers (electrons or holes), thus increasing the conductivity & decreasing the resistivity. The two categories of impurities are n-type & p-type.

1.9 n-type semiconductor

To increase the number of conduction-band electrons in pure, pen-divalent impurity atom are added. These are atoms with five valence electrons such as arsenic, phosphorus & antimony .As illustrated in figure 1-10, each pentavalent atom (antimony, in this case) forms covalent bonds with four adjacent silicon atoms. The electrons are called the majority carriers in n-type material. Holes in an n-type material are called minority carriers.

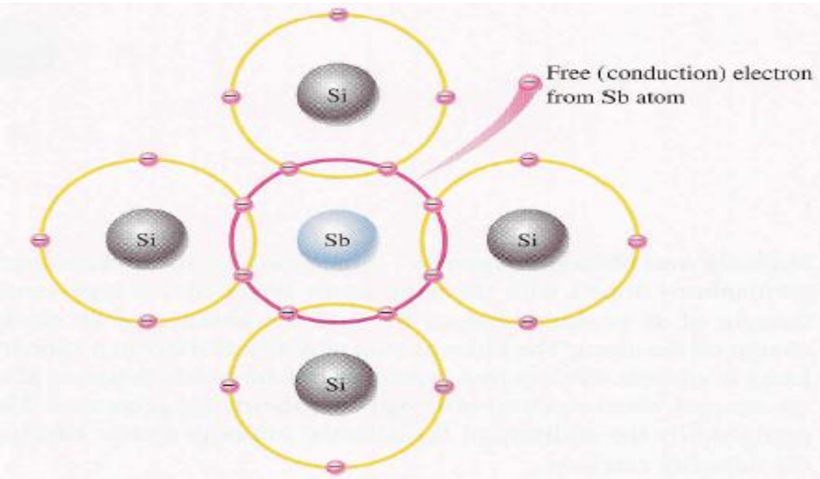


Figure 1-10 Pentavalent impurity atom in a silicon crystal

1.10 p-type semiconductor

To increase the number of holes in pure silicon, trivalent impurity atoms are added. These are atoms with three valence electrons such as aluminum, born & gallium.
As illustrated in figure 1-11, each trivalent atom (born in this case) forms covalent bonds with four adjacent silicon atoms. The number of holes can be controlled by the amount of trivalent impurity added to the silicon. Since most of the current carrier are holes, silicon (or germanium) doped in this way is called a p-type semiconductor material. The holes are the majority carriers in p-type material. Electrons in p-type material are called minority carriers.

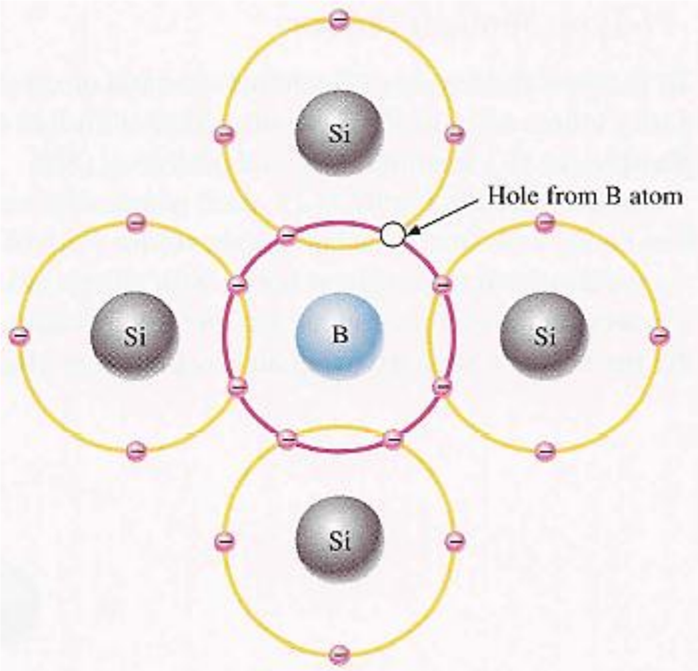


Figure 1-11 Trivalent impurity atom in a silicon crystal

1.11 Pn-junction

When a piece of silicon is doped so that half is n-type & the other half is p-type, a p-n junction is formed between the two regions, as shown in figure 1-12(a). This device is known as a semiconductor diode. The n region has many conduction electrons & the p region has many holes, as shown in figure 1-12(b)

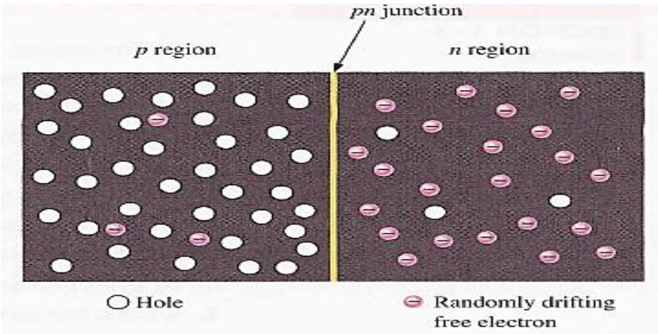


Figure 1-12 Basic pn structure at the instant of junction formation

1.12 The Depletion layer

When no external voltage, the conduction electrons in the n region are aimlessly drifting in all directions. At the instant of junction formation, some of the electrons near the junction diffuse across into the p region & recombine with holes near the junction.

As a result of this recombine process, a large number of positive & negative ions build up near the p-n junction. Thus, as the ion layer build up, area on both sides of the junction becomes essentially depleted of any conduction electrons or holes & is known as the depletion layer. This condition is illustrated in figure 1-13.

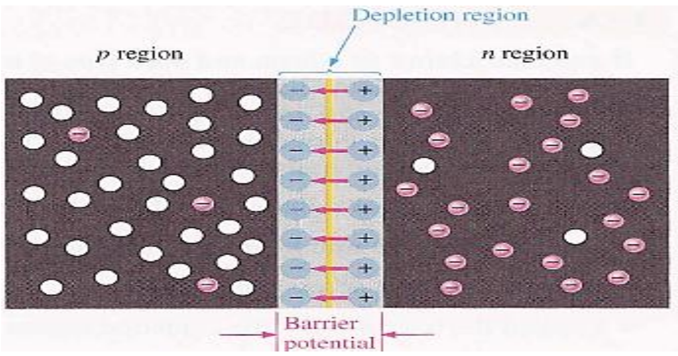


Figure 1-13 Equilibrium condition

The existence of the positive & negative ion on opposite sides of the junction creates a barrier potential (V_B) across the depletion layer, as indicated in the figure .At 25°C, the barrier potential is approximately 0.7V for silicon & 0.3V for germanium.

1.13 Biasing the pn junction

There are two bias conditions for a pn junction: forward & reverse. Either of these conditions is created by application of an external voltage of the proper polarity.

1.13.1 Forward Bias

Forward bias is the condition that permits current across a p-n junction. Figure 1-14 shows a dc voltage connected in a direction to forward-bias the p-n junction.

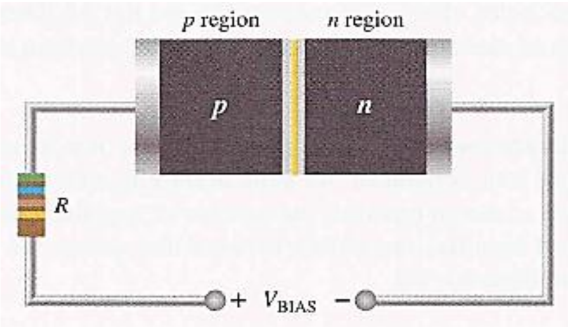


Figure 1-14 Forward-Bias Connection

The negative terminal of the battery pushes the conduction-band electrons in the n region toward the junction, while the positive terminal pushes the holes in the p region also toward the junction, the external voltage source provides the n region electrons with enough energy to penetrate the depletion layer & cross the junction, where they combine with enough the p region holes. Current through the n region is the movement of conduction electrons (majority carriers) toward the junction. One the conduction electrons enter the p region & combine with holes, they become valence electrons. They then move as valence electrons from hole to hole toward the positive connection of the battery, so, current in the p- region is the movement of holes (majority carriers) toward the junction. Figure 1-15 illustrates current in a forward-biased diode.

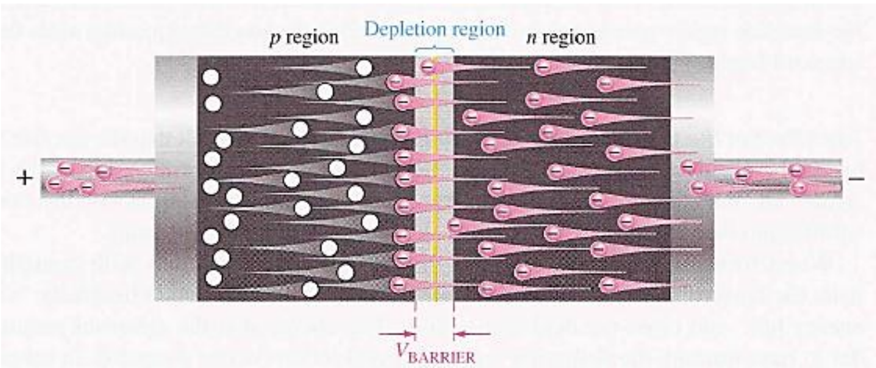


Figure 1-15 Forward current in a diode cases the depletion layer to narrow

1.13.2 The Effect of forward bias on Depletion Region

As more electrons flow into the depletion region, the number of positive ions is reduced. As more holes effectively flow into the depletion region on other side of pn junction, the number of negative ions is reduced. The reduction in positive and negative ions during forward bias causes the depletion region to narrow, as indicated in figure 1-16

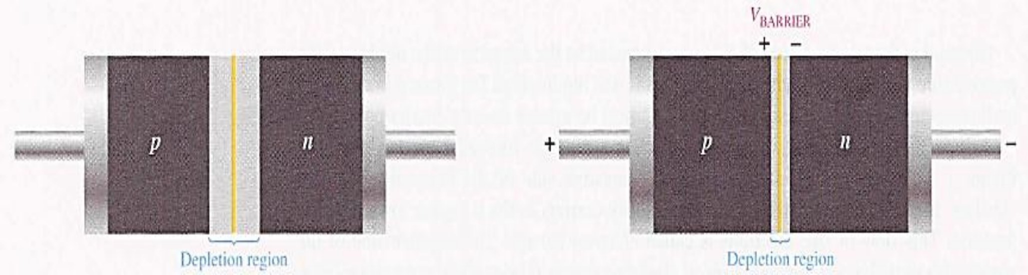


Figure 1-16 Forward bias narrows the depletion region

1.13.3 Reverse Bias

Reverse bias is the condition that prevents current across the p-n junction figure 1-17 shows a dc voltage source connected to reverse-bias the diode. The negative terminal of the battery attracts holes in the p junction, while the positive terminal also attracts electrons away from the junction, the depletion layer widens; more positive ions are created in the n region & more negative ions are created in the p region, as shown in figure 1-17??OR 1-18.

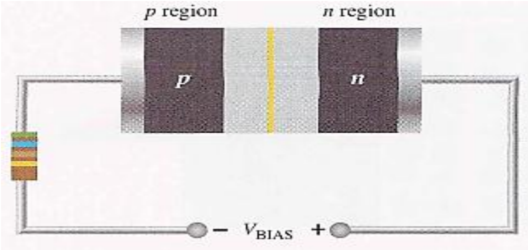


Figure 1-17 Reverse bias

The depletion layer widens until the potential difference across it equals the external bias voltage as indicated in the figure 1-18.

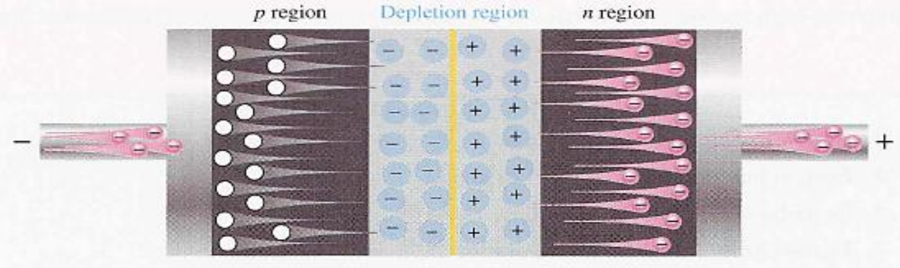


Figure 1-18 Reverse bias

1.13.4 Reverse leakage current

There is a very small leakage current produced by minority carriers during reverse bias. This current is typically in the (μA) or (nA) range. Under the influence of the external voltage, some electrons mange to diffuse across the pn junction before recombination.

The reverse leakage current is dependent primarily on the junction temperature & not on the amount of reverse-biased voltage. If the external reverse-biased voltage is increased to a large enough value, avalanche breakdown occurs. Most diode is normally not operated in reverse breakdown & can be damaged if they are. Reverse leakage current is illustrated in figure 1-19.

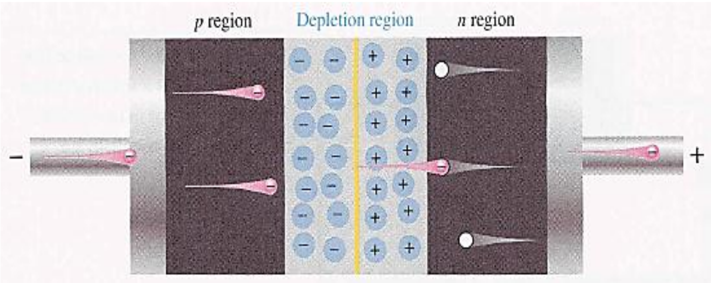


Figure 1-19 The extremely reverse current in a reverse biased

1.14 Diode Characteristic Curve

Figure 1-20 is a graph of diode current versus voltage. The upper right quadrant of the graph represent the forward-biased condition there is very little forward current for forward voltage below the barrier potential .As the forward voltage approaches the value of the barrier potential (0.7V for silicon & 0.3V for germanium), the current begins to increase .Once the forward voltage reaches the barrier potential, the current increases drastically & must be limited by a series resister .The voltage across the forward-biased diode remains approximately equal to the barrier potential.

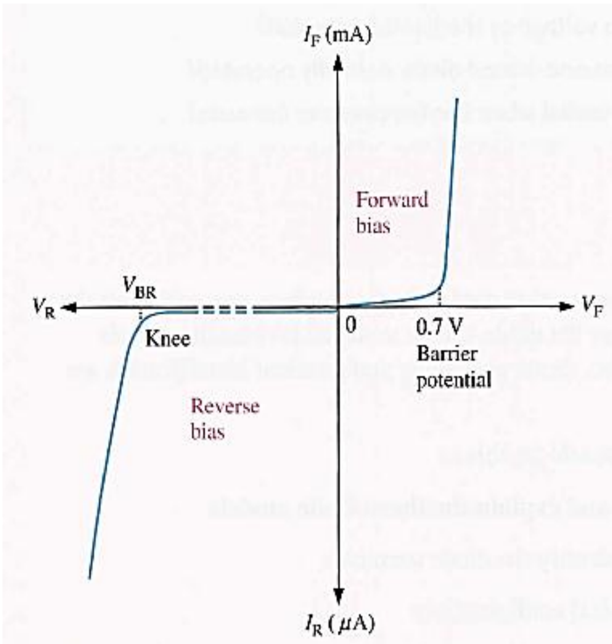


Figure 1-20 Diode characteristic curve

The lower left quadrant of the graph represent the reverse-biased condition .As the reverse voltage increases to the left , the current remains near 0 until the breakdown voltage is reached .When breakdown occurs there is a large reverse current which ,if not limited ,can destroy the diode, the breakdown voltage is greater than 50V for most rectifier diodes .

1.15 Symbol

Figure 1-21(a) and (b) is the standard schematic symbol for a rectifier diode .The arrow point in the direction of conventional current .The two terminal of diode are anode & cathode .When the anode is positive with respect to the cathode ,the diode is forward-biased & current is from anode to cathode ,as shown in figure 1-22. When the anode is negative with respect to the cathode, the diode is reverse-biased, as shown in figure 1-22. Some typical diodes are shown in figure 1-23 to illustrate the variety of physical structures.

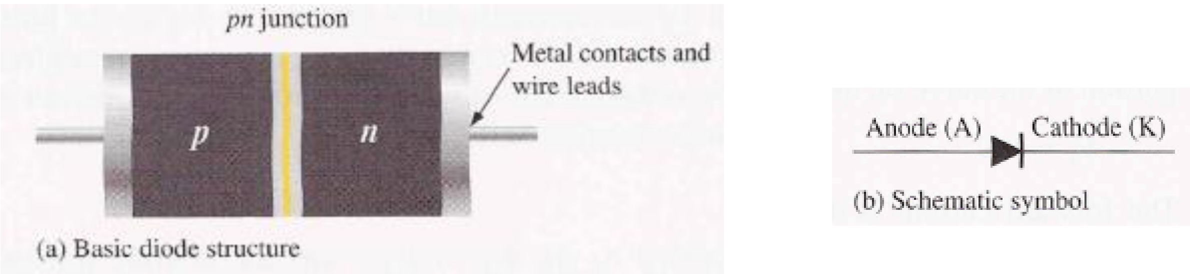


Figure 1-21 Diode structure and schematic symbol

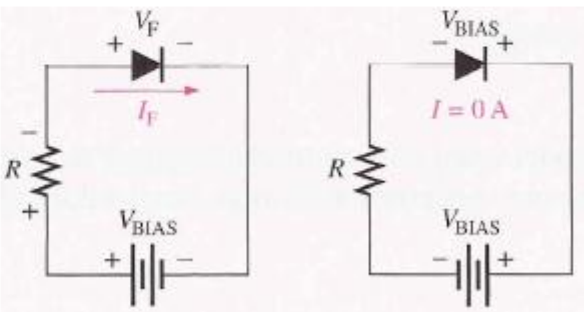


Figure 1-22 Forward bias and revers bias diode

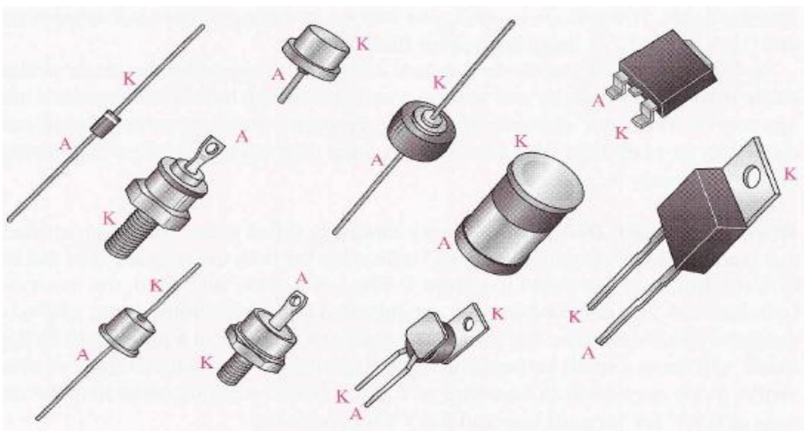


Figure 1-23 Typical diode

1.16 The Ideal Diode Model

The ideal model of a diode is a sample switch. When forward-biased, the diode acts as a closed (on) switch & when reverse-biased it acts as an open (off) switch, as figure 1-24. The characteristic curve for this approximation is also shown. Note that the forward voltage & reverse current are always 0.

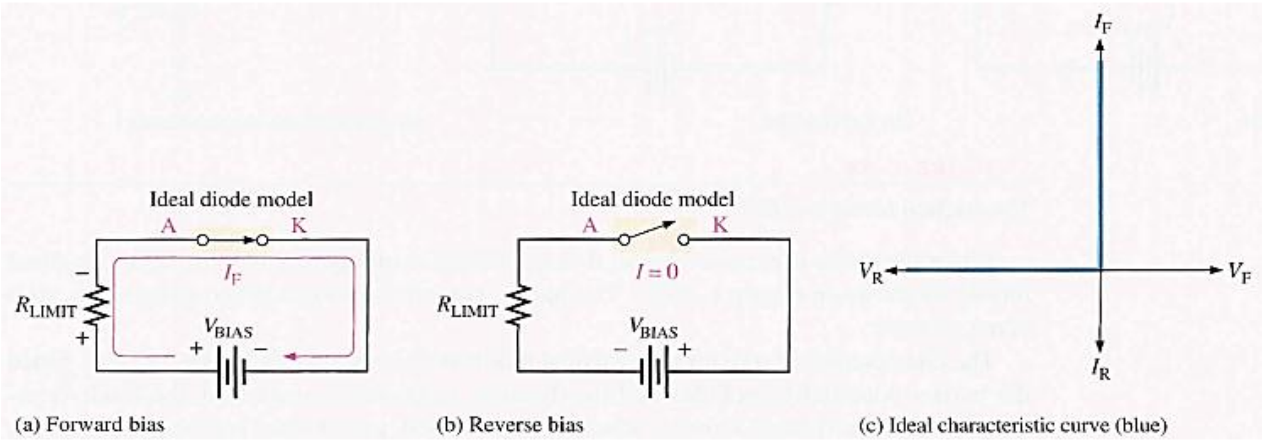


Figure 1-24 The ideal model of a diode

The forward current is determined by the bias voltage and the limiting resistor using Ohm's law

$$I_F = \frac{V_{BAIS}}{R_{LIMIT}}$$

1.17 The Practical Diode Model

The practical model adds the barrier potential to the ideal switch model, the forward-biased diode is represented as a closed switch in series with a small "battery" equal to the barrier potential V_B (0.7V for Si & 0.3V for Ge), as shown in figure 1-25.

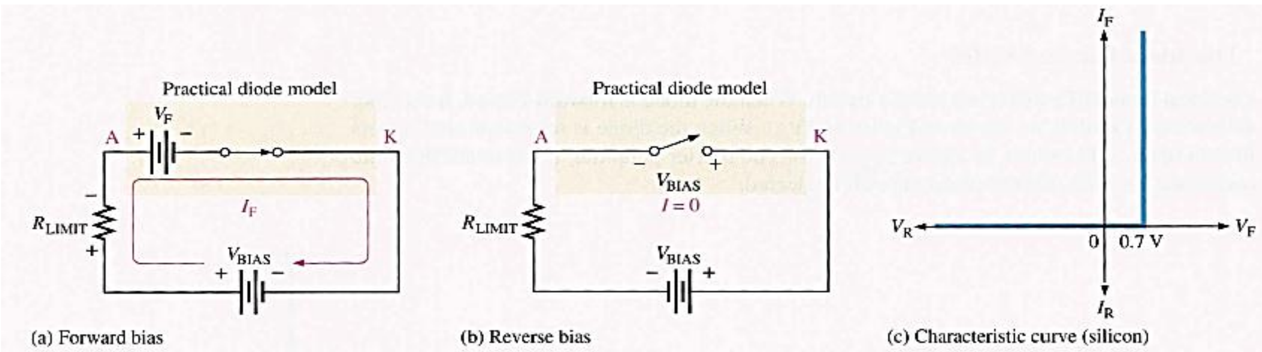


Figure 1-25 The practical model of a diode

The forward current is determined by applying Kirchhoff 's voltage law to figure 1-25

$$V_{BAIS} - V_F - V_{R_{LIMIT}} = 0$$

$$V_{R_{LIMIT}} = I_F\, R_{LIMIT}$$

Substituting and solving for I_F,

$$I_F = \frac{V_{BAIS} - V_F}{R_{LIMIT}}$$

The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis,

$$I_R = 0\ A$$

$$V_R = V_{BAIS}$$

1.18 The Complete Diode Model

The complete model of a diode consists of the barrier potential, the small forward dynamic resistance (r'_d) and the large internal resistance (r'_R).
When the diode is forward-biased, it acts as a closed switch in series with the barrier potential voltage and the small forward dynamic resistance (r'_d), as indicated in figure 1-26(a). When the diode is reverse-biased, it acts as a open switch in parallel with the large internal revers resistance (r'_R), as shown in figure 1-26(b). The barrier potential does not affect reverse bias, so it is not a factor.

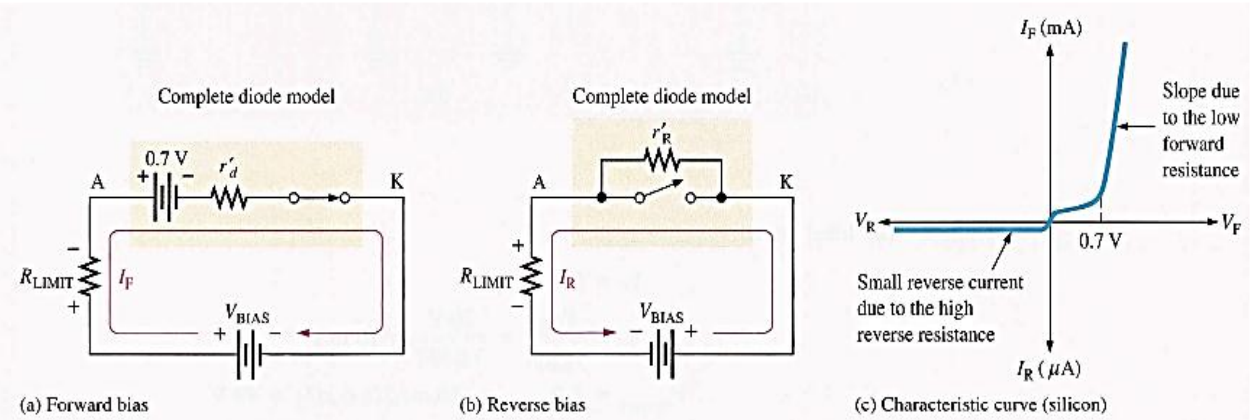


Figure 1-26 The complete model of a diode

The complete model of a silicon diode, the following formulas apply:

$$V_F = 0.7\ V + I_F r'_d$$

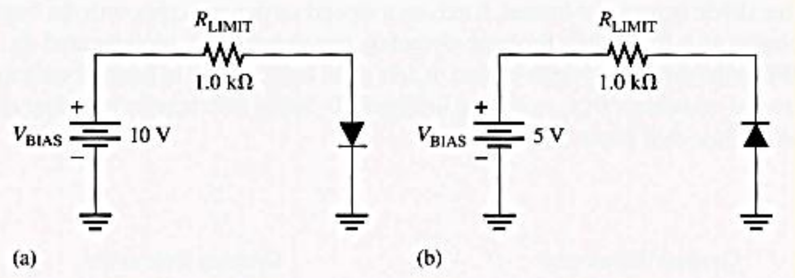
$$I_F = \frac{V_{BAIS} - 0.7\ V}{R_{LMIT} + r'_d}$$

EXAMPLE 1–1

(a) Determine the forward voltage and forward current for the diode in Figure 1–36(a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $r'_d = 10\ \Omega$ at the determined value of forward current.

(b) Determine the reverse voltage and reverse current for the diode in Figure 1–36(b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1\ \mu A$.

FIGURE 1–36



Solution **(a)** Ideal model:

$$V_F = \mathbf{0\ V}$$

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}} = \frac{10\ V}{1.0\ k\Omega} = \mathbf{10\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (10\ mA)(1.0\ k\Omega) = \mathbf{10\ V}$$

Practical model:

$$V_F = \mathbf{0.7\ V}$$

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}} = \frac{10\ V - 0.7\ V}{1.0\ k\Omega} = \frac{9.3\ V}{1.0\ k\Omega} = \mathbf{9.3\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.3\ mA)(1.0\ k\Omega) = \mathbf{9.3\ V}$$

Complete model:

$$I_F = \frac{V_{BIAS} - 0.7\ V}{R_{LIMIT} + r'_d} = \frac{10\ V - 0.7\ V}{1.0\ k\Omega + 10\ \Omega} = \frac{9.3\ V}{1010\ \Omega} = \mathbf{9.21\ mA}$$

$$V_F = 0.7\ V + I_F r'_d = 0.7\ V + (9.21\ mA)(10\ \Omega) = \mathbf{792\ mV}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.21\ mA)(1.0\ k\Omega) = \mathbf{9.21\ V}$$

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{5\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Practical model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{5\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Complete model:

$$I_R = \mathbf{1\ \mu A}$$
$$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\ \mu\text{A})(1.0\ \text{k}\Omega) = \mathbf{1\ mV}$$
$$V_R = V_{BIAS} - V_{R_{LIMIT}} = 5\ \text{V} - 1\ \text{mV} = \mathbf{4.999\ V}$$

Home Work

Choose the correct answer:-

1) The particle of an element that retains the characteristic of that element is
   a- atom b- electron c-proton
2) The basic particle of negative charge is
   a- neutron b- proton c- electron
3) The charge which must orbit only at discrete distance from the nucleus is
   a- proton b- electron
4) The silicon has in its nucleus
   a- 32 protons b- 14 protons c- 16 protons

Circle the correct answer:-

1) Each orbit from the nucleus corresponds to a certain
   a- number of protons b- number of electrons c- energy level
2) When an external energy is absorbed the electrons can jump to
   a- lower orbits b- higher orbits
3) The silicon atom have at its valence orbit
   a- 6 electrons b- 4 electrons c- 14 electrons
4) The atoms within the crystal structure are held together by
   a- atomic banding b- valence bonding c- covalent bonds

Choose the correct answer:-

1) For every electron raised to the conduction band, there is -- left in the valence band.
   a- two holes b- one holes c- three holes
2) The movement of free electrons in the ------ is called electron current
   a- valence level b- conduction band
3) Increases the number of current carriers, thus increasing the ------
   a- resistivity b- conductivity
4) The electrons are called the majority carriers in
   a- p-type b- n-type

Circle the correct answer:-

1) Holes in n-type material are called

   a- minority b-carriers c- majority

2) Since most of the current carriers are holes, silicon doped in this way is called

   a- p-type b- n-type

3) Electrons in p-type material are called

   a- minority curriers b- majority curriers

Choose the correct answer:-

1) At forward bias of pn-junction the region which is connected to negative terminal of the battery is (a- n-region b- p-region).
2) When the pn-junction is forward biased the negative terminal of the battery pushes the ---------- in the n-region toward the junction (a- holes b- electron).
3) For forward biasing pn-junction, the electrons move as------ toward the positive connection of the battery enter the p-region (a- valence electrons b- conduction electron).
4) The external bias voltage must overcome the-----before the diode conducts (a- n-region b- p-region c- barrier potential).

Choose the correct answer:-

1) The depletion layer is build up by

   a- conduction electrons b- valence electrons c- Ions
2) The positive terminal of the battery pushes the-----in the p-region toward the junction at toward biasing the pn-junction

   a- holes b- electron c- Ions
3) For the reverse bias of pn-junction the negative terminal of the battery attracts------ in the p-region away from the pn-junction

   a- Ions b- conduction electrons c- holes
4) Very small leakage current produced by---------carrier during reverse bias pn-junction

   a- minority curriers b- majority curriers

Choose the correct answer:-

1) The voltage across the forward bias diode remain approximately equal to the

   a- barrier potential b- drop voltage of bulk-resister

2) The arrow point in the standard schematic symbol of the diode is in the direction of

   a- reverse current b- forward current

3) The barrier potential of silicon diode is

   a- 0.3V b- 0.7V c- 0.9V

4) The average value of the output for half-wave rectifier is equal to

   a- $3V_{P}/\pi$ b- $2V_{P}/\pi$ c- V_{P}/π

Choose the correct answer:-

1) The PIV occurs at the peak of the half-cycle when the diode is

   a- forward-biased b- reverse-biased

2) The reverse voltage of the silicon diode must be less than

   a- barrier potential b- break-down voltage

3) When the anode is positive with respect to the cathode, the diode is

   a- forward-biased b- reverse-biased

Diode Applications

2-1 The Basic DC Power Supply

The dc power supply converts the standard 110 V, 60 Hz ac available at wall outlets into a constant dc voltage.

Basic block diagrams for a rectifier and complete power supply are shown in figure 2-1. The **rectifier** can be either a half-wave rectifier or a full-wave rectifier. The rectifier converts the ac input voltage to a pulsating dc voltage, which is half-wave rectified as shown in Figure 2-1(a). A block diagram for a complete power supply is shown in part (b). The filter eliminates the fluctuation in the rectified voltage and produces a relatvely smooth dc voltage. The regulator is the circuite that maintains a constant dc voltage for a variations in the input line voltage or in the load. Regulator vary from a single device to more complex integrated circuits. The load is a circuit or device for which the power supply is prproducing the dc voltage and load current.

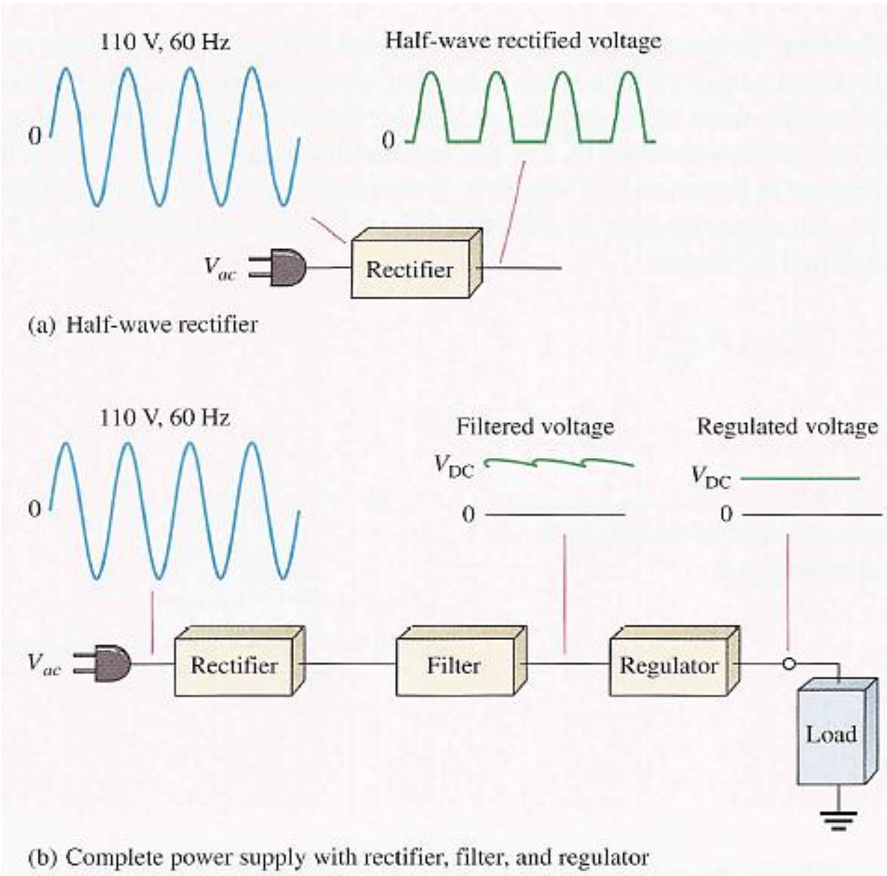


Figure 2-1 Block diagram of a rectifier and dc power supply with a load

2-2 The Half-Wave Rectifier

Rectification is the process of converting ac to pulsating dc. In Figure 2-2, an AC source is connected to a load resister through a diode, when the sine wave goes positive , the diode is forward-biased and conducts current to the load resister ,as shown in part (a). The current develops a voltage across the load which has the same shape as the positive half-cycle of the input voltage.

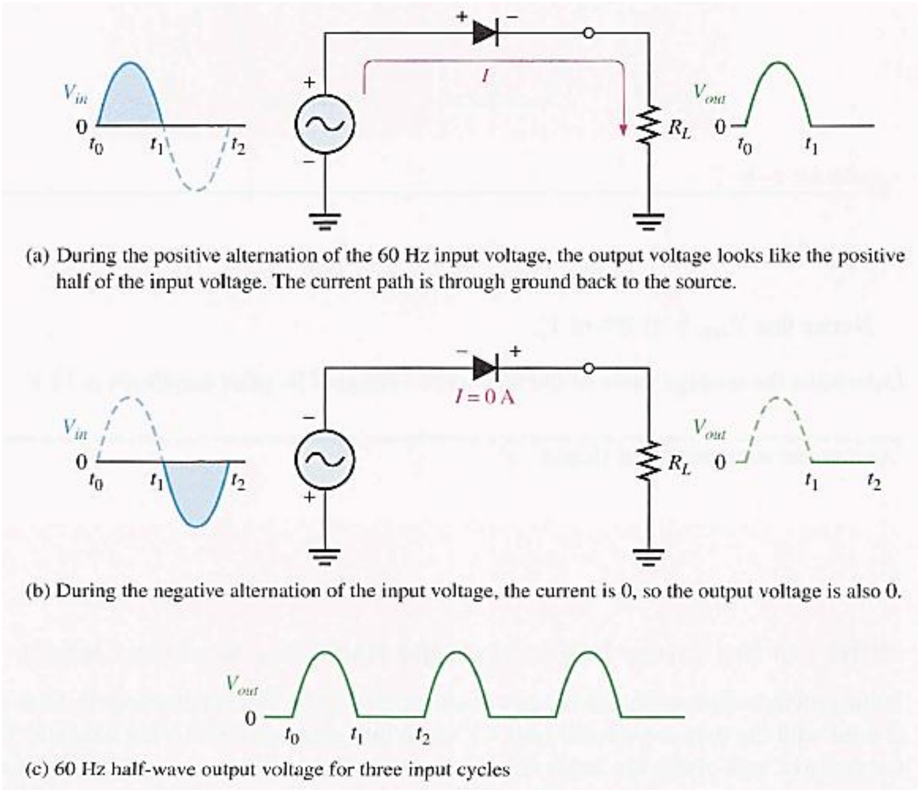


Figure 2-2 Half –Wave Rectifier

When the input goes negative during the second half-cycle, the diode is reverse-biased. There is no current, so the voltage across the load resister is 0, as shown in part (b). The net result is that only the positive half-cycle of the input appear across the load, making the output a pulsing dc voltage as shown in part (c).

2-2-1 Average value of Half –Wave Output Voltage

The average (dc) value of half-wave rectifier output voltage is determine by finding the area under the curve over a full cycle, as in Figure 2-3 we get :

$$V_{AVG} = area/period = 2V_P/2\pi$$

Where V_P is the peak voltage.

$$\boxed{V_{AVG} = \frac{V_P}{\pi}}$$

The average value is the value that would be indicated by a dc voltmeter.

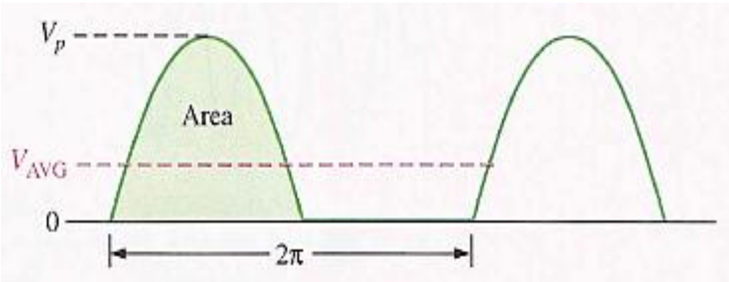
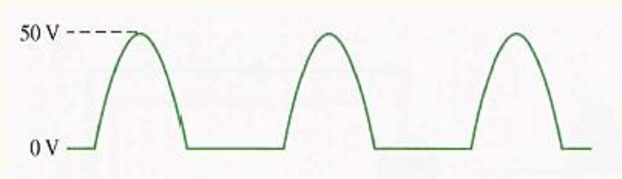


Figure 2-3 average value of Half –Wave Rectifier

EXAMPLE 2–1

What is the average value of the half-wave rectified voltage in Figure 2–4?



▲ FIGURE 2–4

Solution

$$V_{AVG} = \frac{V_p}{\pi} = \frac{50\text{ V}}{\pi} = \mathbf{15.9\text{ V}}$$

Notice that V_{AVG} is 31.8% of V_p.

2-2-2 Effect Barrier potential of Half –Wave Rectifier Output

During the positive half-cycle, the input voltage must overcome the barrier potential before the diode becomes forward-biased, as shown in Figure 2-4.

$$\boxed{Vp_{(out)} = Vp_{(in)} - 0.7\ V}$$

For silicon, and

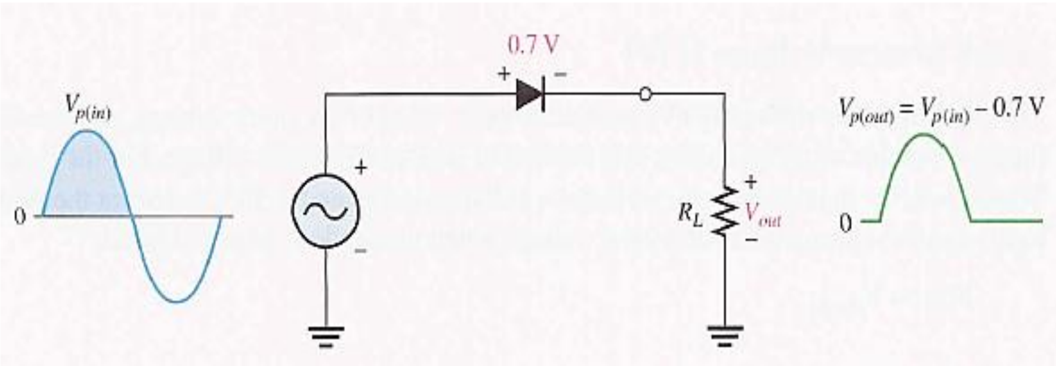
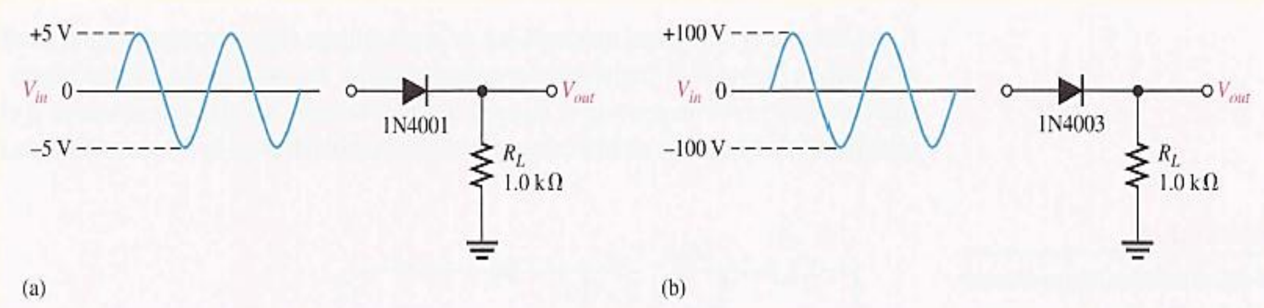


Figure 2-4 Effect Barrier potential of Half –Wave Rectifier Output

EXAMPLE 2–2

Draw the output voltages of each rectifier for the indicated input voltages, as shown in Figure 2–6. The 1N4001 and 1N4003 are specific rectifier diodes.



▲ **FIGURE 2–6**

Solution The peak output voltage for circuit (a) is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 5\text{ V} - 0.7\text{ V} = \mathbf{4.30\text{ V}}$$

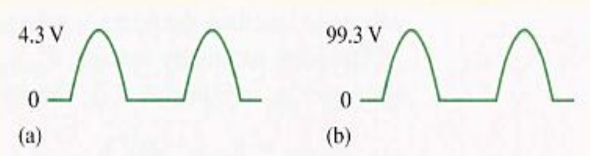
The peak output voltage for circuit (b) is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 100\text{ V} - 0.7\text{ V} = \mathbf{99.3\text{ V}}$$

The output voltage waveforms are shown in Figure 2–7. Note that the barrier potential could have been neglected in circuit (b) with very little error (0.7 percent); but, if it is neglected in circuit (a), a significant error results (14 percent).

▶ **FIGURE 2–7**

Output voltages for the circuits in Figure 2–6. Obviously, they are not shown on the same scale.



2-2-3 Maximum Reverse Voltage

The maximum value of reverse voltage, sometimes designated as peak inverse voltage (PIV), occurs at the negative alternation of the input cycle when the diode is reversed-biased. This condition is illustrated in Figure 2-5. The PIV equals the peak value of the input voltage.

$$\boxed{PIV = Vp_{(in)}}$$

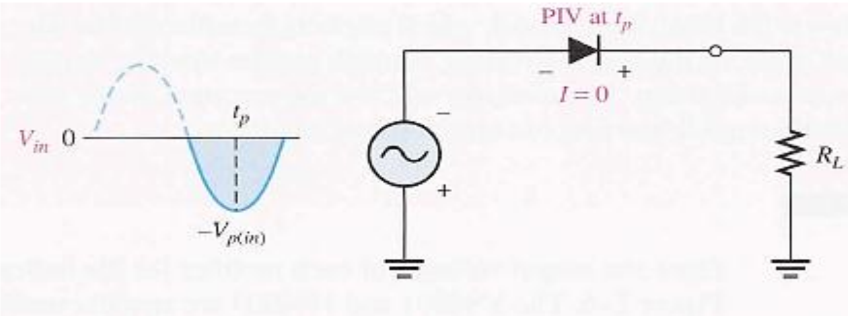


Figure 2-5 The* PIV *occurs at the peak of the half-cycle

2-2-4 Half-Wave Rectifier with Transformer-Coupled Input Voltage

A transformer is often used to couple the ac input voltage from the source to the filter, as shown in Figure 2-6. Transformer coupling provides two advantages. First, it allows the source voltage to be stopped up or stepped down as needed. Second, the ac source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.

The turn's ratio will be defined as the ratio of secondary terns N_{sec} to primary turns, N_{pri}: $n = N_{sec}/N_{pri}$,

$$\boxed{V_{sec} = n\, V_{pri}}$$

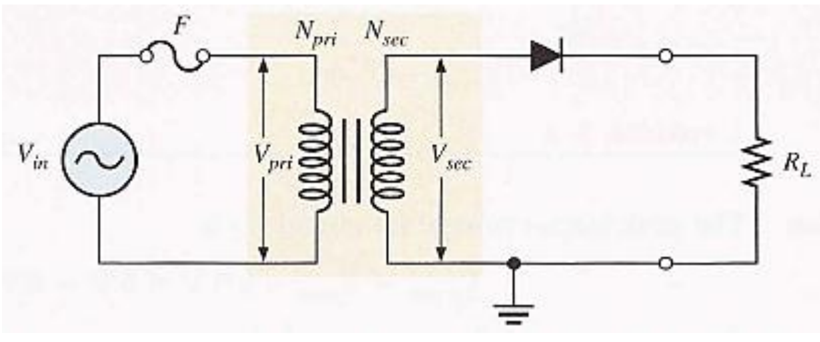


Figure 2-6 Half-Wave Rectifier with Transformer

The peak secondary voltage, $V_{p(sec)}$ in a transformer-coupled half-wave rectifier is the same as $V_{p(in)}$

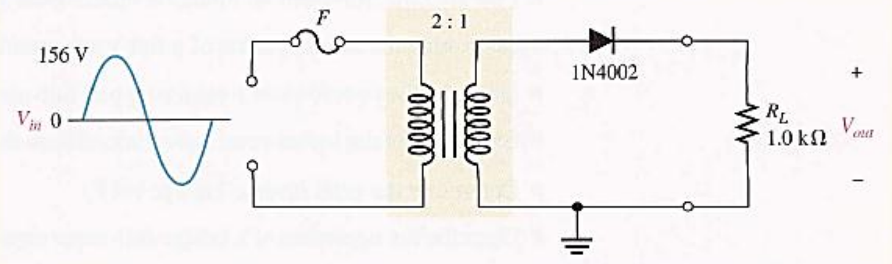
$$Vp_{(out)} = Vp_{(sec)} - 0.7 \text{ V}$$

and $\text{PIV} = Vp_{(sec)}$

EXAMPLE 2–3

Determine the peak value of the output voltage for Figure 2–10 if the turns ratio is 0.5.

FIGURE 2–10



Solution

$$V_{p(pri)} = V_{p(in)} = 156\ \text{V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.5(156\ \text{V}) = 78\ \text{V}$$

The rectified peak output voltage is

$$V_{p(out)} = V_{p(sec)} - 0.7\ \text{V} = 78\ \text{V} - 0.7\ \text{V} = \mathbf{77.3\ V}$$

where $V_{p(sec)}$ is the input to the rectifier.

2-3 Full–Wave Rectifiers

A full-wave rectifier allows unidirectional (one-way) current through the load during the entire 360° of the input cycle, whereas a half-wave rectifier allows current through the load during one-half of the cycle. The result of full-wave rectification is an output voltage with a frequency twice the input frequency that pulsates every half-cycle of the input, as shown in Figure 2-7

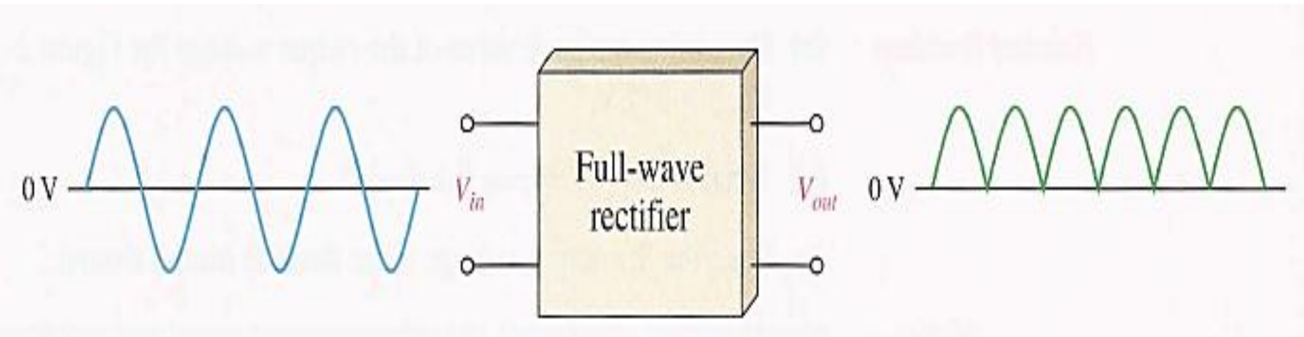


Figure 2-7 Full–Wave Rectifier

The average value for full–wave rectifier voltage is twice that of the half- wave is:-

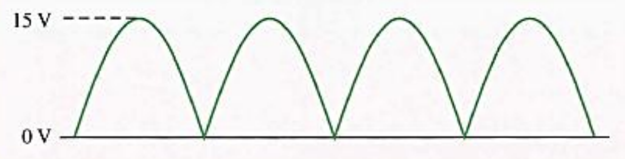
$$\boxed{V_{AVG} = \frac{2V_P}{\pi}}$$

V_{AVG} is approximately 63.7% of V_P for a full-wave rectifired voltage.

EXAMPLE 2–4

Find the average value of the full-wave rectified voltage in Figure 2–12.

FIGURE 2–12



Solution

$$V_{AVG} = \frac{2V_p}{\pi} = \frac{2(15\text{ V})}{\pi} = \mathbf{9.55\ V}$$

V_{AVG} is 63.7% of V_p.

2-4 Center-tapped Full–Wave Rectifier

A Center Rectifier is a type of full-wave rectifier that uses two diodes connected to the secondary of a center-tapped transformer, as shown in Figure 2-8. The input voltage is coupled through the transformer to the center-tapped secondary. Half of total secondary voltage appears between the center tap and each end of the secondary winding as shown.

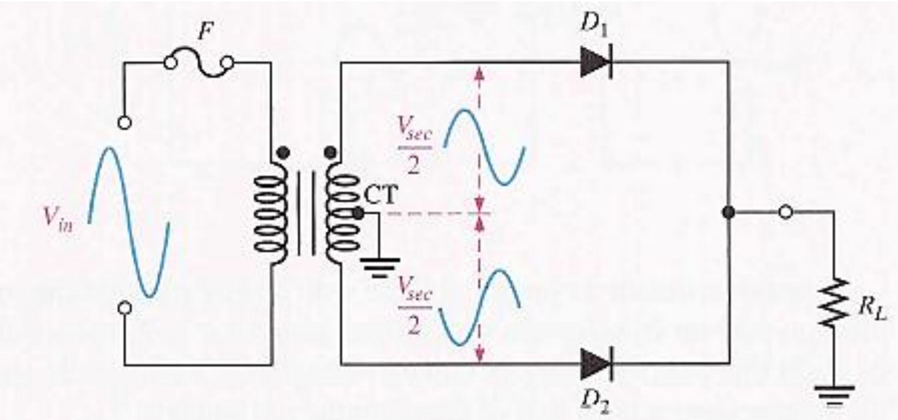


Figure 2-8 Center-tapped Full–Wave Rectifier

For a positive half-cycle of the input voltage, the polarities of the secondary voltages are shown in Figure 2-9 (a) this condition forward-biased the upper diode D_1 and reverse-biased the lower diode D_2.

For a negative half-cycle of the input voltage the voltage polarities of the secondary voltages are shown in Figure 2-9 (b) this condition reverse-biased the upper diode D_1 and forward-biased the lower diode D_2. Because the output current during both the positive and negative portions of the input cycle is in the same direction through the load, the output voltage developed across the load resistor is a full-wave rectified dc voltage, as shown.

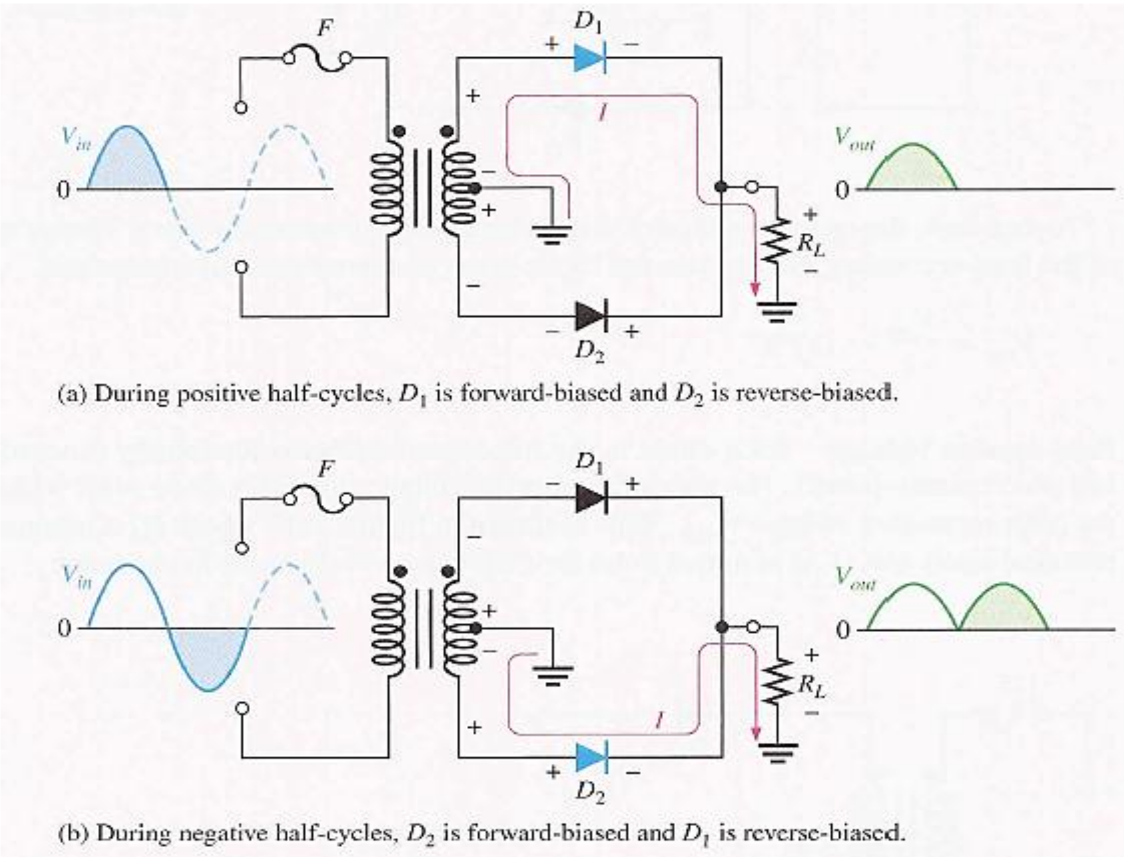


Figure 2-9 Operation of Center-tapped Full–Wave Rectifier

2-4-1 Effect of the Turns Ratio on Full–Wave Output Voltage

If the transformer turns ratio is one, the peak value of the rectified output voltage equals half the peak value of the primary input voltage less the barrier potential (diode drop), as illustrated in Figure 2-10. In order to obtain an output voltage equal to the input (less the barrier potential), as step-up transformer with a turns ratio of one-to-two must be used, as shown in figure 2-11. In any case, the output of a center-tapped full-wave is always one-half of the total secondary voltage, no matter what the turn's ratio is:

$$\boxed{V_{out} = \frac{V_{sec}}{2} - 0.7\ V}$$

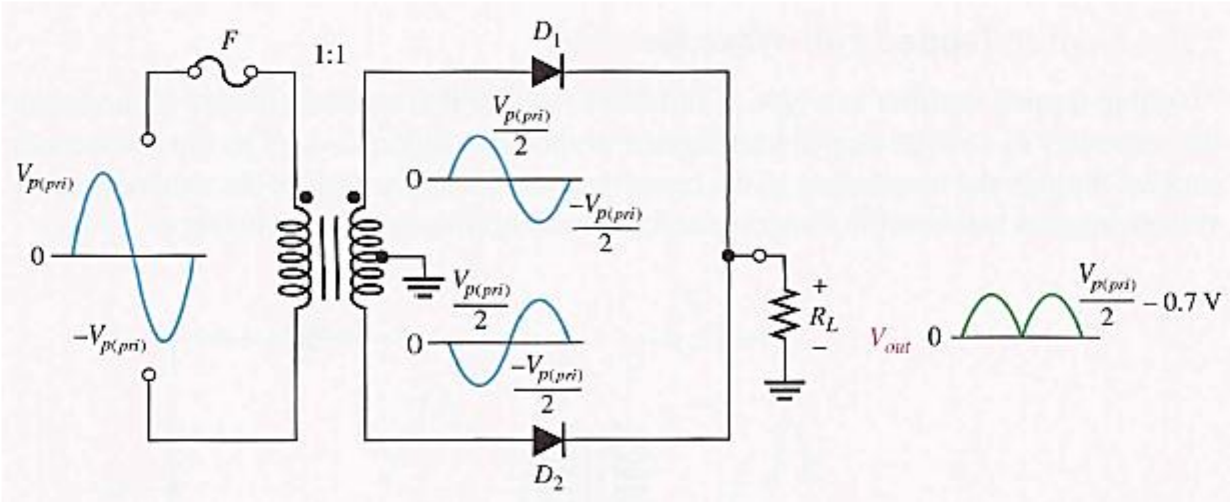


Figure 2-10 Center-tapped Full–Wave Rectifier with a transformer turns ratio of 1

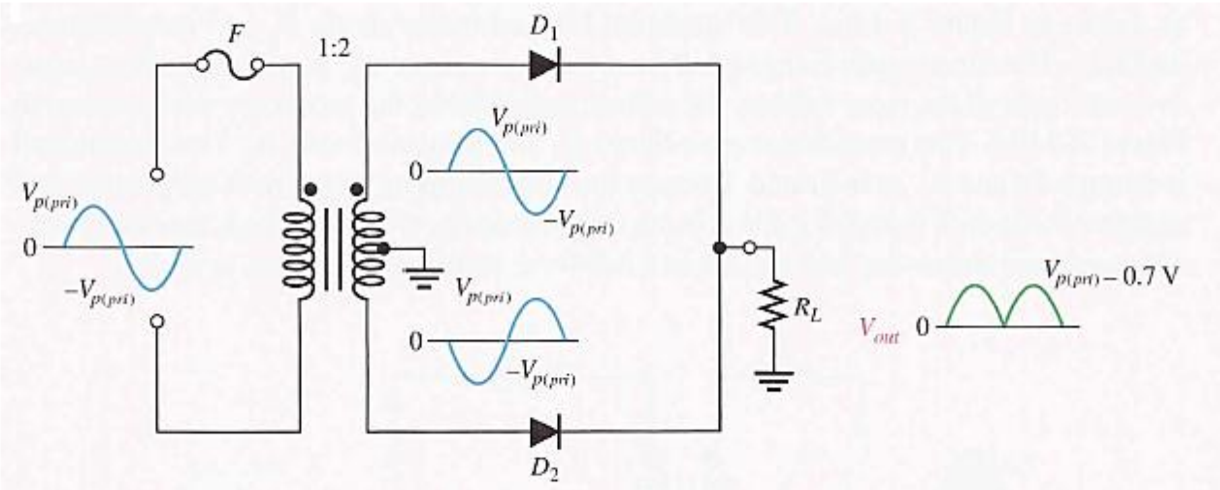


Figure 2-11 Center-tapped Full– Wave Rectified with a transformer turns ratio of 2

2-4-2 Peak Inverse voltage

Each diode in the full-wave rectifier is alternately forward-biased & then reverse-biased. The max reverse voltage that each diode must withstand is the peak secondary voltage $V_{P(\text{sec})}$. This can be examining Figure 2-12:

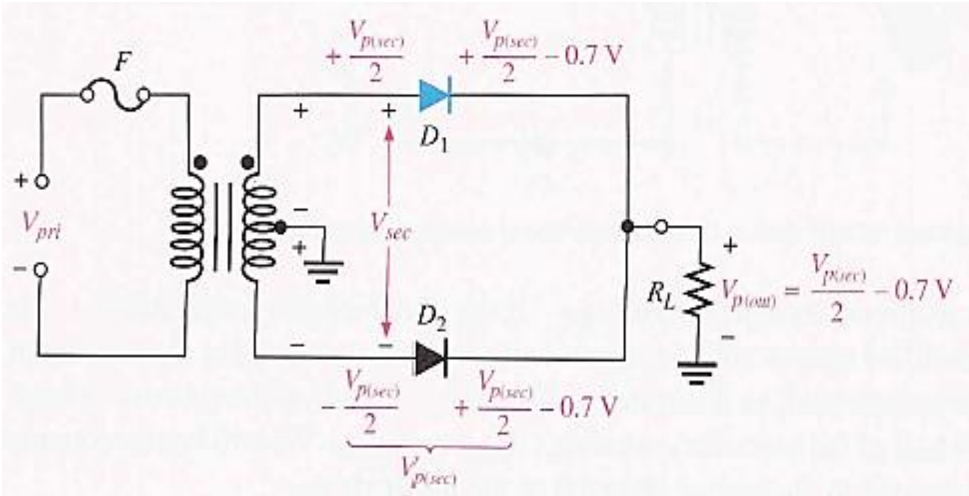


Figure 2-12 Diode reverse voltage (D2 shown reverse-biased)

$$\text{PIV} = \left(\frac{V_{P(\text{sec})}}{2} - 0.7\ \text{V}\right) - \left(-\frac{V_{P(\text{sec})}}{2}\right) = \frac{V_{P(\text{sec})}}{2} + \frac{V_{P(\text{sec})}}{2} - 0.7\ \text{V}$$

$$= V_{P(\text{sec})} - 0.7\ \text{V}$$

Since $V_{P(\text{out})} = V_{P(\text{sec})}/2 - 0.7$ V, then by multiplying each tearm by 2 and transposing,

$$V_{P(\text{sec})} = V_{P(\text{out})} + 1.4\ \text{V}$$

Therfore, by substitution, the peack inverse voltage across either diode in a full-wave center-tapped rectifier is

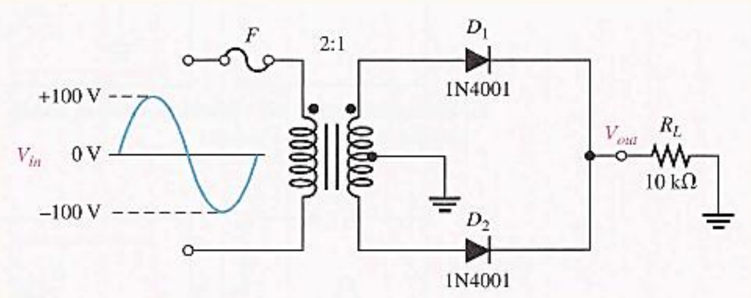
$$\boxed{PIV = 2V_{P(out)} + 0.7\ V}$$

EXAMPLE 2–5

(a) Show the voltage waveforms across each half of the secondary winding and across R_L when a 100 V peak sine wave is applied to the primary winding in Figure 2–18.

(b) What minimum PIV rating must the diodes have?

FIGURE 2–18

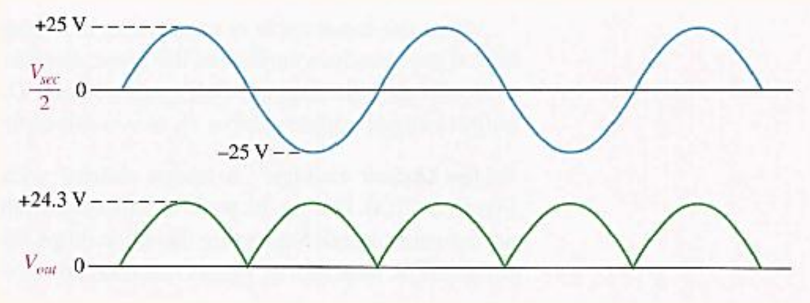


Solution (a) The transformer turns ratio $n = 0.5$. The total peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.5(100\text{ V}) = 50\text{ V}$$

There is a 25 V peak across each half of the secondary with respect to ground. The output load voltage has a peak value of 25 V, less the 0.7 V drop across the diode. The waveforms are shown in Figure 2–19.

▶ FIGURE 2–19

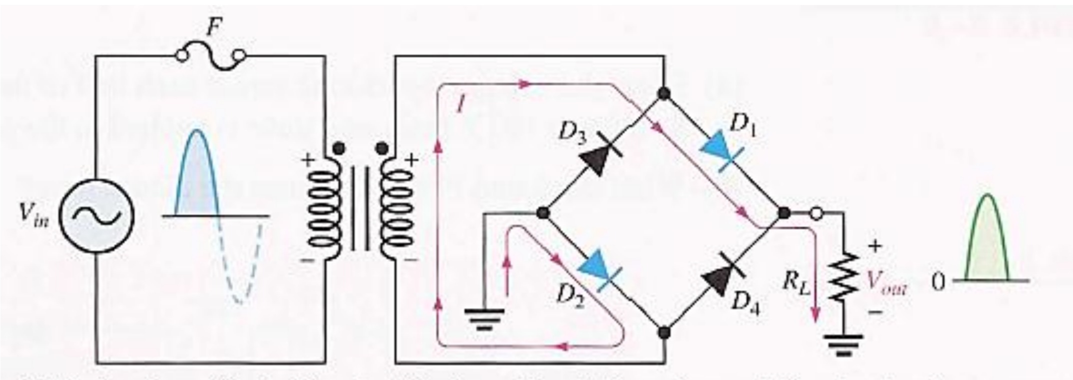


(b) Each diode must have a minimum PIV rating of

$$\text{PIV} = 2V_{p(out)} + 0.7\text{ V} = 2(24.3\text{ V}) + 0.7\text{ V} = \mathbf{49.3\text{ V}}$$

2-5 Full–Wave Bridge Rectifier

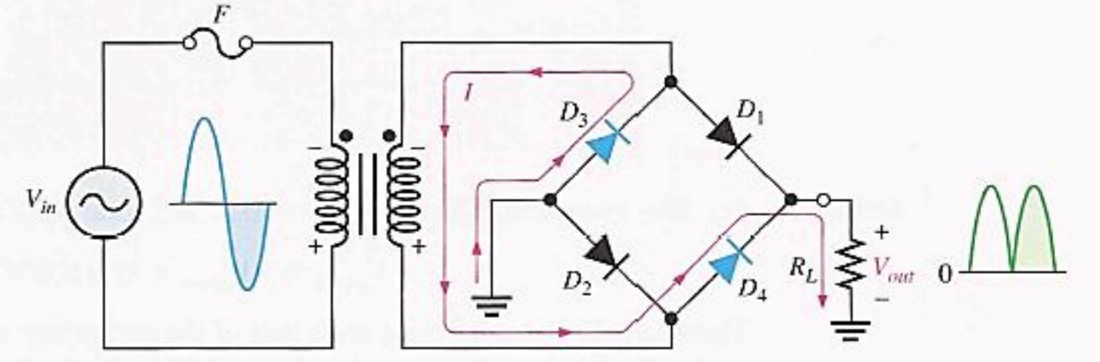
This type of full-wave rectifier uses four diode, as shown in figure 2-12 (a). When the input cycle is positive as in part (a), diodes D_1 and D_2 are forward-biased and conduct current in the direction shown. A voltage is developed across R_L which looks like the positive half of the input cycle. During this time D_3 and D_4 are reverse-biased.



(a) During the positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.

Figure 2-12 (a) Bridge Rectifier operation

When the input cycle is negative as in Figure 2-12 (b), diodes D_3 and D_4 are forward-biased and conduct current in the same direction through R_L as during the positive half-cycle. During the negative half-cycle D_1 and D_2 are reverse-biased. A full-wave rectifier output voltage appears across R_L as a result of this action.



(b) During the negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

Figure 2-12 (b) Bridge Rectifier operation

2-5-1 Bridge Output Voltage

A bridge rectifier with a transformer-coupled input is shown in Figure 2-13 (a). During the positive half-cycle of total secondary voltage, diodes D_1 and D_2 are forward-biased. Neglecting the diode drops, the secondary voltage appears across the load resistor. The same is true when D_3 and D_4 are forward-biased during the negative half-cycle.

$$V_{P(\text{out})} = V_{P(\text{sec})}$$

In Figure 2-13 (b) could see, two diodes are in series with the load resistor during both the positive and negative half-cycles. If these diode drops are taken into account, the output voltage is

$$\boxed{V_{P(\text{out})} = V_{P(\text{sec})} - 1.4\text{ V}}$$

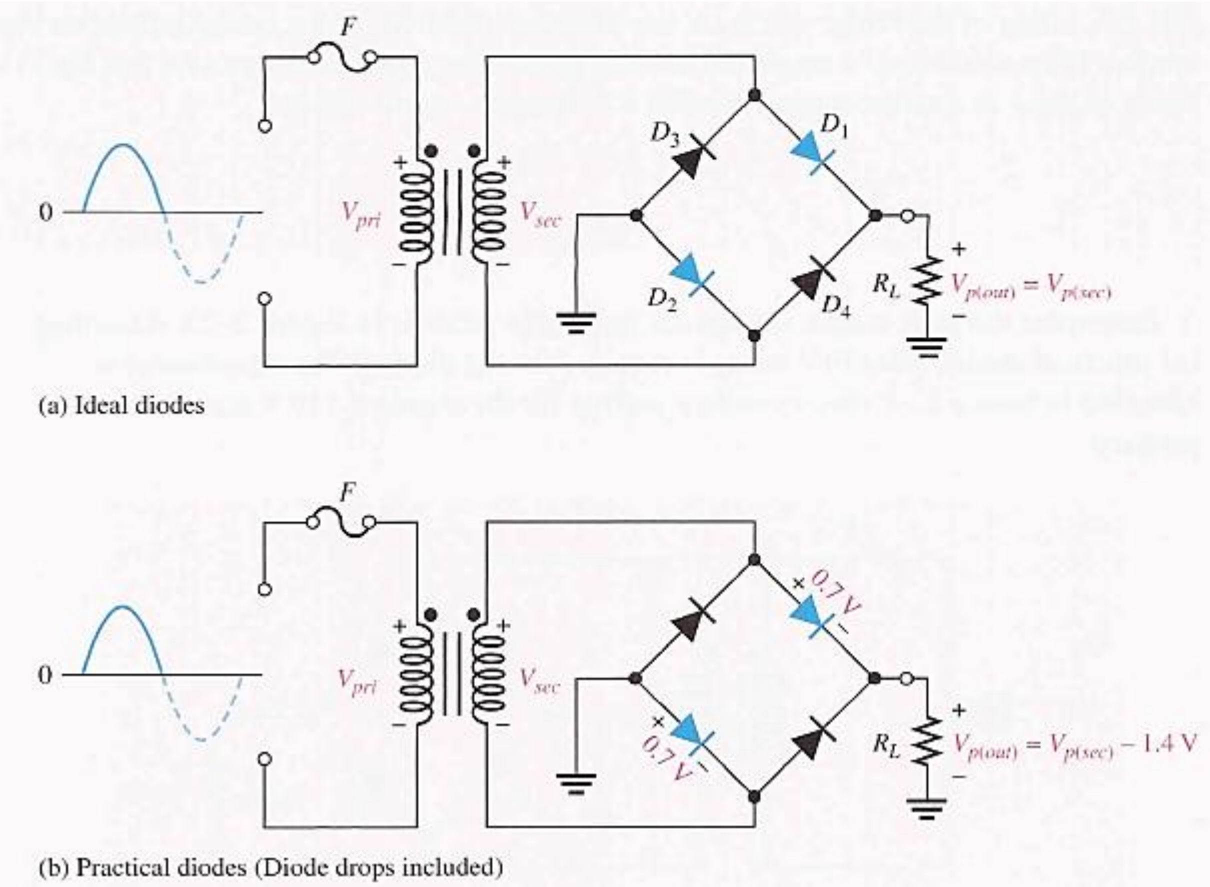


Figure 2-13 Bridge Operation

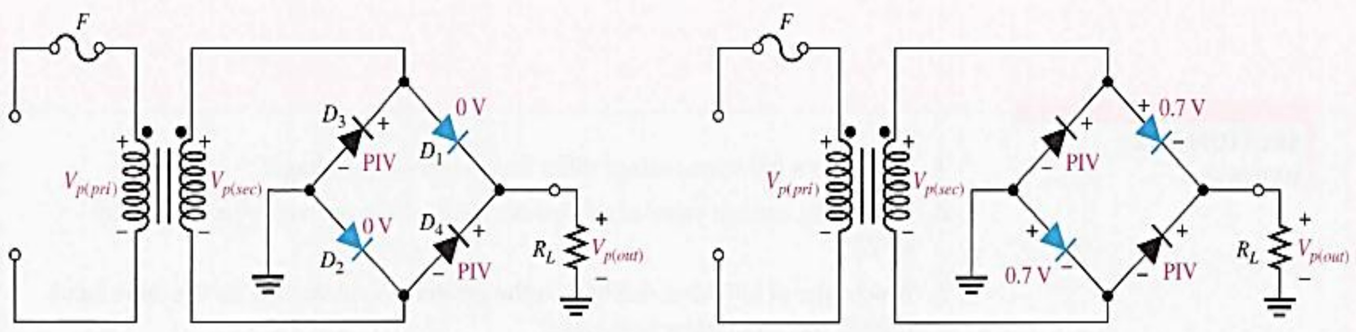
2-5-3 Peak Inverse Voltage

Assuming that D_1 and D_2 are forward-biased and examine the reverse voltage across D_3 and D_4. Visualizing D_1 and D_2 as shorts (ideal model), as in Figure 2-14(a), could see that D_3 and D_4 have a peak inverse voltage equal to the peak secondary voltage. Since the output is ideally equal to the secondary voltage,

$$\text{PIV} = V_{P(\text{out})}$$

If the diode drops of the forward-biased are included as shown in Figure 2- 14(b), the peak inverse voltage across each revers-biased diode in terms of $V_{P(\text{out})}$ is

$$\boxed{\text{PIV} = V_{P(\text{out})} + 0.7\text{ V}}$$



(a) For the ideal diode model (forward-biased diodes D_1 and D_2 are shown in blue), PIV = $V_{p(out)}$.

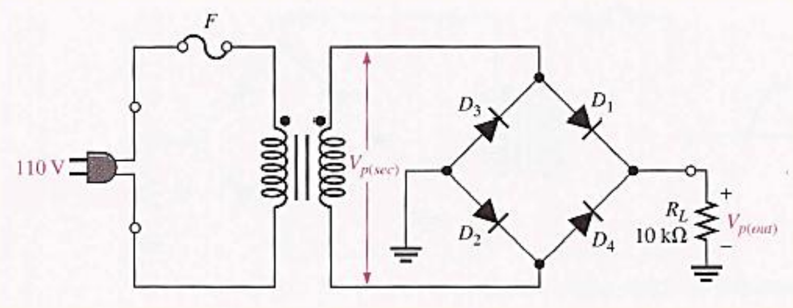
(b) For the practical diode model (forward-biased diodes D_1 and D_2 are shown in blue), PIV = $V_{p(out)} + 0.7$ V.

Figure 2-14 Peak Inverse voltage in a Bridge Rectifier operation

EXAMPLE 2–6

Determine the peak output voltage for the bridge rectifier in Figure 2–23. Assuming the practical model, what PIV rating is required for the diodes? The transformer is specified to have a 12 V rms secondary voltage for the standard 110 V across the primary.

FIGURE 2–23



Solution The peak output voltage (taking into account the two diode drops) is

$$V_{p(sec)} = 1.414V_{rms} = 1.414(12\text{ V}) \cong 17\text{ V}$$

$$V_{p(out)} = V_{p(sec)} - 1.4\text{ V} = 17\text{ V} - 1.4\text{ V} = \mathbf{15.6\text{ V}}$$

The PIV rating for each diode is

$$\text{PIV} = V_{p(out)} + 0.7\text{ V} = 15.6\text{ V} + 0.7\text{ V} = \mathbf{16.3\text{ V}}$$

2-6 Power Supply Filters and Regulators

A power supply filter ideally eliminates the fluctuations in the output voltage of a half-wave or full-wave rectifier and produces a constant-level dc voltage. Figure 2-15 illustrates the filtering concept showing a nearly smooth dc output voltage from the filter. The small amount of fluctuation in the filter output voltage is called ripple.

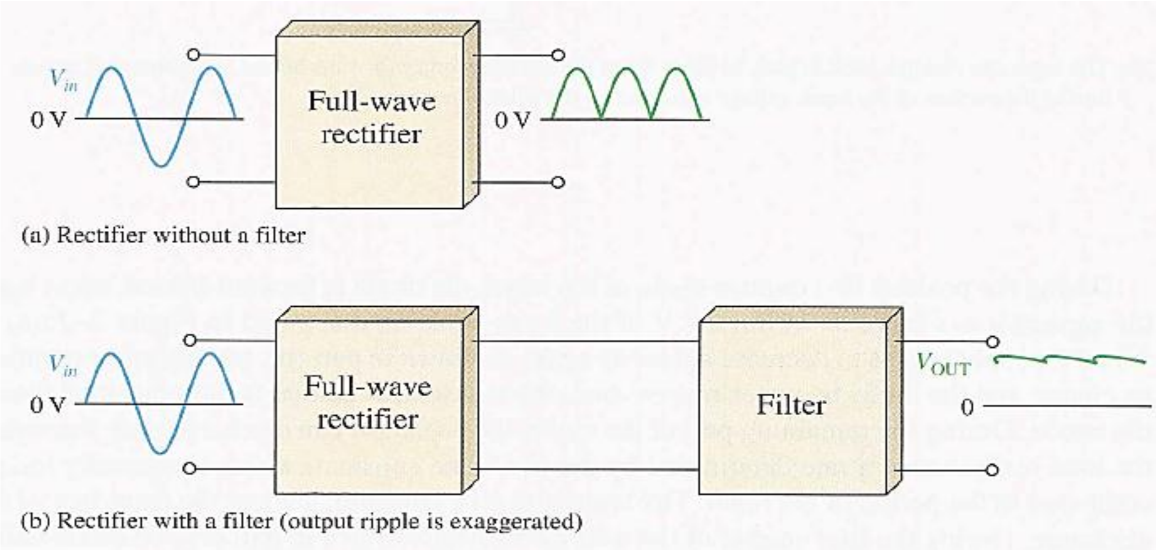
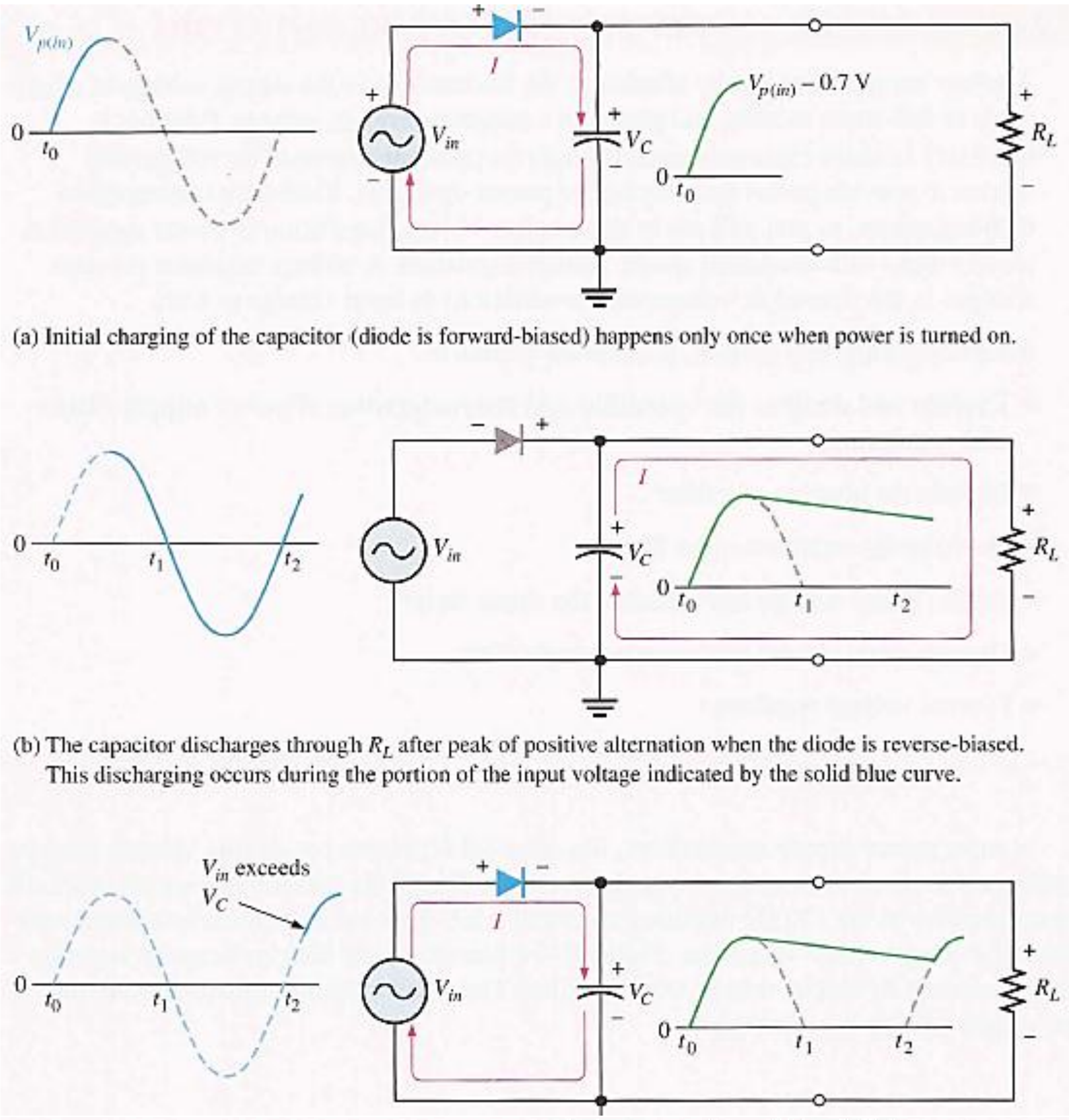


Figure 2-15 power supply filter

2-6 Rectifier Filters

A half-wave rectifier with a capacitor-input filter is shown in Figure 2-16. R_L represents the equivalent resistance of a load.

During the positive first quarter-cycle of the input, the diode is forward-biased, allowing the capacitor to charge to within 0.7 V of the input peak, as illustrated in Figure 2-16(a). When the input begins to decrease below its peak, as shown in part (b), the capacitor retains its charge and the diode becomes reverse-biased .During the remaining part of the cycle, the capacitor can discharge only through the load resistor at a rate determine by the R_LC time constant .The larger time constant ,the less capacitor will discharge.



(a) Initial charging of the capacitor (diode is forward-biased) happens only once when power is turned on.

(b) The capacitor discharges through R_L after peak of positive alternation when the diode is reverse-biased. This discharging occurs during the portion of the input voltage indicated by the solid blue curve.

(c) The capacitor charges back to peak of input when the diode becomes forward-biased. This charging occurs during the portion of the input voltage indicated by the solid blue curve.

Figure 2-16 Half-wave rectifier with a capacitor-input filter

During the first quarter of the next cycle, the diode will again become forward-biased when the input voltage exceeds the capacitor voltage by approximately a diode drop. This is illustrated in part (c).

2-6-1 Ripple Voltage

The variation in the capacitor voltage due to the charging and discharging is called the ripple voltage. Generally, ripple is undesirable; thus, the smaller the ripple, the better filtering action, as illustrated in Figure 2-13.

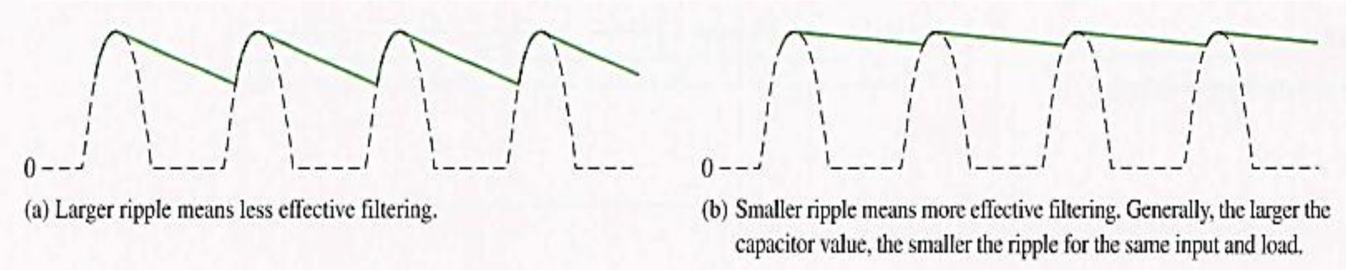


Figure 2-13 Half-wave ripple voltage (green line)

For a given input frequency, the output frequency of a full-wave rectifier is twice that of a half-wave rectifier, as illustrated in Figure 2-14 .This makes a full-wave rectifier easier to filter because the shorter time between peaks.

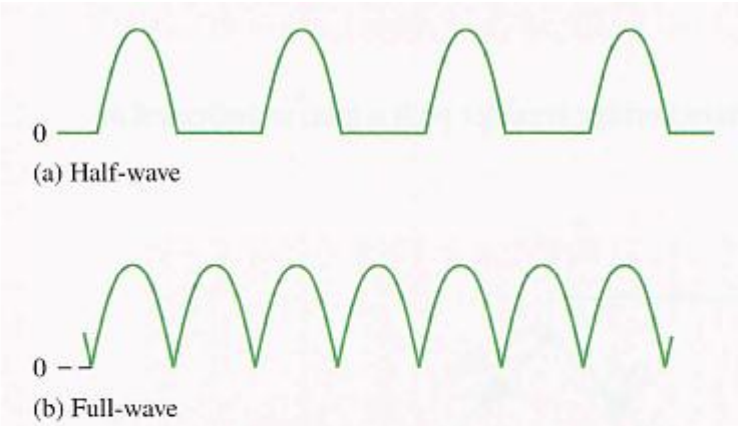


Figure 2-14 frequency of Half-wave & full-wave signal

When filtered, the full-wave rectified voltage has a smaller ripple than does a half-wave voltage for the same load resistance and capacitor values. The capacitor discharges less during the shorter interval between full-wave pulses, as shown in Figure 2-15.

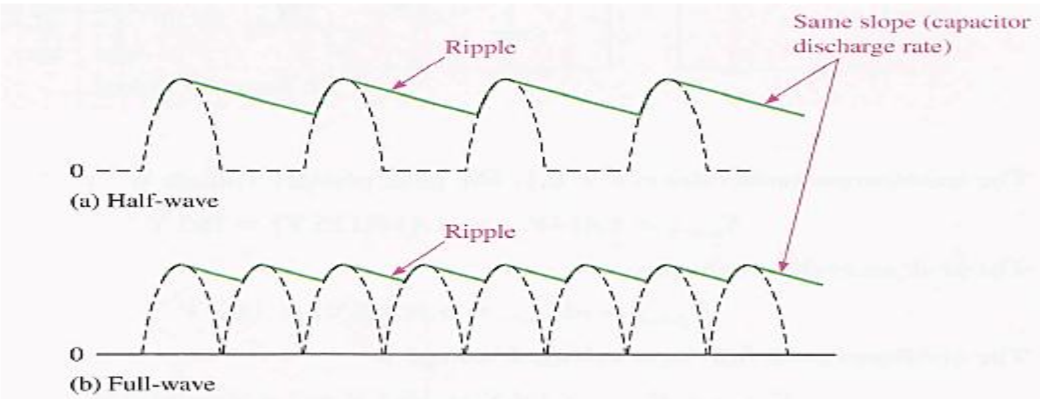


Figure 2-15 The ripple voltage for the same filter

2-6-2 Ripple Factor

The ripple factor is an indication of the effectiveness of the filter & is defined as

$$\boxed{r = \frac{V_{r(PP)}}{V_{DC}}}$$

Where $V_{r(PP)}$ is the peak-to-peak ripple voltage and V_{DC} is the dc (average) value of the filters output voltage, as illustrated in figure 2-16. The lower the ripple factor, the better filter. The ripple factor can be lowered by increasing the value of the filter capacitor or increasing the load resistance.

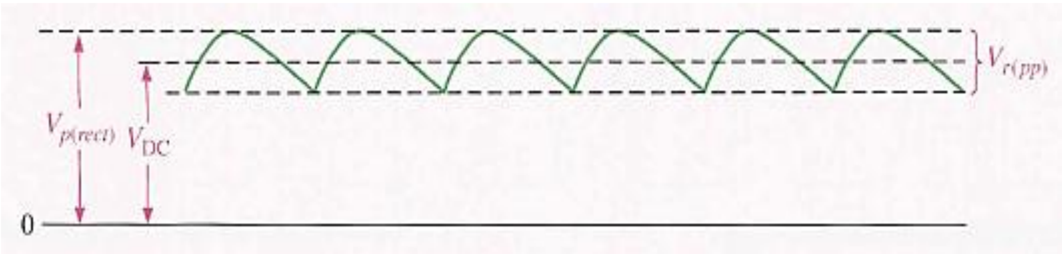


Figure 2-16 $V_{r(PP)}$ ***&*** V_{DC} ***determine the ripple factor***

For a full-wave rectifier with a capacitance-input filter, approximations for the peak-to-peak ripple voltage, $V_{r(PP)}$, and the dc value of the filter output voltage, V_{DC}, are given in the following expressions. The variable $V_{P(rect)}$ is the unfiltered peak rectified voltage.

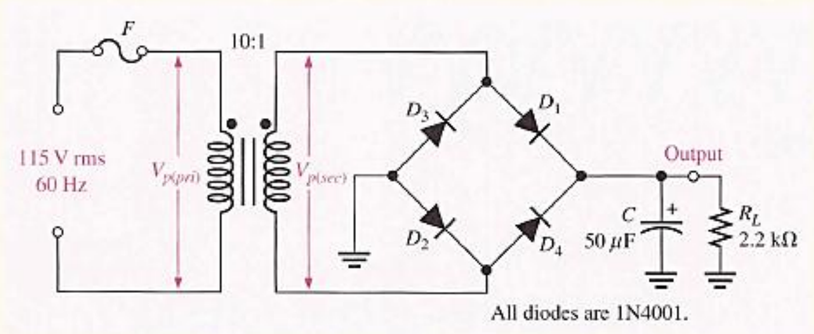
$$\boxed{V_{r(PP)} = (\frac{1}{fR_LC})V_{P(rect)}}$$

$$\boxed{V_{DC} = (1 - \frac{1}{2fR_LC})V_{P(rect)}}$$

EXAMPLE 2–7

Determine the ripple factor for the filtered bridge rectifier with a load as indicated in Figure 2–30.

FIGURE 2–30



Solution The transformer turns ratio is $n = 0.1$. The peak primary voltage is

$$V_{p(pri)} = 1.414V_{rms} = 1.414(115\text{ V}) = 163\text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.1(163\text{ V}) = 16.3\text{ V}$$

The unfiltered peak full-wave rectified voltage is

$$V_{p(rect)} = V_{p(sec)} - 1.4\text{ V} = 16.3\text{ V} - 1.4\text{ V} = 14.9\text{ V}$$

The frequency of a full-wave rectified voltage is 120 Hz. The approximate peak-to-peak ripple voltage at the output is

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)} = \left(\frac{1}{(120\text{ Hz})(2.2\text{ k}\Omega)(50\ \mu\text{F})}\right)14.9\text{ V} = 1.13\text{ V}$$

The approximate dc value of the output voltage is determined as follows:

$$V_{DC} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)} = \left(1 - \frac{1}{(240\text{ Hz})(2.2\text{ k}\Omega)(50\ \mu\text{F})}\right)14.9\text{ V} = 14.3\text{ V}$$

The resulting ripple factor is

$$r = \frac{V_{r(pp)}}{V_{DC}} = \frac{1.13\text{ V}}{14.3\text{ V}} = \mathbf{0.079}$$

The percent ripple is 7.9%.

2-7 Voltage Regulator

While filter can reduce the ripple from power supplies to a low value, the most effective approach is a combination of a capacitor-input filter used with a voltage regulator. A voltage regulator is connected to the output of filtered rectifier and maintains a constant output voltage (or current) despite changes in the input, the load current, or the temperature.

The capacitor-input filter reduces the input ripple to the regulator to an acceptable level. The combination of a large capacitor and a voltage regulator helps produce an excellent power supply.

Three-terminal regulators designed for fixed output voltage require only external capacitor to complete the regulation portion of the power supply, as shown in Figure 2-17. Filtering is accomplished by a large-value capacitor between the input voltage and ground.

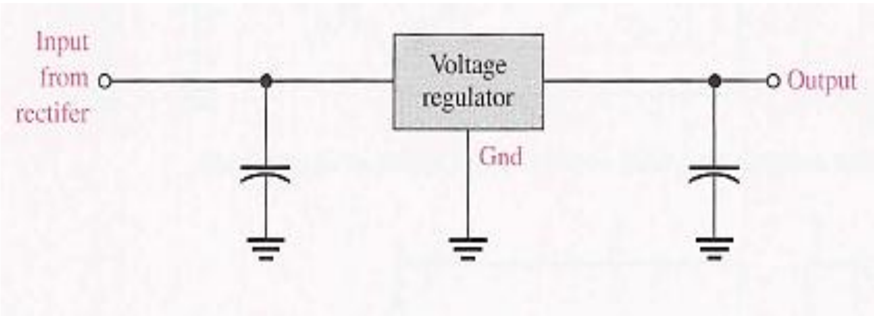


Figure 2-17 A voltage regulator with input and output capacitor

Percent Regulation

2-7-1 Line regulation

Line regulation specifies how much change occurs in the output voltage for a given change in the input voltage. It is typically defined as a ratio of change in output voltage for a corresponding change in input voltage expressed as a percentage.

$$\boxed{\text{Line regulation} = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right)100\%}$$

2-7-2 Load regulation

Load regulation specifies how much change occurs in the output voltage over certain rang of load current values, usually from minimum current (no load, NL) to maximum current (full load, FL). It is normally expressed as a percentage and can be calculated with the following formula.

$$\boxed{\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\%}$$

where V_{NL} is the output voltage with no load and V_{FL} is the output voltage with full (maximum) load.

EXAMPLE 2–8

A certain 7805 regulator has a measured no-load output voltage of 5.18 V and a full-load output of 5.15 V. What is the load regulation expressed as a percentage?

Solution Load regulation $= \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\% = \left(\frac{5.18\text{ V} - 5.15\text{ V}}{5.15\text{ V}}\right)100\% = \mathbf{0.58\%}$