Chapter 2: Diode and Application

Diode

A diode is a semiconductor device, made from a small piece of semiconductor material, such as silicon, in which half is doped as a p region and half is doped as an n region with a pn junction and depletion region in between. The p region is called the ***anode*** and n region is called the ***cathode***. It conducts current in one direction and offers high resistance in other direction. The basic diode structure and symbol are shown in Fig.1.

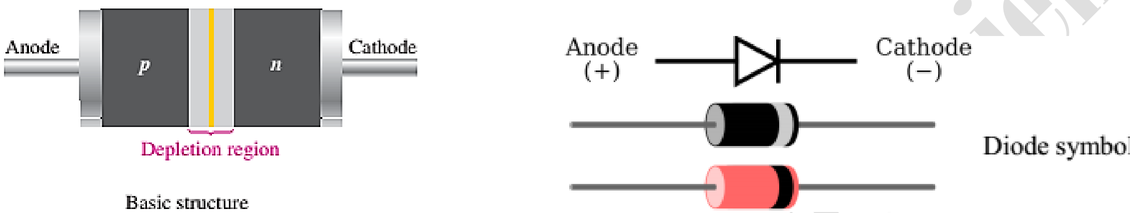


Figure 1.

Forward Bias

Bias is the application of a dc voltage to a diode to make it either conduct or block current. Forward bias is the condition that allows current through the pn junction. This external bias voltage is designated as V_{BIAS}. The resistor limits the forward current to a value that will not damage the diode. In the forward bias, the negative side of V_{BIAS} is connected to the n region of the diode and the positive side is connected to the p region. The bias voltage V_{BIAS}, must be greater than the barrier potential; bias must be greater than 0.3V for germanium or 0.7V for silicon diodes.

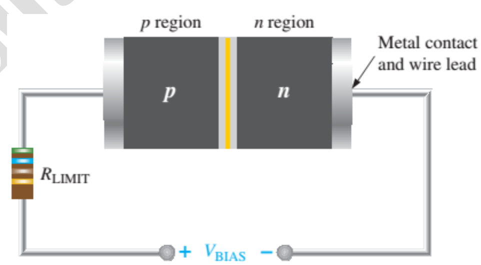


Figure 2: A diode connected for forward bias.

Negative side of bias voltage 'pushes' free electrons towards pn junction. The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the n region as shown in Figure 3. The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the p region. Since unlike charges attract, the positive side of the bias-voltage source attracts the valence electrons toward the left end of the p region. The holes in the p region provide the medium for these valence electrons to move through the p region. The holes, (majority in p region), move to the right toward the junction.

As the electrons flow out of the p region through the external connection (conductor), these electrons become conduction electrons in the metal conductor. As more electrons move into the depletion region, the number of positive ions is reduced. As more holes flow into the depletion region on the other side of the pn junction, the number of negative ions is reduced. This reduction in positive and negative ions causes the depletion region to narrow.

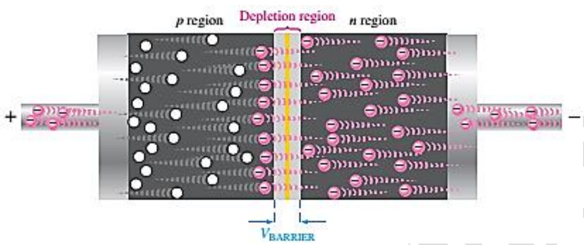


Figure 3: A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

Reverse Bias

Reverse bias is the condition that essentially prevents current through the diode. Figure 4 shows a dc voltage source connected across a diode in the direction to produce reverse bias. The positive side of V_{BIAS} is connected to the n region of the diode and the negative side is connected to the p region. Also, note that the depletion region is shown much wider than in forward bias or equilibrium. The positive side of the bias-voltage source pulls the free electrons, (majority in n region), away from the pn junction. As electrons move away from junction, more positive ions are created. This results in a widening of the depletion region and a depletion of majority carriers.

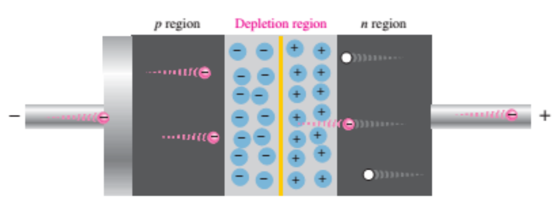


Figure 4

In p region, electrons from negative side of battery enter as valence electrons. It moves from hole to hole toward the depletion region, creating more negative ions. This can be viewed as holes being pulled towards the negative side. The electric field increases in strength until the potential across depletion region equals the bias voltage. At this point, very small reverse current exist that can usually be neglected.

Reverse Breakdown

Normally, the reverse current is so small that it can be neglected. If the external reverse-bias voltage is increased to a value called the ***breakdown voltage***, the reverse current will drastically increase.

The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the p region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band. The newly created conduction electrons have high energy, and repeat the process, they quickly multiply. They have high energy to move though pn junction, and not combine with holes. The multiplication of conduction electrons just discussed is known as **the avalanche effect**.

Voltage-Current (V-I) Characteristic of A Diode

V-I Characteristic for Forward Bias

The current in forward biased called **forward current** and is designated I_f. At 0V (V_{bias}) across the diode, there is no forward current. Figure 5 illustrates what happens as the forward-bias voltage is increased positively from 0 V. The resistor is used to limit the forward current to a value that will not overheat the diode and cause damage. With gradual increase of V_{bias}, the forward voltage and forward current increases. A portion of forward-bias voltage (V_f) drops across the limiting resistor. Continuing increase of V_f causes rapid increase of forward current but the voltage across the diode increases only gradually above 0.7V. The resistance of the forward-biased diode is not constant but it changes over the entire curve. Therefore, it is called **dynamic resistance**.

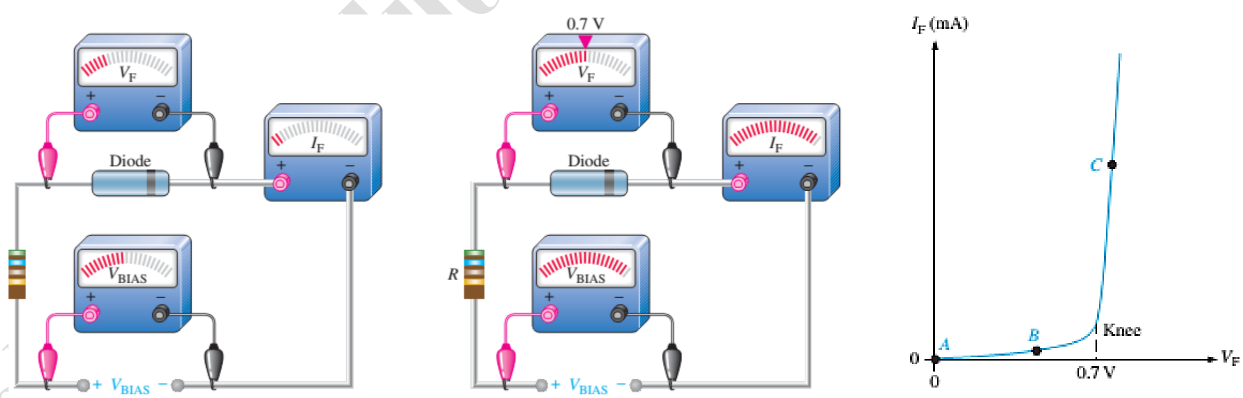


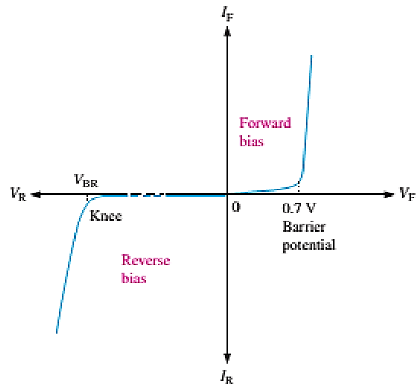
Figure 5: Relationship of voltage and current in a forward-biased diode.

V-I Characteristic for Reverse Bias

With 0V reverse voltage there is no reverse current. There is only a small current through the junction as the reverse voltage increases. At a point, reverse current shoots up with the breakdown of diode. The voltage called **breakdown voltage**. This is not normal mode of operation. After this point the reverse voltage remains at approximately V_{BR} but I_R increase very rapidly. Break down voltage depends on doping level, set by manufacturer.

Combine the curves for both forward bias and reverse bias, and you have the complete V-I characteristic curve for a diode, as shown in Figure 6.

Figure 6

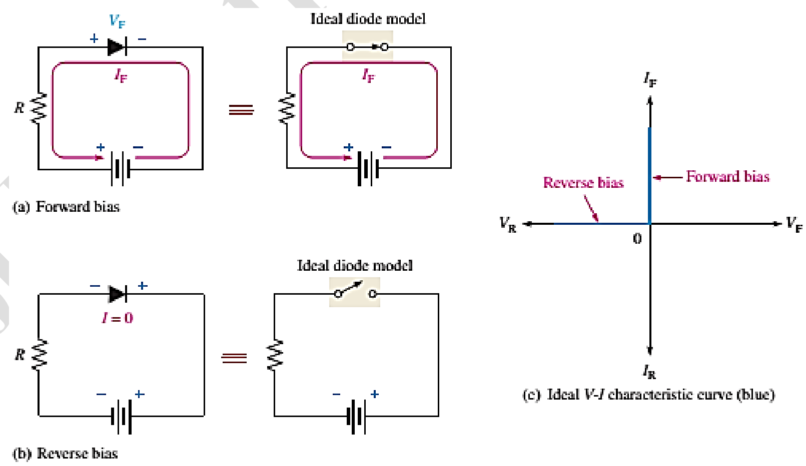


Diode models

The Ideal Diode Mode

When the diode is forward-biased, it ideally acts like a closed (on) switch, as shown in Figure 7. When the diode is reverse-biased, it ideally acts like an open (off) switch, as shown in part (b). The barrier potential, the forward dynamic resistance, and the reverse current are all neglected. In Figure 7c, the ideal V-I characteristic curve graphically depicts the ideal diode operation.

Figure 7



The Practical Diode Model

The practical model includes the barrier potential. The characteristic curve for the practical diode model is shown in Figure 8c. Since the barrier potential is included and the dynamic resistance is neglected, the diode is assumed to have a voltage across it when forward-biased, as indicated by the curve to the right of the origin. The practical model is useful in lower-voltage circuits and in designing basic diode circuits. The forward current is determined using first Kirchhoff's voltage law to Figure 8a:

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

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

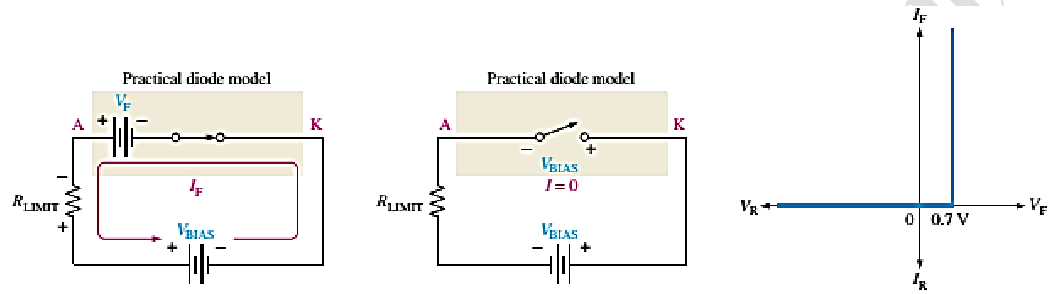
Substituting and solving for I_F

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

The diode is assumed to have zero reverse current,

$V_F = 0.7V$, $V_R = V_{BIAS}$, $I_R = 0A$

Figure 8

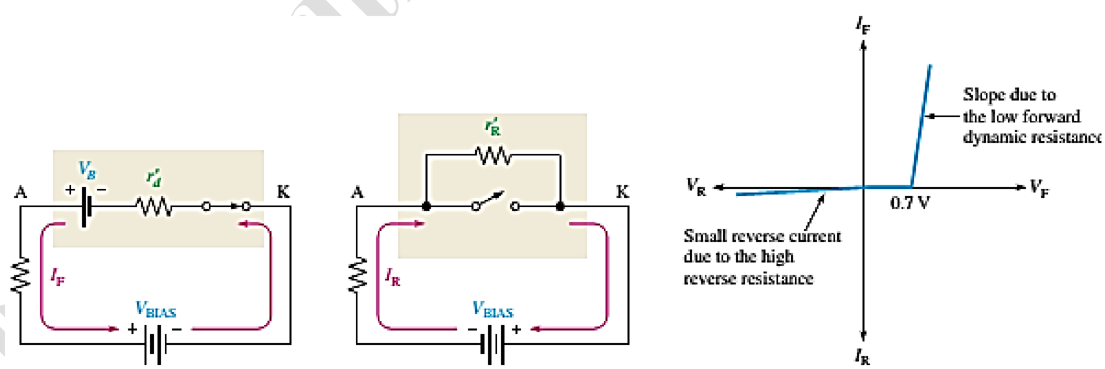


(a) Forward bias (b) Reverse bias (c) Characteristic curve (silicon)

The Complete Diode Model

The complete model of a diode includes the barrier potential, the small forward dynamic resistance ($\acute{r}_d$) and the large internal reverse resistance ($\acute{r}_R$). The reverse resistance is taken into account because it provides a path for the reverse current, which is included in this diode model.

Figure 9

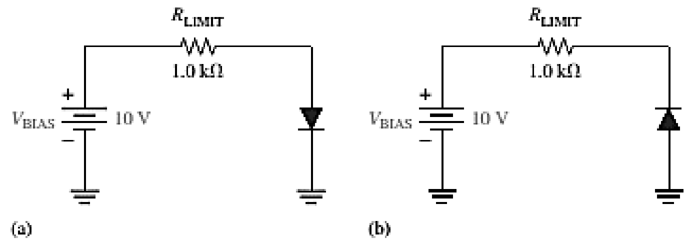


(a) Forward bias (b) Reverse bias (c) V-I characteristic curve

Example 1: (a) Determine the forward voltage and forward current for the diode in Figure 10(a) for each of ideal and practical diode models. Also, find the voltage across the limiting resistor in each case.

(b) Determine the reverse voltage and reverse current for the diode in Figure 10(b) for each of the diode models. Also, find the voltage across the limiting resistor in each case. Assume $I_R = 1\mu A$. (**H.W.**)

Figure 10



Solution:

(a) Ideal model:

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

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

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

Practical model:

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

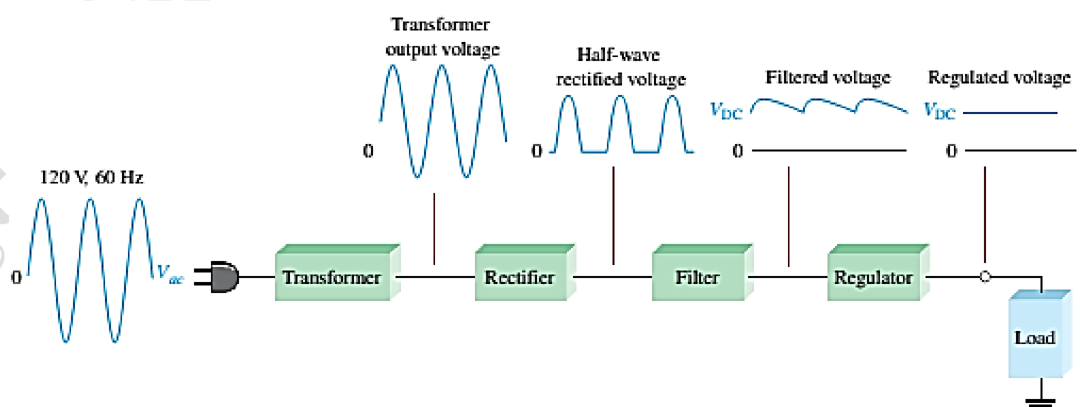
$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}} = \frac{10\ \text{V} - 0.7\ \text{V}}{1.0\ \text{k}\Omega} = \frac{9.3\ \text{V}}{1.0\ \text{k}\Omega} = \mathbf{9.3\ mA}$$

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

The DC power supply

A power supply is an essential part of each electronic system from the simplest to the most complex. A basic block diagram of the complete power supply is shown in Figure 11. The ***transformer*** changes ac voltages based on the turns ratio between the primary and secondary. The ***rectifier*** converts the ac input voltage to dc voltage. The ***filter*** eliminates the fluctuations in the rectified voltage and produces a relatively smooth dc voltage. The ***regulator*** is a circuit that maintains a constant dc voltage for variations in the input line voltage or in the load.

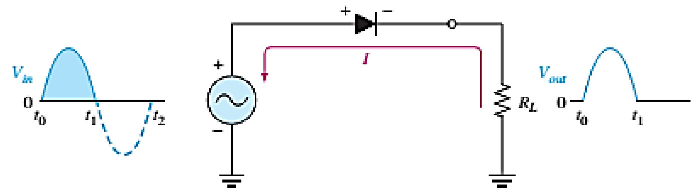
Figure 11



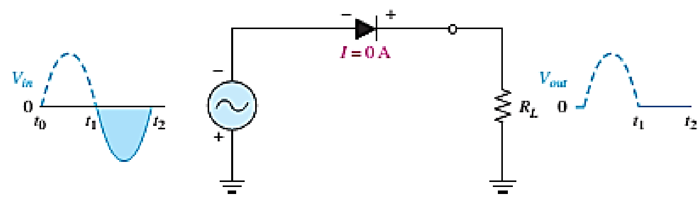
Half-Wave Rectifiers

Because of their ability to conduct current in one direction and block current in the other direction, diodes are used in circuits called **rectifiers** that convert ac voltage into dc voltage. Rectifiers are found in all dc power supplies that operate from an ac voltage source. When connected with ac voltage, diode only allows half cycle passing through it and hence convert ac into dc. As the half of the wave get rectified, the process called **half-wave rectification**. The output frequency is the same as the input.

Figure 12



(a) During the positive alternation of the 60 Hz input voltage, the output voltage looks like the positive half of the input voltage. The current path is through ground back to the source.



(b) During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.

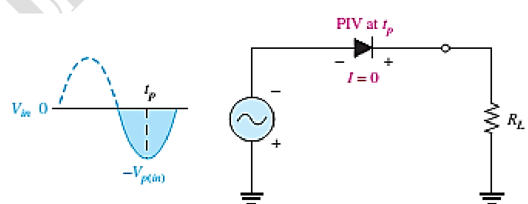
The average value (V_{AVG}) of half-wave rectified voltage if its peak amplitude is 50 V is

$V_{AVG} = V_P/\pi = 50/3.14 = 15.9V$, V_{AVG} is approximately 31.8% of Vp

PIV= $V_{p(in)}$

PIV: **Peak inverse voltage**=is the maximum voltage occurs at the peak of each half-cycle of the input voltage when the diode is reverse-biased. The diode must be capable of withstanding this amount voltage.

Figure 13

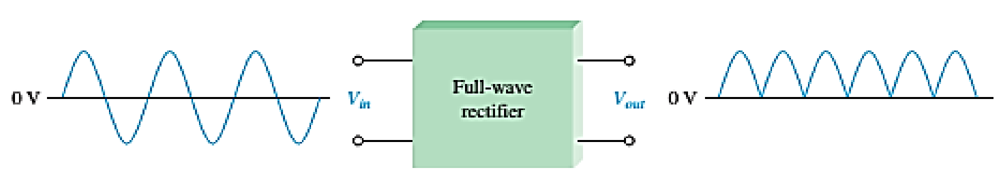


Full wave rectifiers

Although half-wave rectifiers have some applications, the full-wave rectifier is the most commonly used type in dc power supplies. A full-wave rectifier allows unidirectional (one-way) current through the load during the entire of the input cycle, whereas a half-wave rectifier allows current through the load only during one-half of the cycle. The output voltage have twice the input frequency.

$V_{AVG} = 2V_P/\pi =$ V_{AVG} is approximately 63. 7% of Vp

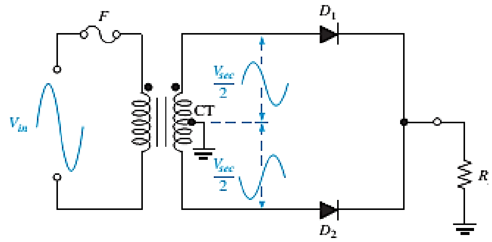
Figure 14

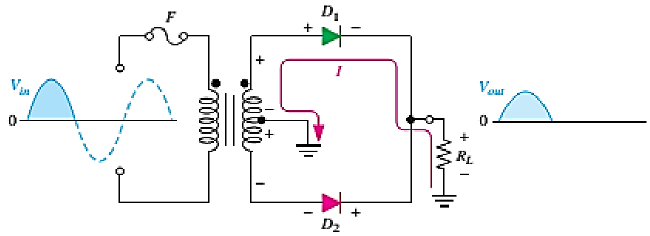


Center-Tapped Full-Wave Rectifier Operation

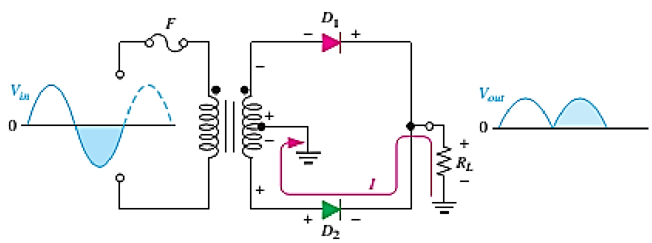
A center-tapped rectifier is used two diodes that connected to the secondary of a center-tapped transformer, as shown in Figure 14.

Figure 15





(a) During positive half-cycles, D_1 is forward-biased and D_2 is reverse-biased.

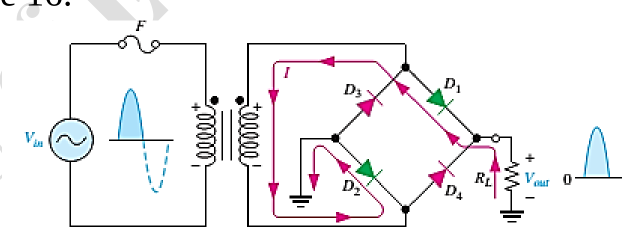


(b) During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased.

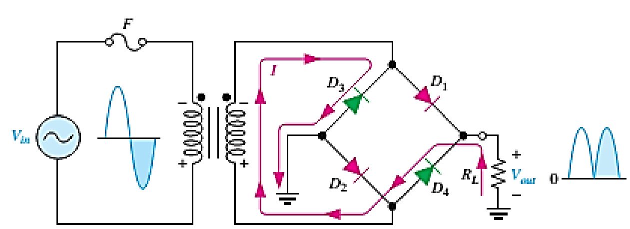
Figure 16: Basic operation of a center-tapped full-wave rectifier.

The Bridge Full-wave rectifiers

The Bridge Full-Wave rectifier uses four diodes connected across the entire secondary as shown in Figure 16.



(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.

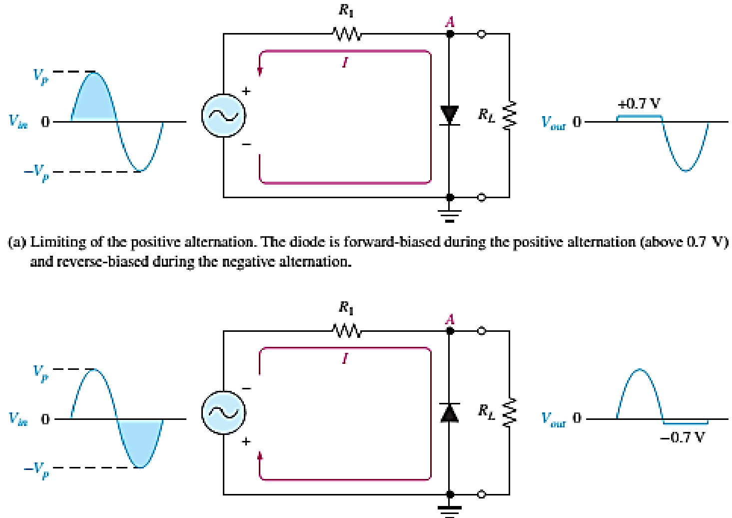


(b) During the negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

Figure 17: Operation of a Bridge rectifier

Diode Limiters

Diode circuits, called limiters or clippers, are used to clip off portions of signal voltages above or below certain levels. Point A is limited to +0.7V when the input voltage exceeds this value (Figure 18(a)). If the diode is turned around, as in Figure 18(b), the negative part of the input voltage is clipped off. When the diode is forward-biased during the negative part of the input voltage, point A is held at -0.7V by the diode drop.



(a) Limiting of the positive alternation. The diode is forward-biased during the positive alternation (above 0.7 V) and reverse-biased during the negative alternation.

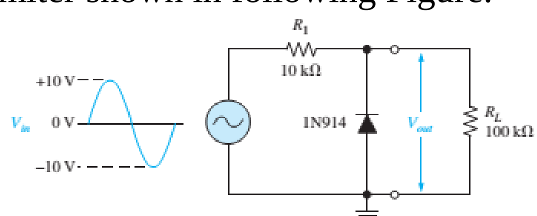
(b) Limiting of the negative alternation. The diode is forward-biased during the negative alternation (below −0.7 V) and reverse-biased during the positive alternation.

Figure 18: Examples of diode limiters (clippers).

The desired amount of limitation can be attained by a power supply or voltage divider. The amount clipped can be adjusted with different levels of V_{BIAS}. The peak output voltage across R_L is determine by the following equation:

$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right) V_{in}$$

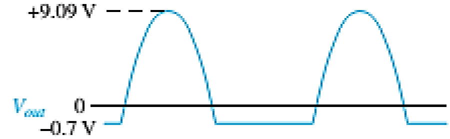
Example 2: What would you expect to see displayed on an oscilloscope connected across R_L in the limiter shown in following Figure.



Solution: The diode is forward-biased and conducts when the input voltage goes below -0.7V. So, for the negative limiter, determine the peak output voltage across R_L by:

$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right) V_{in} = \left(\frac{100\text{k}\Omega}{110\text{k}\Omega}\right) 10\text{V} = 9.09\text{V}$$

The scope will display an output waveform as shown in following Figure



Diode Clampers

Another type of diode circuit, called a clamper, is used to add or restore a dc level to an electrical signal. The capacitor charges to the peak of the supply minus the diode drop. Once charged the capacitor acts like a battery in series with the input voltage. The AC voltage will "ride" along with the DC voltage. The polarity arrangement of the diode determines whether the DC voltage is negative or positive.

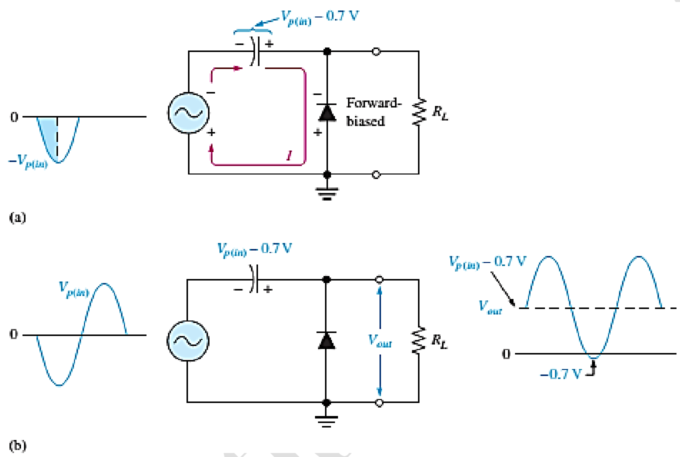


Figure 19: Positive clamper operation.

Voltage multiplier

Voltage multipliers use clamping action to increase peak rectified voltages without the necessity of increasing the transformer's voltage rating. Multiplication factors of two, three, and four are common. Voltage multipliers are used in high-voltage, low-current applications such as cathode-ray tubes (CRTs) and particle accelerators. In the Figure 20 a half-wave voltage doubler, a voltage doubler is a ***voltage multiplier*** with a multiplication factor of two. Once C_1 and C_2 charges to the peak voltage they act like two batteries in series, effectively doubling the voltage output. The current capacity for voltage multipliers is low.

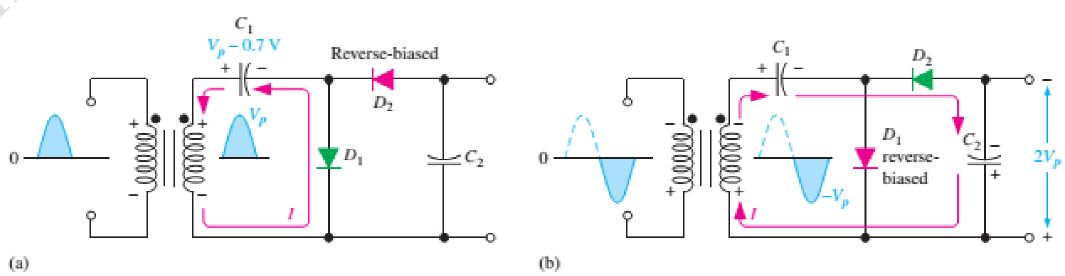


Figure 20: Half-wave voltage doubler operation.

The full-wave voltage doubler arrangement of diodes and capacitors takes advantage of both positive and negative peaks to charge the capacitors giving it more current capacity. Voltage triplers and quadruplers utilize three and four diode-capacitor arrangements, respectively.

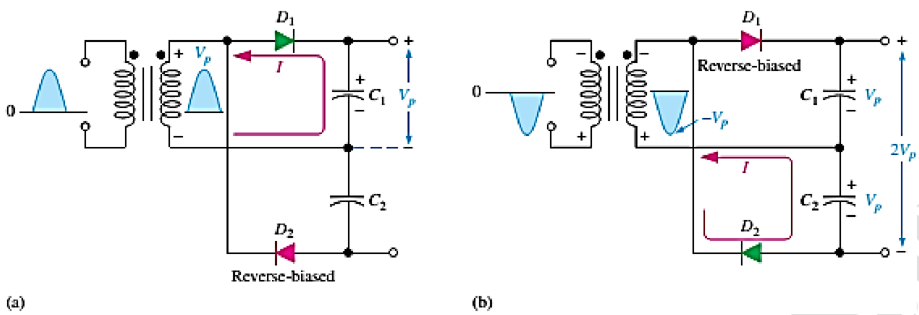
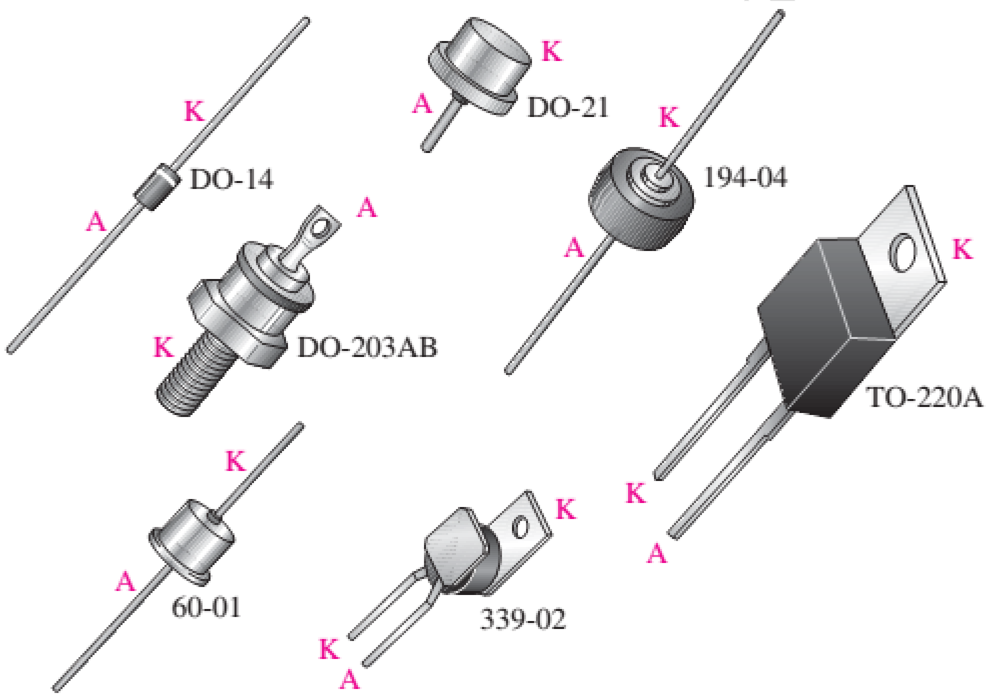


Figure 21: Full-wave voltage doubler operation.



Typical diode packages with terminal identification. The letter K is used for cathode to avoid confusion with certain electrical quantities that are represented by C. Case type numbers are indicated for each diode.