SEMICONDUCTOR THEORY

Most of the people employed in the field of electronics are aware of the importance of the transistor. Yet few people, not directly involved with them, really udnerstand what a transistor is or its basic operation. The transistor is only one phase of the vast field of electronics that falls under the heading of *SOLID STATE* or *SEMICONDUCTOR* electronics.

The purpose of this chapter is to introduce solid state physics and semiconductor theory as a basis for the study of transistors and integrated circuits. To understand semiconductor theory, a knowledge of atomic structure is needed.

PN JUNCTION

A semiconductor diode is made by taking a single crystal (for example, germanium) and adding a donor impurity to one region and an acceptor impurity to the other. This gives a single crystal with an N section and a P section. Where the two sections meet is a junction. Contacts are fastened to the two ends of the crystal. The result is a simple PN junction or junction diode.

One portion of the crystal is P type material; that is, the portion containing the acceptor impurity. The other portion is N type material. This region contains the donor impurity. The end contacts are large surfaces that make a good connection with the crystal. If the connections were not good, there might be rectifying properties where they come in contact with the crystal.

PN Junction Symbol and Characteristics

The schematic symbol of a PN junction diode is shown in figure 1-1. The bar represents the *cathode* (N type material) and the bar arrow represents the *anode* (P type material). Electron flow is against the arrow.

Biased PN Junction

An external potential applied to a PN junction is called *bias*. A battery connected across PN junction develops a *bias* across the junction. If the battery is connected so that its voltage *opposes* the junction field, it will reduce the height and width of the junction barrier and thereby aid current flow through the junction. The junction is then *forward biased* (low resistance direction). If the battery is connected across the junction so that its voltage *aids* the junction field, it will increase the height and width of the junction barrier and thereby oppose current flow through the junction. The junction is then *reverse biased* (high resistance direction). (See figure 1-2 for symbol.)

Diodes drop up to 7/10 of one volt

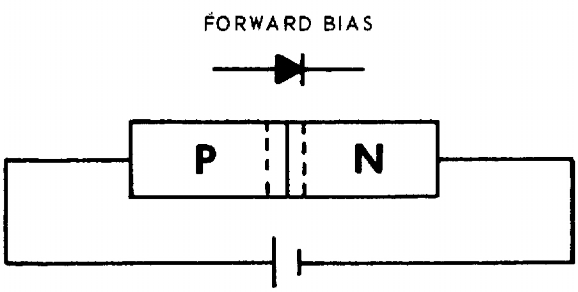

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Figure 1-1. PN Junction with Forward Bias Symbol and Characteristics

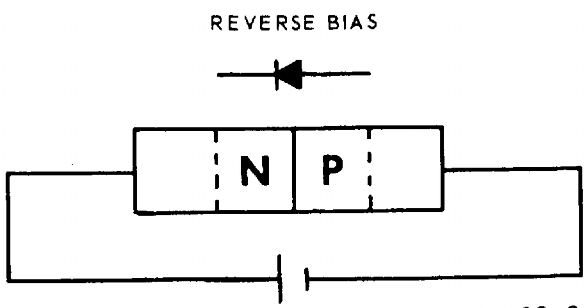

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Figure 1-2. PN Junction with Reverse Bias Junction and Characteristics

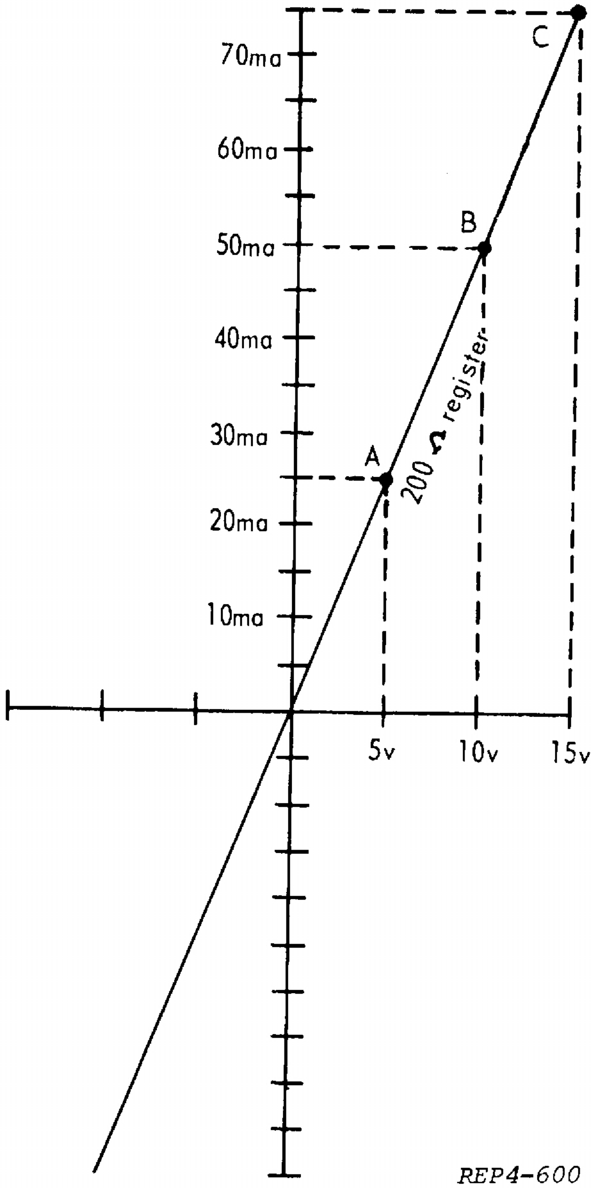

Figure 1-3. Current Voltage Relations for a 200 Ohm Resistor

A PN junction diode is a NONLINEAR device, whereas, a resistor is a LINEAR device. The differences can be seen by plotting the current-voltage relationships of each device and then comparing the resullt. The chart in figure 1-3 shows the result of plotting voltage against current for a 200 ohm resistor. Various points can be determined by the formula $E=IR$ or $I=E/R$.

At point *A* in figure 1-3, the voltage applied to the 200 ohm resistor is 5 volts, resulting in 24mA of current. At point *C*, the voltage is 15 volts, and the current has increased to 75mA. Notice the linear change in current through a resistor with a change in voltage. Tripling the voltage applied results in three times the current flow.

The voltage-current relationship (characteristic curve) of a PN junction diode is shown in figure 1-4. The resistance can be determined from the curve by using the formula $R=E/I$. At point *A* in figure 1-4, the forward voltage is 1 volt and the forward current is 5mA. This represents 200 ohms of resistance *(1 V/5mA=200 ohms).* At point *B*, the voltage is 3 volts and the current is 50mA. This gives 60 ohms of resistance for the diode. Notice that, when the forward bias voltage was tripled (1 volt to 3 volts), the current increased 10 times (5mA to 50mA). This illustrates the NONLINEAR relationship between voltage and current in a PN junction. Note also that resistance decreased from 200 ohms to 60 ohms when forward bias voltage increased.

The diode conducts very little when reverse biased. At point *C* in figure 1-4, the reverse bias voltage is 80 volts and the current is 100 microamps. The diode has 800K ohms of resistance, which is very much larger than the resistance of the junction with forward bias. This also indicates the nonlinear characteristics of a PN diode.

Notice on the curve at point *D* the current increases rapidly. This rapid increase in reverse current is called *avalanche current.* This avalanche current is caused by excessive reverse bias voltage.

The PIN diode is a bar of intrinsic crystal, doped on one end with an acceptor impurity and at the other end with a donor impurity as illustrated in figure 1-5. The PIN diode is designed to operate as an RF switch or RF attenuator. When the PIN diode is forward biased, the capacitance between the P material (or anode) and the N material (or cathode) is great as illustrated in figure 1-6A because the anode and the cathode are effectively closer together. As capacitance becomes greater, the capacitive reactance at the operating frequency decreases and the PIN diode passes the RF signal. As forward bias decreases, the distance between anode and cathode increases, decreasing capacitance as illustrated in figure 1-6B. As capacitance decreases, capacitive reactance of the operating frequency increases which attenuates the RF signal.

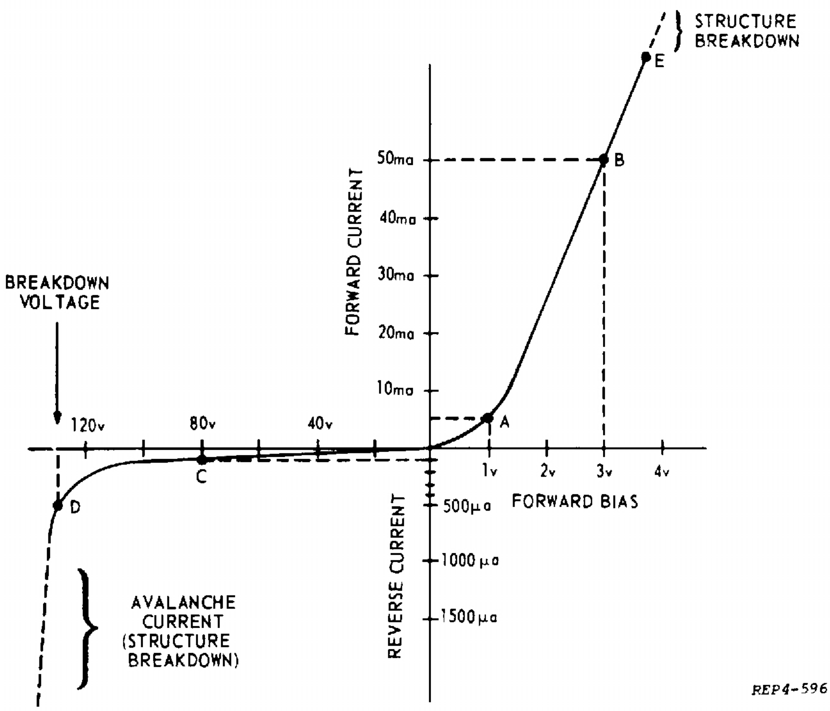

Figure 1-4. Voltage-Current Characteristics of Diodes

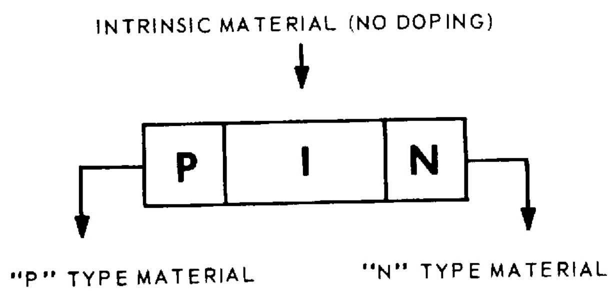

Figure 1-5. PIN Diode Construction

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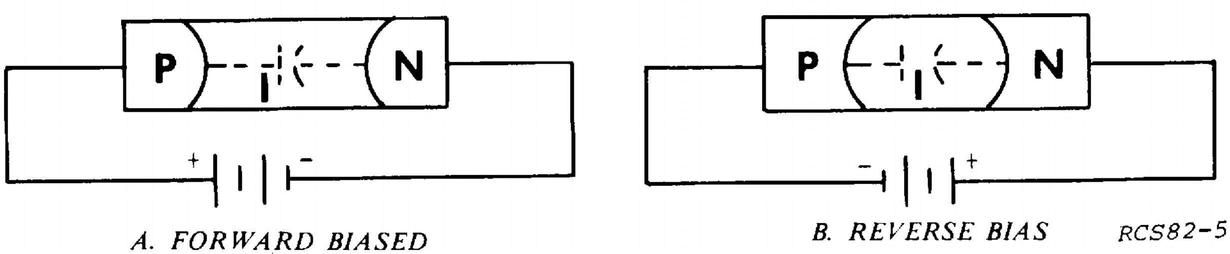

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Figure 1-6. PIN Diode

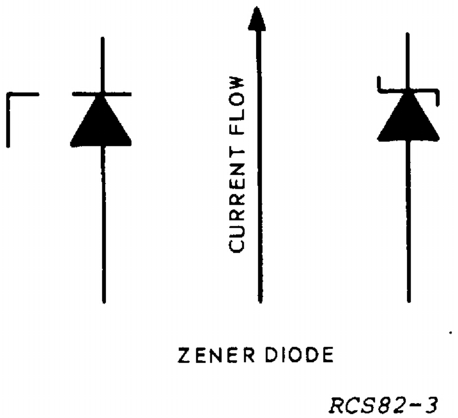

Figure 1-7. Schematic Symbol

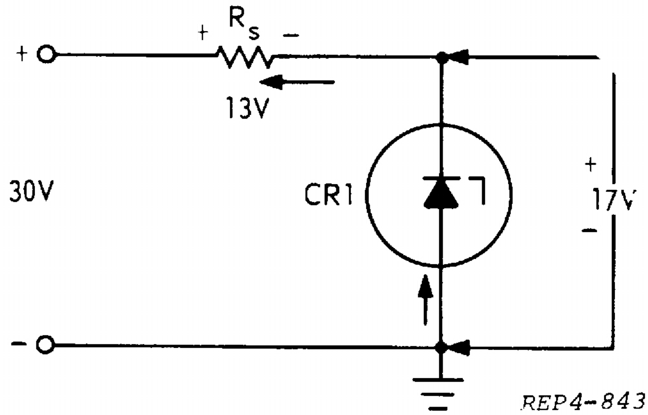

Figure 1-9. Zener Diode Current

The output voltage developed by a source of power changes:

1. With a change in input and
2. When current is drawn from the source.

Many electronic circuits operate satisfactorily with a moderate amount of variation in the supply voltage. Some circuits are very critical and even a slight deviation fom the normal supply voltage will cause unsatisfactory operation. These circuits require the use of a voltage regulating device. Crystal diodes manufactured for this purpose are called *zener diodes*. Sometimes referred to as *avalanche* or *breakdown* diodes, these diodes use the breakdown voltage and the avalanche current region of the PN junction.

ZENER DIODE

Zener is a name given to a family of diodes designed to operate with reverse breakdown voltage. Zener diodes operate in the avalanche region of their characteristic curves without damage. Figure 1-7 shows the schematic symbol.

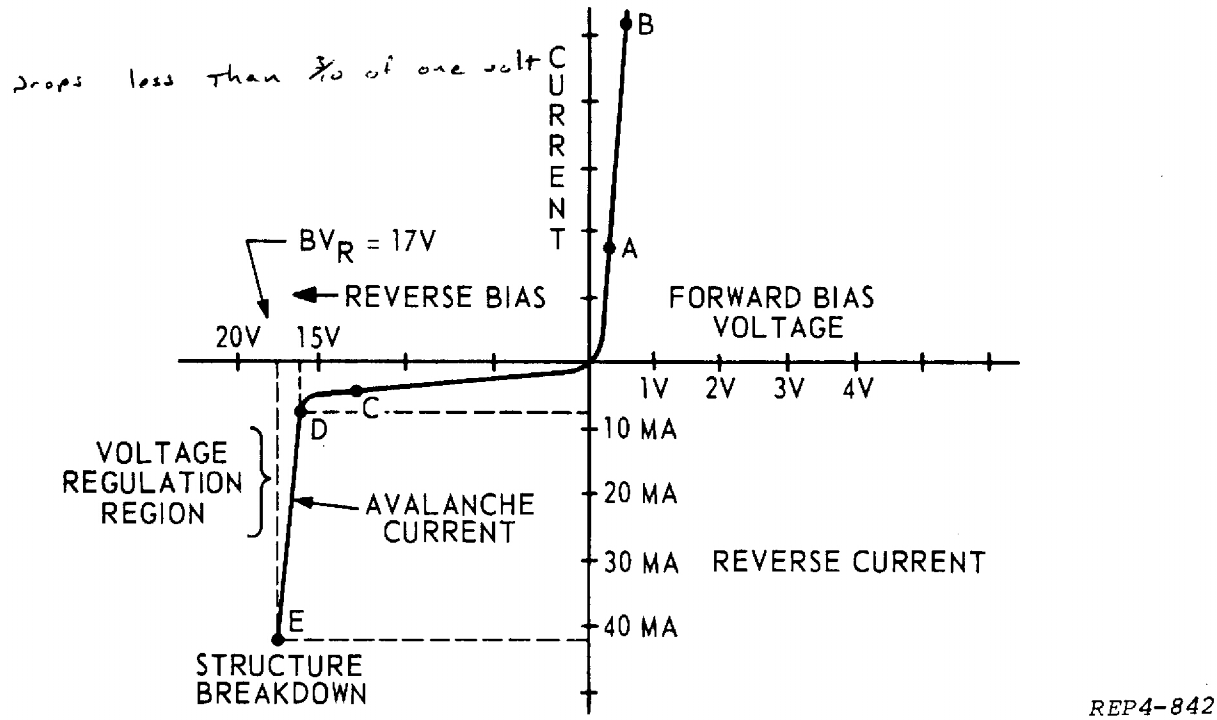

Figure 1-8. Zener Diode Characteristic Curve

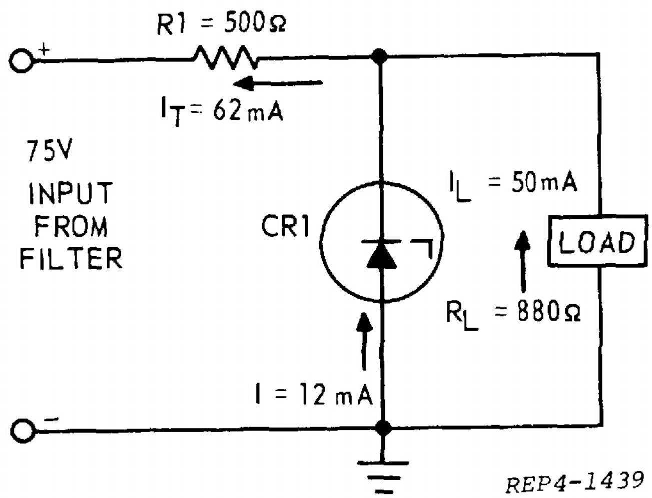

Figure 1-10. Zener Voltage Regulator Circuit

The characteristic curve for the zener diode is basically the same as the PN junction diode. With forward bias applied, the zener diode operates the same as a regular junction diode (points *A* and *B).* Notice that, with reverse bias, the zener diode is able to operate with a large amount of avalanche current before structure breakdown occurs (point *E,* figure 1-8), whereas the regular PN junction is destroyed as soon as the breakdown voltage (BV) is reached.

Between points *D* and *E* in figure 1-8, the voltage changes very little (from 17 to 17.5 volts) for a wide variation in current (from 7mA to 40mA). This region is therefore called the *voltage regulating region,* since the voltage across the zener diode remains relatively constant, or is *regulated,* over a wide range of currents. However, if an excessive amount of current is allowed to flow, the diode will be destroyed due to structure breakdown. Therefore, a current limiting resistor, *Rs,* is used in series with the diode and the power source, as shown in figure 1-9.

The primary purpose of the zener diode should be evident. The zener diode is used to REGULATE VOLTAGE.

Figure 1-10 shows a regulator circuit using a zener diode. CR1 is in parallel with the load. R1 is a current limiting resistor in series with the load. Any change in input voltage or load causes a change in current through CR1; this, in turn, changes the total current through R1 and a change in voltage drop across R1. If, for example, the input voltage decreases, current through CR1 decreases. This causes IT through R1 to decrease, drop less voltage, and hold the load voltage constant. There are two key points to remember. First, the current through CR1 can vary, but the voltage across it remains relatively constant. Second, since R1 is *in series with the load, the voltage drops* across it; and the load must add up to the applied voltage. Any change in current through CR1 causes a change in voltage drop across R1, which always works to hold the voltage across the load constant.

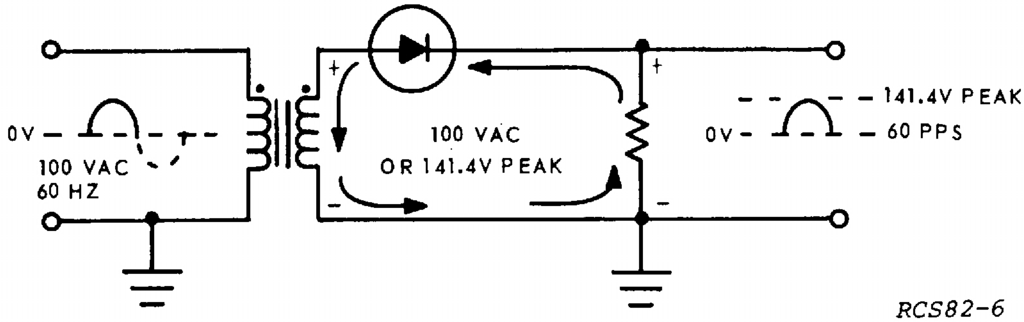

Figure 1-11. Half Wave Rectifier

The variations occur because the diode follows the AC voltage in the secondary of the transformer. The diode conducts to the peak voltage of the transformer secondary. Ignoring the small resistance of the diode when it conducts, the peak voltage of the pulsating DC output is equal to the peak voltage by 1.414, or *Epk=Eff×1.414.* In a half-wave rectifier, the diode conducts on every other alternation; and the DC output varies from zero to the peak of the secondary. Although the output varies, the average can be determined by the formula *Eavg=Epk×.318.* The diode conducts on one alternation and is reverse biased on the other. The reverse bias on the diode when it is not conducting is called the *peak inverse voltage* and is equal to the peak voltage across the secondary. One DC pulse appears at the output each time the diode conducts. These pulsations are called *ripple.* Since the diode conducts once during each cycle of the input AC, the ripple frequency of a half-wave rectifier is equal to the frequency of the input AC. The ripple frequency of the rectifier in figure 1-11 would be 60 pulses per second (PPS).

The purpose of a full-wave rectifier (figure 1-12) is the same as a half-wave rectifier, or to change AC to DC. A full-wave rectifier consists of an input transformer with a center tapped secondary, two diodes, and a load. The diodes are connected in such a way that one of them conducts on EVERY ALTERNATION of the AC input.

Because of the center tapped secondary, the peak output voltage is equal to one-half the peak voltage across the entire secondary. The peak inverse voltage is equal to the peak voltage of the secondary. Average output voltage can be determined by multiplying peak output *(Epk)×.636.* Since there are two diodes conducting on each alternation of the input, the ripple frequency of a full-wave rectifier is equal to TWICE the frequency of the input AC voltage.

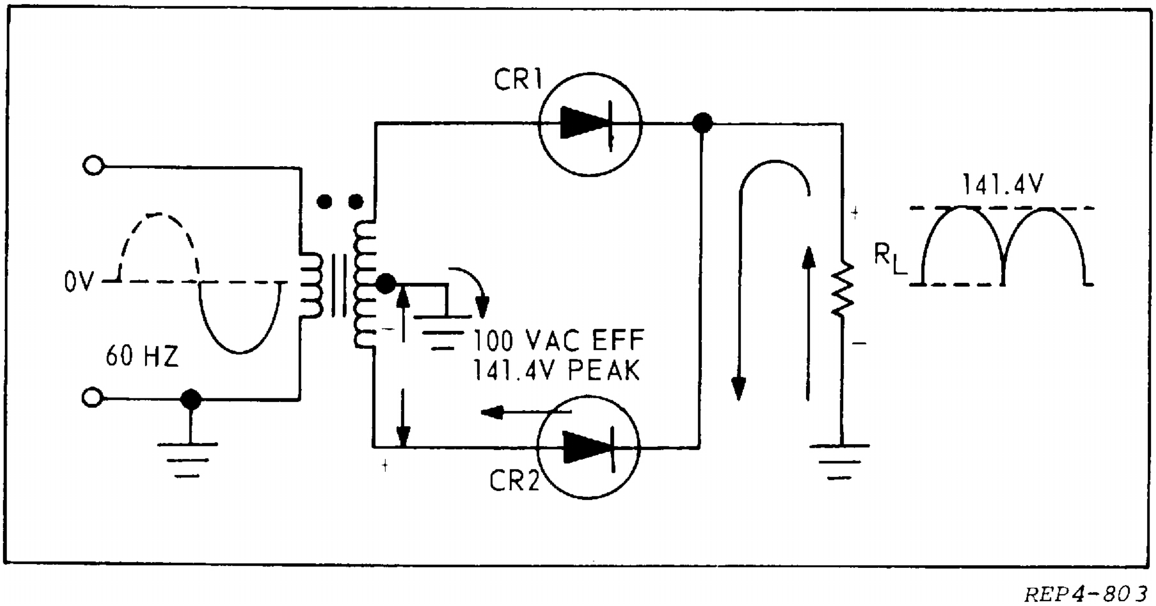

Figure 1-12. Full-Wave Rectifier