10

Automotive Electronics

LEARNING OBJECTIVES

Upon completion and review of this chapter, you should be able to:

- Identify the basic types and construction of solid-state devices used in automotive electronic circuits.
- Identify an ESD symbol and explain its use.
- Explain the use and function of diodes in an automotive circuit.
- Explain forward-biased diodes and reverse-biased diodes.
- Explain the use and function of transistors and the different types used in automotive circuits.
- Explain the operation of a silicon-controlled rectifier (SCR).
- Identify and explain the operation of photonic semiconductors.
- Identify and explain the term integrated circuit and how one uses electronic signals.

KEY TERMS

Anode
Cathode
Diode
Doping
Electrostatic Discharge (ESD)
Field-Effect Transistor (FET)
Forward Bias
Integrated Circuit (ICs)
Light-Emitting Diode (LED)
N-Type Material
P-Type Material
PN Junction
Photonic Semiconductors
Rectifier
Reverse Bias
Semiconductors
Silicon-Controlled Rectifier (SCR)
Transistor
Zener Diode

INTRODUCTION

This chapter will review the basic semiconductors and the electronic principles required to understand how electronic and computer-controlled systems manage the various systems in today's vehicles. A technician must have a thorough grasp of the basis of electronics, it has become the single most important subject area, and the days when technicians could avoid working on an electronic circuit throughout an entire career are long past. This course of study will begin with semiconductor components.

Chapter 3 examined the atom's valence ring, the outermost electron shell. We learned that elements whose atoms have three or fewer electrons in their valence rings are good conductors because the free electrons in the valence ring readily join with the valence electrons of other, similar atoms. We also learned that elements whose atoms have five or more electrons in their valence rings are good insulators (poor conductors) because the valence electrons do not readily join with those of other atoms.

SEMICONDUCTORS

Elements whose atoms have four electrons in their valence rings are neither good insulators nor good conductors. Their four valence electrons cause special electrical properties, which give them the name *semiconductors*. Germanium and silicon are two widely used semiconductor elements. **Semiconductors** are materials with exactly four electrons in their outer shell, so they cannot be classified as insulators or conductors. If an element falls into this group but can be changed into a useful conductor, it is a semiconductor.

When semiconductor elements are in the form of a crystal, they bond together so that each atom has eight electrons in its valence ring: It has its own four electrons and shares four with surrounding atoms (Figure 10-1). In this form it is an excellent insulator, because there are no free electrons to carry current flow. Selenium, copper oxide, and gallium arsenide are all semiconductors, but silicon and germanium are the most commonly used. Pure semiconductors have tight electron bonding; there's no place for electrons to move. In this natural state, the elements aren't useful for conducting electricity.

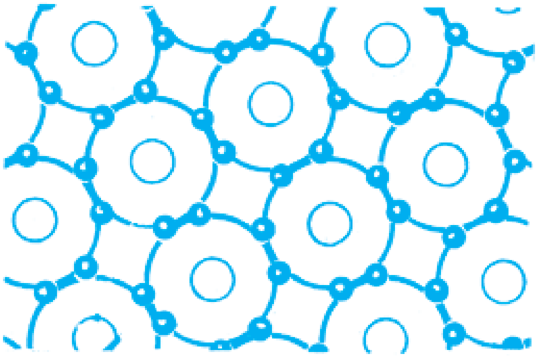

Figure 10-1. Crystalline silicon is an excellent insulator. (Delphi Automotive Systems)

Other elements can be added to silicon and germanium to change this crystalline structure. This is called **doping** the semiconductor. The ratio of doping elements to silicon or germanium is about 1 to 10,000,000. The doping elements are often called impurities because their addition to the silicon or germanium makes the semiconductor materials impure.

Semiconductor Doping

Pure silicon has four electrons in the outer orbit, which makes it a semiconductor. However, the silicon must be very pure without any impurities that can affect its electrical properties. Pure silicon is a crystal that can be created by heating silicon in an electric oven called silicon crystal growers. See Figure 10-2. To make this pure silicon useful for electronic devices, a controlled amount of impurities are added to the pure silicon during the growing process. The amount of the impurities is extremely small. The process of adding impurities to pure silicon is called **doping**. If an element that has only three electrons in the outer orbit, such as boron, is combined with the silicon, the result is a molecule that has an opening, called a **hole**. While the resulting semiconductor is still electrically neutral, this vacant area is a place where an electron could fill. This type of material is called **P-type material**. If the pure silicon is doped using an element with five electrons in its outer orbit, such as phosphorus, the resulting semiconductor material is called **N-type material.**

HISTORICAL NOTE: While the properties of semiconductors have been known since the late 1800s, it was not until the 1930s that silicon and germanium could be produced pure enough to allow accurate control of the doping process. An electric oven is used because it does not use any fuel, and there are no impurities from the heating fuel that could affect the process.

P- and N-Type Material

If there is an excess of free electrons, the semiconductor is **N-type material,** where *N* stands for *negative*. If there is a shortage of free electrons, the semiconductor is **P-type material,** where *P* stands for *positive*. Figure 10-3 shows P- and N-type materials together. In a conductor, we describe current flow as the movement of electrons, in a semiconductor, something else is going on. Just as in a conductor, there is a movement of free electrons, but at the same time, there is a movement of "holes."

Besides silicon, another semiconductor material, germanium, can be used and doped the same way as silicon.

If silicon or germanium is doped with an element such as phosphorus, arsenic, or antimony, each of which has five electrons in its valence ring, there will not be enough space for the ninth electron in any of the shared valence rings. This extra electron is free (Figure 10-4). This type of doped material is called negative or *N-type* material because it already has excess electrons and will repel additional negative charges.

Doping of a semiconductor material, using an element with three electrons in its outer shell called **trivalent**, results in P-type material. Using an element with five electrons in its outer orbit, called **pentavalent**, results in N-type material.

If silicon or germanium is doped with an element such as boron or indium, each of which has only three electrons in its outer shell, some of the atoms will have only seven electrons in their valence rings. There will be a hole in these valence rings (Figure 10-5). This type of doped material is called positive or *P-type* material, because it will attract a negative charge (an electron). In different ways, P-type and N-type silicon crystals may permit an electrical current flow: In the P-type semiconductor, current flow

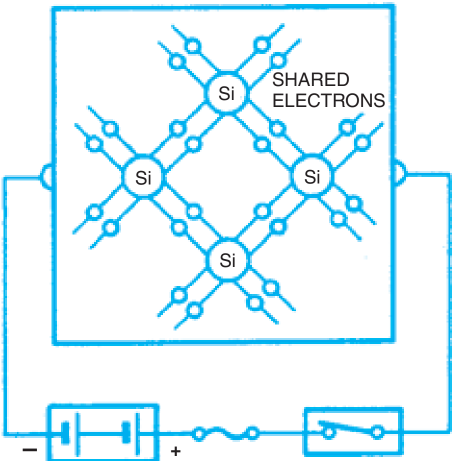

Figure 10-2. Germanium atom in a crystallized cluster with shared electrons.

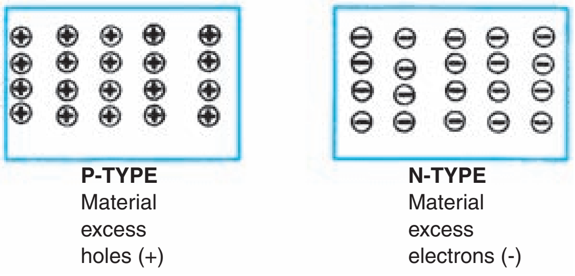

Figure 10-3. P- and N-type material.

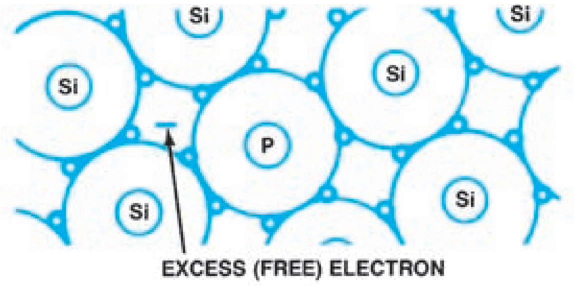

Figure 10-4. N-type material has an extra, or free, electron. (Delphi Automotive Systems)

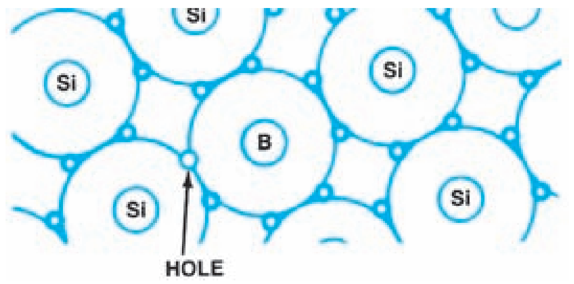

Figure 10-5. P-type material has a "hole" in some of its valence rings. (Delphi Automotive Systems)

is occasioned by a deficit of electrons, while in the N-type semiconductor, current flow is occasioned by an excess of electrons.

PN-Junction

When the two semiconductor materials are brought together, as shown in Figure 10-6, something happens at the area where the two touch. This area is called the **PN junction.** You chemically join P- and N-type materials either by growing them together or fusing them with some type of heat process. Either way they join together as a single crystal structure. The excess electrons in the N-type material are attracted to the holes in the P-type material. Some electrons drift across the junction to combine with holes. As an electron combines with a hole, both effectively disappear. Whenever a voltage is applied to a semiconductor, electrons will flow towards the positive terminal and the holes will move towards the negative terminal. The electron is no longer free and the hole no longer exists. Because of the cancellation of charges, the material at the junction assumes a positive charge in the N-type material and a negative charge in the P-type material; PN-junctions become diodes.

As long as no external voltage is applied to the semiconductors, there is a limit to how many electrons will cross the PN junction. Each electron that crosses the junction leaves behind an atom that is missing a negative charge. Such an atom is called a *positive ion*. In the same way, each hole that crosses the junction leaves behind a *negative ion*. As positive ions accumulate in the N-type material, they exert a force (a potential) that prevents any more electrons from leaving. As negative ions accumulate in the P-type material, they exert a potential that keeps any more holes from leaving.

Eventually, this results in a stable condition that leaves a deficiency of both holes and electrons at the PN junction. This zone is called the *depletion region*. The potentials exerted by the negative and positive ions on opposite sides of the depletion region are two unlike charges. Combining unlike charges creates voltage potential. The voltage potential across the PN junction is called the *barrier voltage*. Doped germanium has a barrier voltage of about 0.3 volt. Doped silicon has a barrier voltage of about 0.7 volt.

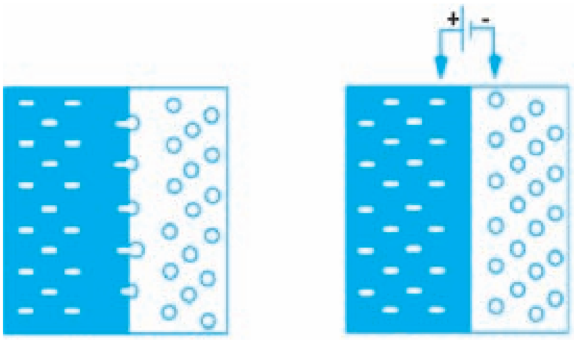

Figure 10-6. PN junction.

Free Electrons and Movement of Holes

In P-type semiconductor material, there is a predominance of *acceptor atoms* and holes. In N-type material, there is a predominance of *donor atoms* and free electrons. When the two semiconductors are kept separate, holes and electrons are distributed randomly throughout the respective materials. A hole is a location where an electron normally resides but is currently absent. A hole is not a particle, but it behaves like one (Figure 10-7).

Because a hole is the absence of an electron, it represents a missing negative charge. As a result, a hole acts like a positively charged particle. Electrons and holes occur in both types of semi-

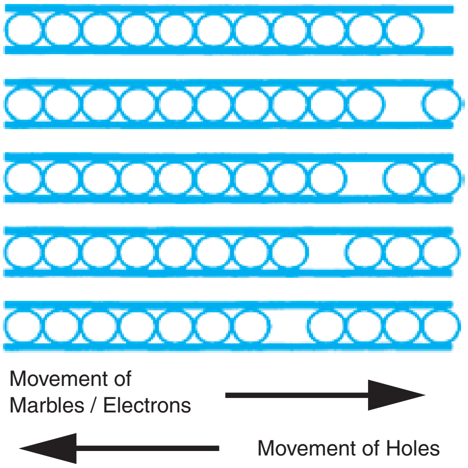

Figure 10-7. Movement of holes. (GM Service and Parts Operations)

conductor material. In P-type material, we describe current flow as holes moving. In N-type material, we describe current flow as electrons moving. Holes cannot actually carry current. When we talk about current flow in terms of holes moving in one direction, we're actually describing the movement of the absent electrons moving in the opposite direction.

ELECTROSTATIC DISCHARGE (ESD)

An electrostatic charge can build up on the surface of your body. If you touch something your charge can be discharged to the other surface. This is called **electrostatic discharge (ESD).** Figure 10-8 shows the ESD symbol indicating that the component is solid-state. Some service manuals use the words *solid-state* instead of the ESD symbol. Look for these indicators and take the suggested ESD precautions when you work on sensitive components.

DIODES

Now that you've learned what a semiconductor is, let's look at some basic examples. The simplest kind of semiconductor is a **diode** (Figure 10-9). It's made of one layer of P-type material and one of N-type material. The diode is the simplest semiconductor device that allows current to flow in only one direction. A diode can function as a switch, acting as either conductor or insulator, depending on the direction of current flow. Diodes turn on when the polarity of the current is correct and turn off when the flow has the wrong polarity. The suffix *-ode* literally means *terminal*. For instance, it is used as the suffix for *cathode* and *anode*. The word *diode* means literally, having two terminals.

Previous sections discussed how both P-type and N-type semiconductor crystals can conduct electricity. Either the proportion of holes or surplus of electrons determines the actual resistance of each type. When a chip is manufactured using both P- and N-type semiconductors, electrons will flow in only one direction. The diode is used in electronic circuitry as a sort of one-way check valve that will conduct electricity in one direction (forward) and block it in the other (reverse).

Figure 10-8. ESD symbol. (GM Service and Parts Operations)

Anode/Cathode

If current flows from left to right in Figure 10-9, it's correct to place a positive plus sign to the left and a negative minus sign to the right of the diode. The positive side of the diode is the **anode** and the negative side is the **cathode.** Associate *anode* with A+ (it's the positive side) and *cathode* with C− (the negative side). The cathode is the end with the stripe. Basically, the following types of diodes are used in automotive applications:

- Regular diodes (used for rectification, or changing AC to DC)
- Clamping diodes (to control voltage spikes and surges that could damage solid-state circuits)
- LEDs (light emitting diodes, used as indicators)
- Zener diodes (voltage regulation)
- Photodiodes

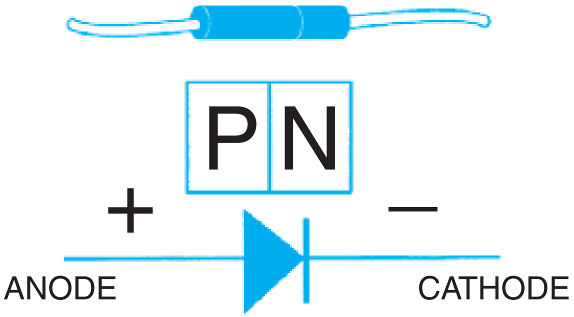

Figure 10-9. Diode.

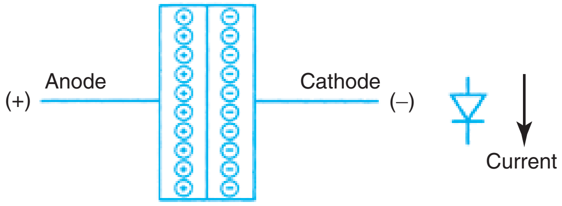

Figure 10-10. Diode triangle.

Diodes allow current flow in only one direction. In Figure 10-10, the triangle in the diode symbol points in the direction current is permitted to flow using conventional current flow theory. Inside a diode are small positive (P) and negative (N) areas, which are separated by the thin boundary area called the PN Junction. When a diode is placed in a circuit with the positive side of the circuit connected to the positive side of the diode, and the negative side of the circuit connected to the negative side of the diode, the diode is said to have *forward bias*. As an electrical one-way check valve, diodes will permit current flow only when correctly polarized. Diodes are used in AC generators (alternators) to produce a DC characteristic from AC and are also used extensively in electronic circuits.

Forward-Biased Diodes

A diode that's connected to voltage so that current is able to flow has **forward bias.** Bias refers to how the voltage is applied. In Figure 10-11, the negative voltage terminal is connected to the N side of the diode, and the positive voltage terminal is connected to the P side.

If you cover up the P-type material in the diode, you can think of this as any other circuit. Electrons are repelled from the negative voltage terminal through the conductor and towards the diode. The electrons at the end of the conductor repel the electrons in the N-type material. If there weren't a barrier voltage, the movement of electrons would continue through the conductor towards the positive terminal.

Now think about the P-type material. The positive voltage terminal repels the electron holes in the P side of the diode. This means that both electrons and electron holes are being forced into the depletion zone.

Unlike electrical charges are attracted to each other and like charges repel each other. Therefore, the positive charge from the circuit's power supply is attracted to the negative side of the circuit. The voltage in the circuit is much stronger than the charges inside the diode and causes the charges inside the diode to move. The diode's P conductive material is repelled by the positive charge of the circuit and is pushed toward the N material, and the N material is pushed toward the P. This causes the PN junction to become a conductor, allowing the circuit's current to flow. Diodes may be destroyed when subjected to voltage or current values that exceed their rated capacity. Excessive reverse current may cause a diode to conduct in the wrong direction and excessive heat can melt the semiconductor material.

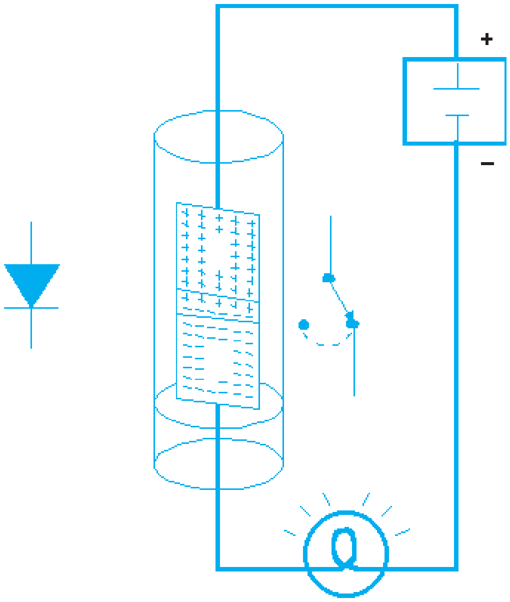

Figure 10-11. Forward-biased diode. (GM Service and Parts Operations)

Reverse-Biased Diode

A diode that's connected to voltage so that current cannot flow has **reverse bias** (Figure 10-12). This means the negative voltage terminal is connected to the P side of the diode, and the positive voltage terminal is connected to the N side. Let's see what happens when voltage is applied to this circuit. The electrons from the negative voltage terminal combine with the electron holes in the P-type material. The electrons in the N-type material are attracted towards the positive voltage terminal. This enlarges the depletion area. Since the holes

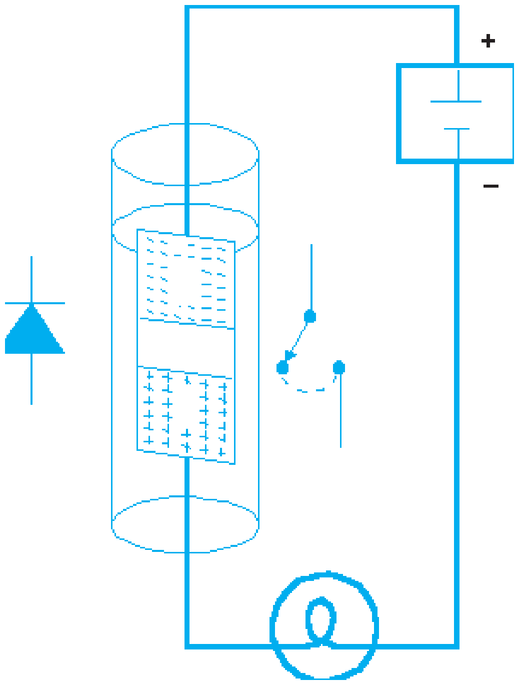

Figure 10-12. Reverse-biased diode. (GM Service and Parts Operations)

and electrons in the depletion area don't combine, current can't flow.

When reverse bias is applied to the diode, the P and N areas of the diode are connected to opposite charges. Since opposites attract, the P material moves toward the negative part of the circuit whereas the N material moves toward the positive part of the circuit. This empties the PN junction and current flow stops.

Diode Types

Diodes are constructed to serve many uses in the automotive electronic circuits, such as:

Small-Signal Diodes

Small-signal diodes are used throughout many automotive circuits and are used to rectify AC to DC as well as for spike or voltage clamping, such as in relays and solenoids.

Power Transistors

Power transistors, also called power rectifiers, are designed to handle more current than small-signal type diodes. To be able to handle higher currents, the case usually uses a heat sink to dissipate the heat to help protect the diode from damage.

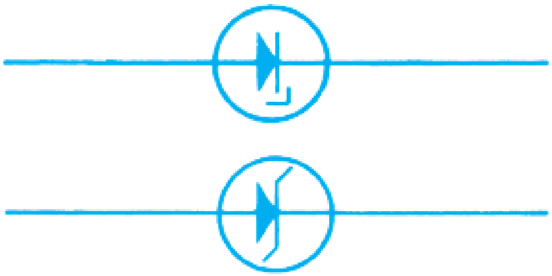

Figure 10-13. Zener diode.

Zener Diodes

In 1934, Clarence Melvin Zener invented a diode that can be used to control voltage. **Zener diodes** (Figure 10-13) work the same way as regular diodes when forward biased, but they are placed backwards in a circuit. When the Zener voltage is reached, the Zener diode begins to allow current flow but maintains a voltage drop across itself. The Zener diode is designed to block reverse-bias current but only up to a specific voltage value between 2 and 200 volts. When this reverse breakdown voltage (V_2) is attained, it will conduct the reverse-bias current flow without damage to the semiconductor material. The major difference between a Zener diode and a conventional diode is that the Zener diode is more heavily doped and is therefore able to withstand being operated in reverse bias without harm.

PHOTONIC SEMICONDUCTORS

Photonic semiconductors, like the photodiode in Figure 10-14, emit and detect light or *photons*. Photons are produced when certain electrons excited to a higher-than-normal energy level return to a more normal level. Photons act like waves, and the distance between the wave nodes and anti-nodes (wave crests and valleys) is known as wavelength. Electrons are excited to higher energy levels and photons with shorter wavelengths than electrons are excited to lower levels. Photons are not necessarily visible, and it is important to note that they may

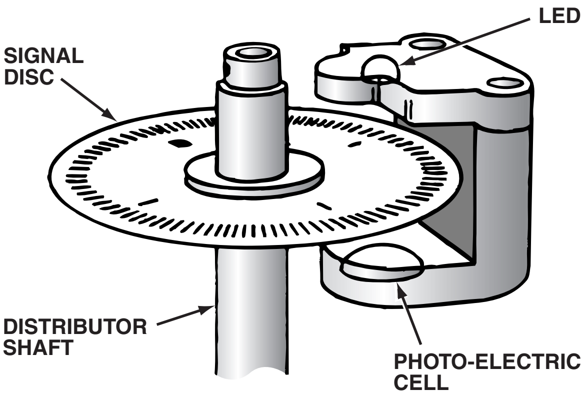

Figure 10-14. Nissan optical signal generator works by interrupting a beam of light passing from the LED to a photodiode. (Courtesy of Nissan North America, Inc.)

only truly be described as *light* when they are visible. Photodiodes are designed specifically to detect light. These diodes are constructed with a glass or plastic window through which the light enters. Often, photodiodes have a large, exposed PN junction region. These diodes are often used in automatic headlamp control systems.

The Optical Spectrum

All visible light is classified as electromagnetic radiation. The specific wavelength of light rays will define its characteristics. Light wavelengths are specified in nanometers, which are billionths of a meter. The optical light spectrum includes ultraviolet, visible, and infrared radiation. Photonic semiconductors can emit or detect near-infrared radiation, so near-infrared is usually referred to as light.

Solar Cells

A solar cell consists of a PN or NP silicon semiconductor junction built onto contact plates. A single silicon solar cell may generate up to 0.5 V in ideal light conditions (bright sunlight), but output values are usually lower. Like battery cells, solar cells are normally arranged in series groups, in which case the output voltage would be the sum of cell voltages, or in parallel, where the output current would be the sum of the cell currents. They are sometimes used as battery chargers on vehicles.

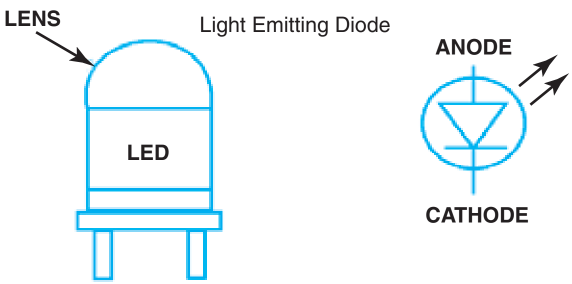

Figure 10-15. Light-emitting diode (LED).

Light-Emitting Diodes (LEDs)

All diodes release energy in operation, usually in the form of heat. Diodes can be constructed from gallium arsenide phosphide to release light when current flows across the P-N junction. These are known as **light-emitting diodes (LEDs)** (Figure 10-15). They are much the same as regular diodes except that they emit light when they are forward biased. LEDs are very current-sensitive and can be damaged if they are subjected to more than 50 milliamps. LEDs also require higher voltages to turn on than do regular diodes; normally, 1.5 to 2.5 volts are required to forward-bias an LED to cause it to light up. LEDs also offer much less resistance to reverse-bias voltages. High reverse-bias voltages may cause the LED to light or cause it to burn up.

A seven-segment LED is capable of displaying letters and numbers and is very efficient at producing light from electrical energy. In complex electrical circuits, LEDs are an excellent alternative to incandescent lamps. They produce much less heat and need less current to operate. They also turn on and off more quickly. LEDs are also used in some steering wheel controls.

Photodiode

An LED produces light when current flows through the P-N junction, releasing photons of light. LEDs can also produce a voltage if light is exposed to the P-N junction. Diodes that incorporate a clear window to allow light to enter are called **photodiodes**.

RECTIFIER CIRCUITS

A **rectifier** (Figure 10-16) converts an undulating (alternating current voltage) signal into a single-polarity (direct current voltage) signal. Rectifiers change alternating current (AC) to direct current (DC). Several diodes are combined to build a diode rectifier, which is also called a bridge rectifier. Bridge rectifiers comprise a network of four diodes that converts both halves of an AC signal.

AC Generator (Alternator)

The most common use of a rectifier in today's automotive systems is in the AC generator. The AC generator produces alternating current (AC). Because automotive electrical systems use direct current, the generator must somehow convert the AC to DC. The DC is provided at the alternator's output terminal. Figure 10-17 shows how a diode rectifier works inside a generator.

Full-Wave Rectifier Bridge Operation

Think about this example in terms of conventional theory (Figure 10-16). First you must understand that the stator voltage is AC. That means the voltage at *A* alternates between positive and negative. When the voltage at *A* is positive, current flows from *A* to the junction between diodes D1 and D2. Notice the direction of the diode arrows. Current can't flow through D1, only through D2. The current reaches another junction. It can't flow through D4, so current must pass through the circuit load. The current continues along the circuit until it reaches the junction of D1 and D3.

Even though the voltage applied to D1 is forward biased, current can't flow because there's positive voltage on the other side of the diode. Current flows through D3 to ground at B. When the stator voltage reverses so that point *B* is positive, current flows along the opposite path. Whether the stator voltage at point *A* is positive or negative, current always flows from top to bottom through the load (R1). This means the current is DC.

The rectifiers in generators are designed to have an output (positive) and an input (negative) diode for each alternation of current. This type of rectifier is called a full-wave rectifier. In this type of rectifier, there is one pulse of DC for each pulse of AC. The DC that's generated is called full-wave pulsating DC. Figure 10-16 is an illustration of full-wave pulsating DC.

This example is simplified to include only one stator and four diodes. In a real AC generator, there are three stator coils and six diodes. The diodes are mounted inside two heat sinks. The heat sinks are cooled by air to dissipate the heat generated in the six diodes. The combination of the six diodes and the heat sink is called a rectifier bridge.

TRANSISTORS

Transistors (Figure 10-18) are semiconductor devices with three leads. A very small current or voltage at one lead can control a much larger current flowing through the other two leads. This means that transistors can be used as amplifiers and switches. There are two main families of transistors: bipolar transistors and field-effect transistors. Many of their functions are either directly or

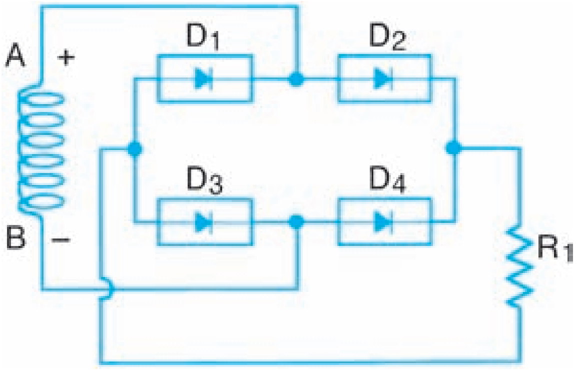

Figure 10-16. Rectifier bridge. (GM Service and Parts Operations)

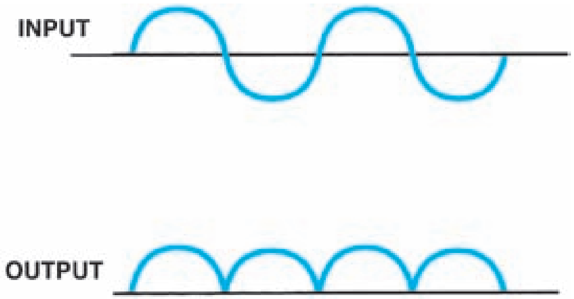

Figure 10-17. AC to DC rectification. (GM Service and Parts Operations)

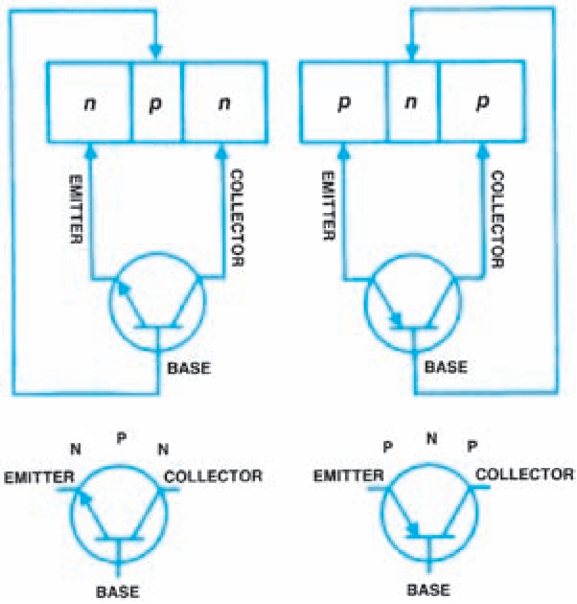

Figure 10-18. Transistors.

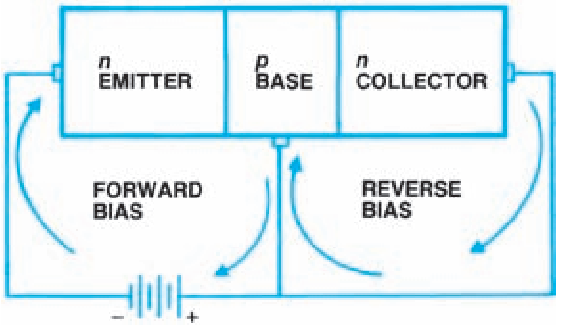

Figure 10-19. Transistor operation.

indirectly associated with circuit switching, and in this capacity they can be likened to *relays* in electrical circuits.

Bipolar Transistors

Add a second junction to a PN junction diode and you get a three-layer silicon sandwich (Figure 10-19). The sandwich can be NPN or PNP. Either way, the middle layer acts like a faucet or gate that controls the current moving through the three layers. The three layers of a bipolar transistor are the emitter, base, and collector. The center section is what determines how the transistor will function. The base material is constructed thinner and with less doping than either the collector or the emitter on either side. The base is the central unit that uses a low amount of current to turn on and off the emitter-collector current.

When the base of an NPN Transistor is grounded (0 volts), no current flows from the emitter to the collector—the transistor is off. If the base is forward-biased by at least 0.6 volt, the current will flow from the emitter to the collector—the transistor is on. When operated in only these two modes, the transistor functions as a *switch* (Figure 10-19). If the base is forward biased, the emitter-collector current will follow variations in a much smaller base current. The transistor then functions as an amplifier. This discussion applies to a transistor in which the emitter is the ground connection for both the input and output and is called the common-emitter circuit. Diodes and transistors share several key features:

- The base-emitter junction (or diode) will not conduct until the forward voltage exceeds 0.6 volt.
- Too much current will cause a transistor to become hot and operate improperly. If a transistor is hot when touched, disconnect the power to it.
- Too much current or voltage may damage or permanently destroy the “chip” that forms a transistor. If the chip isn’t harmed, its tiny connection wires may melt or separate from the chip. Never connect a transistor backwards!

Examples of Bipolar Transistors

Just as with diodes, transistors are available for many different applications.

Small-Signal Switching Transistors

A transistor used for amplifying signals is designed specifically for switching, while others can also amplify signals.

Power Transistors

Power transistors are used to switch on and off units that require up to one ampere of current or more, depending on the design. All power transistors use a heat sink to dissipate heat generated by the voltage drop that occurs across the PN junction of the transistors. Power transistors are also called **driven** because they control current of output devices, such as solenoids.

High Frequency Transistors

High frequency transistors are specifically designed for rapid switching by using a very thin base material.

Transistor Operation

The input circuit for a NPN transistor is the emitter-base circuit (Figure 10-20). Because the base is thinner and doped less than the emitter, it has fewer holes than the emitter has free electrons. Therefore, when forward bias is applied, the numerous free electrons from the emitter do not find enough holes to combine with in the base. In this condition, the free electrons accumulate in the base and eventually restrict further current flow.

The output circuit for this NPN transistor is shown in Figure 10-21 with reverse bias applied. The base is thinner and doped less than the collector. Therefore, under reverse bias, it has few minority carriers (free electrons) to combine with many minority carriers (holes in the collector). When the collector-base output circuit is reverse-biased, very little reverse current will flow. This is similar to the effect of forward-biasing the emitter-base input circuit, in which very little forward current will flow.

When the input and output circuits are connected, with the forward and reverse biases maintained, the overall operation of the NPN transistor changes (Figure 10-22). Now, the majority of free electrons from the emitter, which could not combine with the base, are attracted through the base to the holes in the collector. The free electrons from the emitter are moved by the negative forward bias toward the base, but most pass through the base to the holes in the collector, where they are attracted by a positive bias. Reverse current flows in the collector-base output circuit, but the overall current flow in the transistor is forward.

A slight change in the emitter-base bias causes a large change in emitter-to-collector current flow. This is similar to a small amount of current flow controlling a large current flow through a relay. As the emitter-base bias changes, either more or fewer free electrons are moved toward the base. This causes the collector current to increase or decrease. If the emitter-base circuit is opened or the bias is removed, no forward current will flow through the transistor because the base-collector junction acts like a PN diode with reverse bias applied.

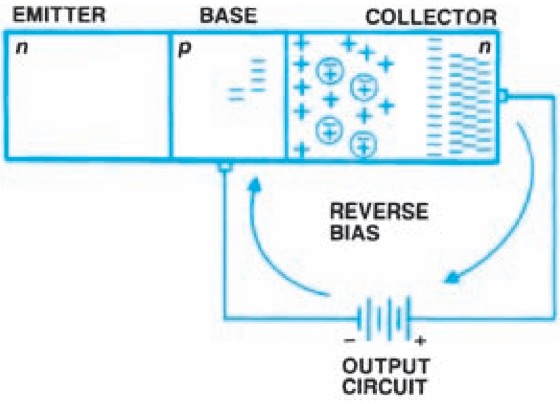

Figure 10-21. Reverse-biased transistor operation.

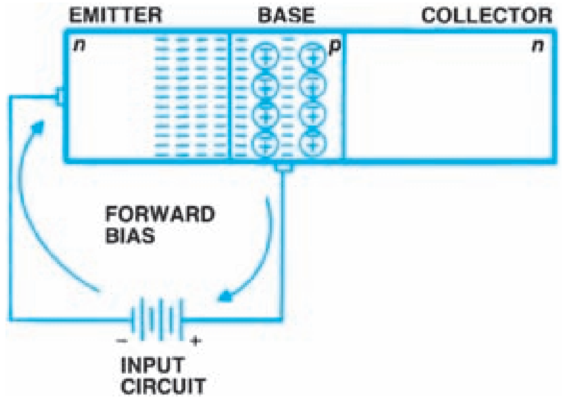

Figure 10-20. Forward-biased transistor operation.

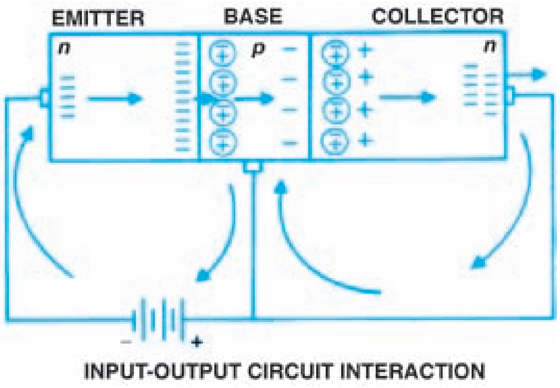

Figure 10-22. Transistor input/output current interaction.

Tran(sfer) + (Re)sistor

The word *transistor* was originally a business trademark used as a name for an electrical part that transferred electric signals across a resistor. Two scientists, John Bardeen and Walter H. Brattain, at Bell Telephone Laboratories in 1948, invented the point-contact transistor. In 1951, their colleague, William Shockley, invented the junction transistor. As a result of their work, these three men received the 1956 Nobel Prize for physics.

Field-Effect Transistors (FETs)

Field-effect transistors (FET) have become more important than bipolar transistors. They are easier to make and require less silicon (Figure 10-23). There are two major FET families, junction FETs and metal-oxide-semiconductor FETs. In both kinds, a small input voltage and practically no input current control an output current.

Junction FETs (JFETs)

Field effect transistors are available in two designs: an N-channel and a P-channel. The channel acts like a resistance path between the source and the drain. The resistance of the channel is controlled by the voltage (not the current) at the gate. By varying the voltage at the gate, this design transistor can perform switching and amplification. The higher the voltage at the gate, the more the conductive path (channel) is increased in resistance.

Current can be completely blocked if the voltage at the gate is high enough.

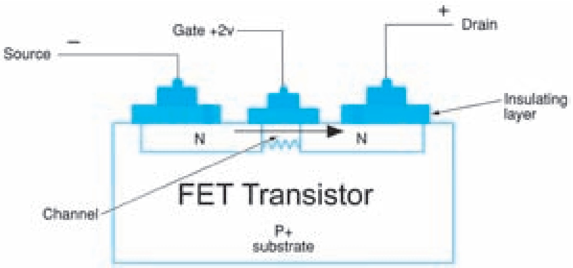

Figure 10-23. Field-effect transistor (FET).

Since JFETs are voltage-controlled, they have the following important advantages over current-controlled bipolar transistors:

- The gate-channel resistance is very high and therefore has very little effect on any other circuits that could be connected to the gate.
- The gate circuit has such a high resistance that current flow is almost zero. The high resistance is present because the gate and channel effectively form a reversed-biased diode. If a diode is reversed biased, the resistance will be high.

Like bipolar transistors, JFETs can be damaged or destroyed by excessive current or voltage.

Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs)

Most electronic devices today use metal-oxide semiconductor FETs (MOSFETs). Most microcomputer and memory integrated circuits are arrays of thousands of MOSFETs on a small sliver of silicon. MOSFETs are easy to make, they can be very small, and some MOSFET circuits consume negligible power. New kinds of power MOSFETs are also very useful. The input resistance of the MOSFET is the highest of any transistor. This and other factors give MOSFETs the following important advantages:

- The gate-channel resistance is almost infinite. This means the gate pulls no current from external circuits.
- MOSFETs can function as voltage-controlled variable resistors. The gate voltage controls channel resistance.

Like other field-effect transistors (FETs), MOSFETs can be classified as P-type or N-type. In a MOSFET, the gate is electrically isolated from the source and the drain by a silicon oxide insulator. When the voltage at the gate is positive, the resistance of the channel will increase, reducing current flow between the source and the drain. The voltage level at the gate determines the resistance of the path or channel allowing MOSFET device to act as either a switch or a variable resistor. The gate-channel has such high resistance that little, if any, current is drawn from an external circuit that may be connected to the gate.

Unijunction Transistor (UJT)

A unijunction transistor is a simple electronic switch, which is not capable of amplification. A UJT has been described as a three-terminal diode that uses either base I or base II as output terminal. Like a diode, it requires a certain voltage level to cause the UJT to be conductive and once this level is reached, allows current to flow between base I and base II.

Darlington Pairs

A **Darlington pair** consists of two transistors wired together. This arrangement permits a very small current flow to control a large current flow. The Darlington pair is named for Sidney Darlington, an American physicist for Bell Laboratories from 1929 to 1971. Darlington amplifier circuits are commonly used in electronic ignition systems, computer engine control circuits, and many other electronic applications. See Figure 10-24.

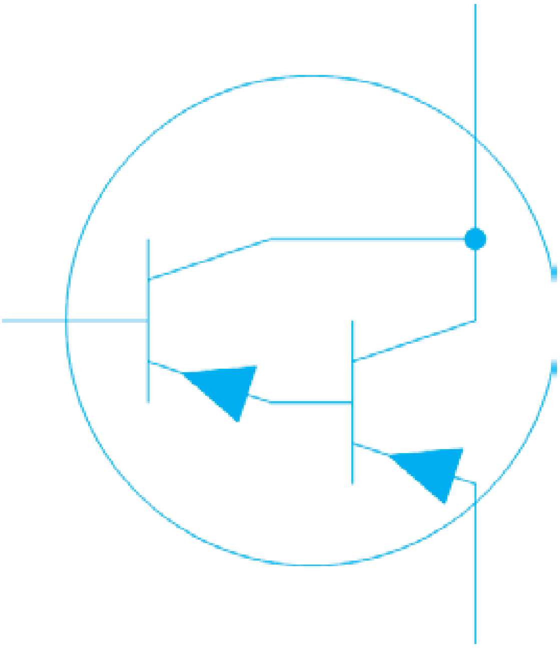

Figure 10-24. Darlington pairs.

SILICON-CONTROLLED RECTIFIERS (SCRs)

A silicon-controlled rectifier, as shown in Figure 10-25, is an electrical switch that is used to control DC current. SCRs use four layers of semiconductor materials with three P-N junctions or similar to two diodes connected end-to-end. Like a diode, the P-N junction becomes forward biased when the voltage is higher at the anode compared to the cathode. The difference between a diode and an SCR is that not only must the anode be more positive than the cathode, but the voltage at the gate allows the second set of P-N junctions to be forward biased and therefore, causes current to flow. SCRs are used for switching in ignition and other electronic circuits.

A TRIAC consists of two SCRs in parallel and is used to control either AC or DC current flow. The internal construction of a TRIAC results in the gate being more remote from the current-carrying region, enabling the TRIAC to switch high current when gate current is present.

Thyristor

Thyristors are a type of SCR that has three terminals and acts as a solid-state switch. A thyristor is a controlled rectifier where the current flow from an anode to a cathode is controlled by a small signal current that flows from the gate to the cathode. Thyristors are electronic switches, which can be either on or off and can switch either AC or DC current. Thyristors are

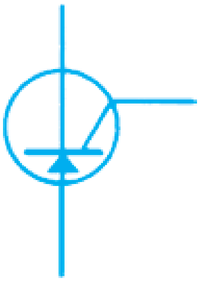

Figure 10-25. Silicon-controlled rectifiers (SCR).

used in electronic circuits along with other devices and usually are not a discrete (individual) replaceable component.

INTEGRATED CIRCUITS

An **integrated circuit** (abbreviated **IC**) is a section of silicon semiconductor material on which thousands of diodes, resistors, and transistors are constructed. See Figure 10-26. Integrated circuits are created by etching the circuits in a clean room. Integrated circuits work by using the presence or absence of voltage with little, if any, current flow. The integrated circuits are small and are usually encased in plastic with terminals arranged so that it can be installed in a circuit board. A common type of integrated circuit package uses two rows of pins and is called a **DIP** (**dual in-line package**). DIPs were commonly used until the mid 1990s as PROM chips in vehicle computers.

USING ELECTRONIC SIGNALS

Electronic *signals* are simply on and off voltage pulses that are used by other electronic devices, such as power transistors to turn something on or off. For example, a cooling fan motor can be varied in speed by controlling the percentage of time that current is allowed to flow to the motor. This action of variable control is called **pulse-width modulation**.

Some electrical signals are analog, such as those from magnetic sensors, and must be converted into digital on-and-off signals for use by a digital computer. Most of these signals are weak and can be affected by electromagnetic interference, often called electronic noise. MOSFETS are particularly sensitive to electronic interference. To reduce the possibility of interference, components containing MOSFETs are usually isolated physically from sources of high voltage, such as secondary ignition system components.

HISTORICAL NOTE: The integrated circuit was invented by two people at about the same time in two different companies. The two credited for the invention of a circuit on a chip in 1959 are Jack Kilby of Texas Instruments and Robert Noyce of Fairchild. The two companies agreed to grant license to each other since both conceded that each had some right to the invention.

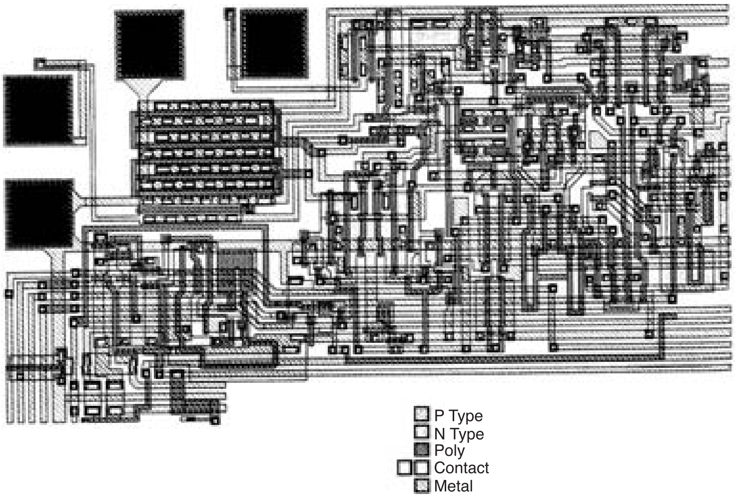

Figure 10-26. Integrated circuits. (GM Service and Parts Operations)

SUMMARY

Semiconductors are, by definition, elemental materials with four electrons in their outer shells. Silicon is the most commonly used semiconductor material. Semiconductors must be doped to provide them with the electrical properties that can make them useful as electronic components. After doping, semiconductor crystals may be classified as having N or P electrical properties. Diodes are two-terminal semiconductors that often function as a sort of electrical one-way check valve. Zener diodes are commonly used in vehicle electronic systems; they act as voltage-sensitive switches in a circuit.

Transistors are three-terminal semiconductor chips. Transistors can be generally grouped into bipolar and field effect types. Essentially a transistor is a semiconductor sandwich with the middle layer acting as a control gate, a small current flow through the base-emitter will ungate the transistor and permit a much larger emitter-collector current flow. Many different types of transistor are used in vehicle electronic circuits, but their roles are primarily concerned with switching and amplification. The optical spectrum includes ultraviolet, visible, and infrared radiation. Optical components conduct, reflect, refract, or modify light. Vehicle electronics are using increased amounts of fiber optics components.

Integrated circuits consist of resistors, diodes, and transistors arranged in a circuit on a chip of silicon. A common integrated circuit chip package used in computer and vehicle electronic systems is a DIP with either 14 or 16 terminals. Many different chips with different functions are often arranged on a primary circuit board also known as a motherboard.

Review Questions

1. Semiconductors are made into good conductors through which of these processes:
   a. Electrolysis
   b. Purification
   c. Ionization
   d. Doping

2. In an electrical circuit, a diode functions as a:
   a. Timing device
   b. Switch
   c. Resistor
   d. Energy storage device

3. What is the purpose of a diode rectifier circuit?
   a. To convert AC voltage to DC
   b. To convert DC voltage to AC
   c. To smooth out voltage pulsations
   d. To convert DC voltage to AC

4. The positive terminal of a diode is correctly called an:
   a. Electrode
   b. Cathode
   c. Anode
   d. Emitter

5. Semiconductors are elements that have how many electrons in their valence rings?
   a. Two
   b. Four
   c. Six
   d. Eight

6. A diode is a simple device which joins:
   a. P-material and N-material
   b. P-material and P-material
   c. N-material and N-material
   d. P-material and a conductor

7. Which of the following is *not* true of forward bias in a diode?
   a. Free electrons in the N-material and holes in the P-material both move toward the junction.
   b. N-material electrons move across the junction to fill the holes in the P-material.
   c. Negatively charged holes left behind in the N-material attract electrons from the negative voltage source.
   d. The free electrons which moved into the P-material continue to move toward the positive voltage source.

8. When reverse bias is applied to a simple diode, which of the following will result?
   a. The free electrons will move toward the junction.
   b. The holes of the P-material move toward the junction.
   c. No current will flow across the junction.
   d. The voltage increases.

9. Under normal use, a simple diode acts to:
   a. Allow current to flow in one direction only
   b. Allow current to flow in alternating directions
   c. Block the flow of current from any direction
   d. Allow current to flow from either direction at once

10. “Breakdown voltage” is the voltage at which a Zener diode will:
    a. Allow reverse current to flow
    b. Stop the flow of reverse current
    c. Sustain damage as a result of current overload
    d. Stop the flow of either forward or reverse current

11. Which of the following combinations of materials can exist in the composition of a transistor?
    a. NPN
    b. PNN
    c. ABS
    d. BSA

12. To use a transistor as a simple solid-state relay:
    a. The emitter-base junction must be reverse-biased, and the collector-base junction must be forward-biased.
    b. The emitter-base junction must be forward-biased, and the collector-base junction must be reverse-biased.
    c. The emitter-base junction and the collector-base junction both must be forward-biased.
    d. The emitter-base junction and the collector-base junction both must be reverse-biased.

13. Which of the following is *not* commonly used as a doping element?
    a. Arsenic
    b. Antimony

c. Phosphorus
d. Silicon

14. The display faces of digital instruments are often made of:
a. Silicon-controlled rectifiers
b. Integrated circuits
c. Light-emitting diodes
d. Thyristors

15. All of the following are parts of a field-effect transistor (FET), *except* the:
a. Drain
b. Source
c. Base
d. Gate

16. All of the following are characteristics of an integrated circuit (IC), except:
a. It is extremely small.
b. It contains thousands of individual components.
c. It is manufactured from silicon.
d. It is larger than a hybrid circuit.