Electrical Tech Note — 520

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Semiconductors and Diodes

In any fluid flow system a check valve is a useful device to allow flow in one direction, but not in the opposite direction. An ideal check valve requires no pressure to open, offers no resistance to flow in the forward direction, can withstand high pressure in the reverse direction, and when closed does not leak. This also describes the desired action of a diode in an electronic circuit where the flow is electrical current. A diode allows current to flow in one direction, but if the polarity is reversed, current is prevented from flowing in the opposite direction. Figure 520.1 shows a diode in series with a resistor where the current flows only in one direction resulting in a pulsing voltage across the resistor. Diodes are useful tools in electronic circuits and they have many useful applications. The characteristics of a diode in an electronic circuit can be created in various ways, and in the early days of electronics the most common diodes were vacuum tubes that were bulky and required a lot of energy for their operation. In the 1940's it was discovered that diodes could be made from semiconducting materials resulting in a significant reduction of energy loss and size. This Tech Note will briefly discuss semiconductors and how they work as a diode. Also discussed are some basic characteristics and specifications of semiconducting diodes. An important application for diodes, covered in this Tech Note is their use in power supplies that convert alternating current to direct current.

The symbol for a diode is a triangle with a line across the point as shown in Figure 520.1. Assuming conventional current flow from positive (+) to negative (–), the triangle points in the direction of current flow. The flat side of the triangle is the anode (+) and the point of the triangle is the cathode (–).

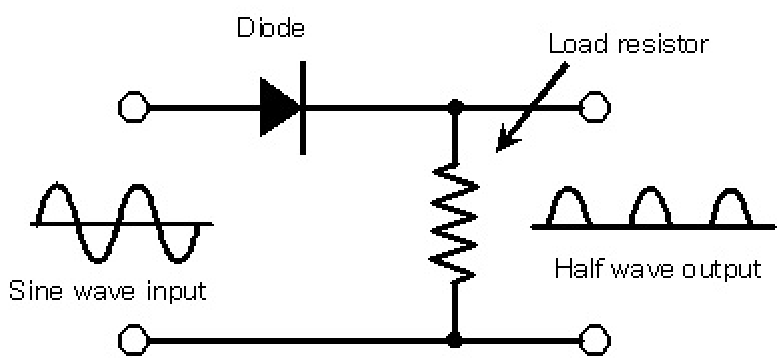

Figure 520.1 *The diode only permits the current to flow in one direction, therefore, there is a voltage across the resistor for only half of the alternating current cycle.*

What Is A Semiconductor: Silicon and germanium atoms have four electrons in their outer or valence orbit. When these atoms group together to form a solid they combine in a geometric pattern with adjacent atoms and share valence electrons so that each atom will have eight electrons in it’s outer orbit. Since silicon and germanium atoms each have four valence electrons, they can share one electron with each of four other atoms. Some of these valence electrons will absorb enough external energy to become movable through the crystal and with the addition of an external voltage source a very small current will flow. Silicon and germanium crystals become more conductive as the temperature rises. This current is too small to make it a useful conductor, but too large to make the crystal a useful insulator. Thus pure silicon and germanium crystals are known as *intrinsic semiconductors*. Thermal energy can break the valence bond and electrons become mobile leaving a positive charge behind called a *hole*. These free electrons and holes are referred to as charge carriers. Holes and free electrons are produced simultaneously in equal numbers so the electrical neutrality of the crystal is maintained. Generally it takes a considerable quantity of external energy to break the valence bonding and produce charge carriers in a pure crystal of silicon and germanium.

The addition of certain impurities can increase the conductivity of the silicon and germanium crystal to a useful level. This process is called *doping*. Atoms such as arsenic, antimony, and phosphorus have five valence electrons (*pentavalent*) in the outer orbit and when they are added to the formation of a silicon crystal they combine with adjoining silicon atoms with nine shared valence electrons. This extra electron upsets the even geometric structure of eight shared electrons, so it is set free to drift about the crystal. By the addition of enough of these free valence electrons, the conductivity of the crystal can be increased to a useful level. Even though the doped crystal is electrically neutral, there are free electrons drifting about the crystal, so it is called an N-type semiconductor. If a voltage source is attached to the N-type semiconductor, a useful level of current will flow. The level of current flow depends upon the amount of doping of the crystal. Increased doping decreases the *bulk resistance* of the semiconductor. It is important to consider the bulk resistance of the semiconductor when designing a solid state electronic circuit. A representation of a crystal structure with an atom of arsenic added is shown in Figure 520.2. The doping ratio is one atom of impurity to 10^8 to 10^6 atoms of the crystal.

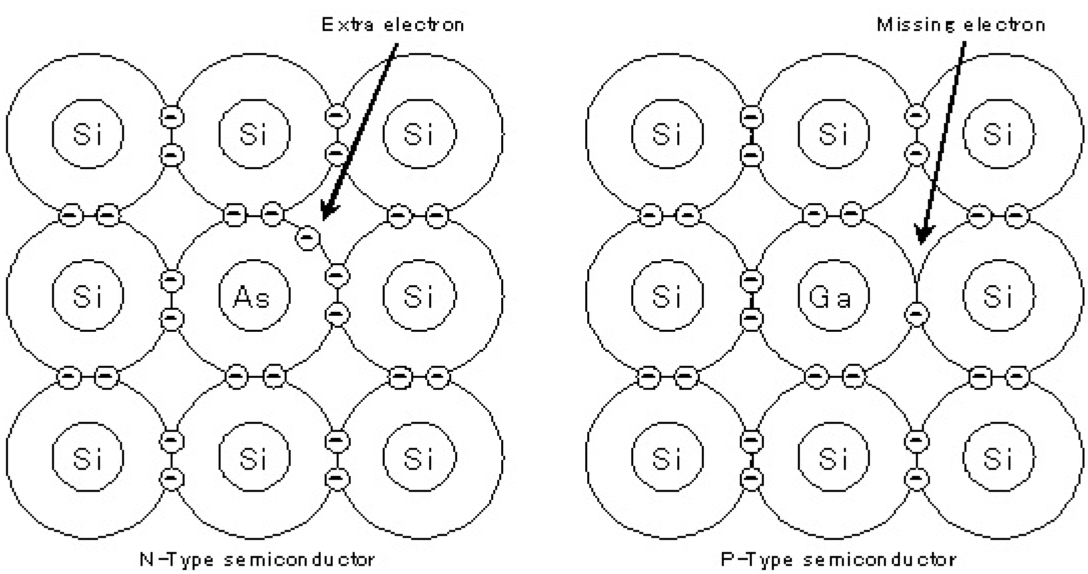

Figure 520.2 *A representation of a silicon crystal structure with an atom of arsenic added to form an N-type semiconductor and an atom of gallium added to from a P-type semiconductor.*

Atoms such as aluminum, boron, gallium, and indium have only three valence electrons in the outer orbit and when combined with silicon or germanium there are only seven electrons in the valence orbit to share with the neighboring atoms. The atomic structure of the crystal is most stable when there are eight electrons in the valence orbit, and with this impurity in the structure there are only seven. This creates what is known as an electronic *hole* that tries to attract a free electron to complete a set of eight valence electrons. Evan though the crystal is electrically neutral, the holes attract electrons and act like a positive charge, so it is called a P-type semiconductor.

If a voltage source is attached to the P-type semiconductor, a useful level of current will flow. The level of current flow depends upon the amount of doping of the crystal. The free electrons in the N-type semiconductor and the holes in the P-type semiconductor are referred to as *majority carriers*. An increase in temperature will cause these majority carriers to become more active and the conductivity of the semiconductor increases with increasing temperature. The majority carriers are more active in a semiconductor made from germanium than made from silicon at room temperature. Current tends to flow easier through a semiconductor made of germanium than made from silicon. For some applications this can be an advantage, but for most applications this means leakage currents will be higher for a germanium semiconductor.

PN Junction (Diode): When N-type and P-type semiconductors are brought in contact with each other, the attraction of the holes in the P-type material is great enough for free electrons in the N-type material to cross the barrier and fill the holes in a thin layer near the barrier. The valence orbits on each side of the barrier now have eight shared electrons, but there is a negative charge near the barrier on the P-type side of the barrier and a positive charge near the barrier on the N-type side of the barrier. This is illustrated in Figure 520.3 where a voltage builds up at the barrier of the two semiconducting materials. In the case of silicon this barrier voltage is approximately 0.7 volt at room temperature, and for germanium the barrier voltage is approximately 0.3 volt. This area near the barrier is called the *depletion region* and it is basically a nonconducting region that tries to prevent current flow.

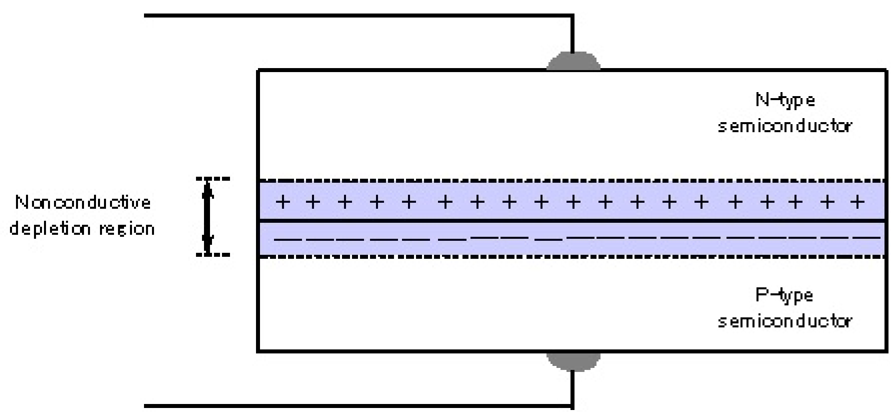

Figure 520.3 *When N-type and P-type semiconducting materials are brought in contact electrons are pulled across the barrier from the N-type side to the P-type side to satisfy the need for stability of the valence electron orbits in the crystalline structure resulting in a barrier potential of 0.7 volt for silicon and 0.3 volt for germanium.*

The PN junction is considered to be *forward biased* when the positive terminal of an external source is connected to the P-type semiconductor and the negative terminal of the source is connected to the N-type semiconductor. The depletion region at the barrier has become a stable nonconducting region and it takes 0.7 volts in the case of silicon to force it back into conduction. When more than 0.7 volts is applied across the semiconducting material current will flow. The resistance of the silicon semiconductor is quite small once conduction occurs and it acts basically like a closed switch. The *bulk resistance* (R_b) is generally in the range of 1Ω to 25Ω and compared to the resistance of the other components of the circuit it is generally considered negligible. It is often important to consider that 0.7 volts is lost from the circuit forcing the PN junction into conduction. If current flow is not limited by external circuit resistance, the semiconductor will soon become overheated and destroyed. A PN junction connected for forward bias and connected for reverse bias is shown in Figure 520.4.

The PN junction is considered to be *reverse biased* when the negative terminal of the external source is connected to the P-type semiconductor and the positive terminal of the source is connected to the N-type semiconductor. This action will draw electrons out of the N-type semiconductor and supply electrons to the P-type semiconductor causing the depletion region to grow wider. The barrier potential within the semiconductor will increase to match the external voltage source thus blocking current flow. Actually there is a small leakage current that increases slightly as the reverse bias voltage increases. Generally the leakage current is in the micro-ampere range. This leakage current increases as the operating temperature of the diode increases. This process continues until a point is reached where the barrier potential can no longer hold back the external source and current flow quickly reaches a level that destroys the semiconductor. The reverse breakdown voltage of a diode decreases as the temperature increases. There is one type of PN junction that is specifically designed to function in this reverse mode and that is the zener diode which will be discussed later.

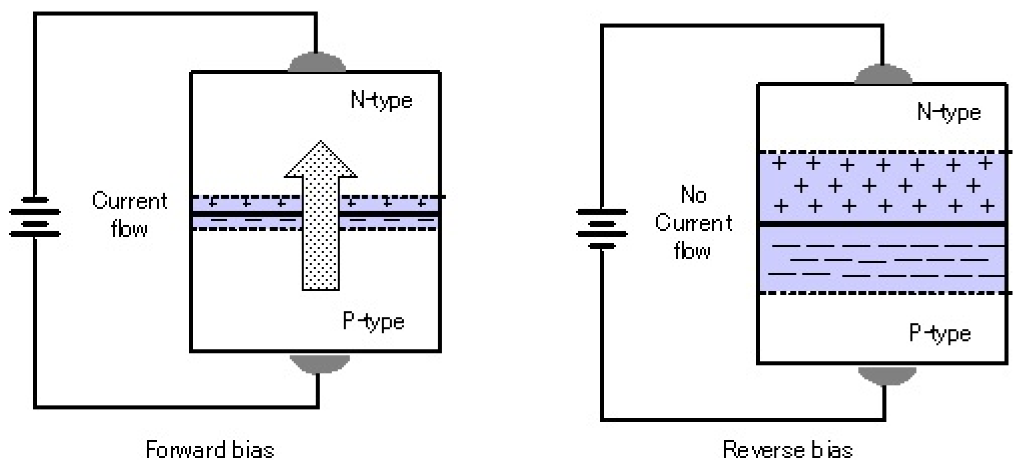

Figure 520.4 *The PN junction will conduct current when connected forward bias where the source positive terminal is connected to the P-type semiconductor, and it does not conduct when connected reverse biased with the negative terminal of the source connected to the P-type semiconductor.*

Diode Specifications: A diode is a PN junction as described earlier. Diodes permit current flow when forward biased above the barrier potential, and block current flow when reverse biased. The symbol for a semiconductor diode is shown in Figure 520.1. The flat line designates the negative cathode which is connected to the negative end of the circuit to be forward biased. An important specification for a diode is the *peak inverse voltage* (PIV) rating which gives the maximum reverse voltage the diode can withstand. It is important to understand that when connected to an alternating current source this value is the maximum peak voltage not the rms voltage. If a diode is installed in a circuit that operates at 125 volts rms, the peak voltage (E_{PEAK}) is actually 1.414 times the rms voltage (E_{RMS}) which would be 177 volts. Diodes can be connected in series if the PIV for one diode is too low. For example, two diodes with a PIV rating of 100 volts could be connected in series for an application where the reverse voltage is as high as 177 volts. It is best to use matched diodes for such an application.

Another important specification for a diode is the maximum current rating (I_{MAX}). The current requirement of an application needs to be determined to make sure it does not exceed the rating of the diode. Diodes can be connected in parallel to deal with high current loads where a single diode is not available with a sufficient current rating. For example if an application calls for a maximum current rating of 1.25 ampere and the rating of the diode is only 1.0 ampere, two of the diodes can be connected in parallel to handle the load. This is an application where the diodes need to be matched to make sure they are working in unison and that the current is dividing equally. Connecting diodes in parallel to increase current capacity is a little more tricky than connecting them in series to deal with a high PIV. There is a small bulk resistance to a semiconductor and this results in heat being produced in high current applications. Some diodes are required to be connected to a heat sink and some are also required to be force ventilated. In all cases where diodes are installed, make sure they are installed so that air can circulate around them to avoid overheating or burnout.

It is important to be able to interpret the characteristic current voltage curve for diodes and other electronic components. Figure 520.5 is a current voltage characteristic curve for a typical diode. The vertical axis is current with forward current above the horizontal line and reverse current below the line. To the right of the vertical axis is forward bias voltage and to the left is reverse bias voltage. It may be helpful to also refer to Figure 520.4 for forward and reverse bias connections. Note also that the forward voltage scale is different than the reverse voltage scale. This characteristic curve is for a silicon diode and forward conduction occurs at 0.7 volts with current increasing rapidly at higher voltages. The diode is not destroyed if the circuit limits the current to the maximum rating of the diode. When the polarity of the external source is reversed, current does not flow unless the breakdown voltage rating is exceeded. For a typical application such as for a rectifier of a dc power supply there is little resistance in the circuit to limit current if the breakdown voltage is exceeded and the diode is destroyed. Other components may also be destroyed if there is no fuse to cut off current flow.

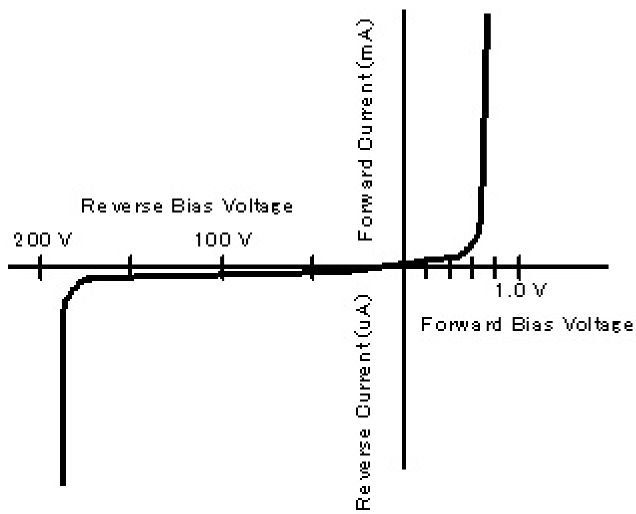

Figure 520.5 *The voltage and current characteristic curve for a silicon diode shows that current is blocked when reverse biased less than the breakdown voltage and current flow occurs when forward biased at more than 0.7 volts.*

The performance of a solid state diode can change if there is a significant change in operating temperature. The barrier potential (0.7 volt at room temperature) decreases as temperature increases at a rate of 2.5 mV/°C (0.0025 V). At 75°C the barrier potential of a silicon semiconductor has dropped below 0.6 volts.

Varactor Diode: Since the depletion zone near the PN junction is nonconductive, it acts like an insulator or dielectric. The barrier voltage across this nonconductive depletion zone acts like a capacitor. For some applications a diode operating in the reverse bias mode is used as a variable capacitor where the capacitance decreases as the reverse bias voltage increases. Keep in mind that as the reverse bias voltage increases the thickness of the depletion zone increases and this increases thickness of the dielectric results in a decrease in capacitance (see Tech Note 513). The varactor diode operates with a reverse bias voltage between and the breakdown voltage with capacitance generally varying between 15 pf and 30 pf.

Light Emitting Diodes (LEDs): When a forward bias is applied to a diode, electrons cross the barrier and fall into holes. Energy is releases as heat or as light depending upon the type of impurities that were added to the crystal. Common wavelengths that can be produced are green, yellow, red, and infrared. Advantages of using LEDs over incandescent lamps is longer life, operation at lower voltages, and fact on-off switching in the range of nonoseconds. Typical LEDs produce optimum light output with a current of from 15 mA to 20 mA. A resistor is required in series with the LED to limit the current to the optimum level.

Photodiode: A rise in ambient temperature will cause an increase in reverse bias leakage current through a diode. A photodiode works on the same principle except that light is directed to the PN junction through a lense. When light is concentrated at the PN junction the reverse bias leakage current increases. A photodiode is connected to a voltage source in reverse bias and supplied to an amplifier since the current levels are of the order of microamperes. Switching time for a photodiode is very fast. A digital electrical signal can be converted to light pulses using an LED, transported by means of optical fibers, and then converted back into an electrical signal with a photodiode.

Photovoltaic Cell: A photovoltaic cell is actually a PN junction with a large surface area. When light is received at the junction, electrons absorbing the energy cross the barrier from the P-type semiconductor to the N-type semiconductor. Electrodes are attached to the semiconductors to collect the electrons which can flow to the other semiconductor through a load connected to the photovoltaic cell. A photovoltaic cell can be used to measure light intensity if operated in a short circuit mode where current flow is proportional to the intensity of light received.
Diode Switching Time:

Schottky Diode: The PN junction diode has a switching limit of a few hundred Mhz. The Schottky diode is made for high speed applications of generally above 300 Mhz. It has no PN junction and no depletion zone. A metal plate of gold, silver, or platinum is attached directly to a semiconductor. Generally N-type semiconductor is used. The symbol for a Schottky diode is shown in Figure 520.6 along with the symbol for a zener diode.

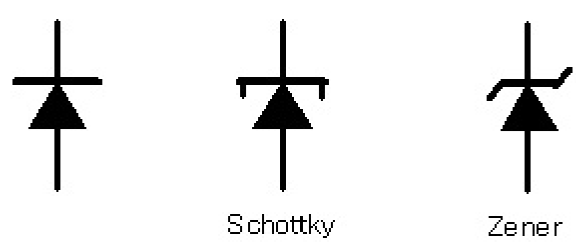

Figure 520.6 *The symbol on the left is for a PN junction diode, the one in the middle is a Schottky diode and the one on the right if a zener diode.*

Zener Diode: A zener diode is designed to operate in the reverse bias mode. The purpose of a zener diode is to block current flow up to a specified voltage, then conduct current when the voltage exceeds the rating of the zener. The symbol for a zener diode is shown in Figure 520.6 and the voltage-current characteristic curve is shown in Figure 520.7. The rating of a zener diode is the reverse breakdown or avalanche voltage as indicated on the characteristic curve of Figure 520.7.

If the circuit does not have adequate resistance to limit the current through the zener diode, then a series load resistor may be required. When zener diodes are connected in series their breakdown voltages are additive.

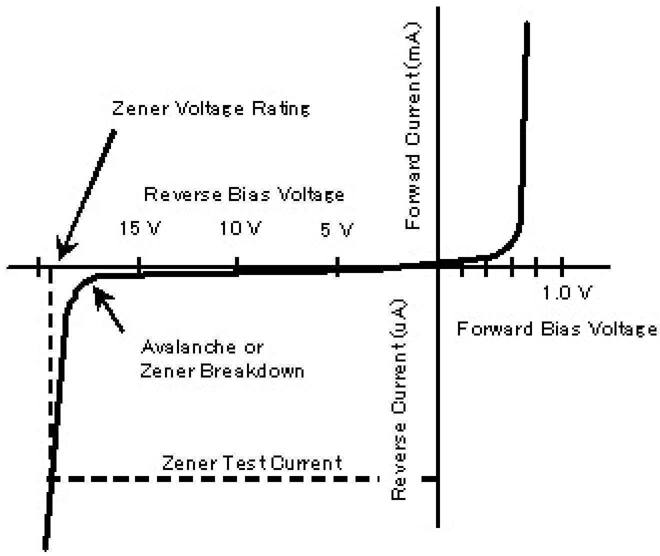

Figure 520.7 *A zener diode is designed to be connected to a circuit as reverse bias, and the zener rating is the reverse breakdown voltage. Zener diodes are installed in circuits as voltage limiters.*