Analog Electronics – Lesson 4

Diodes

Objectives and Overview:

This lesson will introduce p- and n-type material, how they form a junction that rectifies current, and familiarize you with basic p-n junction behavior. Current-voltage characteristics are explained and the lesson compares the basic silicon diode types, including Zeners and LEDs.

Student Preparation:

None.

Introduction:

The word "diode" means "two elements" and makes no distinction between the elements being pieces of a metal in a vacuum tube or infinitesimal pieces of impurity-laden silicon in an integrated circuit. Diodes in the form of cat's-whisker detectors were the first semiconductor element used in radio. It's important to understand the fundamentals of the semiconductor diode, since it is such an integral part of modern analog electronics.

Definition of rectification

Let's start at the beginning and the definition of *rectification*. Rectification of current means to allow current flow in only one direction. A rectifier is any device (mechanical, vacuum tube, or solid-state) that performs rectification. It is often said that rectifiers "convert" ac current into dc current, but there is no actual transformation of electron flow. Since the rectifier only permits one-way current flow, it performs more of a sorting function than a conversion. Combinations of rectifiers can be arranged (such as in the *full-wave rectifier*) to reorganize an ac current flow into dc.

Rectification can occur naturally wherever dissimilar conductors make contact, such as corroded metals, two different kinds of metal, or metal and a conducting fluid. Because the two materials hold on to their electrons with different levels of tenacity, there is a preference for electrons to move towards the material that allows them freer movement. This is a weak form of rectification, but was popular before the invention of the silicon rectifier. For example, strips of metal immersed in a conducting solution made a "slop jar" rectifier.

P- and N-type Material

In a vacuum tube, electrons flow from cathode (negatively charged) to anode or plate (positively charged). This also occurs in a semiconductor diode. (Remember the convention of showing current as the flow of positive charges requires that the current arrow is drawn from anode to cathode.) In a semiconductor, the actual positive charges do not move, but "holes" (the absence of a negatively-charged electron) play that role. As an electron moves from hole to hole from left to right, a hole (the space it formerly occupied) moves from right to left. The hole is not really a physical void, it is just a place where an electron *would* be if the material was pure.

Imagine the electron as a marble on a Chinese Checkers game board. As the marble/electron moves, it fills one hole while opening another. Looking at the holes, they move at the same speed and volume as the electrons, but in the opposite direction. In any conducting material, some electrons are free to move around in the material, leaving holes behind. This is what makes the materials conductors–the presence of these rambling electrons that can move in response to an applied electric field or voltage and create a current.

Silicon and other semiconducting materials like germanium have fewer free electrons than good conductors like metals. Rather than being a drawback, this means that we can control whether the silicon has more free electrons than normal (N-type materials) or a lack of free electrons (P-type material). This is done by adding small amounts of impurities (the process called *doping*) whose atoms either add to or subtract from the crowd of free electrons present in pure silicon. Silicon doped so that it has fewer electrons (more holes) is called *P-type* material and *N-type* material if it has more electrons.

The P-N Junction

The two different materials in a semiconductor rectifier are the P-type and N-type silicon. When these are placed directly against one another, a P-N junction is formed. These are not separate bits of material brought together mechanically, but rather formed in place by selectively adding the impurity atoms to different regions of pure silicon. Semiconductor engineers have gotten so good at this process that the diodes in use on integrated circuits are less than a nanometer (one billionth of a meter) from end to end! On a semiconductor diode, the cathode is generally represented by a colored bar or line printed on one end of the component near the lead.

Rectification by a P-N Junction

How does a P-N junction perform rectification? First, let’s see what happens at the junction without any applied voltage or current as if the two pieces of material had just been put in contact. In a very narrow region (about one micrometer wide) near where the materials are in contact (the *junction*) the excess electrons are attracted by the excess holes on the other side and move to fill them. Very rapidly, the mobile electrons drop into the holes and stop moving. Farther from the junction, the free electrons aren’t as strongly attracted and so don’t move all the way across the junction. The result is that in that narrow region on both sides of the junction, there are no excess holes or electrons. This is called the *depletion region*.

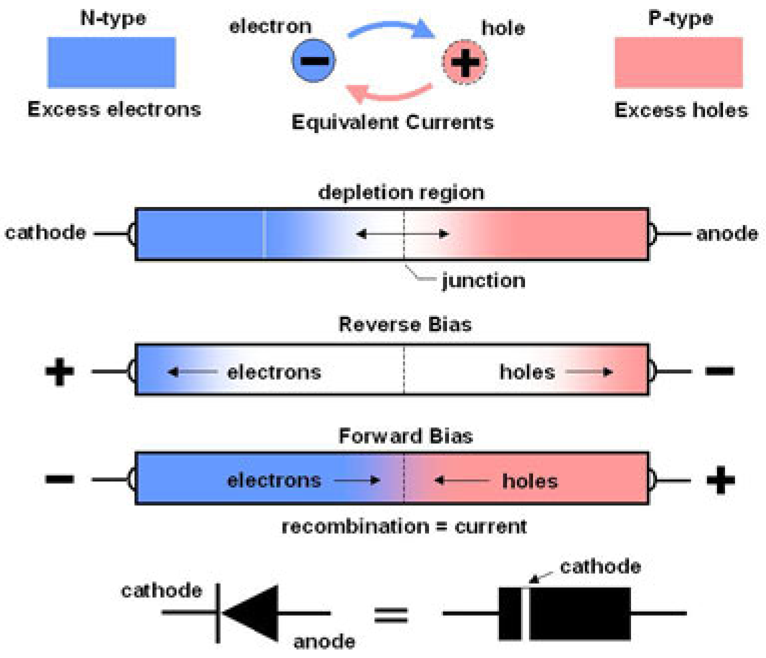


Figure 4-1 - Rectification occurs at a p-n junction as electrons and holes recombine in response to an applied voltage from p to n. Reversing the applied voltage causes the electrons and holes to separate, resulting in no current flow.

So what? Now let’s apply some voltage across the junction by attaching some wires and hooking them up to a power supply. If we attach the positive lead to the N-type side (full of free electrons) and the negative lead to the P-type side (full of holes) the free electrons are pulled away from the junction in the N-type material. In the P-type material whatever free electrons are still left move away from the negative lead and that can be viewed as the holes moving towards the negative lead. The net result is like that of a junior high dance, the boys all hang around on one side of the gym and the girls on the other. No current flows across the junction. This is the polarity of applied voltage in which the diode does NOT conduct, positive on N-type and negative on P-type.

If the voltage is applied to the opposite types of material, negative on N-type and positive on P-type, the free electrons in the N-type material are pushed towards the junction just as the holes in the P-type material are and the result is that they get close enough to combine with each other, leaving the junction clear for more electrons and holes to rush in. The boys and girls are now dancing in the middle of the room and that *recombination* of holes and electrons is what allows current to flow. Back at the wires, electrons are moving into the N-type material to replace those that combined with holes and electrons are moving out of the P-type material, creating more holes that can “move” towards the junction. The amount of voltage it takes to push the free electrons and holes close enough to combine is called the *forward voltage drop*, or V_f, and it’s always present when the diode is conducting. If the amount of applied voltage drops below the required amount, current rapidly stops flowing.

Current-Voltage Characteristics of Diodes

In an ideal diode, V_f would be 0 V or at least very, very small. In real diodes, not only is V_f greater than 0 V, but the current doesn't "snap" on when V_f is reached. It increases slowly from zero until the applied voltage begins to approach V_f and then increases very, very rapidly. In fact, it increases exponentially (which is a Greek word meaning "very, very rapidly"). The best way to describe this is not with words, but with a picture, as in Figure 4-2.

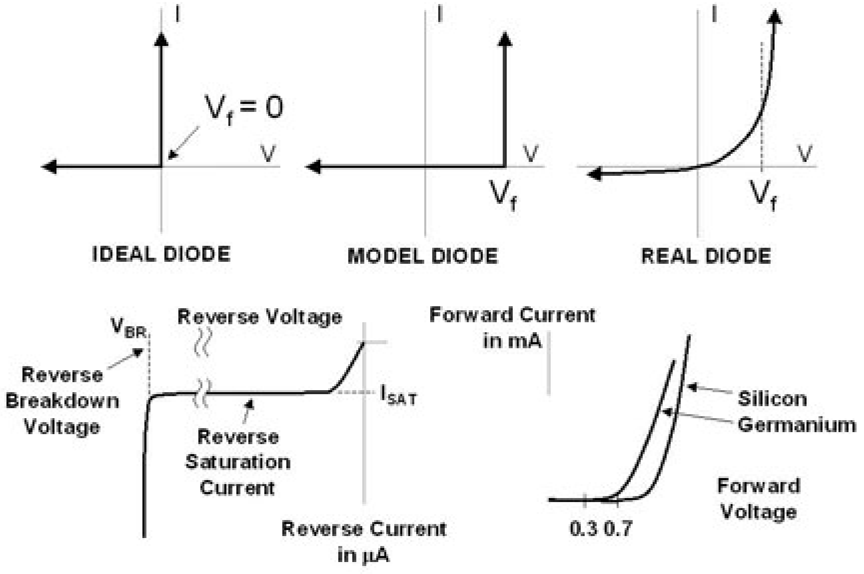


Figure 4-2 – Current-Voltage Characteristics of Diodes

A graph of current flow on the vertical axis versus applied voltage on the horizontal axis is called a *current-voltage (or I-V) characteristic*. For any device with two leads, the I-V characteristic tells you almost everything you need to know about how that device behaves electronically. I-V characteristics can be drawn for any electronic device, such as a power supply, motor, or transistor.

The I-V characteristics for the Ideal Diode are in the upper left. This diode has $V_f = 0$, which is a good approximation if your circuit uses fairly large voltages. In the center, the Model Diode is shown with a "snap-action" current that turns on instantly as V_f is reached. This model is often used in simple circuit analysis. The Real Diode has a more complex I-V curve with a small leakage current for reverse voltage and a gradual turn-on for forward voltages.

The two graphs at the bottom show the Real Diode behavior in more detail. In the reverse direction, there is a small current of a few μA caused by a few rogue electrons crossing the junction. This current stays fairly constant at the *reverse saturation current* until the applied voltage gets so high that it overcomes the normal distribution of electrons and holes, pulling electrons across the junction. When this happens, current increases very rapidly and often destroys the junction. This is called *avalanche breakdown* and the voltage at which it occurs is V_{BR}. A diode's *peak inverse or reverse voltage* (PIV or PRV) is somewhat less than V_{BR} for some safety margin.

On the right, the forward characteristics of the Real Diode are shown. Forward current is orders of magnitude greater than reverse current so it looks as if the current is zero until V_f is reached. Once the diode begins to conduct, current increases rapidly, but not vertically, as if it were a perfect conductor. The slope of the I-V characteristic at any point is the *dynamic resistance* of the diode for that applied voltage. Note that diodes made of different materials have slightly different rates at which current increases and different V_f. For silicon diodes, V_f is approximately 0.7 V and for germanium 0.3 V.

Just like a resistor, diodes also dissipate power when they are conducting. The amount of power generated as heat is calculated just like a resistor, V_f x I. The heat is generated in the very small junction area, which can get quite hot, even if the heat is being conducted away from it and out to the environment. The maximum temperature at which the junction of silicon diodes will operate is abbreviated t_{Jmax} and is from 150 to 200 °C. At higher temperatures, the carefully placed impurities begin to move, destroying the junction and the diode characteristics.

One final important characteristic is the diode's *recovery time, t_r*. This is the amount of time it takes for current through a diode to stop once the applied voltage is reversed. Sort of like a game of "stop and go", it takes a little bit of time before the movement of electrons across the junction stops. Typically, the higher the forward current the longer t_r becomes for any given diode.

Rectifier vs. Signal Diodes

Armed with all this knowledge, you can now begin to understand the differences between all the different types of diodes out there. The most common types of diodes are *signal* and *rectifier* diodes. Signal diodes are optimized for use in low-current, high-speed circuits. They have a low PIV (50 V or less), a fast t_r, and low maximum power dissipation. The most common signal diode by far is the silicon 1N4148. For applications that need a low forward voltage, the 1N34 germanium diode is often used.

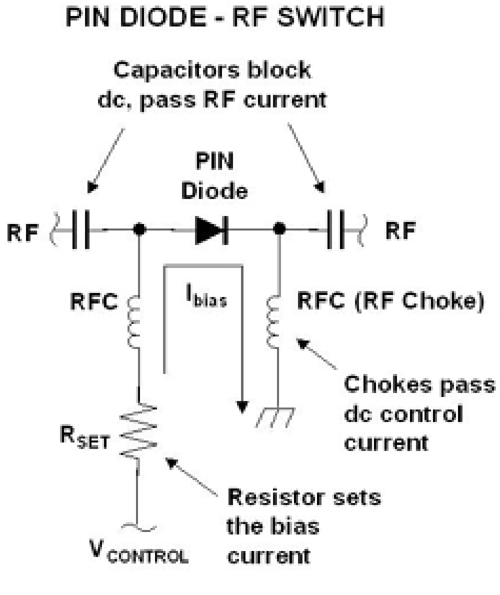
Rectifier diodes, on the other hand, are made for use in power supplies and high current applications. Rectifiers such as the popular 1N400x-series have PIV ratings from 50 to 1000 V. Most have slow t_r because they are used with ac currents of frequencies below 500 Hz. Even a slow recovery time is still insignificant at those frequencies. Rectifiers have a high power dissipation rating due to their heavy leads, more semiconductor material, and packages that radiate heat effectively. Reviewing the equation for power dissipation, a rectifier carrying even a few amps of average current has to handle a few watts and can get quite hot. Rectifiers must also have a high *surge current* rating to handle the temporary inrush of current when voltage is applied to discharged filter capacitors.

A recent entry into the rectifier field is the *fast-recovery rectifier*. Switching power supplies use high-frequency components to generate power, often turning currents on and off at frequencies well above the audio range. The 1N4934, for example, can switch off in 200 ns or less, while carrying 1 A and with a PIV of up to 200 V. Diodes with much higher current carrying and PIV specs are available with similar recovery times.

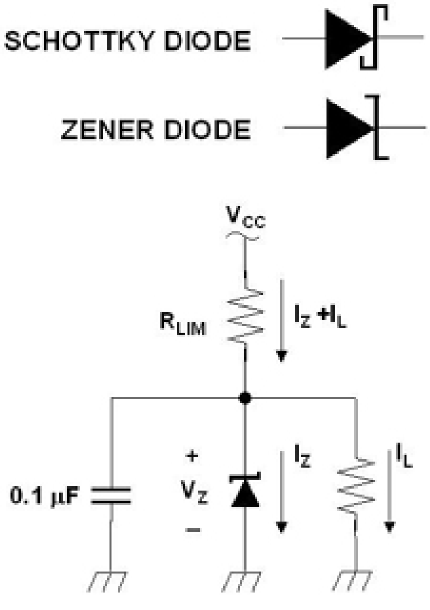
Schottky and PIN Diodes

These diodes have special characteristics because their junction is made differently from regular P-N junctions. The Schottky diode whose symbol is shown in Figure 4-3, is made by depositing a metal layer, such as platinum or gold, directly on N-type silicon. Remember that dissimilar metals in contact have a rectifying effect – this junction is called a *Schottky barrier*. The result is a very low forward voltage (typically around 0.3 V) and extremely fast recovery times of a few tens of nanoseconds. The tradeoff is that Schottky diodes have a high reverse leakage, can't achieve high PIV ratings (limited to 100 V or less), and must limit their maximum junction temperature to 125° C. Schottky diodes are used in switching power supplies where they work efficiently with high-frequency currents.

The PIN has nothing to do with anything sharp. It refers to the diode's construction, made up of a P-type layer, an intrinsic (undoped) layer, and an N-type layer. Not much good as a rectifier because of the undoped layer in the middle, these diodes can conduct RF signals into the microwave regions when they are forward biased, acting like a resistor. This has made them popular as switches. Figure 4-3 shows a useful PIN diode RF switching circuit on the left. Input and output capacitors block the applied DC bias, which is supplied by the RF chokes. When bias current is flowing, the diode also passes the RF signal.



PIN diode passes RF when forward biased



Zener Voltage Regulator

Figure 4-3 – Applications of PIN and Zener diodes

Zener Diodes

Dr. Zener found a way to control V_{BR}, the voltage at which the diodes begins to conduct in the reverse direction. By changing the amount of electron and hole-donating impurities, he found that V_{BR} could be changed from a few volts to tens of volts and the voltage across the diode, called the *Zener voltage*, V_Z, would remain constant for a wide range of reverse current. In the forward direction, Zeners act much like a regular silicon rectifier. The right side of Figure 4-3 shows the Zener diode at work in a popular application, voltage regulation.

Designing a Zener Voltage Regulator Circuit

1. Select a power supply voltage, V_{CC}, at least a few volts above V_Z. Determine P_Z, the maximum amount of power you want the Zener to dissipate – 50% of the Zener's maximum rating works well.

2. Determine the Zener current, $I_Z = P_Z / V_Z$.

3. R_{LIM} is $(V_{CC} – V_Z) / (I_Z)$. The resistor power rating is $(V_{CC} – V_Z)^2 / R_{LIM}$.

4. The maximum amount of load current that can be drawn is $(V_{CC} – V_Z) / R_{LIM}$. Higher currents cause the voltage drop across R_{LIM} to increase so that the output voltage is less than V_Z.

It's also a good idea to place a small capacitor of 0.1 μF or so across the Zener if the voltage is to be used as a reference voltage for other circuitry.

Light-Emitting Diodes (LEDs)

Rarely used as rectifiers, these diodes emit photons carrying the energy released when the electrons and holes combine at the junction. In silicon and germanium, the photons are not visible, they're heat. However, if gallium arsenide (GaAs) is used, the photon has enough energy to be seen as visible light. By adjusting the characteristics of the GaAs material, photons can be created with energy anywhere from infra-red to green wavelengths of light. Blue LEDs use a different material, silicon carbide (SiC). White LEDs are made from a blue LED plus phosphor material (the same as on the inside of a CRT) that converts the blue photons into white light. A GaAs LED has a 1.5 V forward voltage, while SiC LEDs are in the 3 - 5 V range. Both are rather poor rectifiers, with high reverse leakage currents and low PIV of 5 V.

Review:

Rectification of current means to allow current flow in only one direction. A rectifier is any device (mechanical, vacuum tube, or solid-state) that performs rectification.

Silicon doped so that it has fewer electrons (more holes) is called P-type material and N-type material if it has more electrons.

Recombination of holes and electrons is what allows current to flow through a PN junction.

A graph of current flow on the vertical axis versus applied voltage on the horizontal axis is called a current-voltage (or I-V) characteristic.

The amount of voltage it takes to push free electrons and holes close enough to the junction to recombine is called the forward voltage drop, or V_f. V_f is always present when the diode is conducting.

Diodes dissipate power when they are conducting. The amount of power generated as heat is calculated just like a resistor, V_f x I.

Signal diodes are optimized for use in low-current, high-speed circuits. They have a low PIV (50 V or less), a fast t_r, and low maximum power dissipation. Rectifier diodes have PIV ratings from 50 to 1000 V, slow t_r, and high power dissipation. Rectifiers also have a high surge current rating. Fast-recover rectifiers have low t_r, in the tens of nanoseconds.

Schottky diodes are made with a contact between metal and N-type silicon. They have a low V_f and t_r. PIN diodes are made by placing extra undoped material between the P-type and N-type layers. They conduct RF when a bias current is flowing from anode to cathode.

Zener diodes have a controlled V_{BR}, called V_Z. They have a constant reverse voltage for a wide range of reverse currents and are used for voltage regulation.

Now click on the Activities button and proceed with the Student Activities, which are required before moving to the Questions (click on the Question button). Upon completion of these Questions, go to the next Learning Unit.