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STUDENT HANDOUT

DIODES

Terminal Learning Objective: Given a schematic, a faulty generator set electrical system, and applicable tools and test equipment, with the aid of references, repair the generator set electrical system so that it functions properly in accordance with the appropriate equipment technical manual. (1142.01.02)

Enabling Learning Objective(s):

(1) Given a list of characteristics concerning conduction, select the one that describes the conduction process in a semiconductor in accordance with FM 11-62. (1142.01.03ai)

(2) Given a list of circuit characteristics, select the characteristics that describe how to forward bias a PN junction in accordance with FM 11-62. (1142.01.03aj)

(3) Given a list of component operating characteristics, identify the characteristics that apply to the operation of a LED, in accordance with FM 11-62. (1142.01.03ak)

BODY:

1. Semiconductor Theory: To understand why solid state devices function as they do, we will have to examine closely the composition and nature of semiconductor materials.

a. Covalent Bonding is where we will start. The electrical qualities of a material depend on the number of electrons in its valence (outer) shell. Materials with eight electrons in its valence shell are said to be insulators and their outer shell is complete. This kind of material, or element, will not easily bond with other elements and will not give up a free electron for the conduction of electricity. Materials such as copper, which you are familiar with, have only one electron in their outer shell and are good conductors. Notice that by only having that single valence electron, its outer shell is incomplete.

(1) Atoms have a tendency to try and complete their valence shell by "sharing" electrons with other atoms. Shown is the structure of a two dimensional view of a silicon granule. Silicon has four electrons in its outer ring, and each atom shares the electrons of other atoms in order to fill its outer ring for a total of eight electrons.

(2) The sharing of electrons is known as a covalent bond. It is this bond that holds the atoms together in an orderly structure called a crystal. A crystal is just another name for a solid whose atoms or molecules are arranged in a three dimensional geometric pattern commonly referred to as a lattice.

(3) Shown again is the two dimensional view of silicon. As a result of the sharing process, the valence electrons are held tightly together.

(a) The circles represent the nuclei of each atom. The 4 in the circles represent the net charge of the nucleus plus the inner electron shells (minus the valence shell).

(b) The short lines indicate valence electrons. Because every atom in this pattern is bonded to four other atoms, the electrons are not free to move within the crystal.

(c) As a result of this bonding, pure silicon is a poor conductor of electricity. The reason they are not insulators, but semiconductors, is because with the proper application of heat or electrical pressure, electrons can be caused to break free of their bonds and move into a free state.

b. Conduction Process. As stated earlier, energy can be added to electrons by applying heat. When enough energy is absorbed by the valence electrons, it is possible for them to break some of their covalent bonds. Once the bonds are broken, the electrons are free to move to the conduction band where they are capable of supporting electric current. When a voltage is applied to a crystal containing these conduction band electrons, the electrons move through the crystal toward the applied voltage. This movement of electrons in a semiconductor is referred to as electron current flow.

(1) There is still another theory of current flow in a pure semiconductor. This current occurs when a covalent bond is broken and a vacancy is left in the atom by the missing valence electron. This vacancy is commonly referred to as a "hole". The hole is considered to have a positive charge because its atom is deficient by one electron which causes the protons to outnumber the electrons. As a result of this hole, a chain reaction begins when a nearby electron breaks its own covalent bond to fill the hole, leaving another hole. Then another electron breaks its bond to fill the previous hole, leaving still another hole. Each time an electron in this process fills a hole, it enters into a covalent bond. Even though an electron has moved from one covalent bond to another, the most important thing to remember is that the hole is also moving.

(2) Therefore, this process of conduction resembles the movement of holes rather than electrons, it is termed "hole flow". Hole flow is very similar to electron flow except that the holes move toward a negative potential and in an opposite direction to that of the electron. Since hole flow results from the breaking of covalent bonds, which are at the

valence bond level, then the electrons associated with this type of conduction contain only valence bond energy and must remain in a valence bond. However, the electrons associated with electron flow have conduction band energy (free electrons) and can therefore move throughout the crystal. A good example of hole flow is in figure 1-9 in FM 11-62.

c. Doping Process. The pure semiconductor mentioned earlier is electrically neutral. It contains no free electrons. Even with the application of thermal energy (heat), only a few covalent bonds are broken yielding a small current flow. A much more efficient method of increasing current flow in semiconductors is by adding very small amounts of selected additives to them. These additives are called impurities and the process of adding them to crystals is called "doping". The purpose of doping is to increase the number of free charges that can be moved by an externally applied voltage.

(1) When an impurity increases the number of free electrons, the doped semiconductor is negative or N-type, and the impurity is know as an N-type impurity.

(2) However, an impurity that reduces the number of free electrons, causing more holes, creates a positive or P-type material.

(3) Semiconductors doped in this manner, either N-type or P-type, are referred to as extrinsic crystals.

d. N-Type Semiconductor. The N-type impurity loses its extra valence electron easily when added to a semiconductor material, and in so doing increases the conductivity of the material by contributing a free electron.

(1) This type of impurity has five valence electrons and is called a pentavalent impurity. Arsenic, antimony bismuth, and phosphorus are pentavalent impurities.

(2) Because these materials give or donate one electron to the doped material, they are also called donor impurities.

(3) When a donor impurity, like arsenic, is added to germanium it will form covalent bonds with the germanium atoms. This slide illustrates this by showing an arsenic atom (AS) in a germanium (GE) lattice structure.

(a) Notice the arsenic atom in the center of the lattice. It has five valence electrons in its outer shell but uses only four of them to form covalent bonds with the germanium atoms, leaving one electron relatively free in the crystal structure. Pure germanium may be converted to an N-type material by doping it with any donor impurity having five valence electrons in its outer shell.

(b) Since this type of material has a surplus of electrons, the electrons are considered majority carriers, while the holes, being few in number, are the minority carriers.

e. P-Type Semiconductor. The second type of impurity when added to a semiconductor material tends to compensate for its deficiency of one valence electron by acquiring an electron from its neighbor.

(1) Impurities of this type have only three valence electrons and are called trivalent impurities. Aluminum, indium, gallium, and boron are trivalent impurities.

(2) Because these materials accept one electron from the doped material they are also called acceptor impurities.

(3) A trivalent (acceptor) impurity element can also be used to dope germanium. In this case, the impurity is one electron short of the required amount of electrons needed to establish a covalent bond there will be only one electron instead of two. This arrangement leaves a hole in that covalent bond. This slide illustrates this theory by showing what happens when germanium is doped with an indium (IN) atom.

(a) Notice, the indium atom in the figure is one electron short of the required amount of electrons needed to form covalent bonds with four neighboring atoms and therefore creates a hole in the structure. Gallium and boron which are also trivalent impurities exhibit these same characteristics when added to germanium. The holes can only be present in this type material when a trivalent impurity is used.

(b) Note that a hole carrier is not created by the removal of an electron from a neutral atom, but is created when a trivalent impurity enters into covalent bonds with a tetravalent (four valence electrons) crystal structure.

(c) The holes in this type semiconductor (P-type) are considered the majority carriers since they are present in the material in the greatest quantity. The electrons, on the other hand, are the minority carriers.

2. <u>THE SEMICONDUCTOR DIODE</u>:

a. PN Junction Diode: If we join a section of N-type semiconductor material with a similar section of P-type material, we obtain a device known as a PN Junction Diode.

(1) The area where the N and P type materials meet is called the junction. The unusual characteristics of this device make it extremely useful in electronics as a diode rectifier.

(2) The diode rectifier or PN junction/diode performs the same function as its counterpart in electron tubes but in a different way. The diode is nothing more than a two element semiconductor device that makes use of the rectifying properties of a PN junction to convert A.C. into D.C. by permitting current flow in only one direction.

(3) The schematic symbol of a PN junction diode is shown here. The vertical bar represents the <u>cathode</u> (N-type material) since it is the source of electrons and the arrow represents the <u>anode</u> (P-type material)

since it is the destination of the electrons. The cable "CR1" is an alpha numerical code used to identify the diode. In this figure we have only one diode so it is labeled CR1 (crystal rectifier number one). If there were four diodes shown in the diagram then the last diode would be labeled CR4. The heavy dark line shows electron flow. Notice it is against the arrow. For further clarification, a pictorial diagram of a PN junction and an actual diode (one of many types) are also shown.

b. PN Junction Construction: Merely pressing together a section of P material and a section of N material is not sufficient to produce a PN junction. To form a proper PN junction, the semiconductor should be in one solid piece, but divided into a P-type impurity region and an N-type impurities into a single crystal during the manufacturing process. By doing so, a P-region is grown over part of a semiconductor's length and an N-region is grown over the other part.

(1) Another way to produce a PN junction is to melt one type of impurity into a semiconductor of the opposite type impurity.

EXAMPLE: A pellet of acceptor impurity is placed on a wafer of N-type germanium and heated. Under controlled temperature conditions, the acceptor impurity fuses into the wafer to form a P-region within it, as shown in view B of this slide. This type of junction is know as a "Alloy" or "Fused-Alloy" junction and it is one of the most commonly used junctions.

(2) "Point-Contact" is another type of construction. It consists of a fine metal wire, called a cat-whisker, that makes contact with a small area on the surface of an N-type semiconductor. The PN union is formed in this process by momentarily applying a high surge current to the wire and the N-type material. The heat generated by this current converts the material nearest the point of contact to a P-type material.

(3) Still another process is to heat a section of semiconductor material to near melting and then diffuse impurity atoms into a surface layer. Regardless of the process, the object is to have a perfect bond everywhere along the union between the P and N materials.

c. PN Junction Operation: Now that we are familiar with P and N type materials, how they are joined to form a diode, and the function of the diode, we will continue our discussion with the operation of the PN junction. Before we can understand how the PN junction works, we must first consider current flow in the materials that make up the junction and then what happens initially within the junction when these two materials are joined together.

(1) Conduction in the N-Type Material: Conduction in the N-type crystal is similar to conduction in a copper wire. With voltage applied across the material, electrons will move through the crystal just as current would flow in a copper wire.

(a) The positive potential of the battery will attract the free electrons in the crystal. These electrons will leave the crystal and flow into the positive terminal of the battery. As an electron

leaves the crystal, an electron from the negative terminal of the battery will enter the crystal, thus completing the current path.

(b) Therefore, the majority current carriers in the N-type material (electrons) are repelled by the negative side of the battery and move through the crystal toward the positive side of the battery.

(2) Conduction in the P-Type Material: Conduction in the P-Type material is by the movement of positive holes instead of negative electrons. The hole moves from the positive terminal of the P material to the negative terminal.

(a) Electrons from the external circuit enter the negative terminal of the material and fill holes in the vicinity of this terminal.

(b) At the positive terminal, electrons are removed from the covalent bonds, thus creating new holes. This process continues as the steady stream of holes (hole current) moves toward the negative terminal.

(3) Notice in both N-type and P-type materials, current flow in the external circuit consists of electrons moving out of the negative terminal of the battery and into the positive terminal of the battery Hole flow, on the other hand only exists within the material itself.

d. Junction Barrier. Although the N-type material has an excess of free electrons, it is still electrically neutral. This is because the donor atoms in the N material were left with positive charges after free electrons became available by covalent bonding (the protons outnumbered the electrons). Therefore, for every free electron in the N material there is a corresponding positively charged atom to balance it. The end result is that the N material has an overall charge of zero. By the same reasoning, the P-type material is also electrically neutral because of holes in this material are exactly balanced by the number of electrons. Keep in mind that the holes and electrons are still free to move in the material because they are only loosely bound to their parent atoms.

(1) It would seem that if we joined the N and P materials together by one of the processes mentioned earlier that all the holes and electronics would pair up. On the contrary, this does not happen. Instead, the electrons in the N material diffuse (move or spread out) across the junction into the P material and fill some of the holes. At the same time the holes in the P material diffuse across the junction into the N material and are filled by N material electrons. This process is called "Junction Recombination" and reduces the number of free electrons and holes in the vicinity of the junction. Because there is a depletion, this area is called the "Depletion Region".

(2) The loss of an electron from the N-type material created a positive ion in the N material while the loss of hole from the P material created a negative ion in the material. These ions are fixed in place in the crystal lattice structure and cannot move. Thus, they make up a layer of fixed charges on the two sides of the junction.

(a) On the N side of the junction there is a layer of

positively charged ions; on the P side of the junction there is a layer of negatively charged ions. An electrostatic field, is established across the junction between the opposite charged ions.

(b) The diffusion of electrons and holes across the junction will continue until the magnitude of the electrostatic field is increased to the point where the electrons and holes no longer have enough energy to overcome it, and are repelled by the negative and positive ions respectively.

(c) At this point equilibrium is established and for all practical purposes the movement of carriers across the junction ceases. For this reason, the electrostatic field created by the positive and negative ions in the depletion region is called a barrier.

(d) The action just described occurs almost instantly when the junction is formed. Only the carriers in the immediate vicinity of the junction are affected. The carriers throughout the remainder of the N and P material are relatively undisturbed and remain in a balanced condition.

e. Forward Bias: An external voltage applied to a PN junction is called Bias.

EXAMPLE: If a battery is used to supply bias to a PN junction, it will be connected so that it’s voltage opposes the junction field. This will reduce the junction barrier and therefore aid current flow through the junction. This type of bias is known as forward bias and it causes the junction to offer only minimum resistance to the flow of current.

(1) To forward bias a PN junction the positive terminal of the bias battery is connected to the P-type material and the negative terminal is connected to the N-type material.

(a) The positive potential repels holes toward the junction where they neutralize some of the negative ions.

(b) At the same time the negative potential repels electrons toward the junction where they neutralize some of the positive ions.

(c) Since ions on both sides of the barrier are being neutralized, the width of the barrier decreases. Thus, the effect of the battery voltage in the forward bias direction is to reduce the barrier potential across the junction and to allow majority carriers to cross the junction.

(d) Current flow in the forward biased PN junction is relatively simple.

1 An electron leaves the negative terminal of the battery and moves to the terminal of the N-type material. It enters the N-material where it is the majority carrier and moves to the edge of the junction barrier.

2 Due to forward bias, the barrier offers less opposition to the electron and it will pass through the depletion region into the P-type material.

3 The electron loses energy in overcoming the opposition of the junction barrier, and upon entering the P material combines with a hole. The hole was produced when an electron was extracted from the P material by the positive potential of the battery.

4 The created hole moves through the P material toward the junction where it combines with an electron.

(e) It is important to remember that in the forward bias condition, conduction is by majority current carriers (holes in P material and electrons in N material). Increasing the battery voltage will increase the number of majority carriers arriving at the junction and will therefore increase the current flow. If the battery voltage is increased to a point where the barrier is greatly reduced, a heavy current will flow and the junction may be damaged from the resulting heat.

f. Reverse Bias: If the battery mentioned earlier is connected across the junction so that its voltage aids the junction, it will increase the junction barrier and thereby offer a high resistance to the current flow through the junction. This type of bias is know as reverse bias.

(1) To reverse bias a junction diode, the negative battery terminal is connected to the P-type material, and the positive battery terminal to the N-type material.

(a) The negative potential attracts holes away from the edge of the junction barrier on the P side, while the positive potential attracts the electrons away from the edge of the barrier on the N side.

(b) This action increases the barrier width because there are more negative ions on the P side of the junction, and more positive ions on the N side of the junction.

(c) The increase in the number of ions prevents current flow across the junction by majority carriers. However, the current flow across the barrier is not quite zero because of the minority carriers crossing the junction.

1 As you recall, when the crystal is subjected to an external source of energy (light, heat, etc.) electron hole pairs are generated. The electron hole pairs produce minority carriers. There are minority current carriers in both regions, holes in the N material and electrons in the P material.

2 With reverse bias, the electrons in the P material are repelled toward the junction by the negative terminal of the battery. As the electron moves across the junction it will neutralize a positive ion in the N-type material. Similarly, the holes in the N-type material will

be repelled by the positive terminal of the battery toward the junction. As the hole crosses the junction it will neutralize a negative ion in the P-type material.

3 This movement of minority carriers is called "Minority Current Flow" because the holes and electrons involved come from the electron hole pairs that are generated in the crystal lattice structure and not from the addition of impurity atoms.

4 Therefore, when a PN junction is reverse biased, there will be no current flow due to majority carriers but a very small amount of current due to minority carriers crossing the junction. However, at normal operating temperatures this small current may be neglected.

(2) The most important point to remember about the PN junction diode is its ability to offer very little resistance to current flow in the forward bias direction but maximum resistance to current flow when reverse biased.

(3) Characteristic Curve: A good way of illustrating this point is by plotting a graph of the applied voltage versus the measured current. A characteristic curve shows the voltage-current relationship for a typical PN junction diode.

(a) To determine the resistance from the curve in this figure we can use Ohm's Law, R = E/I.

(b) For example, at point A the forward bias voltage is 1 volt and the forward bias current is 5 milliamperes. This represents 200 ohms of resistance (1 volt/5 ma - 200 ohms).

(c) However, at point B the voltage is 3 volts and the current is 50 milliamperes. This results in 60 ohms of resistance for the diode.

(d) Notice that when the forward bias voltage was tripled, the current increased ten times. At the same time the forward bias voltage increased, the resistance decreased from 200 ohms to 60 ohms.

(e) In other words, when forward bias increases, the junction barrier gets smaller and its resistance to current flow decreases. On the other hand, the diode conducts very little when reverse biased.

(f) Notice at point C the reverse bias voltage is 80 volts and the current is only 100 micro amps. This results in 800k ohms of resistance which is considerably larger than the resistance of the junction with forward bias.

(g) Because of these unusual features the PN junction diode is often used to convert alternating current into direct current.

3. LED Light Emitting Diode:

a. As the name implies, a light-emitting diode or LED is a special diode that gives off light. The LED has many things in common with a PN Junction diode, but some important differences, too. In this period of instruction, we'll begin our studies of LED's by learning how to test these important devices with an ohmmeter.

b. A PN junction diode is made up of two types of silicon or germanium that form the PN junction. This type of diode doesn't give off light, primarily because the semiconductor material is opaque (that is, doesn't light). LED's on the other hand, are made of a translucent material that allows the light generated at the PN junction to be given off by the device. Two materials commonly used for LED's are GALLIUM ARSENIDE, which gives off red light, and GALLIUM PHOSHIDE, which gives off green light.

c. The amount of light produced by either of these materials is very small. Consequently, it's usually necessary to increase the brightness of the device by using a special plastic lens within the case itself to "amplify" the light. Many LED's - including the one you'll use in this experiment - use such an arrangement.

d. LED's act much like ordinary diodes, in that they pass current easily when forward-biased, but block current when reverse-biased. A LED must be forward-biased before it will produce any light, and certain precautions must be taken when doing so. Like regular diodes, LED's can handle only a limited amount of current; otherwise, they're permanently damaged. So care must be taken when forward-biasing a LED - even during resistance measurements - or the device will almost surely fail. The normal operating voltage for an LED is 1.6 volts in forward bias. (Even when reverse-biased, a LED can fail if the voltage is too high. The maximum reverse voltage for many LED's is only about 3 V; therefore, we'll have to be careful when we make our measurements.

e. The standard schematic symbol for a LED is shown. You may note that the symbol is similar to the one for an ordinary diode, except for the two arrows pointing away from the junction, indicating light emission. The flat spot on the case marks the cathode; the anode lead is generally longer than the cathode lead as shown.

f. Since a LED acts much like a PN junction diode, we can make use of these characteristics to test LED's with an ohmmeter. As you'll recall, a PN junction diode is tested by making two resistance measurements. When the diode is forward-biased, its resistance will be low; conversely, its resistance will be high when the diode is reverse-biased. The same principles apply when testing LED's - except that the measurement is easier! Since the LED will emit light when forward-biased, an ohmmeter connected so as to forward bias a LED will show whether it's good or bad without having to look at the resistance reading.

NOTE: Since the LED you'll be using is limited to a forward current of about 50 mA, be careful not to damage the device by exceeding this

current limit. Make your forward-resistance measurements on the lowest range, where the current will be less than 50 mA.

References:

1. FM 11-62