APPLICATION TRAINING GUIDE

Basic Semiconductor Theory

Semiconductor is an appropriate name for the device because it perfectly describes the material from which it's made -- not quite a conductor, and not quite an insulator. To produce a useful device, semiconductor material is processed into MOSFET, IGBT, SCR, or diode devices, etc.

All IR semiconductor products originate from silicon wafers. Silicon is one of the most common elements on earth. It is the basis of sand and glass in the form of silicon dioxide (SiO_2). After being refined, silicon is supplied as amorphous silicon which means that the atoms are randomly arranged in the material. Under the proper conditions, silicon can be manufactured into epitaxial chunks which basically means a single crystal. Most gems are examples of single crystals. Diamonds, for example, are merely carbon atoms arranged in a particular 3-D or lattice structure shown in Figure 9. We make use of silicon in a similar lattice form to manufacture semiconductors.

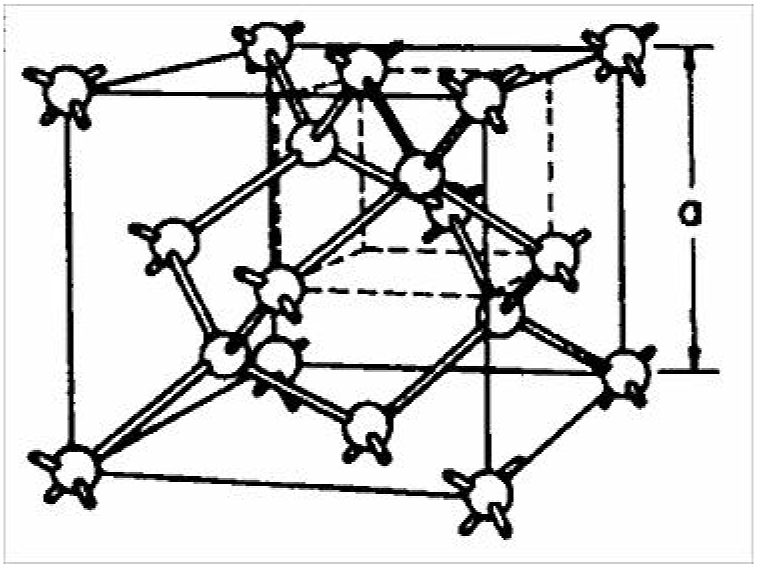

Figure 9. Silicon Lattice Structure.

A pure silicon lattice is a good insulator because the atoms are arranged so that all electrons are bonded to a silicon nucleus. In order to change the resistivity of the silicon, it is necessary to introduce impurities, which changes the number of electrons in the lattice structure. This is called doping, and may result in extra electrons (called n-type), or missing electrons (called p-type) in the lattice. Typical dopants include boron and phosphorous.

Missing electrons are also called *holes.* There is no physical basis for this nomenclature, but it is easy to understand how it came about. Assume that you have six paper cups and five balls. Line the cups in a row, and put balls in the five right cups. Now move the ball in the second cup to the first, the ball in the third to the second cup and so on. It appears that the empty cup is moving to the right when in reality, the balls are merely shifting to the left. This movement is possible because of the different number of cups and balls. The significance of this is that electrons can move approximately two times faster than holes, and as such, n-type material is much preferred to p-type material.

Semiconductor devices can also be divided into two groups based on how current is conducted through the material. A device in which the current is conducted by the charges dominant in the lattice is called a majority carrier device (e.g., electrons in n-type material, or holes in p-type material. If the current is conducted by charges not dominant in the lattice, the resulting device is called a minority carrier device (e.g., electrons in p-type material, or holes in retype material). This very important distinction has a large bearing on the device's operation, especially the recovery characteristics. A fish tank can be used to illustrate how current is conducted through silicon. If you put an *air* hose onto the bottom of the fish tank, it takes some time for the air to bubble out of the tank. This is analogous to a minority carrier device (current carrier is different from the bulk media). On the other hand, if you put a *water* hose onto the bottom of the tank, it doesn't take any time for the water to reach equilibrium. This is analogous to a majority carrier device (current carrier is the same as the bulk media).

Basic Semiconductor Processing

Wafers are sliced from a single silicon crystal which has to be "grown." This is done by melting silicon in a crucible. Pure silicon occurs in two forms - either as a single crystal, or as a collection of atoms with no particular arrangement, called polysilicon. A "seed" or a small silicon crystal is inserted into the crucible holding the molten polysilicon. As the seed is slowly drawn out, the molten silicon aligns with the crystal lattice in the seed. As it cools, the molten silicon expands on this crystal lattice forming an ingot as shown in Figure 10. The entire ingot is drawn out as a single crystal made up of many silicon atoms. This ingot is then sliced into thin wafers, and each wafer is polished to a mirror-like finish. The mirror-like finish of the silicon wafer needs to have a pattern etched into it to make a useful circuit, or circuit element (discrete).

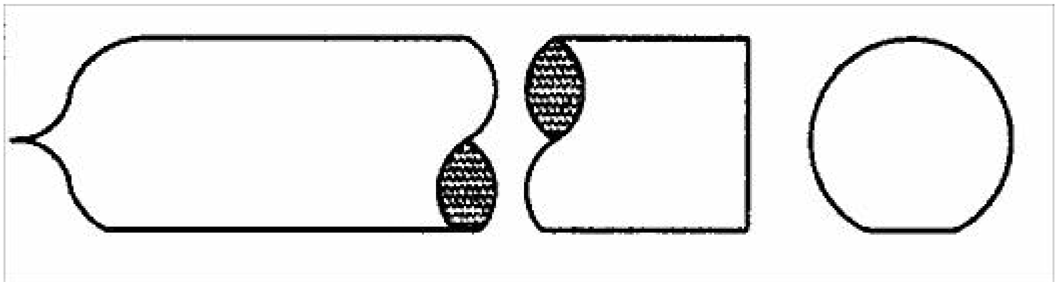

Figure 10. Monocrystalline Silicon Ingot.

Figure 11 depicts a mask used to transfer the desired pattern onto the silicon wafer. The mask pattern (either positive or negative) is then projected onto the wafer by one of several different methods. A particular device, or design, requires a number of different masks - this collection is known as a mask set. The fewer masks in the mask set. the lower the processing costs.

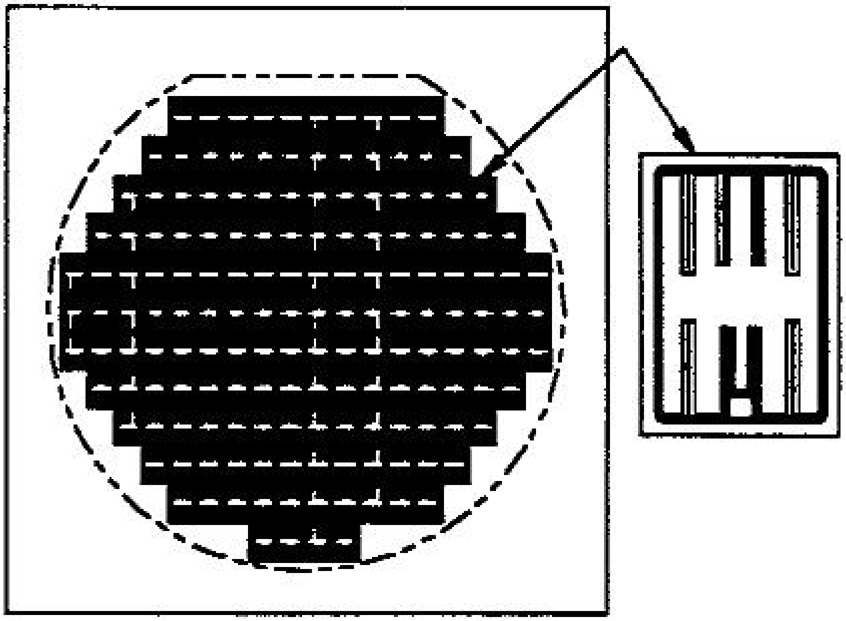

Figure 11. Mask.

The mask contains one image repeated numerous times. The masks are used in the photolithography process to transfer the patterns to the silicon wafer. A photo-sensitive material is applied to the wafer, and the mask exposes certain areas of the wafer. This causes a chemical change in the photo-sensitive material. A chemical is then used to etch portions away, leaving a pattern on the wafer. This is repeated a number of times, with some or all of the following intermediate steps occurring between mask steps.

Diffusion is the process by which dopants are added to the wafer. By using the appropriate mask, a certain pattern is diffused into the wafer. Diffusion is usually followed by a drive-in step by heating the wafer for a particular amount of time. Controlling the time and temperature defines the profile diffused into the wafer.

The diffusion process must be tightly controlled. With advances in IC processing, a method called ion implantation has been developed. Instead of controlling the time and temperature of a diffusion furnance, ion implantation makes use of an extremely high voltage electron gun which accelerates the dopants, and "shoots" them into the wafer. By adjusting the high voltage, the implant depth is controlled. It is possible to get very precise profiles by using this method.

The "wires" of the integrated circuit world are constructed using either metal, or polysilicon, which may be heavily doped to reduce its resistance. Either of these materials can be used to cover the entire surface, or to make tightly controlled patterns via the aforementioned processes. Sometimes problems happen with "step coverage" of the metal as shown in Figure 12., when the metal has to cover what looks like a single stair step. The metal thickness tends to thin at the outer most portion of the step, and can lead to failure if the metal becomes discontinuous across this step. Silicon dioxide is commonly used to insulate the metal from contacting other layers.

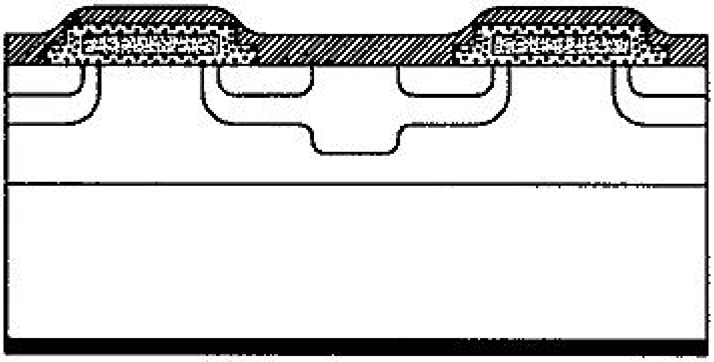

Figure 12. Metal Step Coverage.

Device Cross Section

The following sections show the cross sectional views and describes the operation of six different devices. More detailed information is available in each device's specific Training Module. The goal of this section is to compare and contrast the various devices: pn diode, Schottky diode, SCR, MOSFET, IGBT, and Control IC.

pn Diode

As shown in Figure 13, the top metal is the anode, while the bottom is the cathode. The action occurs at the interface, called the junction, between the implanted p-type and n-type materials. When a positive voltage is applied between the anode and cathode, current will flow through the diode, provided the voltage is greater than "a diode drop" which, for standard pn diodes, is usually around 0.7V. As the forward current (I_F) increases, the voltage drop (V_F) will also increase. However, most of the voltage drop is the initial 0.7V drop which occurs when any amount of current flows through the diode.

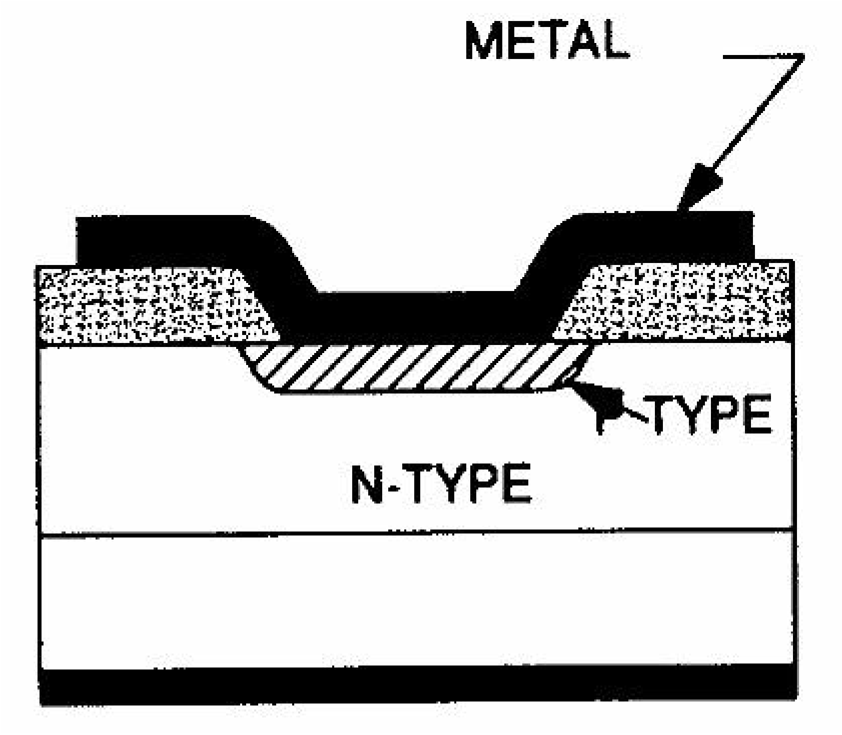

Figure 13. PN Diode

If a negative voltage is applied across the pn junction (anode to cathode), the device exhibits very high resistance to current flow, and the small amount of current that does conduct is called the leakage current (I_{RM}).

When a diode is conducting in the forward direction and is asked to block in the reverse direction, it "forgets" it is a diode for a period of time and allows current to conduct. After this short period of time, called the reverse recovery time, or trr, the diode "remembers" it is a diode and begins blocking current. However, during this recovery time, a large current conducts through the diode, called reverse recovery current, or Irr. The shape of the waveforms during this period are critical to the operation of the rest of the circuit, which is why IR has developed the HEXFRED® diode, an ultra-fast, but ultra-soft diode unlike snappier diodes from our competitors that usually cause excessive voltage ringing in the circuit. As temperature increases, the forward voltage decreases, while the reverse recovery current and charge increase.

Schottky Diode

As shown in Figure 14, the Schottky diode is very similar to a standard pn diode, but instead of having an implanted p-layer, the action occurs at the interface between the barrier metal and the silicon. The guard rings are used to make the device's reverse breakdown characteristics more rugged. Since both metal and the silicon are n-type materials, the conduction occurs through majority carriers only, with no minority carrier injection, storage, or recombination . This explains the Schottky diode's lack of reverse recovery, making it ideal for high frequency applications.

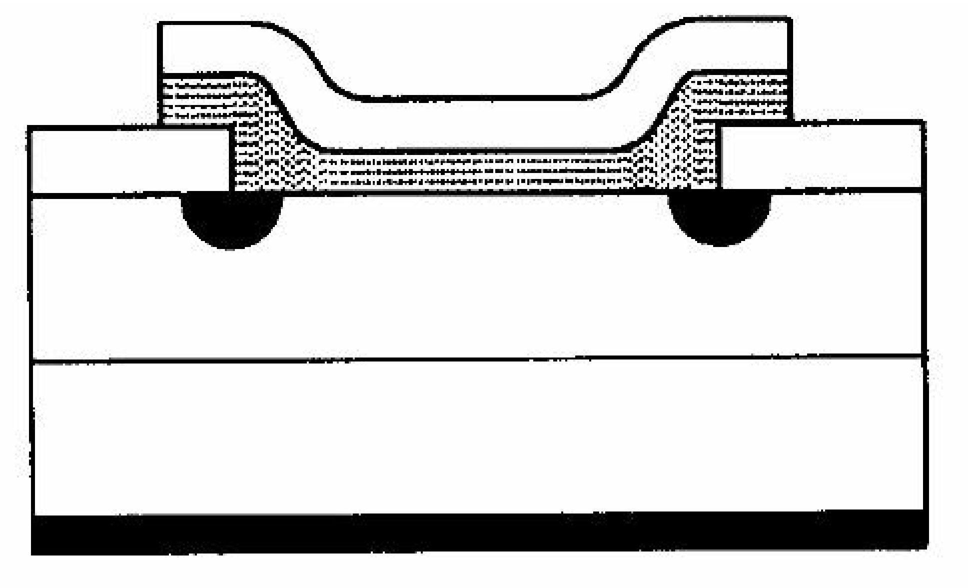

Figure 14. Schottky Diode

The barrier metal also is responsible for the Schottky diode's low forward voltage drop, making it ideal for use in low voltage systems. Of course, the tradeoff is the reverse leakage current, which is many times that seen in pn-junction diodes. In some applications, and especially during burn-in, this leakage current may cause the device to exceed its rated junction temperature. It needs to be included in any junction temperature calculations. As temperature increases, the forward drop decreases, while the reverse leakage current greatly increases.