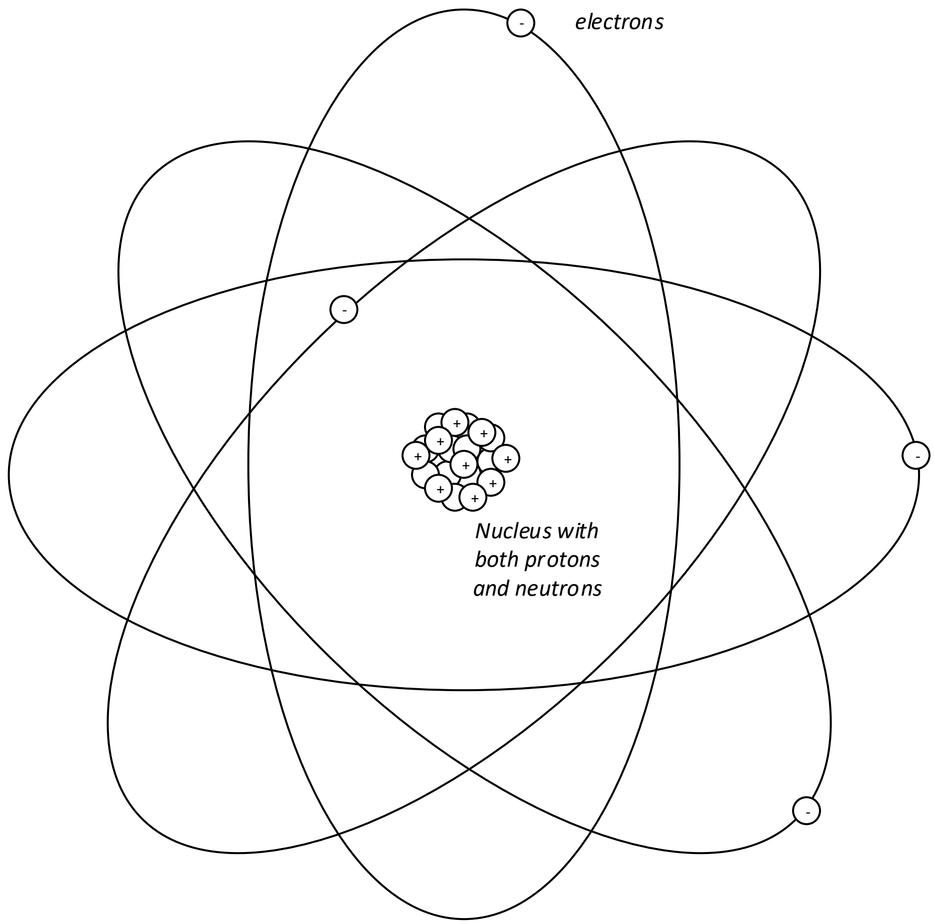
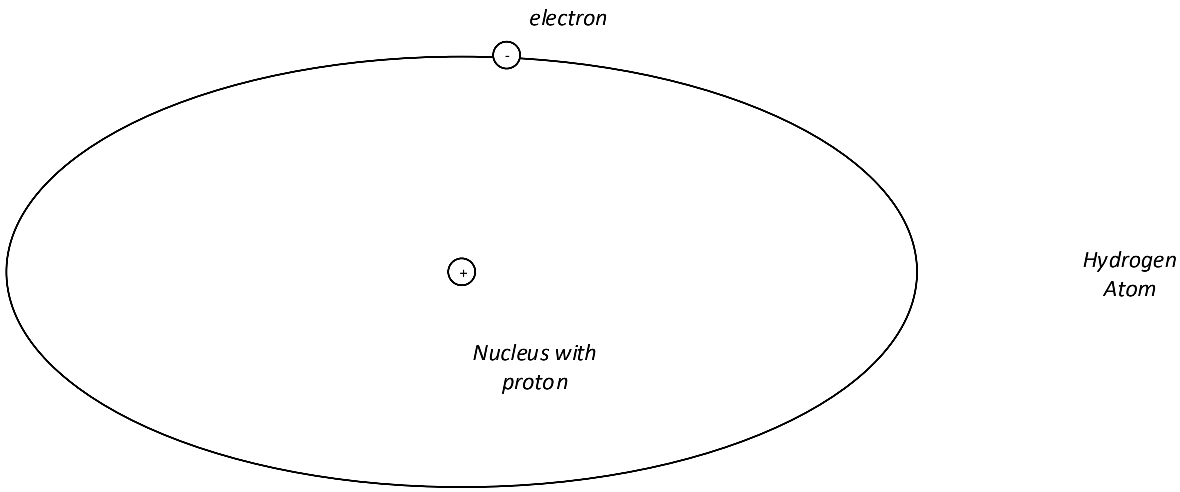
10 Semiconductors - Diodes

When we worked problems in earlier chapters involving a switch, we were actually working problems with a semiconductor switch. Transistor switching has been assumed from the start of this book. We will begin the study of semiconductors with a look at the atomic structure of semiconductors. Then we will look quickly at diodes, transistors and finally op-amps to get a sense of the breadth of their uses. They are the common building blocks of all electronic circuits.

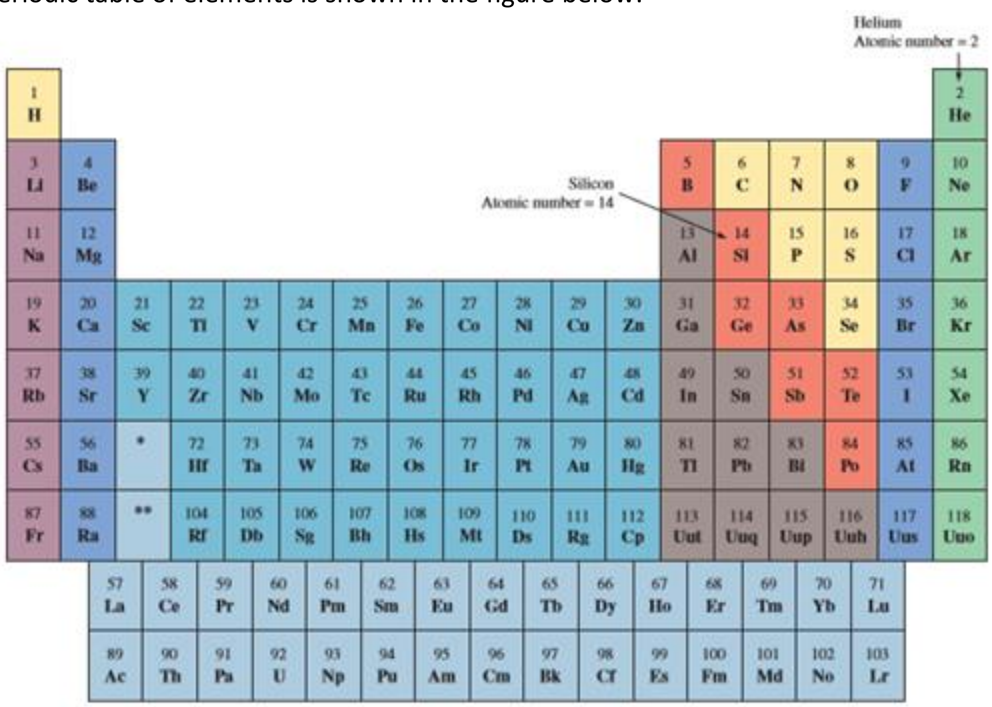
"The atom is the smallest particle of an element that retains the characteristics of that element." The atom gives the element the characteristic of a particular material that identifies it. The atom is composed of a nucleus holding protons and neutrons. Electrons orbit around the nucleus at various levels. The elements have an atomic number or the count of the number of protons in the nucleus. For the atom to be balanced, an equal number of electrons circle the nucleus. These are shown in the following diagram.



The first two atoms in the periodic chart are hydrogen and helium. Hydrogen is shown below:



The entire periodic table of elements is shown in the figure below:

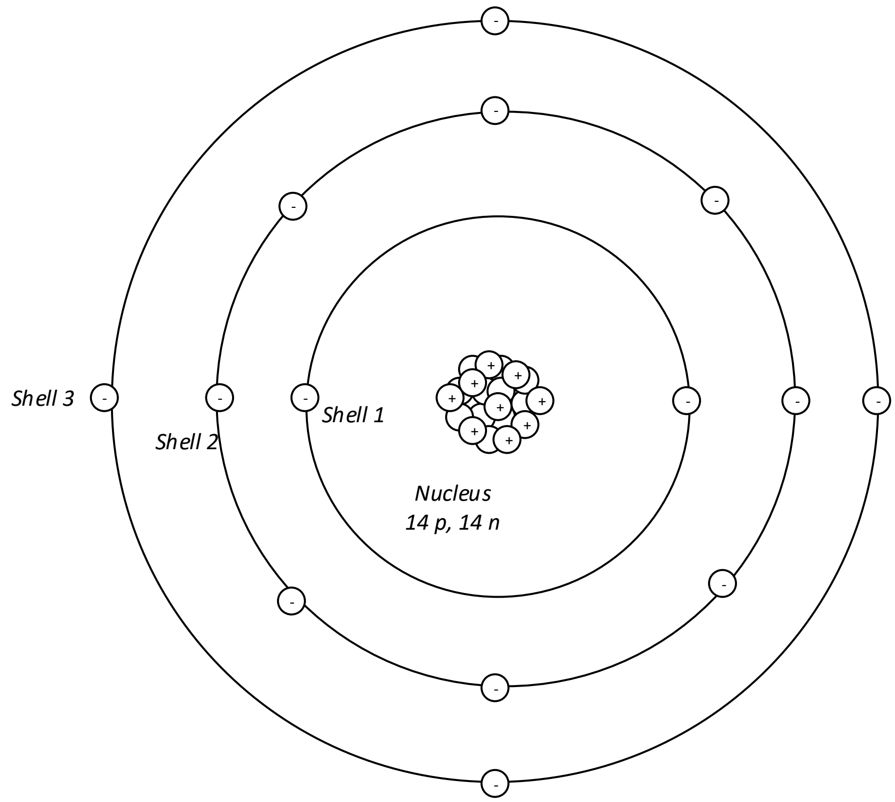


Electrons orbit the nucleus at various distances. Their energy level is higher the farther away from the nucleus. Electrons orbit at certain distances from the nucleus called shells. An atom has a number of shells that correspond to the number of electrons filling each shell. The shells are numbered with the first containing two electrons, the next eight, etc. The formula for a maximum number of electrons in a shell is:

$$N_e = 2n^2$$

where *n* is the number of the shell. The maximum number of electrons that can be found in any shell is this number. The number of electrons in shell 2 is 8, shell 3 is 18, shell 4 is 32, etc. The outer shell of any atom is known as the valence shell and electrons in this shell are referred to as valance electrons. These electrons can be moved from atom to atom and combine with the outer shell of other atoms to form compounds. These electrons can also move from atom to atom and become electrical currents.

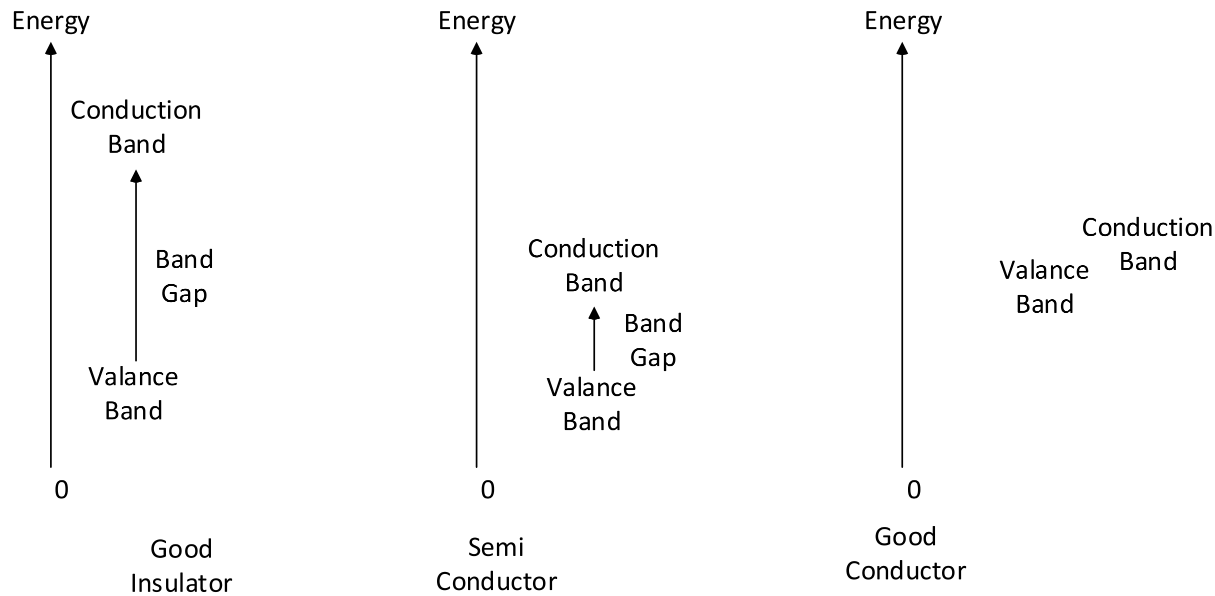
The following is a model of silicon with 14 nuclei and 14 electrons. Notice the 4 electrons in the outer valence shell:



Silicon at atomic number 14 and Germanium at atomic number 32 make up a special type of atom known as semi-conductors. They conduct but not well. Their outer valence band can be combined to form a rather stable outer shell. However, when doped with other semiconductors with either a 3 or 5 outer shell they conduct under certain conditions.

Other materials can fall into groups that either conduct or don't conduct and are commonly referred to as insulators or conductors. Insulators do not conduct electrical current under normal conditions and conductors do conduct. Materials such as rubber or plastic or glass are good insulators. Materials such as copper, silver, or gold are good conductors.

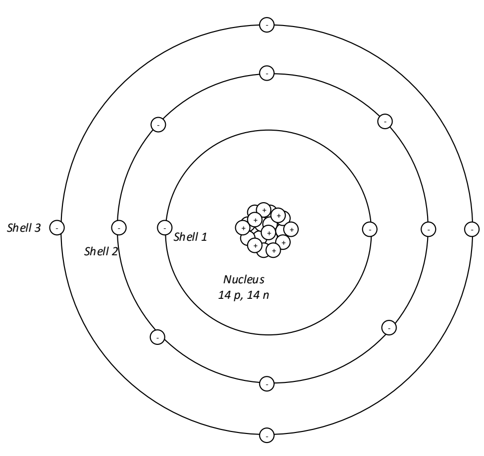
While the outer band of an atom is referenced as the valence band, the electrons are free to jump from this band to a further out band called the conduction band. This band is further removed from the nucleus by a distance and energy referenced as the band gap. The difference in energy from the valence band to the conduction band is the energy or band gap. Now the electrons are free to move between atoms. Insulators, semiconductors and conductors all have varying band gaps as pictured below:



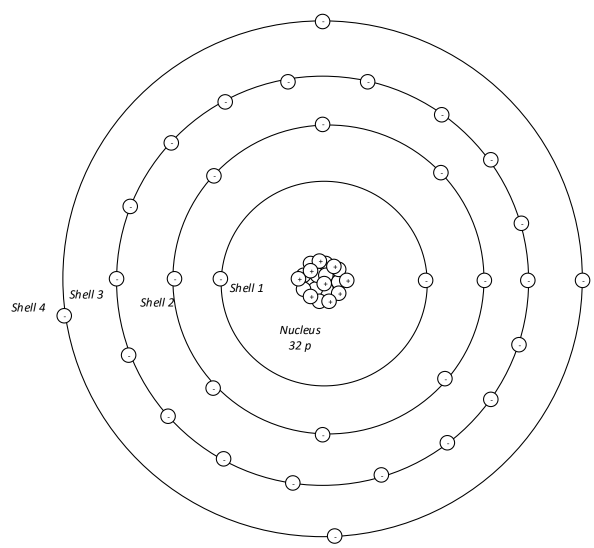
At left is an insulator, then a semiconductor and at right a good conductor. Note that there is an overlap between the conduction and valence bands with a good conductor. The difference between the atomic make-up of a silicon atom and a copper atom is that the silicon atom has four electrons in the valence band while copper has only one electron in this outer band. The valence electron in the copper atom is very lonely in the fourth band while the four electrons in the third or valence band of silicon is relatively stable.

The valence electrons in silicon are free to move but not as easily as the copper. This can be seen both from the observation that valence electrons of copper are further from the nucleus as well as that there is only one electron in the outer shell. It is easier for valence electrons of copper to escape from the valence shell and move to the conduction shell.

Two elements, silicon and germanium, have long been considered the best semiconductor materials. Both have four electrons in their outer shell. Silicon wins the battle of which to use due to its relatively cheaper cost.



Silicon

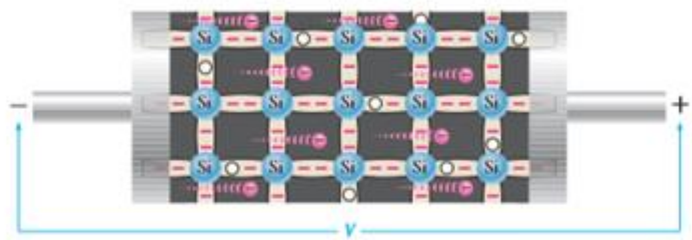


Germanium

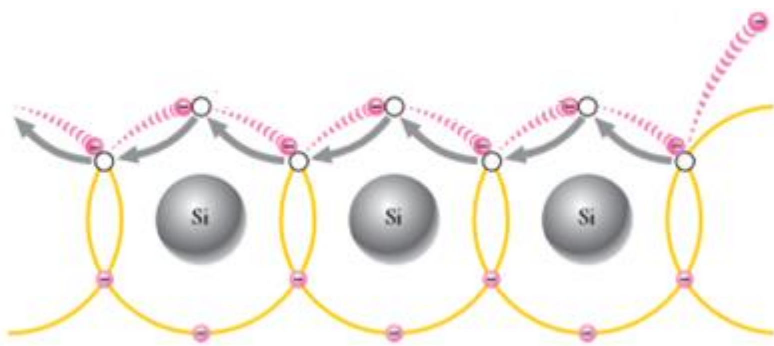
The silicon atoms bond with other silicon atoms in a rectangular shape called a crystal. The four adjacent atoms share electrons with the center atom in an arrangement shown below. The electrons form valence bands with eight electrons giving a stable state for the valence band.

When heated, electrons can jump from the valence band to the conduction band of silicon. The intrinsic silicon crystal allows some electrons to move up to the conduction band and conducting. When the electron jumps, it creates a vacancy called a hole in the valence band. The electron and hole form a pair called an electron-hole pair which can recombine later.

Movement of electrons occurs when voltage is applied across the material. Electrons move toward the positive end and this is called electron current.



Electron flow also occurs in the valence band with hole/electron flow in this band. These electrons are attached to their atoms but move in the crystal structure in a random pattern through the lattice although attached at the valence level. This current is referenced as hole current. The two types of current, electron current and hole current both are active in a semiconductor which is very different from current in a conductor. With conductors such as copper, electrons are stripped from the valence band and are not part of any atom. The hole current does not exist in a conductor, only in a semi-conductor.

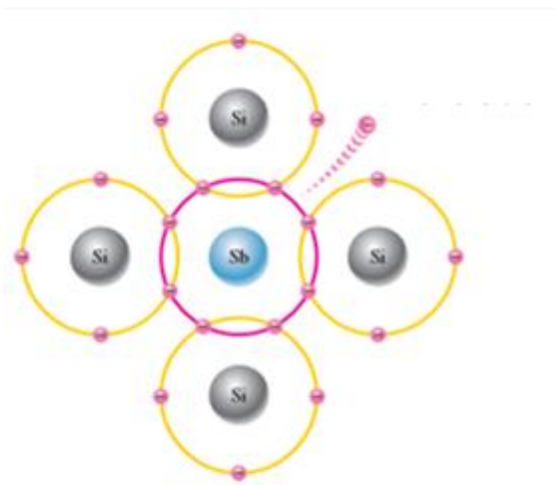


While the bad news is that semiconductors conduct poorly, if there is a little impurity added, the semiconductor can conduct much better. The impurity is either an atom with three or five electrons in the valence band. The three-electron atoms are p-type and the five-electron atoms are n-type. To add the impurity a process called doping is introduced.

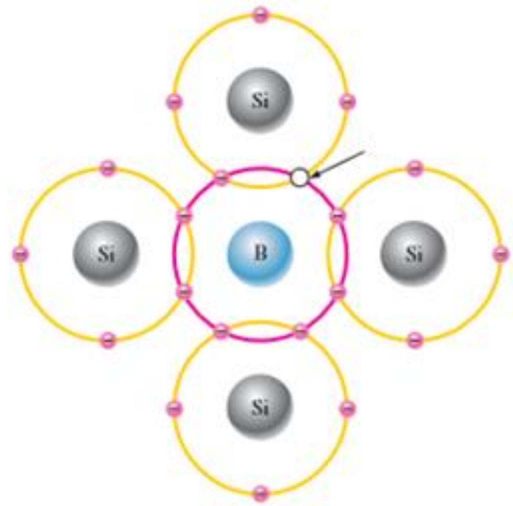
N and P Type Semiconductors

To dope a semiconductor, we need an atom with either three or five electrons in the outer shell to give an extra electron or an extra absence of an electron in the outer shell. The atoms with five valence electrons are arsenic (As), phosphorus (P) bismuth (Bi) and antimony (Sb). Atoms with three electrons in the outer shell are boron (B), indium (In) and gallium (Ga).

The five electron atoms are referred to as n-type dopants and the three electron atoms are referred to as p-type dopants. When inserted in the lattice structure, these atoms create either an extra electron or an extra hole (absence of electron) at that point in the structure. The semiconductors that we will discuss all have either n or p-type dopant in the structure.

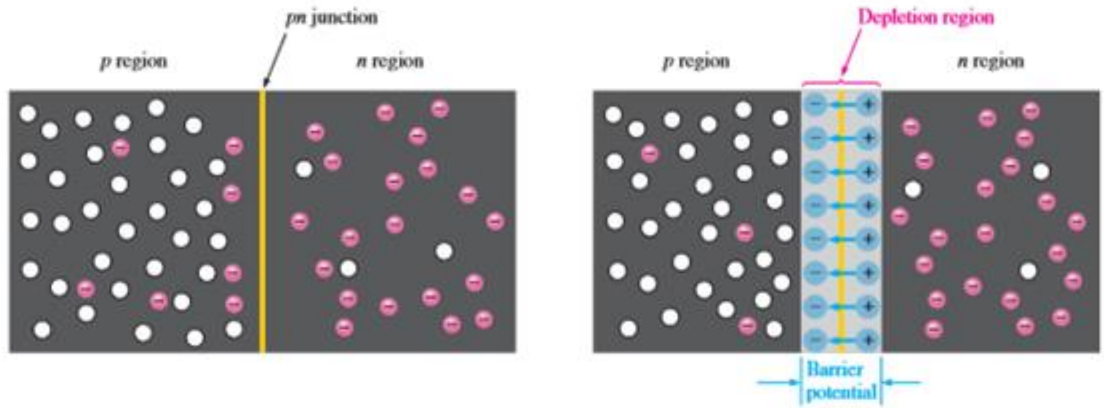


This atomic structure shows an excess electron in the crystal.



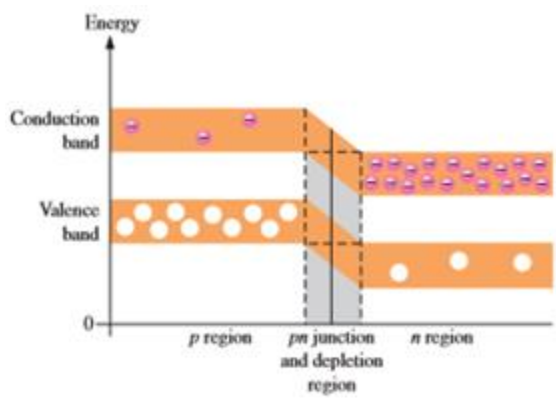
This atomic structure shows a hole in the crystal.

With both dopants in silicon, we have a barrier called the pn junction. Remember that the p region has many holes and the n region has excess electrons that want to flow over the pn junction to the other side. If an electric field exists to separate the two regions, there is little flow. This is called a depletion region. If there is an electron field that encourages the flow of electrons and holes across the pn junction the flow is enhanced and the depletion region is gone. This implies there is a point at which the barrier collapses and this is the case. This is referred to as the barrier potential, sometimes called the electron hill that electrons must overcome to move through to the other side of the barrier.



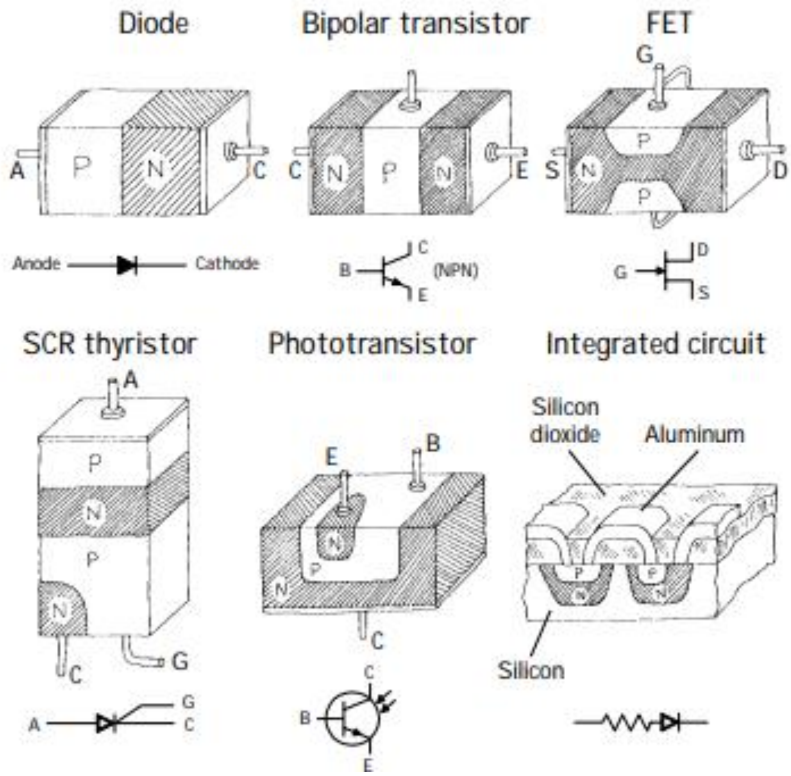
Another term is used in describing the current is majority and minority carriers. In p-type material, holes are the majority carrier and in n-type, electrons are the majority carrier. Remember that majority carriers in the n region are in the conduction band while the p-type majority carriers are holds in the valence band. The energy to cross from the n-region conduction band to the p-region valance band is the barrier potential.

The figure below shows the increase of energy or voltage in the p region and the ease with which electrons can flow in this energy level.



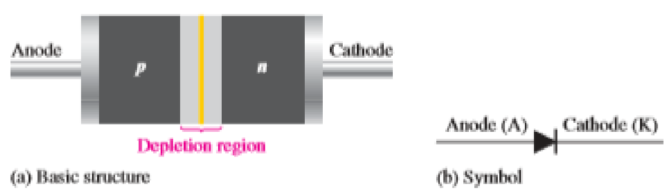
Energy to provide a flow of electrons is measured at 0.7 V for silicon and 0.3 V for germanium.

When silicon is doped with n and p material, we can get a lot of different devices. The following are a sampling:

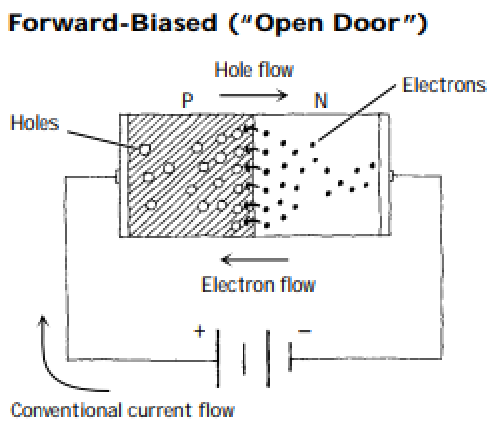


Diodes

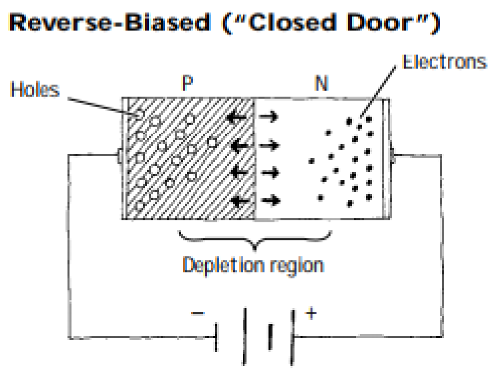
The diode is a semiconductor with a sandwich in the middle with one side of the sandwich p-type and the other side n-type. There is nothing in the middle except a depletion region if the diode is not biased with a voltage source. The p-type material is called the anode and the n-type material the cathode.



The following show what happens when the diode is forward-biased and reverse-biased with a voltage source:

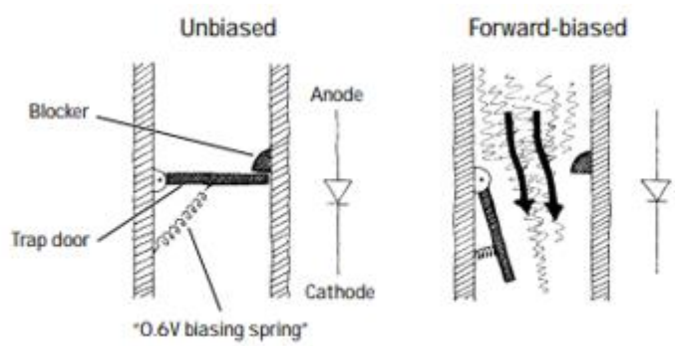


The forward biased diode shows an acceptance of electron flow through the barrier region



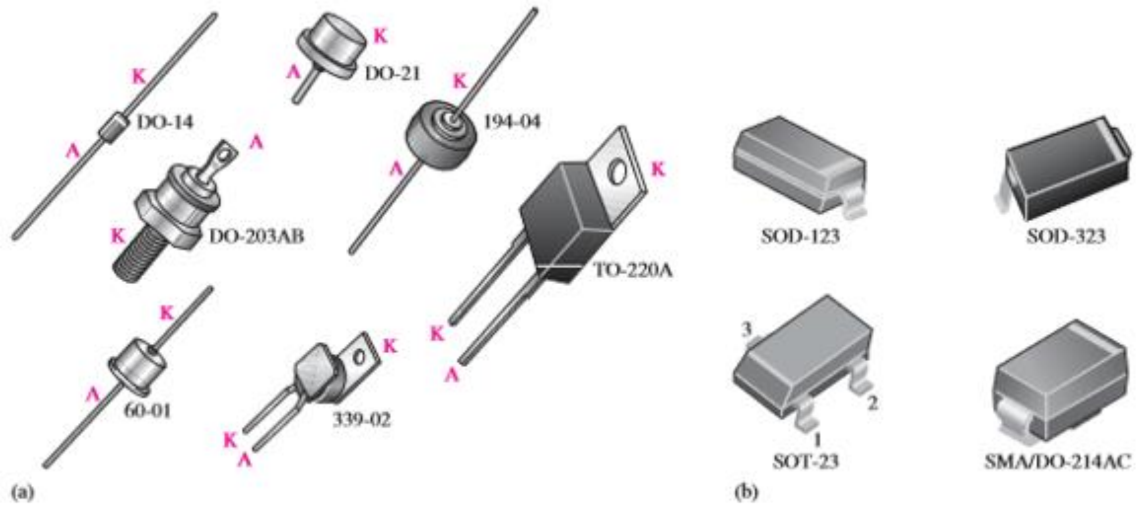
The reverse biased diode shows a resistance to electron flow through the barrier region

This device is a one-way device in that flow of electrons only occur in one direction, the direction of the arrow. The water analogy below shows this same physical analogy with water:

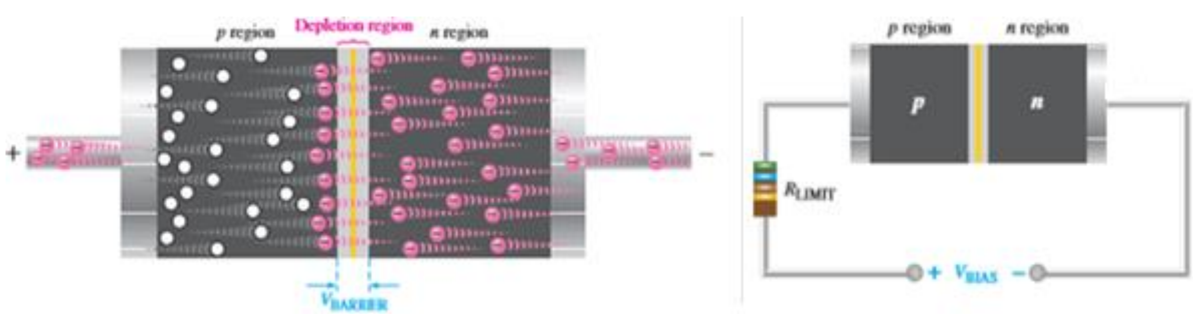


In the analogy, we see a spring holding the water until enough force is applied to over-come the spring. In the reverse direction, there is no flow.

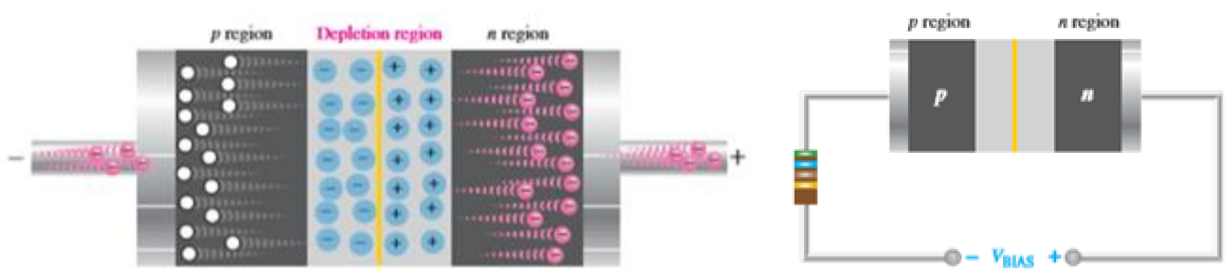
Different package arrangements are available for diodes depending on the way the diode is used and mounted:



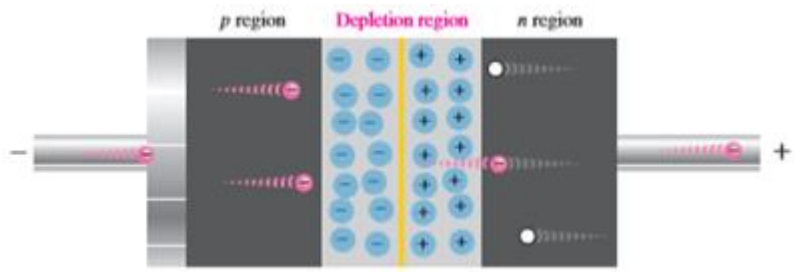
Using the water analogy from above, we see that when the diode is forward biased with voltage applied as in the figure below, we get a rushing of electrons through the depletion region. The holes in the p region provide a pathway for flow in the circuit. The depletion region is reduced due to the effect of forward bias. The number of ions in the depletion region is reduced and the region narrows. This all happens when the barrier potential of the material is reached, the electron hill of 0.3 or 0.7 V.



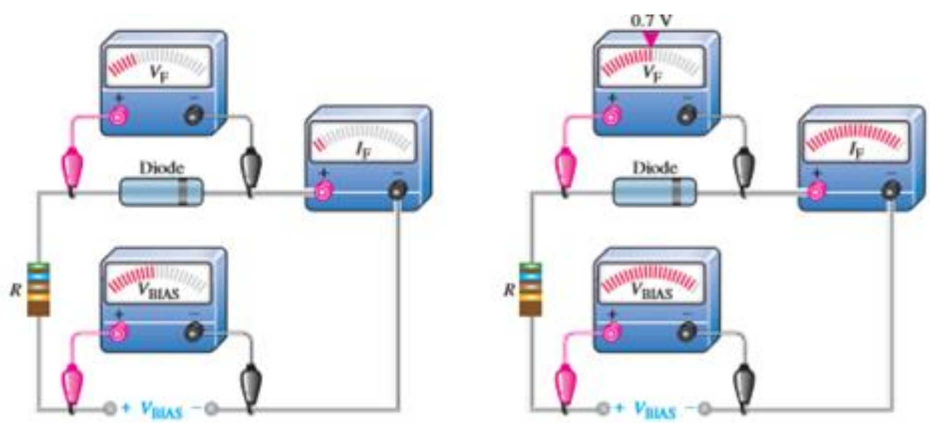
The reverse happens when the bias of the voltage supply is reversed. The depletion region grows repelling the flow of electrons and holes in the material. The current-carrying capacity of the diode shuts down similar to the spring closing the water valve in the water example above.



There is a point, however, in the reverse bias direction that all the blocking capacity of the depletion region breaks down and there is a rush of electrons through the diode in the reverse direction. This is usually very bad and the diode is no longer a diode when this happens. However, there are diodes that are specifically built to work in this reverse region called zener diodes. This is called reverse breakdown.



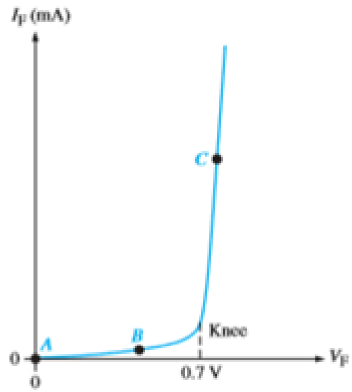
Checking to verify the diode characteristics above, use the following configuration and change the bias voltage:



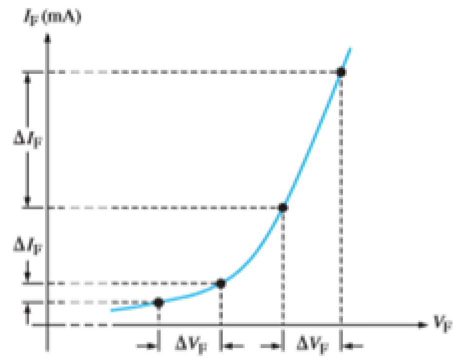
(a) Testing for V-I Curve for small values of V

(b) Testing for V-I Curve for larger values of V

From the above, we can draw the V/I graph in the forward direction for the diode as the following:

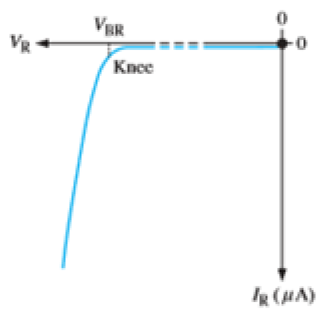


(a) V-I Characteristic curve for forward bias

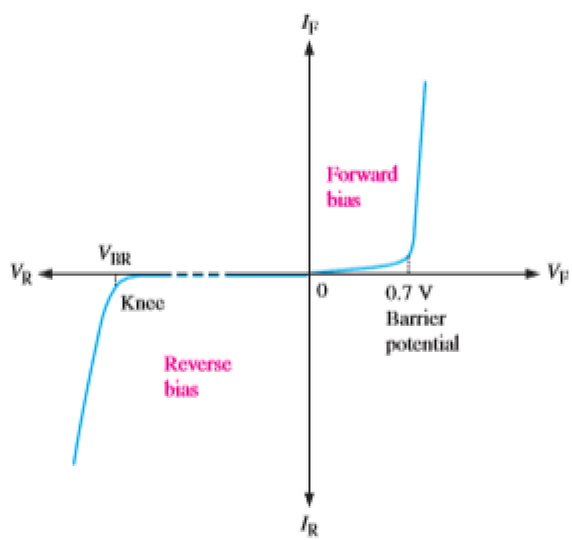


(b) Expanded View of forward bias

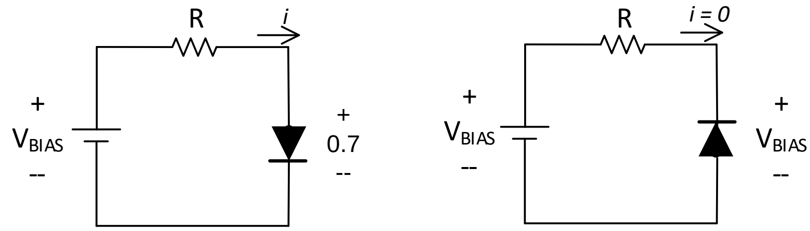
Then, when we turn the diode around and turn up the voltage, we can find the following. The vBR voltage will destroy the diode so care should be taken not to approach this point unless the diode is expendable.



Together, the two halves of the graph look like this:

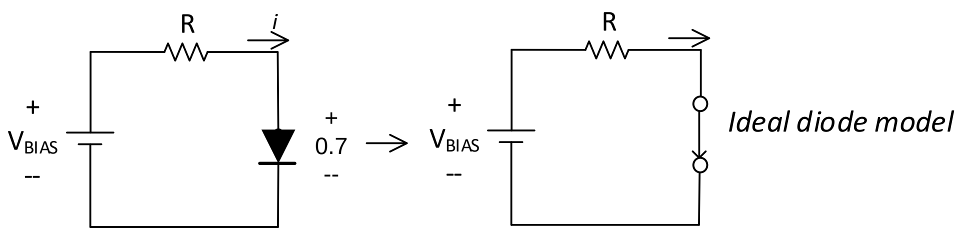


We can draw the diode using its symbol showing the flow of electrons (opposite positive flow) when the diode is forward biased. Likewise, when reverse biased, the current stops flowing.

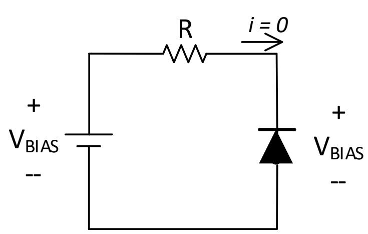


(a) Forward Bias *(b) Reverse Bias*

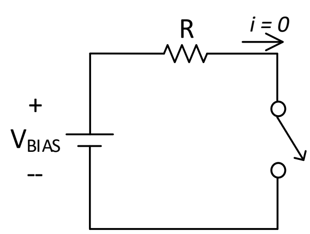
We now look for a model that we can use for the diode. The first approximation of a diode is the following. Notice the switch is closed in the forward direction and open in the reverse, an exact copy of the water analogy above. The graph at right shows the flow in the forward direction only.



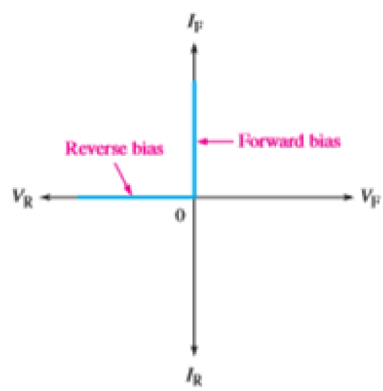
(a) Forward Bias



(b) Reverse Bias

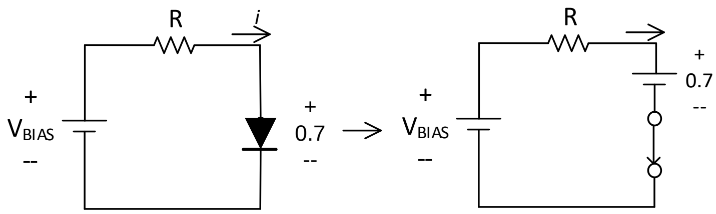


(b) Reverse Bias



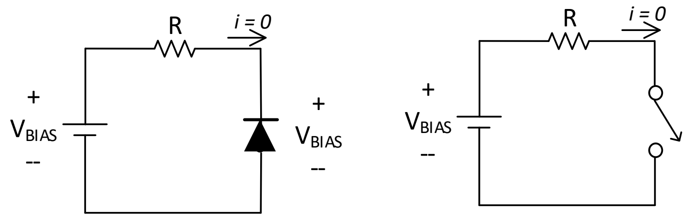
(c) Ideal diode model V-I Curve

Adding some sophistication to the model would be to add the voltage of the forward bias or electron hill. This voltage of 0.7 V is added to the closed switch in the forward direction. In the reverse direction, the battery is ignored.

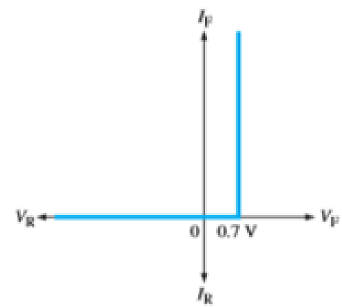


(a) Forward Bias

Practical diode model



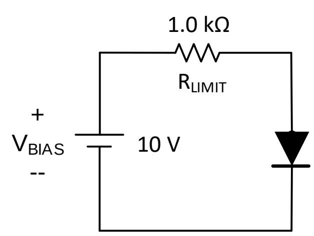
(b) Reverse Bias



(c) Practical diode model V-I Curve

We now use the diode's model to determine current flow in each of the figures below:

Determine the forward voltage and forward current for the diode in the following figure:



a) For the ideal model:

$$V_F = 0\ V$$

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}} = \frac{10\ V}{1.0\ k\Omega} = 10\ mA$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (10mA)(1.0\ k\Omega) = 10\text{ V}$$

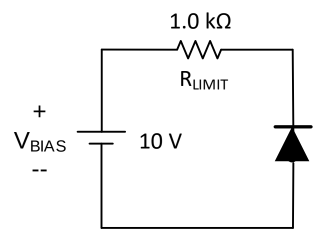
Practical model:

$$V_F = 0.7\ V$$

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}} = \frac{10\ V - 0.7\ V}{1.0\ k\Omega} = \frac{9.3\ V}{1.0\ k\Omega} = 9.3\ mA$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.3\ mA)(1.0\ k\Omega) = 9.3\ V$$

Determine the reverse voltage and reverse current for the diode below. Assume I_R = 1 µA:



b) For the ideal model:

$$I_R = 0\ A$$

$$V_R = V_{BIAS} = 10\ V$$

$$V_{R_{LIMIT}} = 0\ V$$

Practical Model

c)

$$I_R = 0\ A$$

$$V_R = V_{BIAS} = 10\ V$$

$$V_{R_{LIMIT}} = 0\ V$$

Zener Diodes

The diode is designed to be operated in either positive bias voltage or a range in the reverse direction that does not 'destroy' the diode. The Zener diode is designed to be operated in the reverse direction at a value that allows the diode to give a stable voltage across a range of current. The zener diode is useful to give a reduced voltage in a range. For example, if you need a 5 volt dc supply but only have a 12 V dc supply, you may include a zener diode attached to the circuit to be operated in the reverse direction and rated at 5 V. This zener will give a small amount of current at 5 V for use. You will need to identify the current level and not exceed that value to operate the zener in the reverse direction. The value of voltage is referred to as the PIV or Peak Inverse Voltage.

Other Types of Diodes:

The tunnel diode is a two-terminal semiconductor with a negative resistance region. This resistance gives the tunnel diode the capability to be used in switching circuits.

Varactor diodes have characteristics that give them the capacitance of small variable capacitors.

The Schottky diode is used for high speed switching circuits.

The LED is a diode that emits light when forward biased. Like most diodes, when turned on with a forward bias, the LED must be protected from over-current with a resistor. However, if pulsed, they can produce more power for a short period of time. LED's are used in pulsed form for photo-eye applications.

Problems

10.1 To forward bias a diode, to which region must the positive terminal of a voltage source be connected?

10.2 Explain why a series resistor is necessary when a diode is forward-biased.

10.3 Explain how to generate the forward-bias portion of the characteristic curve.

10.4 Determine whether each silicon diode in the following figure is forward or reverse-biased.

10.5 Find the voltage across each diode in the following figure assuming an ideal diode.

10.6 Find the voltage across each diode in the following figure assuming a practical model of the diode.