Lesson 1: Diodes and Applications
Figure 1-1 The Bohr model of an atom showing electrons in orbits around the nucleus, which consists of protons and neutrons. The “tails” on the electrons indicate motion.
Figure 1-2 Two simple atoms, hydrogen and helium.

(a) Hydrogen atom

(b) Helium atom
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Figure 1-3 Energy increases as the distance from the nucleus increases.

- Electrons with the highest energy levels exist in the outermost shell of an atom and are loosely bound to the atom.
- This outermost shell is known as the valence shell and electrons in the shell are called *valence electrons*.
- When an atom absorbs energy from a heat source or from light, for example, the energy levels of the electrons are raised.
- When an electron gains a certain amount of energy, it moves to an orbit farther from the nucleus.
- The process of losing an electron is called ionization.
- The escaped valence electron is called a *free electron*.
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Figure 1-5 Energy diagrams for the three types of materials.

(a) Insulator
(b) Semiconductor
(c) Conductor

Energy diagrams illustrating the energy bands for insulators, semiconductors, and conductors.
Semiconductors are crystalline materials that are characterized by specific energy bands for electrons. Between the bands are gaps; these gaps represent energies that electrons cannot possess. The last energy band is the **conduction band**, where electrons are mobile. The next to the last band is the **valence band**, which is the energy level associated with electrons involved in bonding.
Two types of semiconductive materials are silicon and germanium.
Both the silicon and germanium atoms have four valence electrons.
These atoms differ in that silicon has 14 protons in its nucleus and germanium has 32.
The valence electrons in germanium are in the fourth shell while the ones in silicon are in the third shell closer to the nucleus.
This means that the germanium valence electrons are at a higher energy levels than those in silicon and therefore requires a small amount of additional energy to escape from the atom.
This property makes germanium more unstable than silicon at high temperatures.
The sharing of valence electrons produces the covalent bonds that hold the atoms together; each shared electron is attracted equally by two adjacent atoms which share it.
Semiconductors

Figure 1-9 Covalent bonds in a silicon crystal.

- An intrinsic crystal is one that has no impurities.
- Covalent bonding for germanium is similar because it also has four valence electrons.
Figure 1-10 Energy band diagram for an unexcited atom in a pure (intrinsic) silicon crystal. There are no electrons in the conduction band.
Figure 1-11 Creation of electron-hole pairs in a silicon crystal. Electrons in the conduction band are free electrons.

(a) Energy diagram

(b) Bonding diagram
At room temperature, some electrons have enough energy to jump into the conduction band. After jumping the gap, these electrons are free to drift throughout the material and form electron current when a voltage is applied. For every electron in the conduction band, a hole is left behind in the valence band.
Figure 1-12 Electron-hole pairs in a silicon crystal. Free electrons are being generated continuously while some recombine with holes.
Figure 1-13 Electron current in intrinsic silicon is produced by the movement of thermally generated free electrons.
Figure 1-14 Hole current in intrinsic silicon.

When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.
The electrons in the conduction band and the holes in the valence band are the charge carriers. In other words, current in the conduction band is by electrons; current in the valence band is by holes.

When an electron jumps to the conduction band, valence electrons move from hole-to-hole in the valence band, effectively creating “hole current” shown by gray arrows.
Impurities

By adding certain impurities to pure (intrinsic) silicon, more holes or more electrons can be produced within the crystal.

To increase the number of conduction band electrons, pentavalent impurities are added, forming an \( n \)-type semiconductor. These are elements to the right of Si on the Periodic Table.

To increase the number of holes, trivalent impurities are added, forming a \( p \)-type semiconductor. These are elements to the left of Si on the Periodic Table.
Impurities

Figure 1-15 Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.
Figure 1-16 Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.
The \textit{pn} junction diode

When a \textit{pn} junction is formed, electrons in the \textit{n}-material diffuse across the junction and recombine with holes in the \textit{p}-material. This action continues until the voltage of the barrier repels further diffusion. Further diffusion across the barrier requires the application of a voltage.

The \textit{pn} junction is basically a diode, which is a device that allows current in only one direction. A few typical diodes are shown.
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The *pn* junction diode

Figure 1-17 Formation of the depletion region. The width of the depletion region is exaggerated for illustration purposes.

(a) The basic diode structure at the instant of junction formation showing only the majority and minority carriers. Free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.

(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion. The blue arrows between the positive and negative charges in the depletion region represent the electric field.
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The *pn* junction diode

Figure 1-18 Energy diagrams illustrating the formation of the *pn* junction and depletion region.

(a) At the instant of junction formation

(b) At equilibrium
Forward bias

When a *pn* junction is forward-biased, current is permitted. The bias voltage pushes conduction-band electrons in the *n*-region and holes in the *p*-region toward the junction where they combine.

The barrier potential in the depletion region must be overcome in order for the external source to cause current. For a silicon diode, this is about 0.7 V.

The forward-bias causes the depletion region to be narrow.
Figure 1-19 A diode connected for forward bias.
Figure 1-20 A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.
Figure 1-21 The depletion region narrows and a voltage drop is produced across the *pn* junction when the diode is forward-biased.

(a) At equilibrium (no bias)

(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.
Reverse bias

When a $pn$ junction is reverse-biased, the bias voltage moves conduction-band electrons and holes away from the junction, so current is prevented.

The diode effectively acts as an insulator. A relatively few electrons manage to diffuse across the junction, creating only a tiny reverse current.

The reverse-bias causes the depletion region to widen.
Figure 1-22 A diode connected for reverse bias. A limiting resistor is shown although it is not important in reverse bias because there is essentially no current.
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Reverse bias

Figure 1-23 The diode during the short transition time immediately after reverse-bias voltage is applied.
Figure 1-24 The extremely small reverse current in a reverse-biased diode is due to the minority carriers from thermally generated electron-hole pairs.