Diodes

Perhaps the simplest device that can be created with a semiconductor is a diode. A diode is a circuit element that allows electric current to flow in only one direction, like a one-way valve (see Model of Conduction in Metals). A diode is created by joining a p-type semiconductor to an n-type semiconductor (Figure \(\PageIndex{1}\)). The junction between these materials is called a p-n junction. A comparison of the energy bands of a silicon-based diode is shown in Figure \(\PageIndex{1b}\). The positions of the valence and conduction bands are the same, but the impurity levels are quite different. When a p-n
junction is formed, electrons from the conduction band of the \textit{n}-type material diffuse to the \textit{p}-side, where they combine with holes in the valence band. This migration of charge leaves positive ionized donor ions on the \textit{n}-side and negative ionized acceptor ions on the \textit{p}-side, producing a narrow double layer of charge at the \textit{p-n} junction called the \textbf{depletion layer}. The electric field associated with the depletion layer prevents further diffusion. The potential energy for electrons across the \textit{p-n} junction is given by Figure \ref{PageIndex{2}}.

![Figure 1](a) Representation of a \textit{p-n} junction. (b) A comparison of the energy bands of \textit{p}-type and \textit{n}-type silicon prior to equilibrium.

The behavior of a semiconductor diode can now be understood. If the positive side of the battery is connected to the \textit{n}-type material, the depletion layer is widened, and the potential energy difference across the \textit{p-n} junction is increased. Few or none of the electrons (holes) have enough energy to climb the potential barrier, and current is significantly reduced. This is called the \textbf{reverse bias configuration}. On the other hand, if the positive side of a battery is connected to the \textit{p}-type material, the depletion layer is narrowed, the potential energy difference across the \textit{p-n} junction is reduced, and electrons (holes) flow easily. This is called the \textbf{forward bias configuration} of the diode. In sum, the diode allows current to flow freely in one direction but prevents current flow in the opposite direction. In this sense, the semiconductor diode is a one-way valve.
Figure \ref{Figure 2}: At equilibrium, (a) excess charge resides near the interface and the net current is zero, and (b) the potential energy difference for electrons (in light blue) prevents further diffusion of electrons into the p-side.

We can estimate the mathematical relationship between the current and voltage for a diode using the electric potential concept. Consider \( N \) negatively charged majority carriers (electrons donated by impurity atoms) in the n-type material and a potential barrier \( V \) across the p-n junction. According to the Maxwell-Boltzmann distribution, the fraction of electrons that have enough energy to diffuse across the potential barrier is \( \frac{N e^{-eV/k_BT}}{k_BT} \). However, if a battery of voltage \( V_b \) is applied in the forward-bias configuration, this fraction improves to \( \frac{N e^{-e(V-V_b)/k_BT}}{k_BT} \). The electric current due to the majority carriers from the n-side to the p-side is therefore

\[
I = N e^{-eV/k_BT} e^{eV_b/k_BT} = I_0 e^{eV_b/k_BT},
\]

where \( I_0 \) is the current with no applied voltage and \( T \) is the temperature. Current due to the minority carriers (thermal excitation of electrons from the valence band to the conduction band on the p-side and subsequent attraction to the n-side) is \( -I_0 \), independent of the bias voltage. The net current is therefore

\[
I_{net} = I_0 \left( e^{eV_b/k_BT} - 1 \right).
\]

A sample graph of the current versus bias voltage is given in Figure \ref{Figure 3}. In the forward bias configuration, small changes in the bias voltage lead to large changes in the current. In the reverse bias configuration, the current is \( I_{net} \approx -I_0 \). For extreme values of reverse bias, the atoms in the material are ionized which triggers an avalanche of current. This case occurs at the breakdown voltage.
Figure (PageIndex{3}): Current versus voltage across a p-n junction (diode). In the forward bias configuration, electric current flows easily. However, in the reverse bias configuration, electric current flow very little.

Example (PageIndex{1}): Diode Current

Attaching the positive end of a battery to the p-side and the negative end to the n-side of a semiconductor diode produces a current of \(4.5 \times 10^{-1} \text{ A}\). The reverse saturation current is \(2.2 \times 10^{-8} \text{ A}\). (The reverse saturation current is the current of a diode in a reverse bias configuration such as this.) The battery voltage is 0.12 V. What is the diode temperature?

**Strategy**

The first arrangement is a forward bias configuration, and the second is the reverse bias configuration.

**Solution**

The current in the forward and reverse bias configurations is given by

\[
I_{\text{net}} = I_0 \left( e^{\frac{eV_b}{k_BT}} - 1 \right).
\]

The current with no bias is related to the reverse saturation current by

\[
I_0 \approx -I_{\text{sat}} = 2.2 \times 10^{-8} \text{ A}.
\]

Therefore

\[
\frac{I_{\text{net}}}{I_0} + 1 = e^{\frac{eV_b}{k_BT}}.
\]

This ratio is much greater than one, so the second term on the left-hand side of the equation vanishes. Taking the natural log of both sides gives
\[
\frac{eV_b}{k_BT} = 19. \nonumber\]

The temperature is therefore
\[
T = \frac{eV_b}{k_B} \left(\frac{1}{19}\right) = \frac{e(0.12 \, V)}{8.617 \times 10^{-5} \, eV/K} \left(\frac{1}{19}\right) = 73 \, K. \nonumber\]

**Significance**

The current moving through a diode in the forward and reverse bias configuration is sensitive to the temperature of the diode. If the potential energy supplied by the battery is large compared to the thermal energy of the diode’s surroundings, \(k_BT\), then the forward bias current is very large compared to the reverse saturation current.

Exercise \(\PageIndex{1}\)

How does the magnitude of the forward bias current compare with the reverse bias current?

**Solution**

The forward bias current is much larger. To a good approximation, diodes permit current flow in only one direction.

Create a p-n junction and observe the behavior of a simple circuit for forward and reverse bias voltages. Visit this site to learn more about semiconductor diodes.

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**Junction Transistor**

If diodes are one-way valves, transistors are one-way valves that can be carefully opened and closed to control current. A special kind of transistor is a junction transistor. A junction transistor has three parts, including an n-type semiconductor, also called the emitter; a thin p-type semiconductor, which is the base; and another n-type semiconductor, called the collector (Figure \(\PageIndex{4}\)). When a positive terminal is connected to the p-type layer (the base), a small current of electrons, called the base current \(I_B\), flows to the terminal. This causes a large collector current \(I_C\) to flow through the collector. The base current can be adjusted to control the large collector current. The current gain is therefore
\[
I_c = \beta I_B. \nonumber\]
A junction transistor can be used to amplify the voltage from a microphone to drive a loudspeaker. In this application, sound waves cause a diaphragm inside the microphone to move in and out rapidly (Figure \(\PageIndex{5}\)). When the diaphragm is in the “in” position, a tiny positive voltage is applied to the base of the transistor. This opens the transistor “valve” and allows a large electrical current flow to the loudspeaker. When the diaphragm is in the “out” position, a tiny negative voltage is applied to the base of the transistor, which shuts off the transistor valve so that no current flows to the loudspeaker. This shuts the transistor “valve” off so no current flows to the loudspeaker. In this way, current to the speaker is controlled by the sound waves, and the sound is amplified. Any electric device that amplifies a signal is called an **amplifier**.

In modern electronic devices, digital signals are used with diodes and transistors to perform tasks such as data manipulation. Electric circuits carry two types of electrical signals: analog and digital (Figure \(\PageIndex{6}\)). An analog signal varies continuously, whereas a digital signal switches between two fixed voltage values, such as plus 1 volt and zero volts. In digital circuits like those found in computers, a transistor behaves like an on-off switch. The transistor is either on, meaning the valve...
is completely open, or it is off, meaning the valve is completely closed. Integrated circuits contain vast collections of transistors on a single piece of silicon. They are designed to handle digital signals that represent ones and zeroes, which is also known as binary code. The invention of the ic helped to launch the modern computer revolution.

Figure \(\PageIndex{6}\): Real-world data are often analog, meaning data can vary continuously. Intensity values of sound or visual images are usually analog. These data are converted into digital signals for electronic processing in recording devices or computers. The digital signal is generated from the analog signal by requiring certain voltage cut-off value.

### Contributors and Attributions

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