
Real diodes have a more complicated $i$-$v$ characteristic curve than ideal diodes. As shown in the text for a silicon diode:

![Graph showing the diode characteristic curve with regions labeled Forward, Reverse, and Breakdown]

(Fig. 4.8)

The diode has three distinct regions of operation:

1. **Forward bias** – note that when the diode is “on,” the voltage drop is approximately 0.6 V to 0.7 V for a silicon diode.

2. **Reverse bias** – in this region $i = -I_s$, where $I_s$ is called the saturation current. For “small-signal” diodes, $I_s$ is often on the order of fA ($10^{-15}$ A).

3. **Breakdown** – in this region $v \approx -V_{ZK}$ for all $I$, where $V_{ZK}$ is called the breakdown knee voltage. This region of operation is useful in certain applications.

In the forward bias region of operation, it can be shown from first principals that
\[ i = I_s \left( \frac{v}{e^{nV_T} - 1} \right) \]  

(4.1), (1)

where

- \( n \) = “emission constant.” Typically between 1 and 2. Your text uses \( n = 1 \) throughout, which is typical of integrated circuits.
- \( V_T = kT/q \approx 25 \text{ mV} \) at room temperature (20°C). Called the “thermal voltage.”

Notice the highly non-linear relationship between \( i \) and \( v \) in this equation. (You’ll learn where this mathematical expression comes from in EE 362.)

When \( v \ll 0 \) in (1), then

\[ i = I_s \left( e^{nV_T} - 1 \right) \approx -I_s \]  

(2)

which is true for operation in the reverse bias region.

We’ll now take a quick look at the basic semiconductor physics behind the \( pn \) junction, and then follow this up with examples and applications.
pn Junction

Semiconductor junction diodes are made by joining two semiconductors together. A pn junction diode is formed by joining a “p-type” semiconductor to an “n-type” semiconductor:

For a silicon diode, both the p and n regions are silicon, but in each of these regions, small amounts of impurities have been added through a process called “doping.”

To make p and n regions, we begin with a silicon crystal as shown in Fig. 3.1. These atoms are held together by covalent bonds (sharing pairs of electrons).
At $T = 0$, the outermost electron ($e^-$) of each atom is held in covalent bonds. No current is possible since no electrons are available to contribute to conduction.

For $T > 0$, random thermal vibration provides enough energy for some of the $e^-$ to break their covalent bonds (see Fig. 3.2). These $e^-$ can contribute to conduction current.

(Fig. 3.2)

These figures are a planar representation of a real, 3-D silicon lattice. In 3-D, each Si atom is adjacent to four other atoms in a diamond-type lattice. Adjacent atoms share a pair of electrons (i.e., a covalent bond).
Holes

When electrons are thermally excited out of covalent bonds, they also leave a “vacancy” at the bond site, as illustrated above in Fig. 3.2. This is called a hole.

Interestingly, holes can also contribute to conduction current in a semiconductor material (see the figure below). This movement is usually much slower than $e^-$ so the so-called “mobility” of holes is smaller than that of electrons.

Donors and Acceptors

The concentration of holes and free electrons (so-called electron-hole pairs) can be changed in a silicon crystal by adding small amounts of impurities called dopants. This is what makes electronic devices possible!
(1) To create holes, add acceptor dopants to the silicon (see Fig. 3.4). For such “p-type” semiconductors, the silicon is doped with trivalent impurity elements such as boron (having three valence electrons). These impurity atoms displace some of the silicon atoms (having four valence electrons) with boron atoms. Consequently, the regular silicon lattice has “holes,” or locations in the lattice that can accept a free electron. This “hole” can also move through the lattice.

(Fig. 3.4)

(2) To create free electrons, add donor dopants (see Fig. 3.3). For such “n-type” semiconductors, the silicon is doped with pentavalent impurity elements such as phosphorus. These impurities displace silicon atoms (with four valence electrons) with phosphorous atoms (having five valence electrons). Consequently, one extra electron is available to move through the silicon lattice.
Be aware that the entire \( p \)-type and \( n \)-type regions remain charge neutral at all times! The dopant atoms are also charge neutral.

At room temperature, thermal ionization breaks some covalent bonds. In \( n \)-type materials we then have free electrons while in \( p \)-type materials we have free holes.

“\( p \) type” means positive charge carriers predominate while “\( n \) type” means negative charge carriers predominate.

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**Depletion Region**

Something very special occurs when we place \( p \)-type material in contact with \( n \)-type material. There now appears to be an “excess” of holes in the \( p \)-type material and an “excess” of free electrons in the \( n \) type.
Through the mechanism of diffusion (random motion due to thermal agitation), excess holes will migrate to the *n*-type region while excess free electrons will migrate to the *p*-type region.

More specifically, when the *p*- and *n*-type materials are placed in contact (forming a junction), two things happen near the contact region:

1. **Holes diffuse** across the junction into the *n*-type region (diffuse because the hole concentration is higher in *p* type) and recombine with majority electrons.

   ![Diagram of diffusion and recombination](image)

   With this electron now “gone,” we have “uncovered” a positive charge from the dopant atom in the *n*-type region. This forms a positively charged region:

   ![Diagram of positively charged region](image)
(2) Similarly, the majority carriers in the $n$-type region (electrons) diffuse across the junction and recombine with majority holes in the $p$-type region. This uncovers negative bound charge:

![Diagram of electron diffusion and recombination]

This contact region between the $p$ and $n$ regions now has a bound volume electric charge density. It is called the depletion region. This may seem an unexpected name since only in this region is there a net volume charge density (aka space charge)!

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**Reverse and Forward Biased Junction**

There are two important states for a $pn$ junction, the reversed biased and forward biased states:

(1) **Reversed biased state:**

An electric field $E$ is created in the depletion region because of the “uncovered” charges near the junction:
For the reversed biased state of the $pn$ junction, the electric field produced by the battery $E_{\text{battery}}$ adds to this electric field of the space charge $E$ in the depletion region. This increases the width of the depletion region.

Consequently, the “majority carriers” cannot flow through the region: holes in the $p$ material are opposed by $E$ in the depletion region, as are electrons in the $n$ material. Hence, little current flows (only the drift current $I_S$) unless the junction breaks down. This occurs when $E_{\text{battery}}$ is strong enough to strip electrons from the covalent bonds of the atoms, which are then swept across the junction.

(2) Forward biased state:
When $V$ is large enough so that $E_{\text{battery}} > E$, then the majority carriers can flow through the depletion region: (i) holes are swept from the $p$ to $n$ regions, and (ii) electrons are swept from the $n$ to $p$ regions. We now have current!