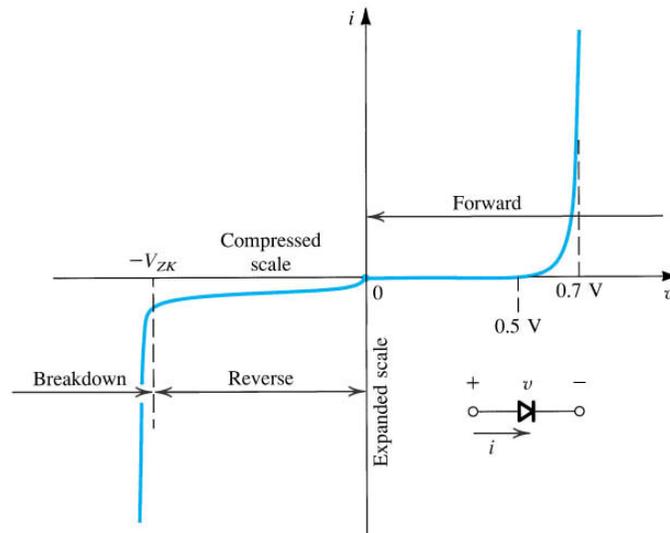


## Lecture 2: Physical Operation of Diodes.

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



(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

$$i = I_S \left( e^{\frac{v}{nV_T}} - 1 \right) \quad (4.1),(1)$$

where

- $n$  = “emission constant.” Typically between 1 and 2. Your text uses  $n = 1$  throughout, which is typical of integrated circuits.
- $V_T = kT/q \approx 25$  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

$$i = I_S \left( e^{\frac{v}{nV_T}} - 1 \right) \approx -I_S \quad (2)$$

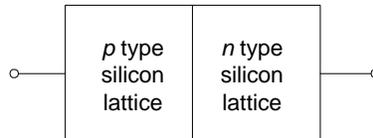
which is true for operation in the reverse bias region.

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.

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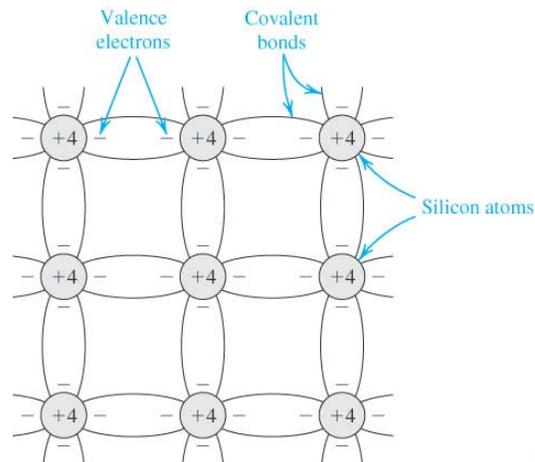
## *pn* Junction

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.”

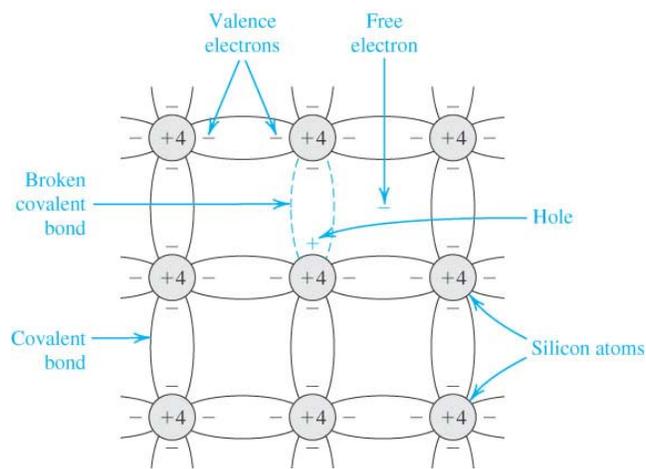
To make *p* and *n* regions, we begin with a silicon crystal as shown in Fig. 3.1. These atoms are held together by covalent bonds (sharing pairs of electrons).



(Fig. 3.1)

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)

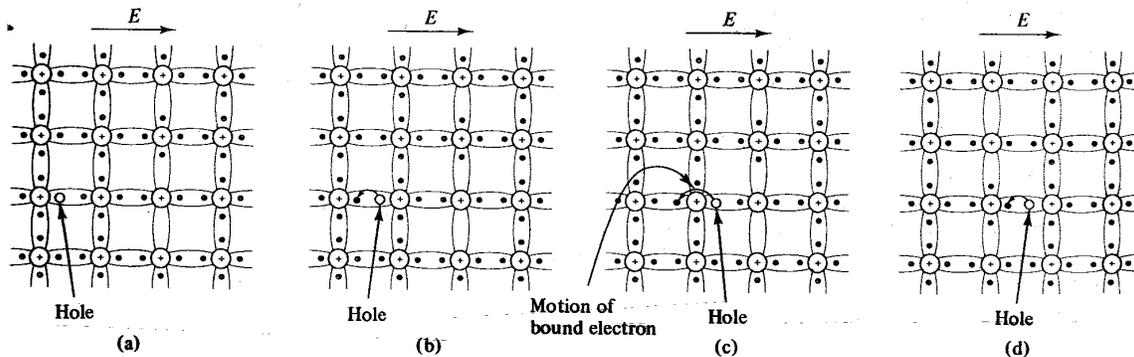
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## Holes

When electrons are thermally excited out of covalent bonds, they 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 mobility of holes is smaller.

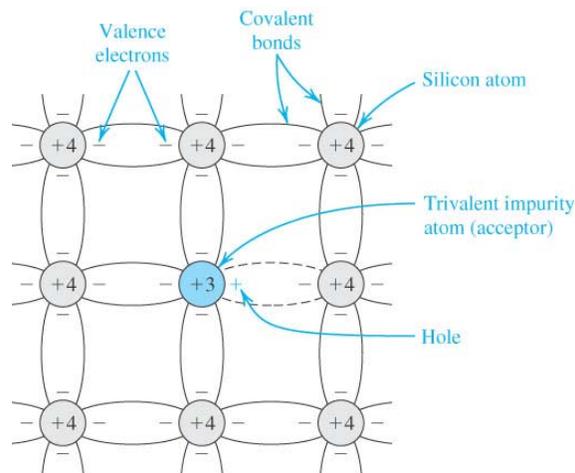


*From Horenstein, Prentice Hall, 1990.*

## Donors and Acceptors

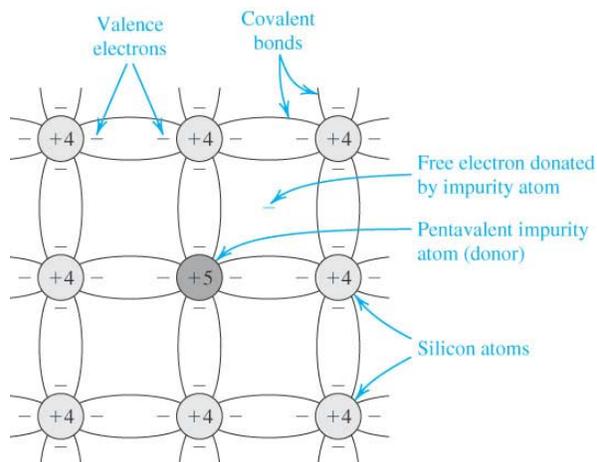
The concentration of holes and free electrons can be changed in a silicon crystal by adding small amounts of impurities called **dopants**. This is what makes electronic devices possible!

- (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. These impurity atoms displace silicon atoms (having four electrons) with boron atoms (having three electrons). 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 phosphorous atoms (having five electrons). Consequently, one extra electron is available to move through the silicon lattice.



(Fig. 3.3)

Be aware that the entire  $p$ -type and  $n$ -type regions remain **charge neutral** at all times! The dopant atoms are also charge neutral.

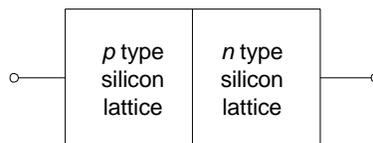
At room temperature, thermal ionization breaks some covalent bonds. In  $n$ -type materials we then have free electrons while in  $p$ -type materials we have free holes.

“ $p$  type” means **p**ositive charge carriers predominate while “ $n$  type” means **n**egative charge carriers predominate.

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## Depletion Region

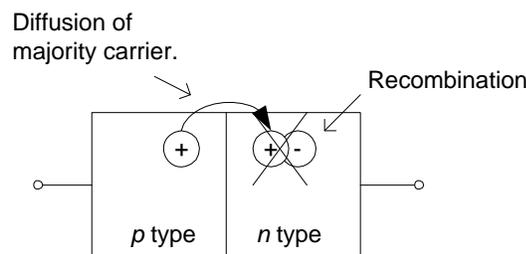
Something very special occurs when we place  $p$ -type material in contact with  $n$ -type material. There now appears to be an “**excess**” of holes in the  $p$ -type material and an “**excess**” of free electrons in the  $n$  type.



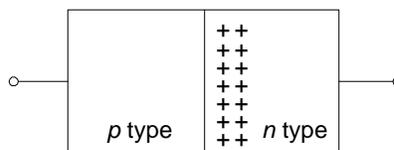
Through the mechanism of **diffusion** (random motion due to thermal agitation), excess holes will **migrate** to the  $n$ -type region while excess free electrons will **migrate** to the  $p$ -type region.

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

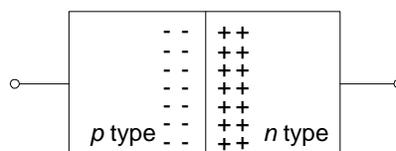
- (1) **Holes diffuse** across the junction (diffuse because the hole concentration is higher in  $p$  type) into the  $n$ -type region and **recombine** with majority electrons.



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.



- (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.



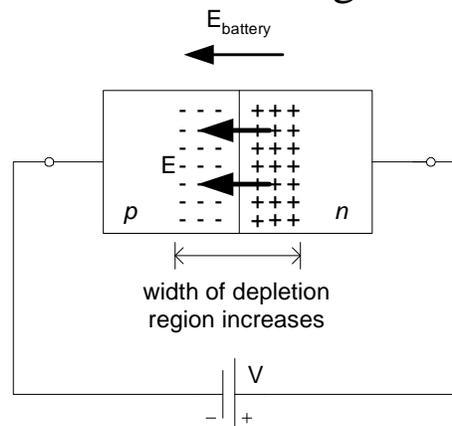
This contact region between the  $p$  and  $n$  regions now has a bound volume electric charge density. It is called the **depletion region**. This may seem an **unexpected name** since only in this region is there a net volume charge density (aka space charge)!

## 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:

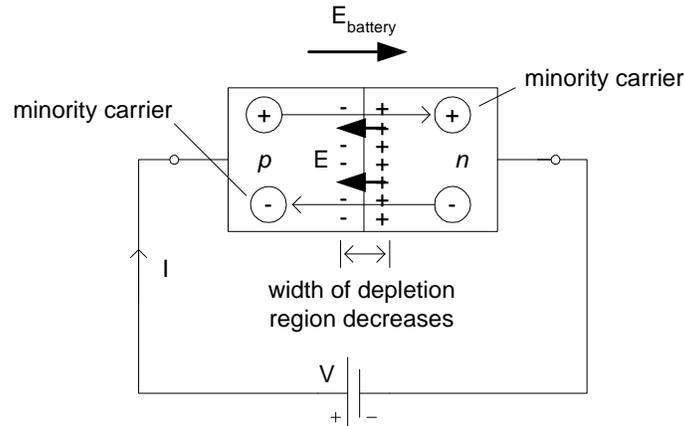
An electric field  $E$  is created in the depletion region because of the “uncovered” charges near the junction:



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 (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!**