Eight Amazing Engineering Stories

Using the Elements to Create Extraordinary Technologies

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Articulate Noise Books

First Edition: April 2012

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Eight Amazing Engineering Stories: Using the Elements to Create Extraordinary Technologies / Bill Hammack - 1st edition (version 1.4)

ISBN 978-0-9839661-3-5 (pbk)

ISBN 978-0-9839661-4-2 (electronic)

ISBN 978-0-9839661-5-9 (hbk)

1. Engineering. 2. Technology --Popular works. 3. Chemical elements. 4. Electronic apparatus and appliances. 5. Engineering design I. Title.

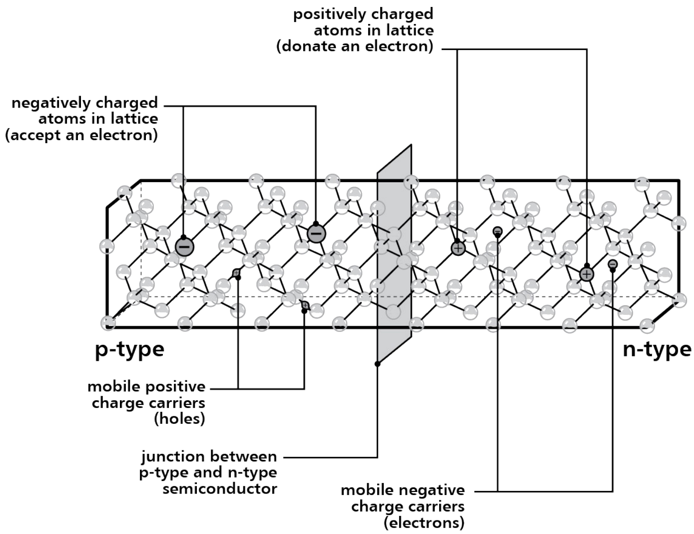
In Depth: Semiconductors, Electrons & Holes

Recall that there are metals that conduct electricity freely, insulators (like rubber) that don't allow electricity to flow, and semiconductors that conduct electricity but not as well as metals. What's most important about semiconductors is that, unlike metals, semiconductors can conduct electricity by two mechanisms: the movement of negative or positive charge carriers. A metal can only transfer by negative charges. We call a semiconductor that uses mostly positive charge carriers (called holes) a *p*-type, and that which conducts electricity by negative charge carriers (electrons) an *n*-type. These two ways to conduct allow engineers to create a solid material where charge can pass in only one direction.

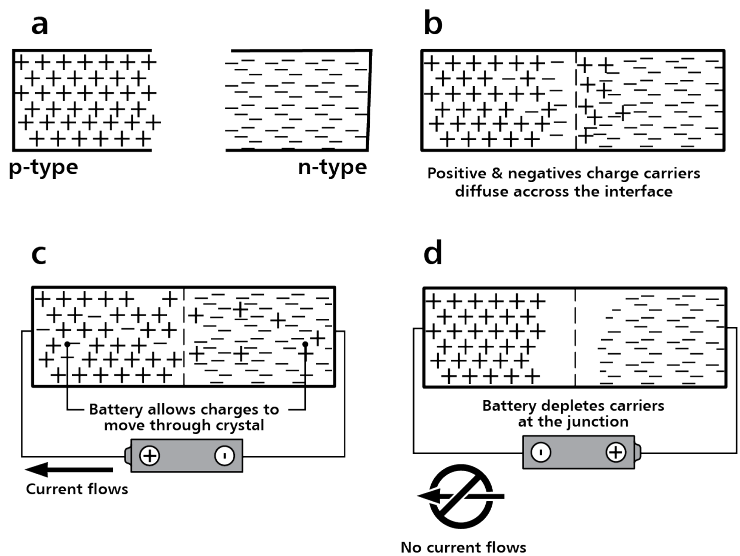
Engineers make a diode by placing *p* and *n* type semiconductors together. The *n*-type has a number of atoms that have an extra electron, and these electrons are mobile. When the electrons move, they leave a fixed positive charge—keep in mind, though, that the atoms themselves aren't mobile. The *p*-type semiconductor has acceptor atoms (fixed in the lattice) that contribute positive charge carriers called holes. When this junction forms, positive holes are attracted to the negative electrons, which will flow across the *pn* junction. You would think these would continue until the charge was even across both semiconductors, but the atoms fixed in place in the lattice prevent this. When a donor contributes a mobile electron, it leaves a positively-charged atom fixed in place. This means that when the positive holes move into the *n*-type semiconductor, they eventually meet a "wall" of fixed positive charges that repels them. Similarly, on the *p*-type side, each mobile hole leaves behind a negatively-charged atom fixed forever in the lattice. This, of course, creates a wall of negative charges, which stops the mobile electrons from moving further.

What Exactly Is a Hole?

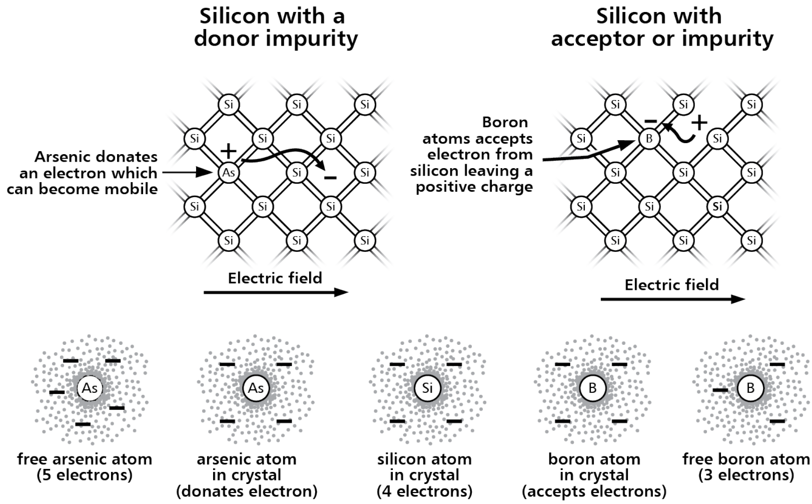
We talk glibly of positive holes in a semiconductor, yet they exist only in the minds of electrical engineers. Holes are a fiction, albeit a clever and useful one. It might seem like a hole is really a positron—the anti-matter counterpart of an electron. It isn't. Positrons exist only for fractions of a second and are generated in huge particle accelerators; holes seemingly, in contrast, flourish in all semiconducting devices. Instead, the notion of holes is a shorthand way to identify one of two different ways electrons can move in a semiconductor and thus conduct charge. If a semiconductor conducts electricity mostly by negative charge carriers (an "electron" in electrical engineering parlance), it is called *n*-type; if it seems to use positive carriers, nicknamed "holes," it is called *p*-type.



A solid-state diode is made from a p*-type and an* n*-type semiconductor. In the* p*-type the mobile carriers are thought of as a positive charge called "holes." In the* n*-type, the mobile charge carriers are negatively charged.*



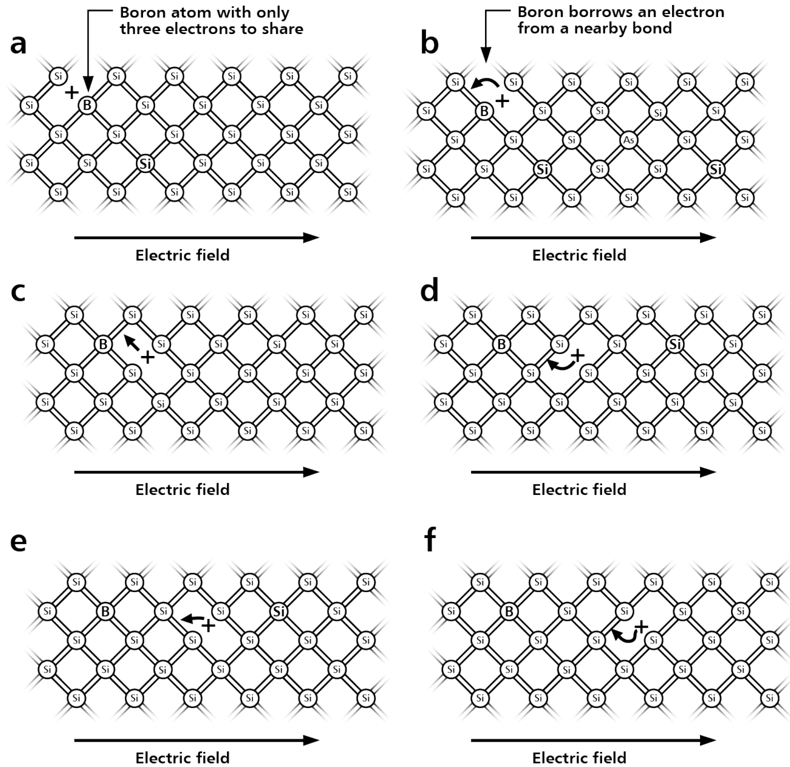
A diode is formed by the junction of p *and* n*-type semiconductors. As shown in (a), we think of the* p*-type as having mobile positive carriers and the* n*-type as having negative charge carriers. When the types are brought together (b), the negative and positive charge carriers diffuse across the interface until an equilibrium is reached. If we hook up a battery (c) such that the negative end is attached to the* n*-type conductor and the positive end to the* p*-type, the negative end of the battery provides a stream of electrons to neutralize the positive charges fixed in the* n*-type semiconductor. This means that the positive holes can flow because the wall of negative fixed charges has been neutralized. Once this has happened, the electrons can flow through the* p*-type. If we reverse the battery (d), a stream of electrons flows toward the* p*-type end. Recall that there was a set of fixed negative charges left from the mobile positive holes, which prevented electrons from moving through the* p*-type. The reversed battery, then, simply worsens the situation, making that end even more negative and thus making it harder for any electrons to move. Thus current comes to a halt.*



Engineers create n*-type semiconductors by adding an atom like arsenic to the silicon lattice. An arsenic atom has five electrons, rather than the four surrounding a silicon atom. This means that arsenic adds an extra electron that can become mobile to a semiconductor. A* p*-type semiconductor is made by adding an atom like boron, which has three electrons. When added to silicon, boron allows an electron to move from bond to bond. As shown in the next figure, this transfer of electrons can be thought of as a positive "hole" carrying charge.*

Engineers can control the type of conduction by replacing some of the silicon atoms with similar atoms. A silicon atom has four electrons that it can share to form bonds. In a pure crystal of silicon, this allows it to bond with four other silicon atoms. If we replace some of these silicon atoms with arsenic atoms—called impurities, which is odd because we want them there!—an extra electron appears. Arsenic has five electrons to share. When we toss it into the silicon lattice, the arsenic shares four of those electrons with neighboring silicon atoms, forming bonds, but the fifth electron is free to roam the crystal. Since the arsenic itself has a charge of +5, it balances that roaming negative charge. Thus the crystal remains electrically neutral over all. At low temperatures, these electrons become bound to the arsenic atoms, but at room temperature, thermal agitation shakes them off and lets them be free to roam. That extra negative charge conducts electricity throughout the crystal. This would be called an *n*-type semiconductor—the "n" stands, of course, for negative.

We could, instead, replace some silicon atoms in pure silicon with an element that has fewer than four electrons. Boron, for example, has only three electrons to share. When substituted for a silicon atom, it cannot complete bonds to all four of the surrounding silicon atoms: It has only three electrons and so forms three bonds. Electrons can jump from one of the neighboring, fully-bonded silicon atoms and completes this bond, leaving of course an electron-deficient bond behind. Now, one could look at this type of motion as an electron moving, although it is different than the electron movement in a *p*-type semiconductor. There an electron wanders from the crystal freely, but here an electron jumps from bond to bond. Now one could look at this as a positive charge carrier that is jumping around the crystal: Every time an electron leaves a bond and completes the fourth bond of the boron, it leaves a positive charge on the bond it left. Most importantly, though, these two mechanisms of charge transfer move in opposite ways to an applied electrical field, just like we would expect positive and negative charge carriers to move.



In a semiconductor, all charge is transferred by electrons, but it occurs in two different ways. Shown here is how an electron jumps in a p*-type semiconductor from bond to bond when an electric field is applied as indicated. Initially, (a) an impurity boron atom has three complete bonds (two shared electrons) and a bond deficient by one electron. As shown in (b), this impure atom can borrow an electron from a nearby bond. This borrowing can repeat itself across the crystal as shown in (c), (d), (e), and (f). Since the electron-deficient bond has a positive charge, this appears to be a positive charge—called a hole—moving from left to right across the crystal.*