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Theory of Semiconductors

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Semiconductor Theory and Devices

- **Band Theory of Solids**
- Semiconductor Theory
- **Semiconductor Devices**
- Nanotechnology

> *It is evident that many years of research by a great many people, both before and after the discovery of the transistor effect, has been required to bring our knowledge of semiconductors to its present development. We were fortunate to be involved at a particularly opportune time and to add another small step in the control of Nature for the benefit of mankind.*
>
> - John Bardeen, 1956 Nobel lecture

Electrical Resistivity and Conductivity of Selected Materials at 293 K

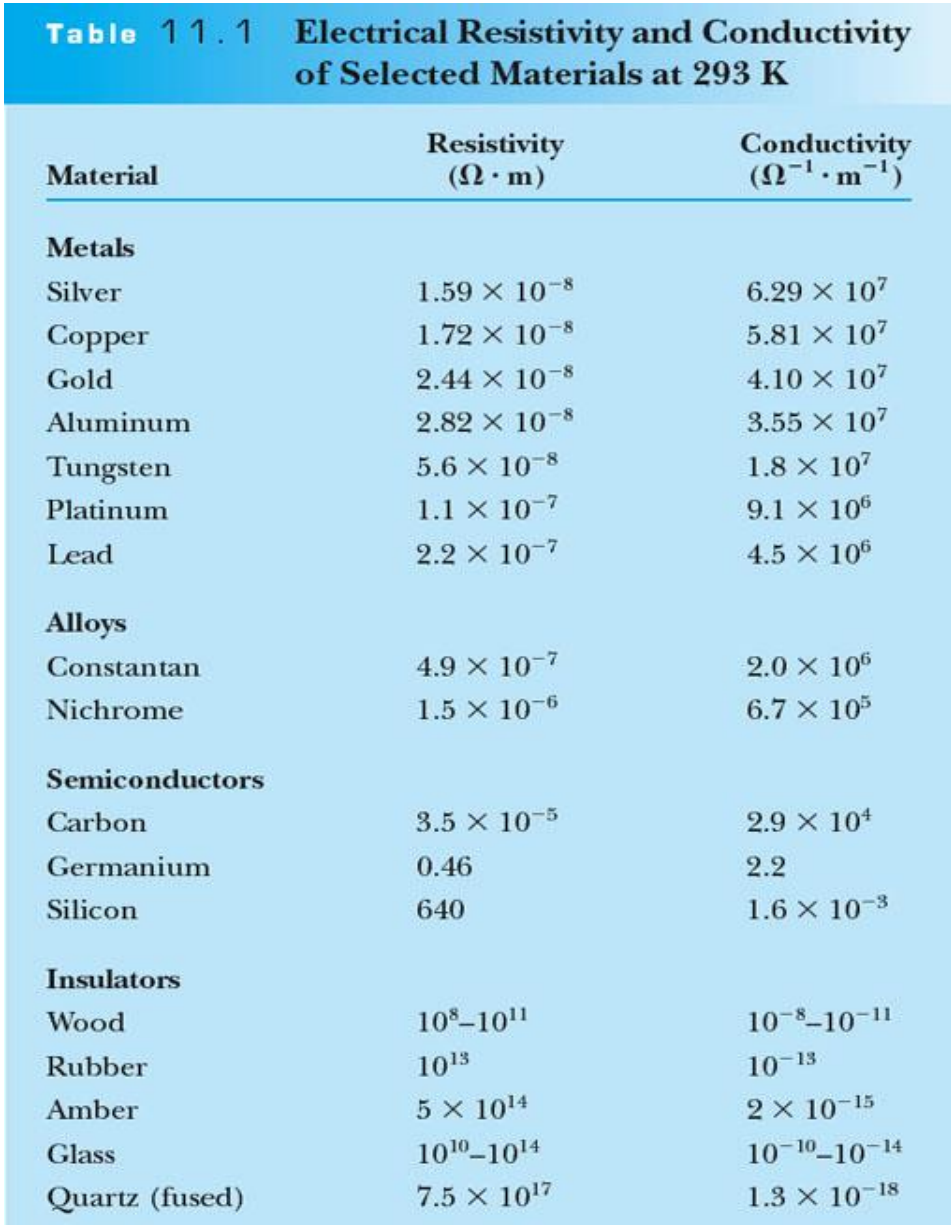


Table 11.1 Electrical Resistivity and Conductivity of Selected Materials at 293 K

Material	Resistivity ($\Omega \cdot m$)	Conductivity ($\Omega^{-1} \cdot m^{-1}$)
Metals		
Silver	1.59×10^{-8}	6.29×10^{7}
Copper	1.72×10^{-8}	5.81×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminum	2.82×10^{-8}	3.55×10^{7}
Tungsten	5.6×10^{-8}	1.8×10^{7}
Platinum	1.1×10^{-7}	9.1×10^{6}
Lead	2.2×10^{-7}	4.5×10^{6}
Alloys		
Constantan	4.9×10^{-7}	2.0×10^{6}
Nichrome	1.5×10^{-6}	6.7×10^{5}
Semiconductors		
Carbon	3.5×10^{-5}	2.9×10^{4}
Germanium	0.46	2.2
Silicon	640	1.6×10^{-3}
Insulators		
Wood	10^{8}–10^{11}	10^{-8}–10^{-11}
Rubber	10^{13}	10^{-13}
Amber	5×10^{14}	2×10^{-15}
Glass	10^{10}–10^{14}	10^{-10}–10^{-14}
Quartz (fused)	7.5×10^{17}	1.3×10^{-18}

Resistivity vs. Temperature

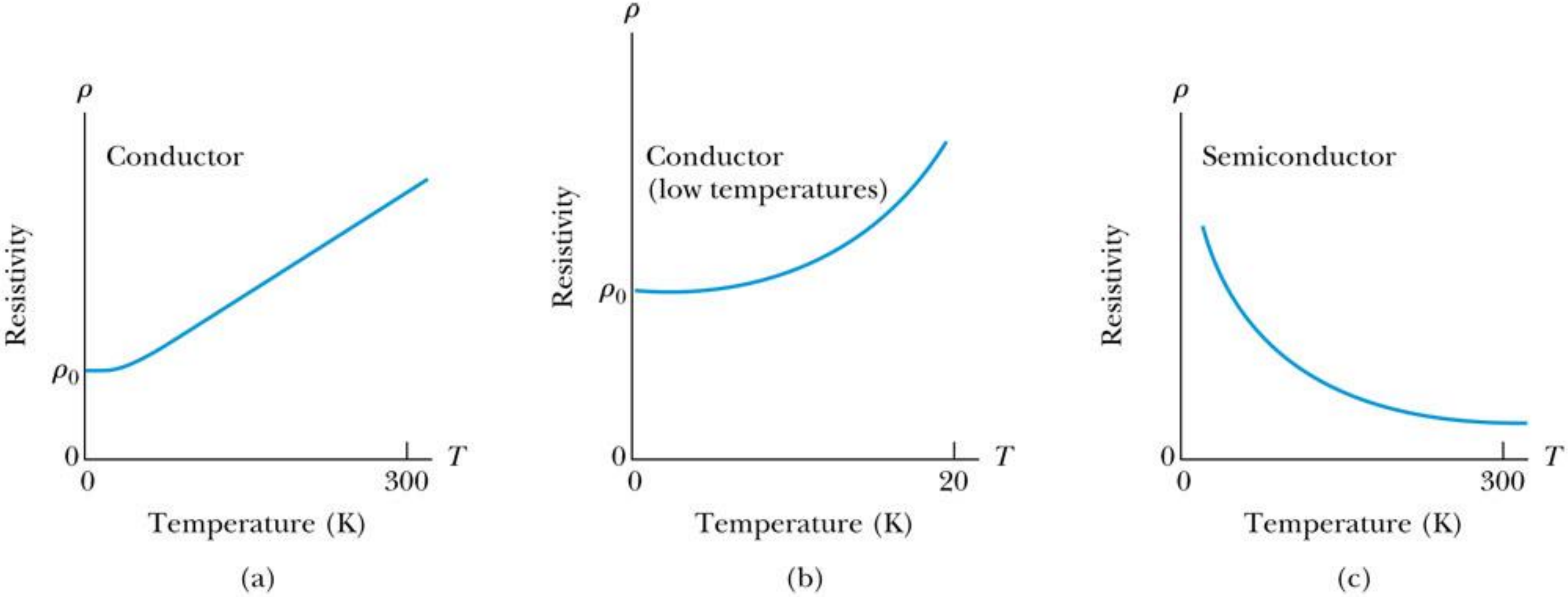


Figure (a) Resistivity versus temperature for a typical conductor. Notice the linear rise in resistivity with increasing temperature at all but very low temperatures. (b) Resistivity versus temperature for a typical conductor at very low temperatures. Notice that the curve flattens and approaches a nonzero resistance as $T \to 0$. (c) Resistivity versus temperature for a typical semiconductor. The resistivity increases dramatically as $T \to 0$.

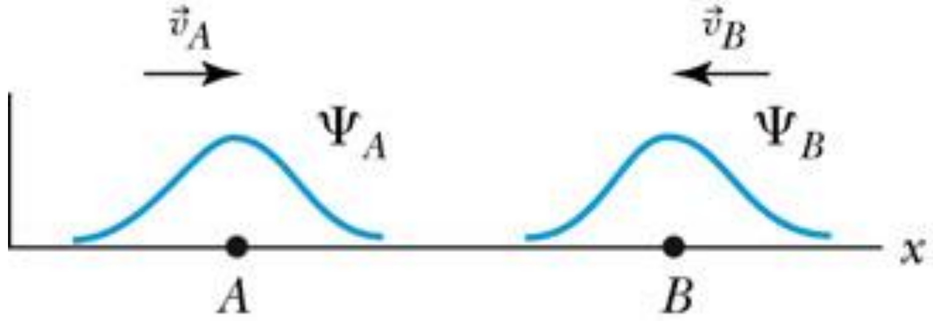
Band Theory of Solids

- In order to account for *decreasing* resistivity with increasing temperature as well as other properties of semiconductors, a new theory known as the **band theory** is introduced.

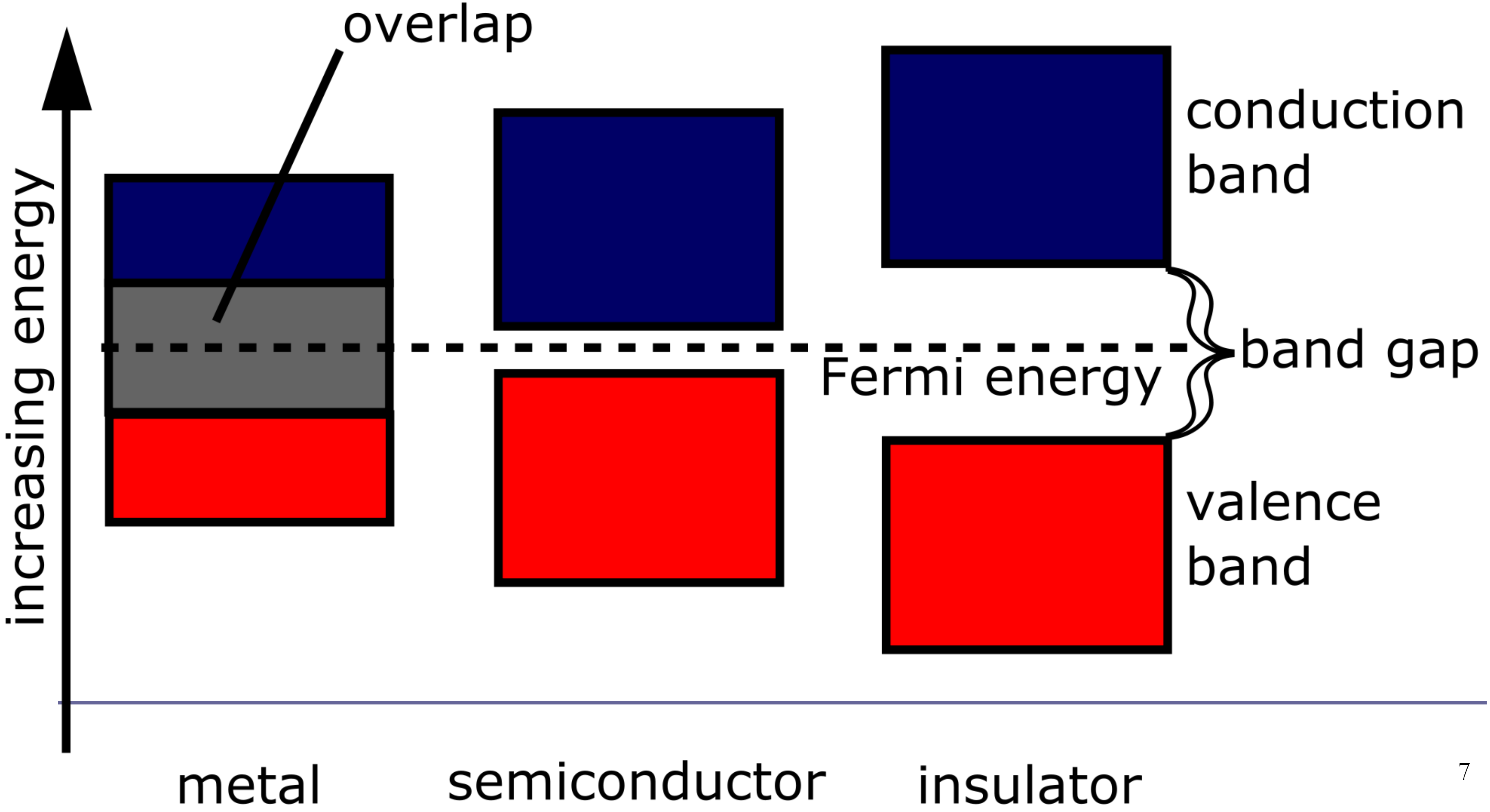
- The essential feature of the band theory is that the allowed energy states for electrons are nearly continuous over certain ranges, called **energy bands**, with forbidden energy gaps between the bands.

Band Theory of Solids

- Consider initially the known wave functions of two hydrogen atoms far enough apart so that they do not interact.



When more atoms are added (as in a real solid), there is a further splitting of energy levels. With a large number of atoms, the levels are split into nearly continuous energy bands, with each band consisting of a number of closely spaced energy levels.



Band Theory and Conductivity

- Band theory helps us understand what makes a conductor, insulator, or semiconductor.
  1) Good conductors like copper can be understood using the free electron
  2) It is also possible to make a conductor using a material with its highest band filled, in which case no electron in that band can be considered free.
  3) If this filled band overlaps with the next higher band, however (so that effectively there is no gap between these two bands) then an applied electric field can make an electron from the filled band jump to the higher level.
- This allows conduction to take place, although typically with slightly higher resistance than in normal metals. Such materials are known as **semimetals**.

Valence and Conduction Bands

- The band structures of insulators and semiconductors resemble each other qualitatively. Normally there exists in both insulators and semiconductors a filled energy band (referred to as the **valence band**) separated from the next higher band (referred to as the **conduction band**) by an energy gap.

- If this gap is at least several electron volts, the material is an **insulator.** It is too difficult for an applied field to overcome that large an energy gap, and thermal excitations lack the energy to promote sufficient numbers of electrons to the **conduction band.**

Smaller energy gaps create **semiconductors**

- For energy gaps smaller than about 1 electron volt, it is possible for enough electrons to be excited thermally into the conduction band, so that an applied electric field can produce a modest current.

  The result is a semiconductor.

Semiconductor Theory

- At $T = 0$ we expect all of the atoms in a solid to be in the ground state. The distribution of electrons (fermions) at the various energy levels is governed by the Fermi-Dirac distribution of Equation (9.34):

$$F_{\mathrm{FD}} = \frac{1}{\exp(\beta(E - E_{\mathrm{F}})) + 1}$$

$\beta = (kT)^{-1}$ and E_F is the Fermi energy.

Holes and Intrinsic Semiconductors

- When electrons move into the conduction band, they leave behind vacancies in the valence band. These vacancies are called **holes**. Because holes represent the absence of negative charges, it is useful to think of them as **positive charges.**

- Whereas the ***electrons move in a direction opposite*** to the applied electric field, ***the holes move in the direction of the electric field*****.**

- A semiconductor in which there is a balance between the number of electrons in the conduction band and the number of holes in the valence band is called an **intrinsic semiconductor.**

  Examples of intrinsic semiconductors include pure carbon and germanium.

Impurity Semiconductor

- It is possible to fine-tune a semiconductor’s properties by adding a small amount of another material, called a *dopant*, to the semiconductor creating what is a called an **impurity semiconductor.**

- As an example, silicon has four electrons in its outermost shell (this corresponds to the valence band) and arsenic has five.

  Thus while four of arsenic’s outer-shell electrons participate in covalent bonding with its nearest neighbors (just as another silicon atom would), the fifth electron is very weakly bound.

  It takes only about 0.05 eV to move this extra electron into the conduction band.

- The effect is that adding only a small amount of arsenic to silicon greatly increases the electrical conductivity.

n-type Semiconductor

- The addition of arsenic to silicon creates what is known as an ***n*-type** semiconductor (*n* for negative), because it is the electrons close to the conduction band that will eventually carry electrical current.

  The new arsenic energy levels just below the conduction band are called **donor levels** because an electron there is easily donated to the conduction band.

Acceptor Levels

- Consider what happens when indium is added to silicon.
  - Indium has one less electron in its outer shell than silicon. The result is one extra hole per indium atom. The existence of these holes creates extra energy levels just above the valence band, because it takes relatively little energy to move another electron into a hole
  - Those new indium levels are called **acceptor levels** because they can easily accept an electron from the valence band. Again, the result is an increased flow of current (or, equivalently, lower electrical resistance) as the electrons move to fill holes under an applied electric field
- It is always easier to think in terms of the flow of positive charges (holes) in the direction of the applied field, so we call this a ***p*-type** semiconductor (*p* for positive).
  - acceptor levels *p*-Type semiconductors
- In addition to intrinsic and impurity semiconductors, there are many **compound semiconductors**, which consist of equal numbers of two kinds of atoms.

Semiconductor Devices

pn-junction Diodes

- Here *p*-type and *n*-type semiconductors are joined together.

- The principal characteristic of a *pn*-junction diode is that it allows current to flow easily in one direction but hardly at all in the other direction.

  We call these situations **forward bias** and **reverse bias**, respectively.

Operation of a pn-junction Diode

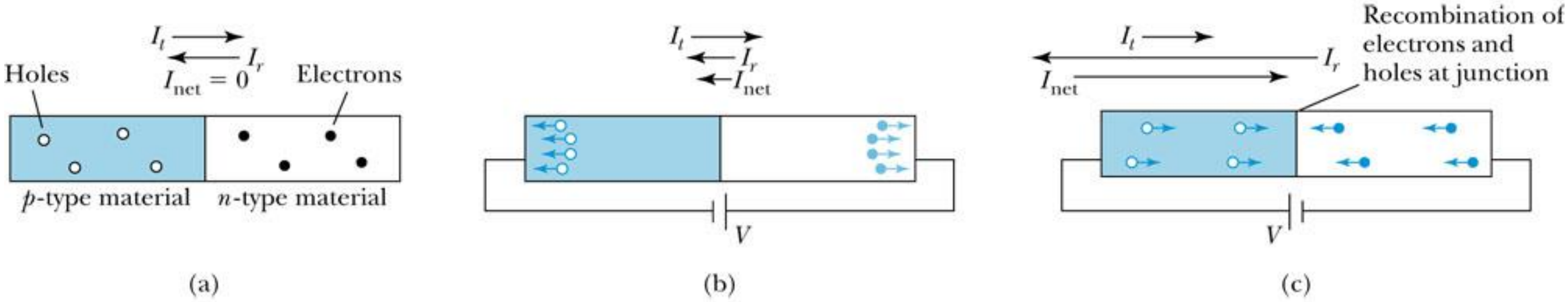


Figure The operation of a *pn*-junction diode. (a) This is the no-bias case. The small thermal electron current (I_t) is offset by the electron recombination current (I_r). The net positive current (I_{net}) is zero. (b) With a DC voltage applied as shown, the diode is in reverse bias. Now I_r is slightly less than I_t. Thus there is a small net flow of electrons from *p* to *n* and positive current from *n* to *p*. (c) Here the diode is in forward bias. Because current can readily flow from *p* to *n*, I_r can be much greater than I_t. [*Note:* In each case, I_t and I_r are electron (negative) currents, but I_{net} indicates positive current.]

Zener Diodes

- The **Zener diode** is made to operate under reverse bias once a sufficiently high voltage has been reached. The ***I-V*** curve of a Zener diode is shown in Figure 11.15. Notice that under reverse bias and low voltage the current assumes a low negative value, just as in a normal *pn*-junction diode. But when a sufficiently large reverse bias voltage is reached, the current increases at a very high rate.

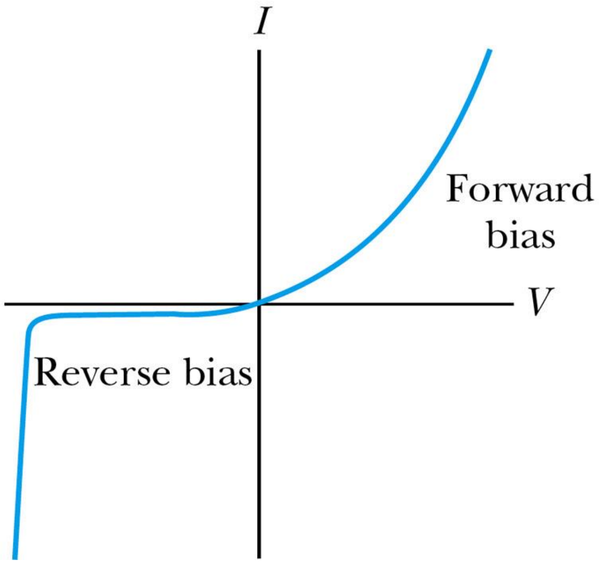


Figure 11.15: A typical *I*-*V* curve for a Zener diode.

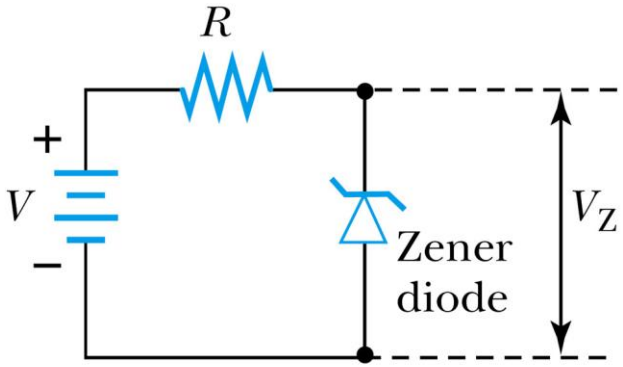
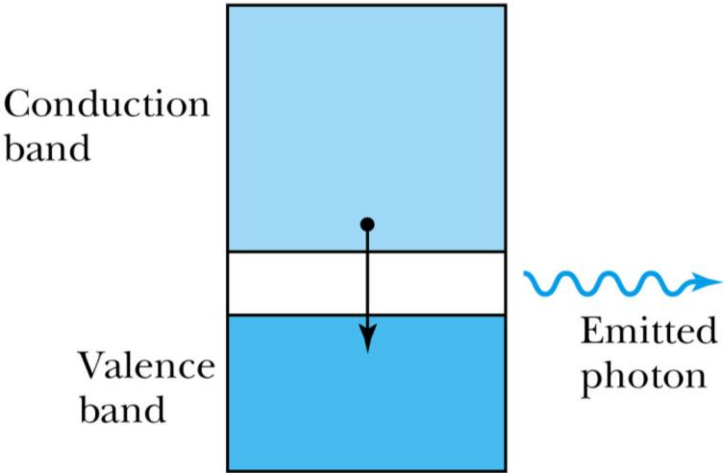


Figure 11.16: A Zener diode reference circuit.

Light Emitting Diodes

- Another important kind of diode is the **light-emitting diode (LED)**. Whenever an electron makes a transition from the conduction band to the valence band (effectively recombining the electron and hole) there is a release of energy in the form of a photon (Figure 11.17). In some materials the energy levels are spaced so that the photon is in the visible part of the spectrum. In that case, the continuous flow of current through the LED results in a continuous stream of nearly monochromatic light.

Figure 11.17: Schematic of an LED. A photon is released as an electron falls from the conduction band to the valence band. The band gap may be large enough that the photon will be in the visible portion of the spectrum.



Photovoltaic Cells

- An exciting application closely related to the LED is the **solar cell**, also known as the **photovoltaic cell**. Simply put, a solar cell takes incoming light energy and turns it into electrical energy. A good way to think of the solar cell is to consider the LED in reverse (Figure 11.18). A *pn*-junction diode can absorb a photon of solar radiation by having an electron make a transition from the valence band to the conduction band. In doing so, both a conducting electron and a hole have been created. If a circuit is connected to the *pn* junction, the holes and electrons will move so as to create an electric current, with positive current flowing from the *p* side to the *n* side. Even though the efficiency of most solar cells is low, their widespread use could potentially generate significant amounts of electricity. Remember that the “solar constant” (the energy per unit area of solar radiation reaching the Earth) is over 1400 W/m^2, and more than half of this makes it through the atmosphere to the Earth’s surface. There has been tremendous progress in recent years toward making solar cells more efficient.

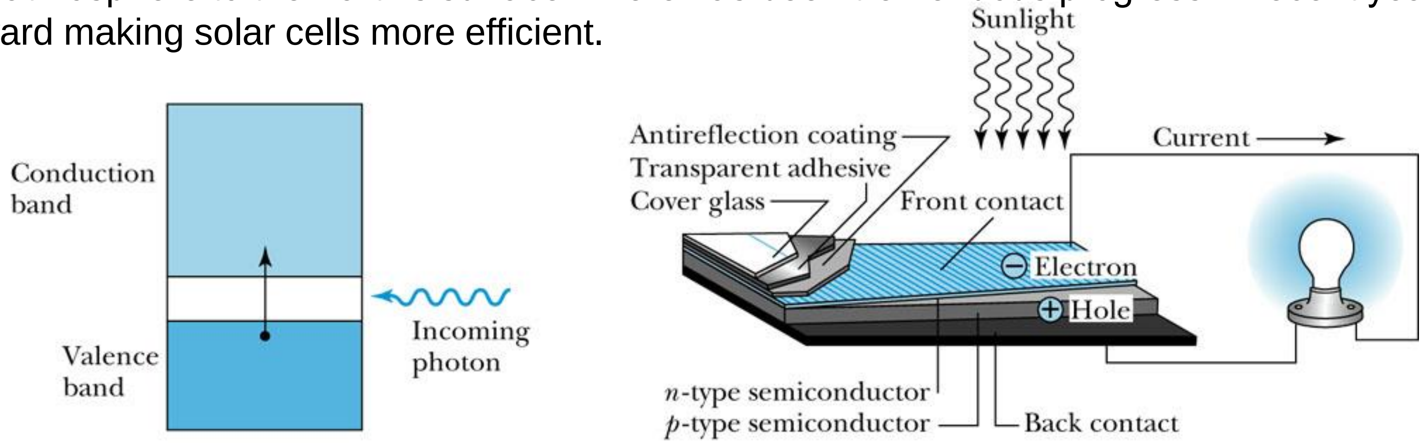


Figure (a) Schematic of a photovoltaic cell. Note the similarity to Figure 11.17. (b) A schematic showing more of the working parts of a real photovoltaic cell. *From H. M. Hubbard, Science 244, 297-303 (21 April 1989).*

Transistors

- Another use of semiconductor technology is in the fabrication of **transistors**, devices that amplify voltages or currents in many kinds of circuits. The first transistor was developed in 1948 by John Bardeen, William Shockley, and Walter Brattain (Nobel Prize, 1956). As an example we consider an ***npn*-junction transistor**, which consists of a thin layer of *p*-type semiconductor sandwiched between two *n*-type semiconductors. The three terminals (one on each semiconducting material) are known as the **collector**, **emitter**, and **base**. A good way of thinking of the operation of the *npn*-junction transistor is to think of two *pn*-junction diodes back to back.

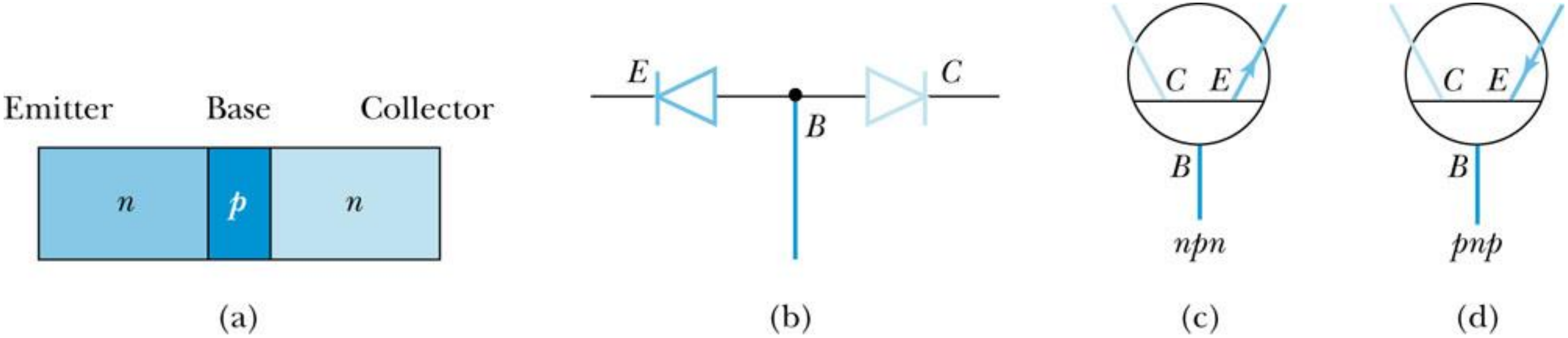


Figure 11.22: (a) In the *npn* transistor, the base is a *p*-type material, and the emitter and collector are *n*-type. (b) The two-diode model of the *npn* transistor. (c) The *npn* transistor symbol used in circuit diagrams. (d) The *pnp* transistor symbol used in circuit diagrams.

Semiconductor Lasers

- Semiconductor lasers operate using population inversion—an artificially high number of electrons in excited states

- In a semiconductor laser, the band gap determines the energy difference between the excited state and the ground state

- Semiconductor lasers use **injection pumping**, where a large forward current is passed through a diode creating electron-hole pairs, with electrons in the conduction band and holes in the valence band.
- One advantage of using semiconductor lasers in this application is their small size with dimensions typically on the order of 10^{-4} m.

A photon is emitted when an electron falls back to the valence band to recombine with the hole.