

perhaps even zero frequency ($f = 0$). According to Quantum Principle (v), such low-frequency electromagnetic oscillations cannot excite an electron to jump a high-energy gap. With $f = 0$, we certainly cannot satisfy the requirement that $h \cdot f$ is greater than E_{GAP} , which is needed for the electron to make an energy jump. This explains why a constant voltage cannot accelerate an electron in an insulator.

12.4.2 Absorption of Light by Metals: The Photoelectric Effect

Typically, most of the visible light that strikes a shiny, polished piece of metal is reflected from the surface. Think of the reflection you can see of your face in the surface of a shiny stainless-steel cooking pan. Although most of the light is reflected, a small amount of the light energy striking the metal can be absorbed by electrons near the surface of the metal.

If the frequency of the light is high enough (in the UV), a curious thing occurs, as illustrated by the energy-level diagram in **Figure 12.7**. An electron can gain enough energy by absorbing a photon that it can escape from the metal altogether. The stick person moving off to the right illustrates this in the figure. The electron is ejected from the metal's surface into the air. The minimum energy needed to eject the electron from the metal is called the threshold energy and is denoted by E_{THR} . The minimum frequency that light must have to cause an electron to be ejected is therefore:

$$f = \frac{E_{THR}}{h}$$

That is, the light's frequency f must be greater than E_{THR}/h to eject an electron. As an example, the metal zinc has threshold energy equal to 0.69 eV. This means that to eject an electron, light must have a frequency greater than

$$f = \frac{E_{THR}}{h} = \frac{0.69 \text{ eV}}{h} = \frac{0.69 \times 10^{-18} \text{ J/photon}}{6.6 \times 10^{-34} \text{ J} \cdot \text{sec/photon}} = 1.04 \times 10^{15} \text{ Hz}$$

The ejection of electrons from metal by light is called the *photoelectric effect*, and was first studied in detail by Phillip Lenard, a Hungarian-German physicist, in 1902. A few years later, in 1905, Albert Einstein offered the explanation that we used in the above paragraphs to explain the effect. For this, he was awarded the Nobel Prize.

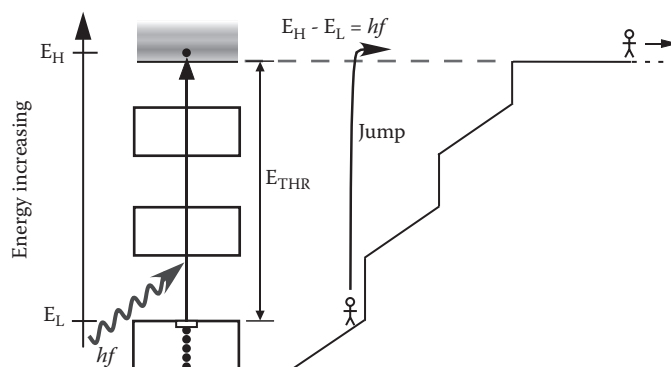


FIGURE 12.7 Photoelectric effect: A photon with high enough energy $h \cdot f$ is absorbed by a metal, causing an electron in the metal to make an upward quantum jump to a sufficiently high energy that it escapes the metal.

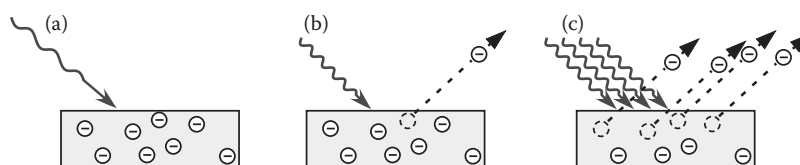


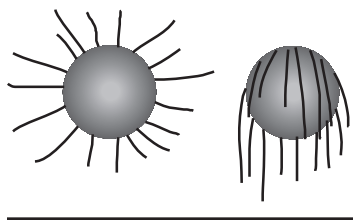
FIGURE 12.8 Photoelectric effect. (a) A photon with low frequency (long wavelength) cannot eject an electron from the surface of a metal. (b) A photon with high enough frequency and short enough wavelength can do so. (c) If the frequency of light is high enough, then increasing the incident photon rate increases the rate of ejecting electrons.

Lenard made several key observations, which allowed Einstein to put forth the explanation that we have discussed:

1. If the light's frequency was below a certain threshold value (which depended on the type of metal used), then no electrons were ejected from the metal (see **Figure 12.8a**). In this case, increasing the light's power had no effect—still no electrons were ejected.
2. If the light's frequency was above the threshold value, then electrons were ejected from the surface at some rate (see Figure 12.8b). In this case, doubling the light power striking the metal surface doubled the rate, that is, the number of electrons ejected per second (see Figure 12.8c).
3. Further increasing the light's frequency above the threshold frequency caused the ejected electrons to have increased kinetic energy (indicated by their speed) after they were ejected.

QUICK QUESTION 12.2

A copper ball has pieces of string glued at various points to its surface, as shown below. If the ball is charged positive or negative, the strings stand on end. This can happen if a plastic rod is rubbed with fur and then touched to the ball. If UV radiation with frequency 1.13×10^{15} Hz is shone on the ball, the strings do not change position. If UV with frequency 1.14×10^{15} Hz is shone on the ball, the strings flop down, as shown. From this observation, estimate the photoelectric threshold energy (in aJ) for copper.



Let's think about why these observations caused Einstein to conclude that light is grainy or lumpy, that is, contains what we call photons. Consider, for a moment, the possibility that light does not contain photons, but is a smooth oscillation of electromagnetic fields, as was thought by most scientists at the time. Such smooth waves would carry energy, and this energy might be partially deposited in the metal gradually as the wave strikes it. One might think that eventually there would be enough light energy deposited in the metal to eject an electron, even if the light's frequency were below the threshold value. But this was not observed. In contrast, if light contains photons—each carrying energy equal to $h \cdot f$, and if each photon is indivisible and acts alone on an electron, then it is easy to see why increasing the light power or simply waiting a long time will not suffice to see electrons being ejected. In this case, each photon by itself simply does not have enough energy to eject any electron. Increasing the light power, or the rate of photons arriving, does not help. There would simply be more ineffective photons striking the metal each second.

The third of Lenard's observations is consistent with the following explanation: An incoming photon must give up all or none of its energy to an electron. If the photon has more than enough energy to eject an electron, then when it gives up its energy, there is excess energy, which goes into kinetic energy of the outgoing electron. This makes it move faster away from the metal.

Table 12.1 lists the threshold energies for ejection of electrons from the surface of various metals by light or other electromagnetic radiation.

TABLE 12.1
Photoelectric Threshold Energies for Various Metals

Aluminum	Zinc	Iron	Copper	Silver	Nickel	Gold
Al	Zn	Fe	Cu	Ag	Ni	Au
0.66 aJ	0.69 aJ	0.72 aJ	0.75 aJ	0.75 aJ	0.80 aJ	0.82 aJ

THINK AGAIN

The explanation just given—that increasing the number of photons striking a material is not necessarily sufficient to cause electrons to be ejected—rests on an assumption. It assumes that each photon acts separately and individually on an electron. Although some rare exceptions to this individualistic behavior are known, for our purposes we will consider this to be an accurate description.

REAL-WORLD EXAMPLE 12.1: SEMICONDUCTOR LIGHT DETECTORS

A photodetector is a device that produces electrical current when exposed to light; that is, it detects the presence of light. The photodetectors used in solar-energy applications, CD players, and in optical communication systems are made with semiconductor *diodes*. Depending on the application being considered, different semiconductor materials are used to make the diode. Recall from Chapter 10, Section 10.3 that a diode consists of an n-type doped semiconductor in contact with a p-type semiconductor, as shown in **Figure 12.9**. The n-type region contains excess electrons contributed by its *dopant* atoms, whereas in the p-type material there is a deficit of electrons (i.e., there are holes) in the outer shells of the atoms making up the crystal. At the junction between n-type and p-type materials, there is a *depletion region*, where excess electrons have diffused from the n-type into the p-type material, creating an imbalance of charge only in this small region. The excess electrons from the n-side are now trapped in the (former) holes in the p-side. The charge imbalance in the depletion region creates an internal battery at the junction, but no charge is flowing, because the electron diffusion is countered by the force created by the internal battery (shown as the large gray arrow in the junction).

In Figure 12.9a, a battery applies voltage across the diode in the backward direction; that is, minus polarity is connected to the diode's p-type side. In this case, no current flows. In Figure 12.9b, with the battery voltage still in the backward direction, light illuminates the depletion region of the diode. If the photons in the light have energy $h \cdot f$ that is greater than the band-gap energy of the crystal E_{GAP} , then electrons in the p-side of the depletion region can jump out of the holes in which they are trapped. These electrons are elevated in energy to the upper conducting band, as shown in the energy-level diagram in **Figure 12.10**.

The liberated electrons will feel a force caused by the internal battery. Because they are in the conduction band, they can be accelerated across the junction, then move through the n-side. Then they are pulled by the battery's voltage through the wire leading to the plus side of the battery. By monitoring how much current flows, we can determine how much light power is striking the detector. When a diode is used in this manner, it is called a *photodiode*.

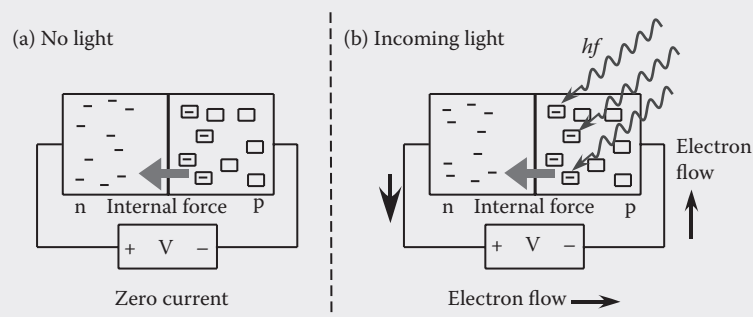


FIGURE 12.9 A semiconductor diode used to detect light.

To design and build useful photodetectors on the basis of these physics principles, we need to be able to predict whether or not a given type of crystal will detect light of a given color or wavelength. This depends on the size of the *energy gap* between the lower and upper bands, as shown in Figure 12.10. For example, a silicon photodiode has a band-gap energy equal to $E_{GAP} = 0.18$ aJ. As we calculated above, any photon whose frequency is greater than 2.7×10^{14} Hz can cause an electron to jump into the conduction band in such a crystal. This means that a silicon photodiode can detect light only if it has frequency greater than 2.7×10^{14} Hz, for example, near-infrared or visible light.

Table 12.2 lists the band-gap energies of several common semiconductor crystals, and the corresponding minimum light frequency (or, equivalently, maximum wavelength in vacuum) that each crystal can detect. For each crystal, the relation between energy and frequency is calculated using Planck's law.

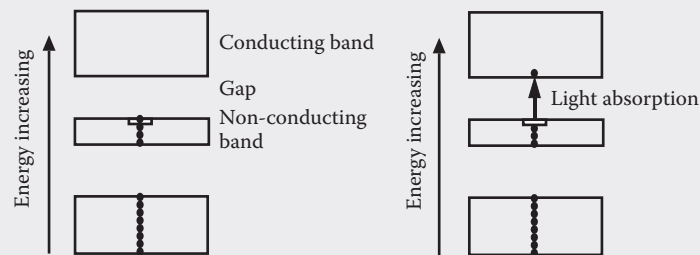


FIGURE 12.10 Light is absorbed by a semiconductor diode if its frequency is high enough so that photons in the light have sufficient energy to cause an electron in the diode to jump to a higher-energy band.

TABLE 12.2
Band-Gap Energies for Various Semiconductor Crystals

Material	Band-Gap Energy (aJ)*	Minimum Frequency (Hz)	Maximum Wavelength (nm)
Indium arsenide (InAs)	0.0577	0.874×10^{14}	3,430
Germanium (Ge)	0.106	1.61×10^{14}	1,870
Silicon (Si)	0.178	2.69×10^{14}	1,110
Gallium arsenide (GaAs)	0.227	3.45×10^{14}	870
Gallium phosphide (GaP)	0.362	5.49×10^{14}	547
Gallium nitride (GaN)	0.550	8.33×10^{14}	360

* In some texts, energy is given in units called electron-volts, or eV. The equivalence is: 0.160 aJ = 1 eV.

12.5 EMISSION OF LIGHT BY ATOMS AND CRYSTALS

Under the proper conditions, electrons in atoms and crystals will emit light. For example, the metal filament in a conventional, incandescent light bulb emits light when heated to high enough temperature by the electric current passing through it. This is easily understood in terms of electromagnetic waves created when the free electrons move randomly as a consequence of the thermal energy. In the remainder of this section, we will discuss light emission by atoms and semiconductor crystals, rather than by metals.

Emission by atoms is the reverse of absorption. To understand this, we can adapt the above-cited Quantum Principle (v). If an electron is in an atomic orbit with high energy,