CLEAN ENERGY GENERATION, INTEGRATION AND STORAGE (EEE-801)

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Lecture-6
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- **A material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be photovoltaic.**
- **A photon with short enough wavelength and high enough energy can cause an electron in a photovoltaic material to break free of the atom that holds it.**
- **The driving force to power photovoltaics comes from the sun, and it is interesting to note that the surface of the earth receives something like 6000 times as much solar energy as our total energy demand.**

Introduction: Basic Semiconductor Physics

- **Photovoltaics use semiconductor materials to convert sunlight into electricity. The technology for doing so is very closely related to the solid-state technologies used to make transistors, diodes, and all of the other semiconductor devices that we use so many of these days.**
- **The starting point for most of the world's current generation of photovoltaic devices, as well as almost all semiconductors, is pure crystalline silicon.**
- **It is in the fourth column of the periodic table, which is referred to as Group IV as given in the Table. Germanium is another Group IV element, and it too is used as a semiconductor in some electronics.**

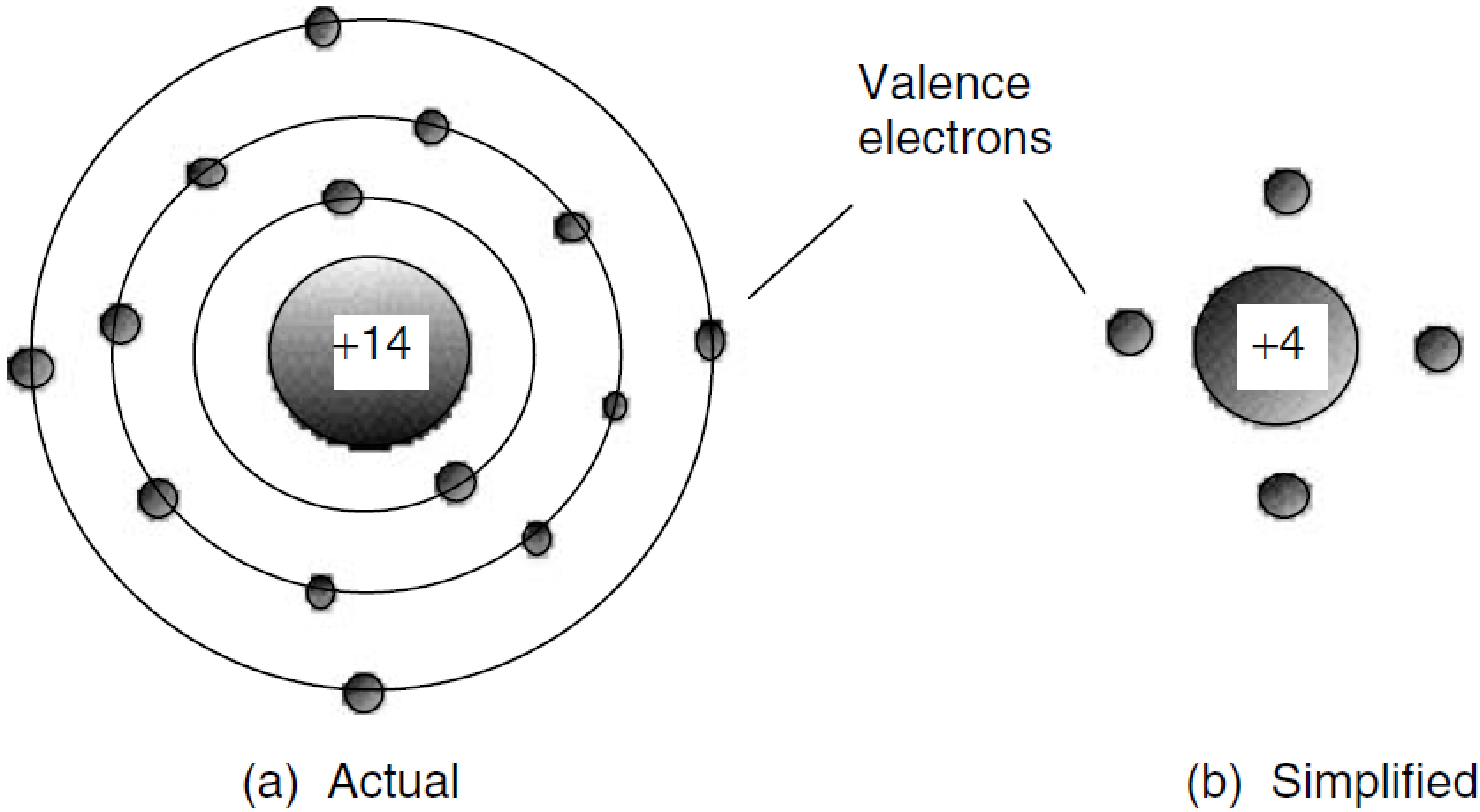
- **Other elements that play important roles in photovoltaics are boldfaced. As we will see, boron and phosphorus, from Groups III and V, are added to silicon to make most PVs. Gallium and arsenic are used in GaAs solar cells, while cadmium and tellurium are used in CdTe cells.**

I	II	III	IV	V	VI
		5 B	6 C	7 N	8 O
		13 Al	**14 Si**	**15 P**	16 S
29 Cu	30 Zn	**31 Ga**	32 Ge	**33 As**	34 Se
47 Ag	**48 Cd**	49 In	50 Sn	51 Sb	**52 Te**

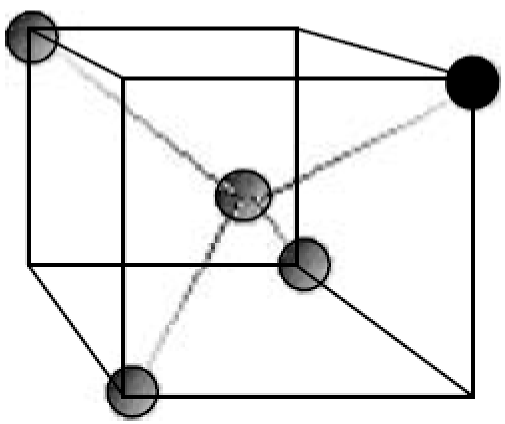
Introduction: Basic Semiconductor Physics (Cont)

- **Silicon has 14 protons in its nucleus, and so it has 14 orbital electrons as well. As shown in Fig. a, its outer orbit contains four valence electrons—that is, it is tetravalent. Those valence electrons are the only ones that matter in electronics, so it is common to draw silicon as if it has a +4 charge on its nucleus and four tightly held valence electrons, as shown in Fig. b.**

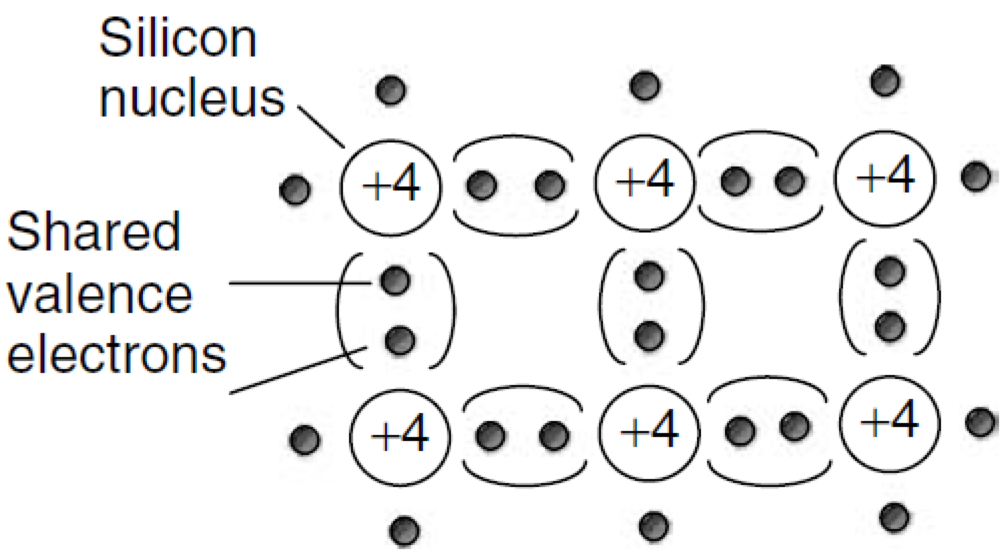
Introduction: Basic Semiconductor Physics (Cont)



- **In pure crystalline silicon, each atom forms covalent bonds with four adjacent atoms in the three-dimensional tetrahedral pattern shown in Fig.a. For convenience, that pattern is drawn as if it were all in a plane, as in Fig.b.**



(a) Tetrahedral



(b) Two-dimensional version

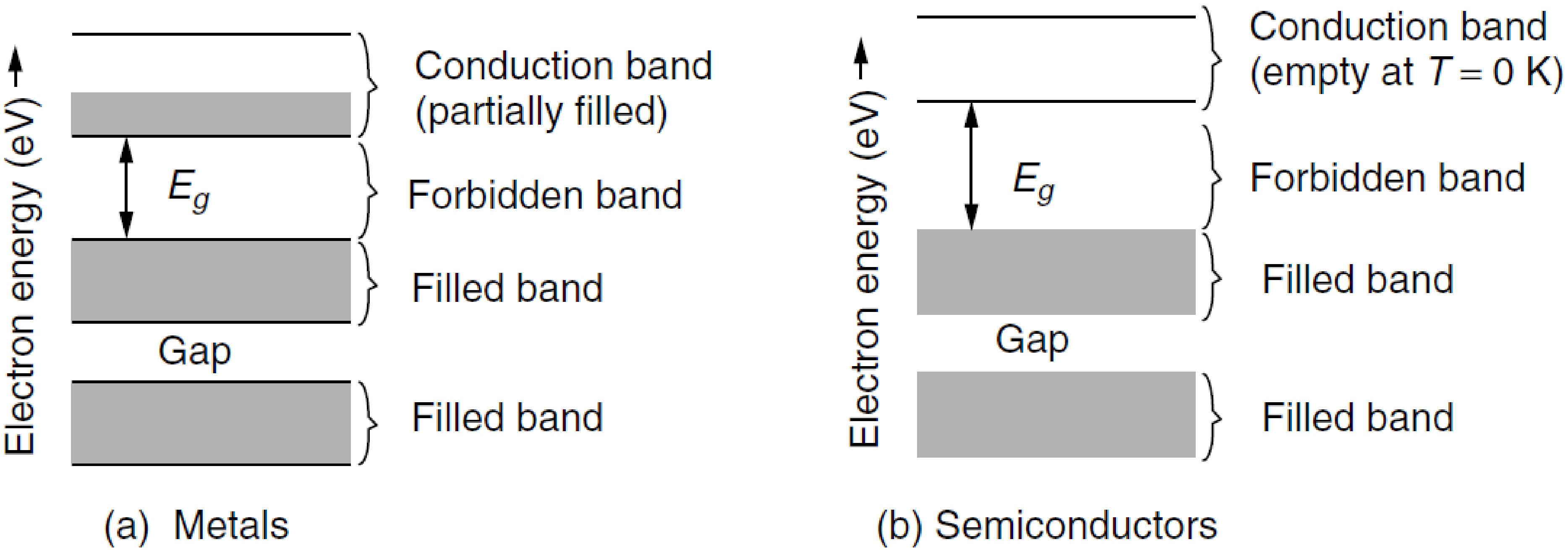
Introduction: The Band Gap Energy

- **At absolute zero temperature, silicon is a perfect electrical insulator. There are no electrons free to roam around as there are in metals. As the temperature increases, some electrons will be given enough energy to free themselves from their nuclei, making them available to flow as electric current.**
- **The warmer it gets, the more electrons there are to carry current, so its conductivity increases with temperature (in contrast to metals, where conductivity decreases).**
- **Silicon's conductivity at normal temperatures is still very low, and so it is referred to as a semiconductor. As we will see, by adding minute quantities of other materials, the conductivity of pure (intrinsic) semiconductors can be greatly increased.**

Introduction: The Band Gap Energy (Cont)

- **Electrons have energies that must fit within certain allowable energy bands. The top energy band is called the conduction band, and it is electrons within this region that contribute to current flow.**
- **As shown in Fig, the conduction band for metals is partially filled, but for semiconductors at absolute zero temperature, the conduction band is empty. At room temperature, only about one out of 10^{10} electrons in silicon exists in the conduction band.**

Introduction: The Band Gap Energy (Cont)



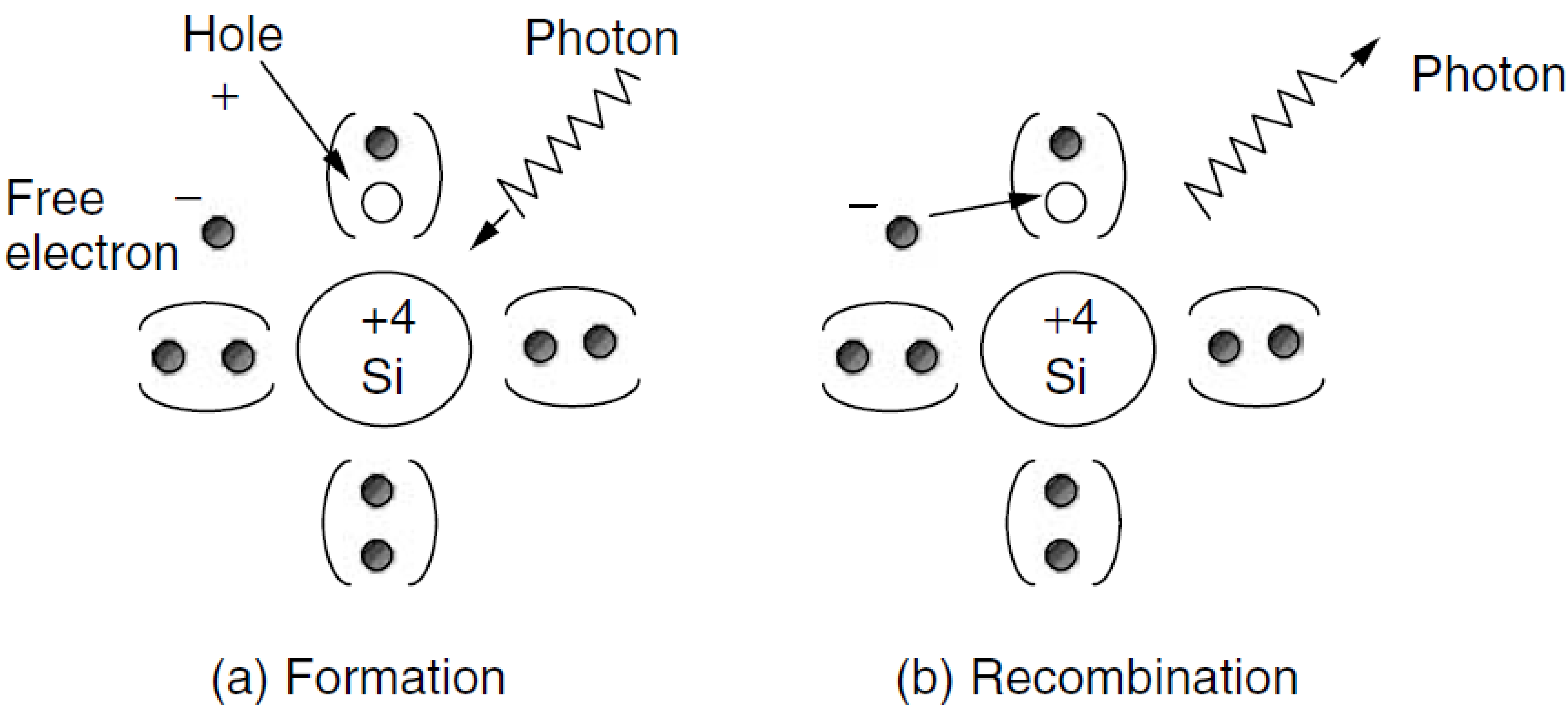
Introduction: The Band Gap Energy (Cont)

- **The gaps between allowable energy bands are called forbidden bands, the most important of which is the gap separating the conduction band from the highest filled band below it. The energy that an electron must acquire to jump across the forbidden band to the conduction band is called the band-gap energy, designated E_g.**
- **The units for band-gap energy are usually electron-volts (eV), where one electron-volt is the energy that an electron acquires when its voltage is increased by 1 V (1 eV = 1.6 × 10^{-19} J).**
- **The band-gap E_g for silicon is 1.12 eV, which means an electron needs to acquire that much energy to free itself from the electrostatic force that ties it to its own nucleus—that is, to jump into the conduction band.**

Introduction: The Band Gap Energy (Cont)

- For photovoltaics, the energy source is photons of electromagnetic energy from the sun. When a photon with more than 1.12 eV of energy is absorbed by a solar cell, a single electron may jump to the conduction band.
- When it does so, it leaves behind a nucleus with a +4 charge that now has only three electrons attached to it. That is, there is a net positive charge, called a hole, associated with that nucleus as shown in Fig.a.
- Unless there is some way to sweep the electrons away from the holes, they will eventually recombine, obliterating both the hole and electron as in Fig.b.

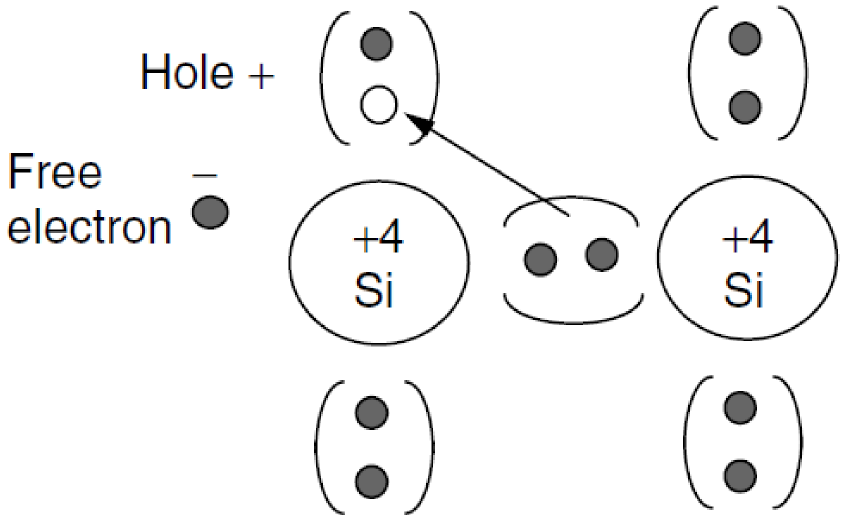
Introduction: The Band Gap Energy (Cont)



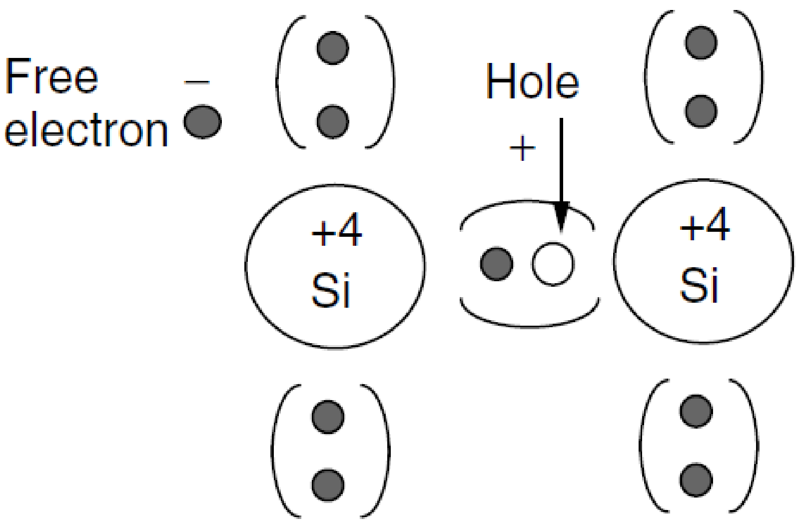
Introduction: The Band Gap Energy (Cont)

- **It is important to note that not only is the negatively charged electron in the conduction band free to roam around in the crystal, but the positively charged hole left behind can also move as well.**
- **A valence electron in a filled energy band can easily move to fill a hole in a nearby atom, without having to change energy bands as shown in Fig.**
- **The important point here is that electric current in a semiconductor can be carried not only by negatively charged electrons moving around, but also by positively charged holes that move around as well.**

Introduction: The Band Gap Energy (Cont)



(a) An electron moves to fill the hole



(b) The hole has moved

Introduction: The Band Gap Energy (Cont)

- **Thus, photons with enough energy create hole–electron pairs in a semiconductor. Photons can be characterized by their wavelengths or their frequency as well as by their energy; the three are related by the following:**
- $$c = \lambda v$$
- **Where c is the speed of light (3 × $1o^{8}$ m/s), *v* is the frequency (hertz), λ is the wavelength (m), and**
- $$E = hv = \frac{hc}{\lambda}$$
- **Where E is the energy of a photon and h is Planck's constant (6.626 × 10^{-34} J-s).**

Problem: No.1

- **What maximum wavelength can a photon have to create hole–electron pairs in silicon? What minimum frequency is that? Silicon has a band gap of 1.12 eV and 1 eV = 1.6 × 10^{-19}J.**
- $\lambda \leq \frac{hc}{E}$
- $v \geq \frac{c}{\lambda}$

$$\lambda \leq \frac{hc}{E} = \frac{6.626 \times 10^{-34}\ \text{J}\cdot\text{s} \times 3 \times 10^{8}\ \text{m/s}}{1.12\ \text{eV} \times 1.6 \times 10^{-19}\text{J/eV}} = 1.11 \times 10^{-6}\ \text{m} = 1.11\ \mu\text{m}$$

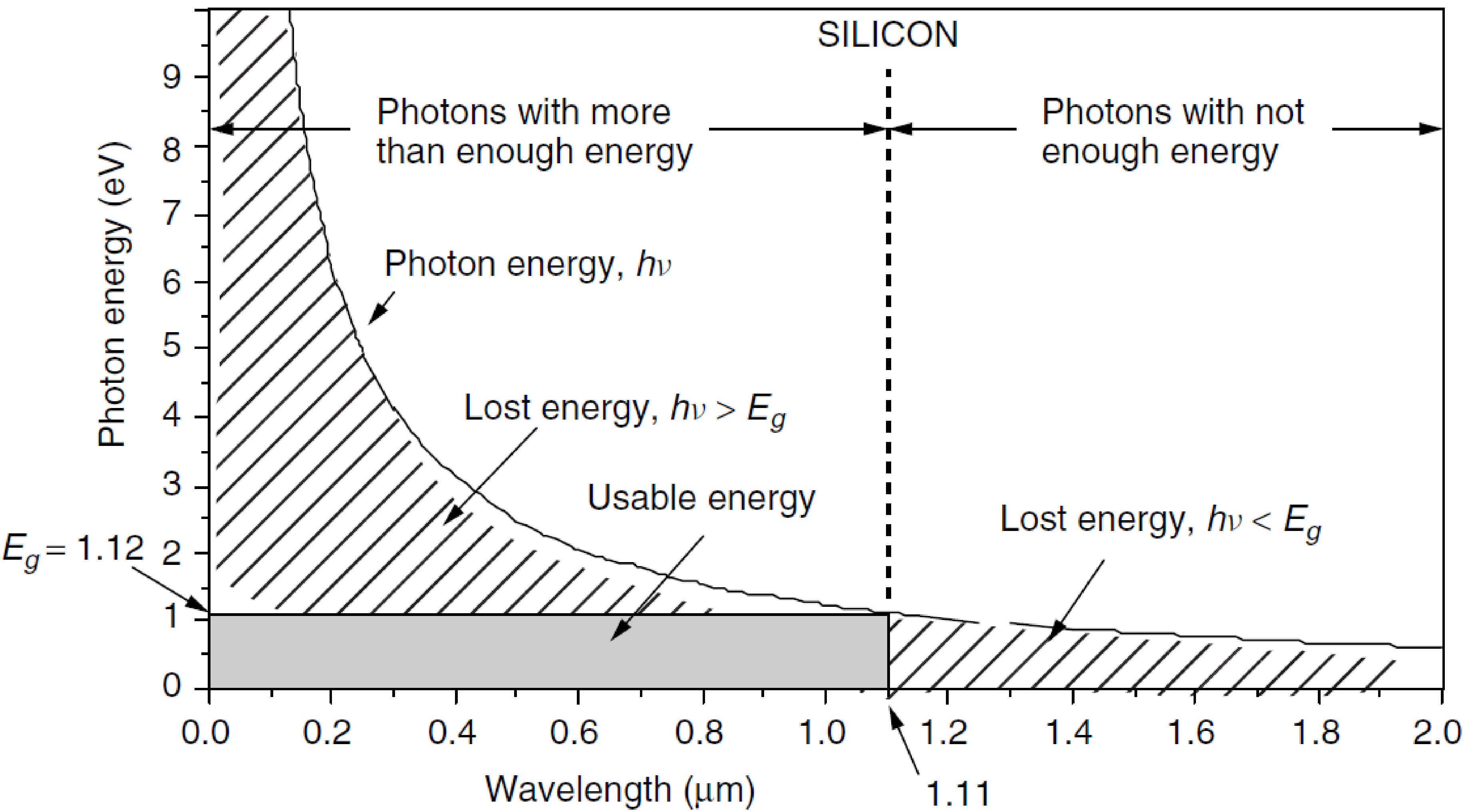
$$\nu \geq \frac{c}{\lambda} = \frac{3 \times 10^{8}\ \text{m/s}}{1.11 \times 10^{-6}\ \text{m}} = 2.7 \times 10^{14}\ \text{Hz}$$

Introduction: The Band Gap Energy (Cont)

- **For a silicon photovoltaic cell, photons with wavelength greater than 1.11 μm have energy hv less than the 1.12-eV band-gap energy needed to excite an electron. None of those photons create hole–electron pairs capable of carrying current, so all of their energy is wasted. It just heats the cell.**
- **On the other hand, photons with wavelengths shorter than 1.11 μm have more than enough energy to excite an electron. Since one photon can excite only one electron, any extra energy above the 1.12 eV needed is also dissipated as waste heat in the cell.**
- **The band gaps for other photovoltaic materials—gallium arsenide (GaAs), cadmium telluride (CdTe), and indium phosphide (InP), in addition to silicon—are shown in Table.**

Quantity	Si	GaAs	CdTe	InP
Band gap (eV)	1.12	1.42	1.5	1.35
Cut-off wavelength (μm)	1.11	0.87	0.83	0.92

Introduction: The Band Gap Energy (Cont)



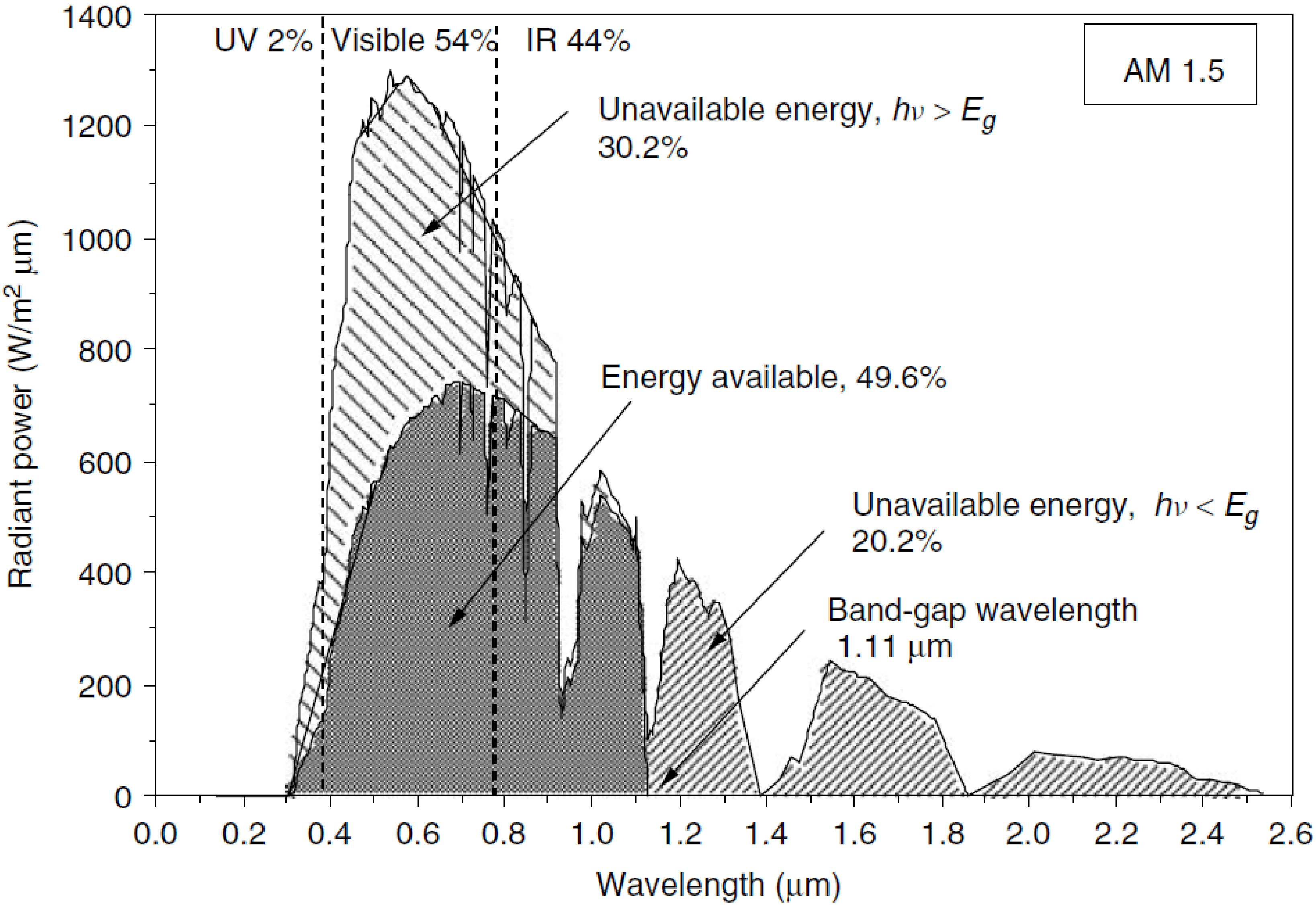
Introduction: The Solar Spectrum

- **As solar radiation passes through the atmosphere, some is absorbed by various constituents in the atmosphere, so that by the time it reaches the earth's surface the spectrum is significantly distorted.**
- **The amount of solar energy reaching the ground, as well as its spectral distribution, depends very much on how much atmosphere it has had to pass through to get there.**
- **The length of the path taken by the sun's rays through the atmosphere to reach a spot on the ground, divided by the path length corresponding to the sun directly overhead, is called the air mass ratio, m.**

Introduction: The Solar Spectrum

- **Thus, an air mass ratio of 1 (designated "AM1") means that the sun is directly overhead. By convention, AM0 means no atmosphere; that is, it is the extraterrestrial solar spectrum.**
- **For most photovoltaic work, an air mass ratio of 1.5, corresponding to the sun being 42 degrees above the horizon, is assumed to be the standard. The solar spectrum at AM 1.5 is shown in Fig.**
- **For an AM 1.5 spectrum, 2% of the incoming solar energy is in the UV portion of the spectrum, 54% is in the visible, and 44% is in the infrared.**

Introduction: The Solar Spectrum



Introduction: Band-Gap Impact on PV Efficiency

- **The band gap for silicon is 1.12 eV, corresponding to a wavelength of 1.11 μm, which means that any energy in the solar spectrum with wavelengths longer than 1.11 μm cannot send an electron into the conduction band.**
- **And, any photons with wavelength less than 1.11 μm waste their extra energy. If we know the solar spectrum, we can calculate the energy loss due to these two fundamental constraints.**
- **The figure on the previous slide shows the results of this analysis, assuming a standard air mass ratio AM 1.5. As is presented there, 20.2% of the energy in the spectrum is lost due to photons having less energy than the band gap of silicon ($h\nu < E_g$), and another 30.2% is lost due to photons with $h\nu > E_g$.**

Introduction: Band-Gap Impact on PV Efficiency (Cont)

- **The remaining 49.6% represents the maximum possible fraction of the sun's energy that could be collected with a silicon solar cell. That is, the constraints imposed by silicon's band gap limit the efficiency of silicon to just under 50%.**
- **There is a trade-off between choosing a photovoltaic material that has a small band gap versus one with a large band gap. With a smaller band gap, more solar photons have the energy needed to excite electrons, which is good since it creates the charges that will enable current to flow.**
- **However, a small band gap means that more photons have surplus energy above the threshold needed to create hole–electron pairs, which wastes their potential.**

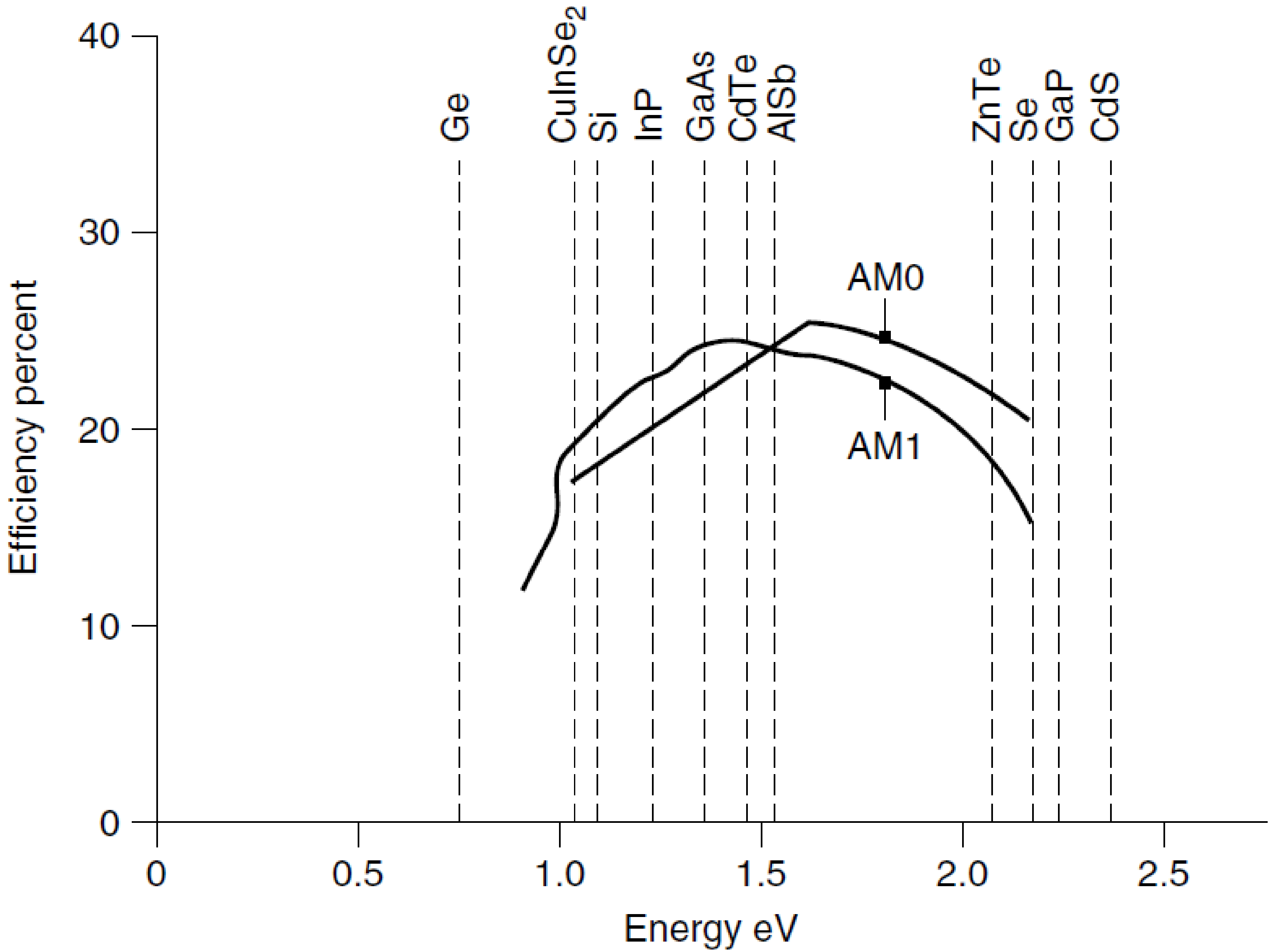
Introduction: Band-Gap Impact on PV Efficiency (Cont)

- **High band-gap materials have the opposite combination. A high band gap means that fewer photons have enough energy to create the current carrying electrons and holes, which limits the current that can be generated. On the other hand, a high band gap gives those charges a higher voltage with less leftover surplus energy.**
- **In other words, low band gap gives more current with less voltage while high band gap results in less current and higher voltage. Since power is the product of current and voltage, there must be some middle-ground band gap, usually estimated to be between 1.2 eV and 1.8 eV, which will result in the highest power and efficiency.**

Introduction: Band-Gap Impact on PV Efficiency (Cont)

- **Figure shows one estimate of the impact of band gap on the theoretical maximum efficiency of photovoltaics at both AM0 and AM1. The figure includes band gaps and maximum efficiencies for many of the most promising photovoltaic materials being developed today.**
- **Notice that the efficiencies in Figure are roughly in the 20–25% range—well below the 49.6% we found when we considered only the losses caused by (a) photons with insufficient energy to push electrons into the conduction band and (b) photons with energy in excess of what is needed to do so.**

Introduction: Band-Gap Impact on PV Efficiency (Cont)



Introduction: Band-Gap Impact on PV Efficiency (Cont)

- **Other factors that contribute to the drop in theoretical efficiency include:**
- **Only about half to two-thirds of the full band-gap voltage across the terminals of the solar cell.**
- **Recombination of holes and electrons before they can contribute to current flow.**
- **Photons that are not absorbed in the cell either because they are reflected off the face of the cell, or because they pass right through the cell, or because they are blocked by the metal conductors that collect current from the top of the cell.**
- **Internal resistance within the cell, which dissipates power.**

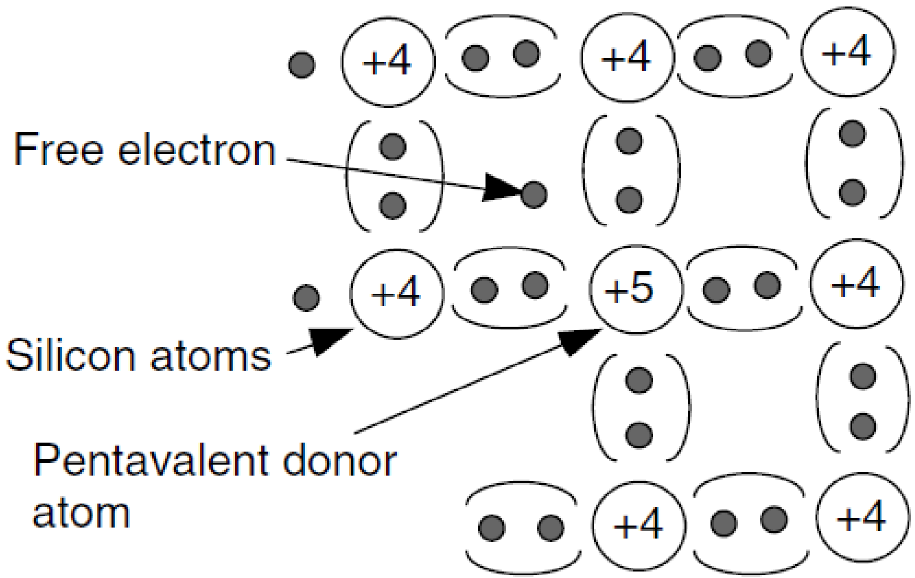
Introduction: The p-n Junction

- **As long as a solar cell is exposed to photons with energies above the bandgap energy, hole–electron pairs will be created.**
- **The problem is, of course, that those electrons can fall right back into a hole, causing both charge carriers to disappear. To avoid that recombination, electrons in the conduction band must continuously be swept away from holes.**
- **In PVs this is accomplished by creating a built-in electric field within the semiconductor itself that pushes electrons in one direction and holes in the other. To create the electric field, two regions are established within the crystal.**

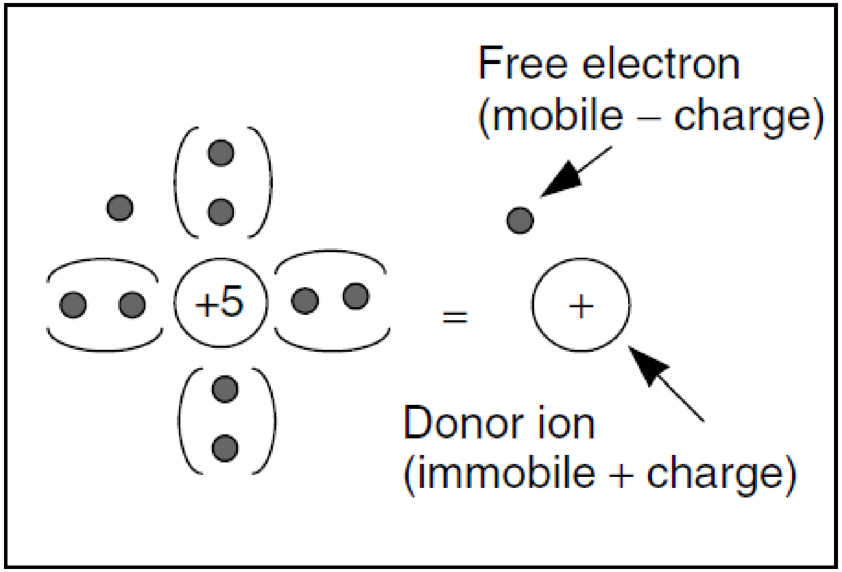
Introduction: The p-n Junction (Cont)

- **On one side of the dividing line separating the regions, pure (intrinsic) silicon is purposely contaminated with very small amounts of a trivalent element from column III of the periodic chart; on the other side, pentavalent atoms from column V are added.**
- **Consider the side of the semiconductor that has been doped with a pentavalent element such as phosphorus. Only about 1 phosphorus atom per 1000 silicon atoms is typical.**
- **As shown in Fig, an atom of the pentavalent impurity forms covalent bonds with four adjacent silicon atoms. Four of its five electrons are now tightly bound, but the fifth electron is left on its own to roam around the crystal.**

Introduction: The p-n Junction (Cont)



(a) The donor atom in Si crystal



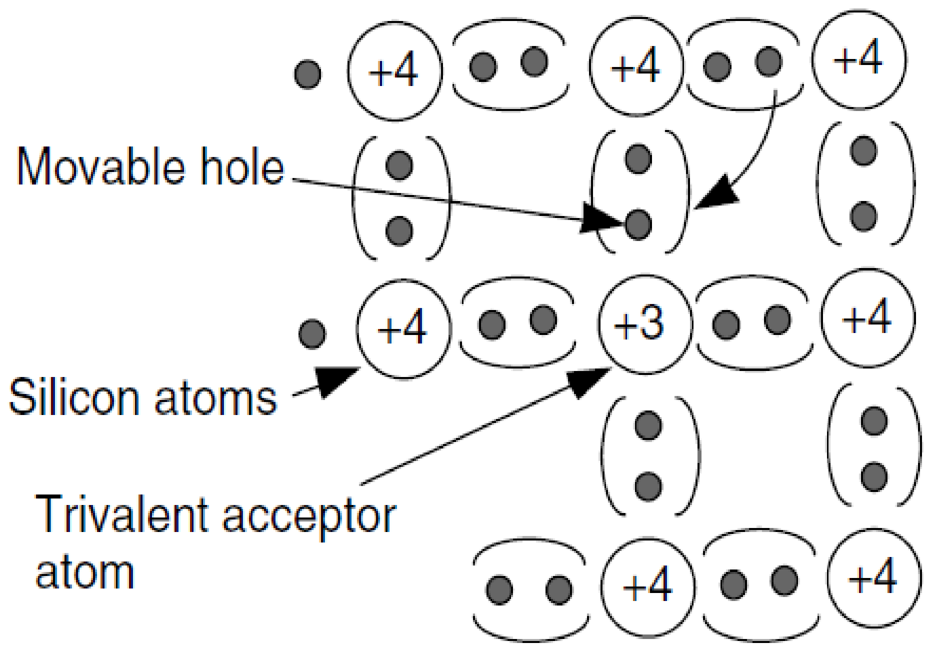
(b) Representation of the donor atom

Introduction: The p-n Junction (Cont)

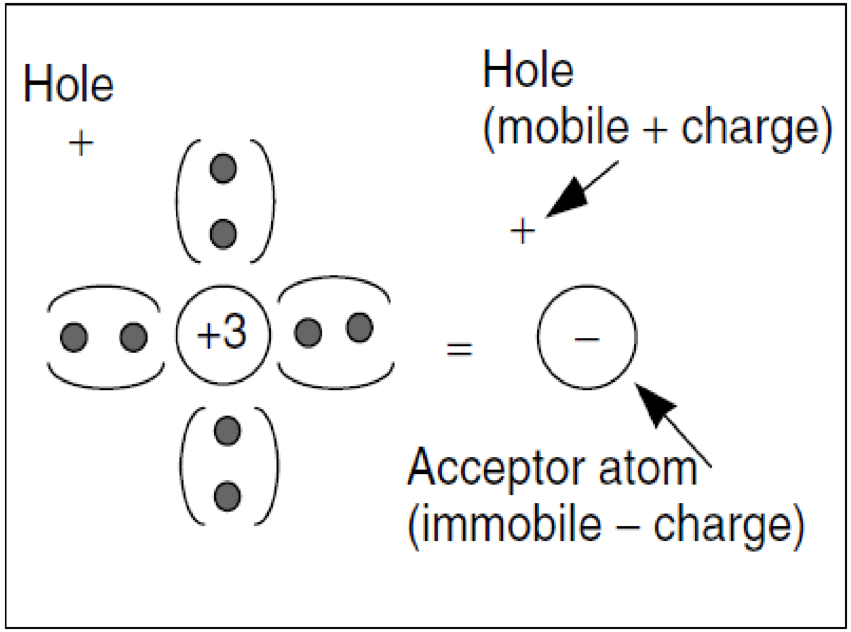
- **When that electron leaves the vicinity of its donor atom, there will remain a +5 donor ion fixed in the matrix, surrounded by only four negative valence electrons. That is, each donor atom can be represented as a single, fixed, immobile positive charge plus a freely roaming negative charge as shown in Fig.b.**
- **Pentavalent i.e., +5 elements donate electrons to their side of the semiconductor so they are called donor atoms. Since there are now negative charges that can move around the crystal, a semiconductor doped with donor atoms is referred to as an "n-type material."**

Introduction: The p-n Junction (Cont)

- **On the other side of the semiconductor, silicon is doped with a trivalent element such as boron. Again the concentration of dopants is small, something on the order of 1 boron atom per 10 million silicon atoms. These dopant atoms fall into place in the crystal, forming covalent bonds with the adjacent silicon atoms as shown in Fig.**
- **Since each of these impurity atoms has only three electrons, only three of the covalent bonds are filled, which means that a positively charged hole appears next to its nucleus. An electron from a neighboring silicon atom can easily move into the hole, so these impurities are referred to as acceptors since they accept electrons.**



(a) An acceptor atom in Si crystal



(b) Representation of the acceptor atom

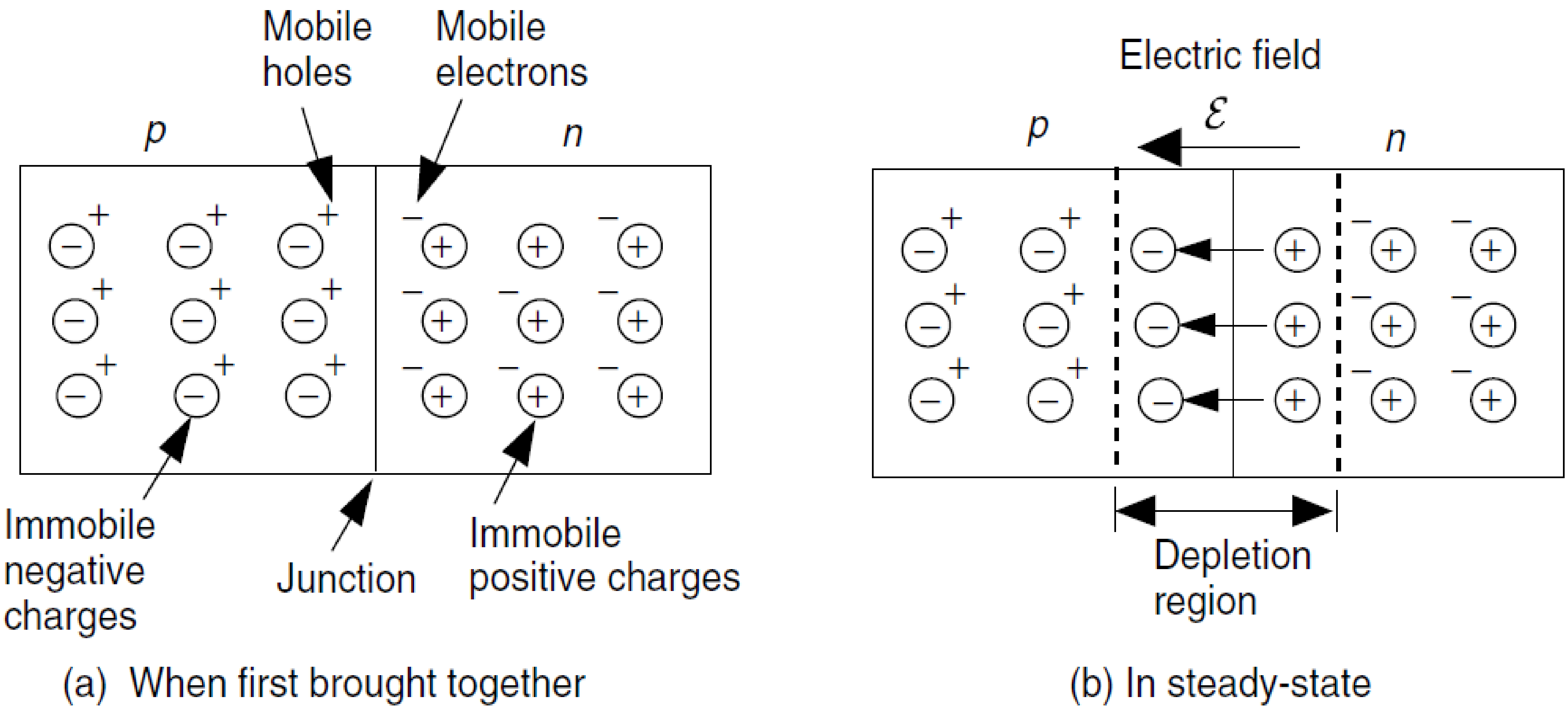
Introduction: The p-n Junction (Cont)

- **The filled hole now means there are four negative charges surrounding a +3 nucleus. All four covalent bonds are now filled creating a fixed, immobile net negative charge at each acceptor atom.**
- **Meanwhile, each acceptor has created a positively charged hole that is free to move around in the crystal, so this side of the semiconductor is called a p-type material.**
- **Now, suppose we put an n-type material next to a p-type material forming a junction between them. In the n-type material, mobile electrons drift by diffusion across the junction. In the p-type material, mobile holes drift by diffusion across the junction in the opposite direction.**

Introduction: The p-n Junction (Cont)

- **As depicted in Fig, when an electron crosses the junction it fills a hole, leaving an immobile, positive charge behind in the n-region, while it creates an immobile, negative charge in the p-region.**
- **These immobile charged atoms in the p and n regions create an electric field that works against the continued movement of electrons and holes across the junction.**
- **As the diffusion process continues, the electric field countering that movement increases until eventually (actually, almost instantaneously) all further movement of charged carriers across the junction stops.**

Introduction: The p-n Junction (Cont)



- **The exposed immobile charges creating the electric field in the vicinity of the junction form what is called a depletion region, meaning that the mobile charges are depleted—gone—from this region.**
- **The width of the depletion region is only about 1 μm and the voltage across it is perhaps 1 V, which means the field strength is about 10,000 V/cm! Following convention, the arrows representing an electric field in Fig.b on the previous slide start on a positive charge and end on a negative charge.**
- **The arrow, therefore, points in the direction that the field would push a positive charge, which means that it holds the mobile positive holes in the p-region (while it repels the electrons back into the n-region).**