UFUG 1504: Honors General Physics II

Chapter 41

Conduction of Electricity in Solids

41.2: The Electrical Properties of Solids: (2 of 2)

We shall examine only **crystalline solids**—that is, solids whose atoms are arranged in a repetitive three-dimensional structure called a **lattice.** We shall not consider such solids as wood, plastic, glass, and rubber, whose atoms are not arranged in such repetitive patterns.

Figure 41-1 shows the basic repetitive units (the **unit cells**) of the lattice structures of copper, our prototype of a metal, and silicon and diamond (carbon), our prototypes of a semiconductor and an insulator, respectively

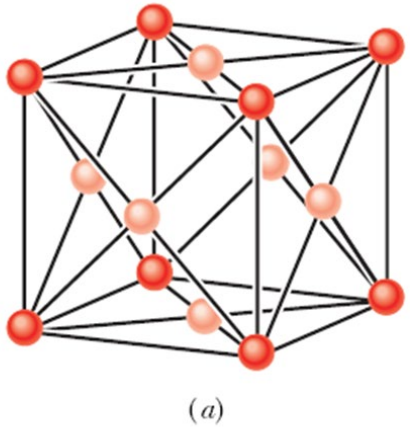


Figure 41-1 (a) The unit cell for copper is a cube. There is one copper atom (darker) at each corner of the cube and one copper atom (lighter) at the center of each face of the cube. The arrangement is called face-centered cubic (FCC).

(b)The unit cell for either silicon or the carbon atoms in diamond is also a cube, the atoms being arranged in what is called a diamond lattice. There is one atom (darkest) at each corner of the cube and one atom (lightest) at the center of each cube face; in addition, four atoms (medium color) lie within the cube. Every atom is bonded to its four nearest neighbors by a two-electron covalent bond (only the four atoms within the cube show all four nearest neighbors).

41.2: The Electrical Properties of Solids: (1 of 2)

The electrical properties of solids can be categorized into following classes:

1. Their resistivity ρ at room temperature, with the SI unit ohm-Meter ($\Omega \cdot \mathrm{m}$);

$$\rho = \frac{m}{e^2 n \tau}. \qquad R = \frac{\rho L}{A}$$

2. Their temperature coefficient of resistivity a, defined as $\alpha = \left(\frac{1}{\rho}\right)\left(\frac{d\rho}{dT}\right)$ and having the S I unit inverse kelvin (K^{-1}). We can evaluate $\alpha$for any solid by measuring ρ over a range of temperatures.

$$\rho = \rho_0(1 + \alpha \Delta T)$$

3. Their number density of charge carriers n. This quantity, the number of charge carriers per unit volume, can be found from measurements of the Hall effect, and from other measurements. It has the SI unit inverse cubic Meter (m^{-3}).

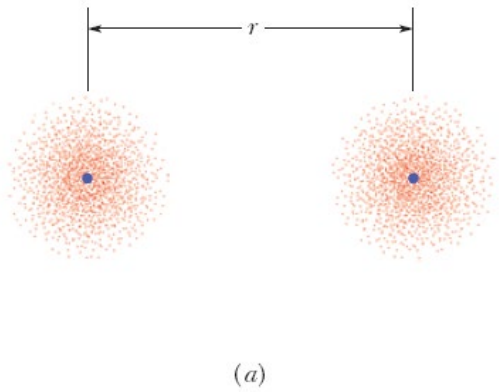
$$n = \frac{Bi}{Vle},$$

41.2: The Electrical Properties of Solids: (1 of 2)

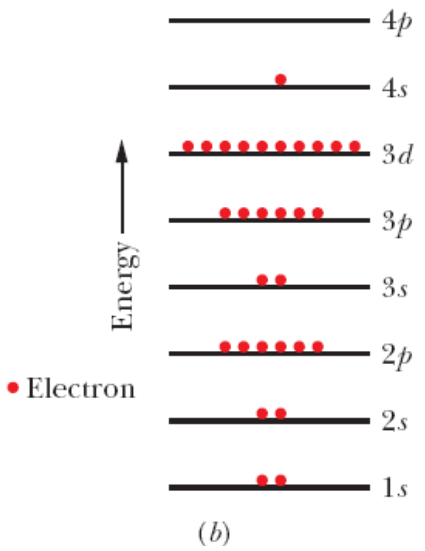
Table 41-1 Some Electrical Properties of Two Materials[a]

Property	Unit	Material	
		Copper	Silicon
Type of conductor		Metal	Semiconductor
Resistivity, ρ	$\Omega \cdot m$	2×10^{-8}	3×10^{3}
Temperature coefficient of resistivity, α	K^{-1}	$+4 \times 10^{-3}$	-70×10^{-3}
Number density of charge carriers, n	m^{-3}	9×10^{28}	1×10^{16}

41.3: Energy Levels in a Crystalline Solid: (1 of 4)



The distance between adjacent copper atoms in solid copper is 260 p



29 electrons in an array of discrete subshells as follows:

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^1.$

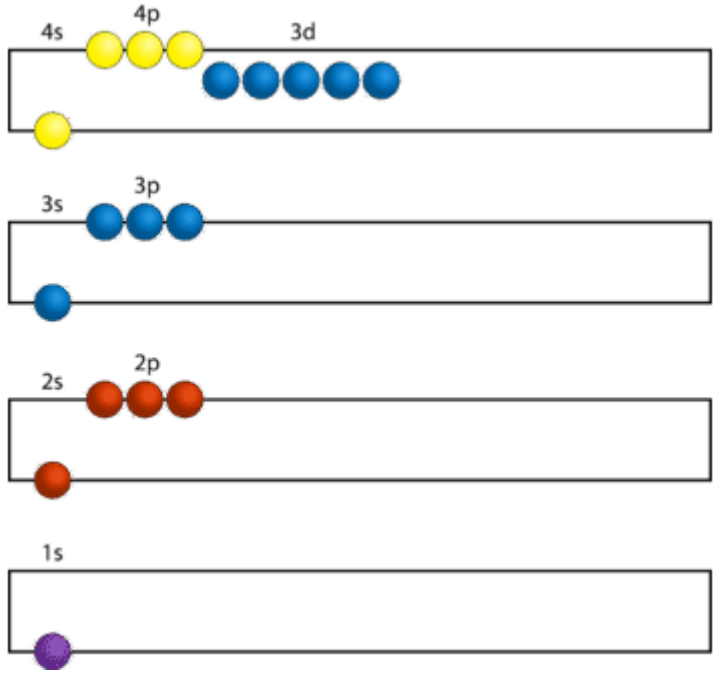
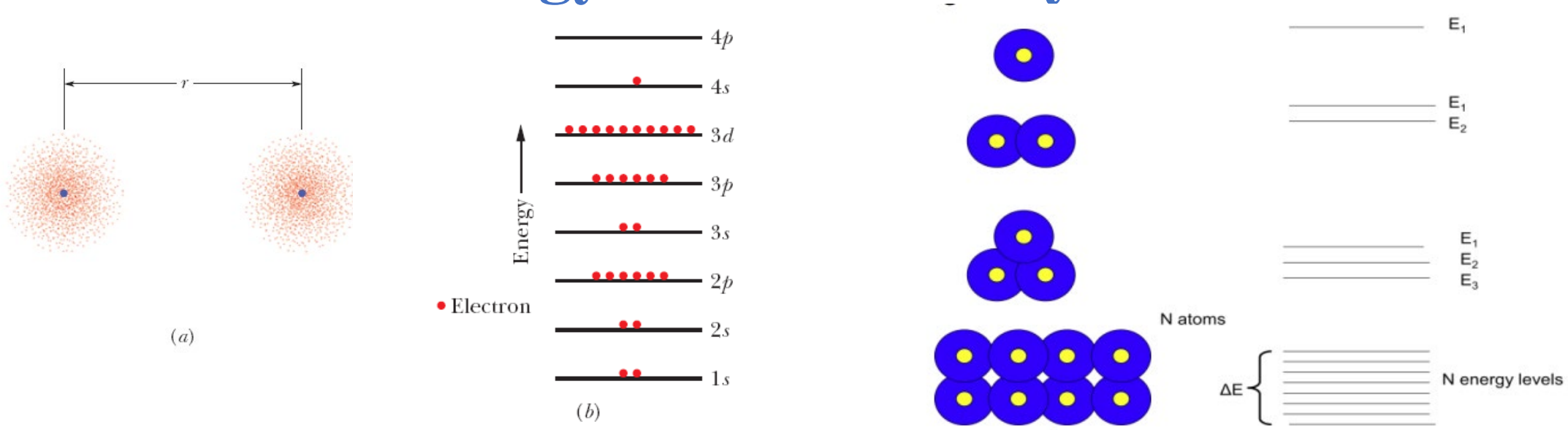


Figure 41-2 (*a*) Two C atoms separated by a large distance; their electron distributions are represented by dot plots. (*b*) Each copper atom has 29 electrons distributed among a set of subshells. In the neutral atom in its ground state, all subshells up through the 3*d* level are filled, the 4*s* subshell contains one electron (it can hold two), and higher subshells are empty. For simplicity, the subshells are shown as being evenly spaced in energy.

41.3: Energy Levels in a Crystalline Solid:



If we bring the atoms of Figure 41-2*a* close together, their wave functions will overlap, beginning with those of the outermost electrons. Then we have a single two-atom system; here the system contains $2 \times 29 = 58$ electrons.

If we bring up more atoms, we gradually assemble a lattice of solid copper. If the lattice contains N atoms, then each level of an isolated copper atom must split into N levels in the solid.

Thus, the individual energy levels of the solid form energy **bands,** adjacent bands being separated by an energy **gap,** with the gap representing a range of energies that no electron can possess.

41.3: Energy Levels in a Crystalline Solid: (3 of 4)

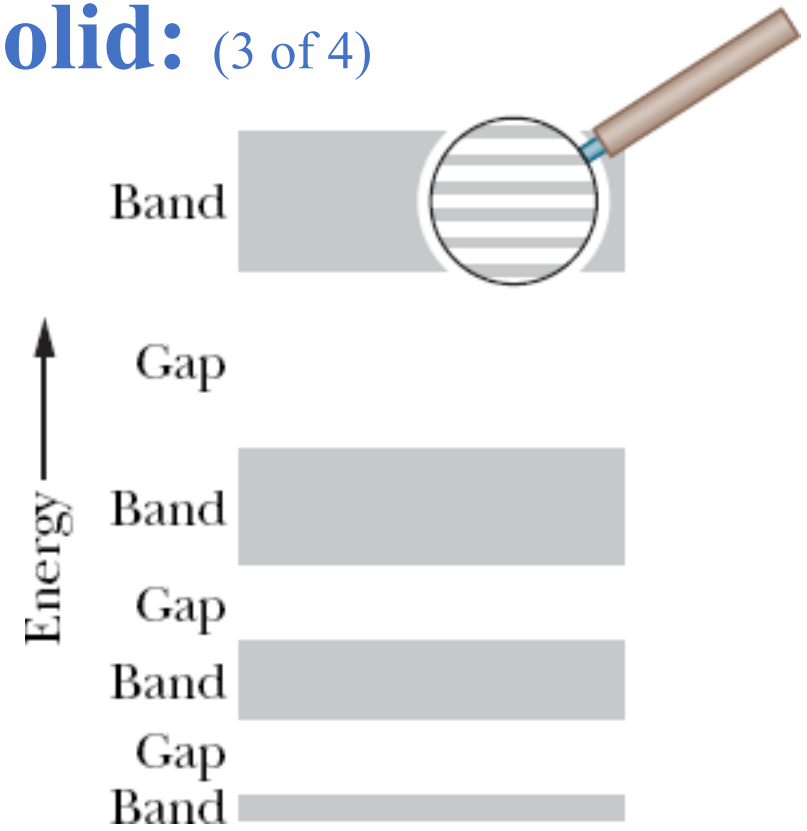


Figure 41-3 The band–gap pattern of energy levels for an idealized crystalline solid. As the magnified view suggests, each band consists of a very large number of very closely spaced energy levels.

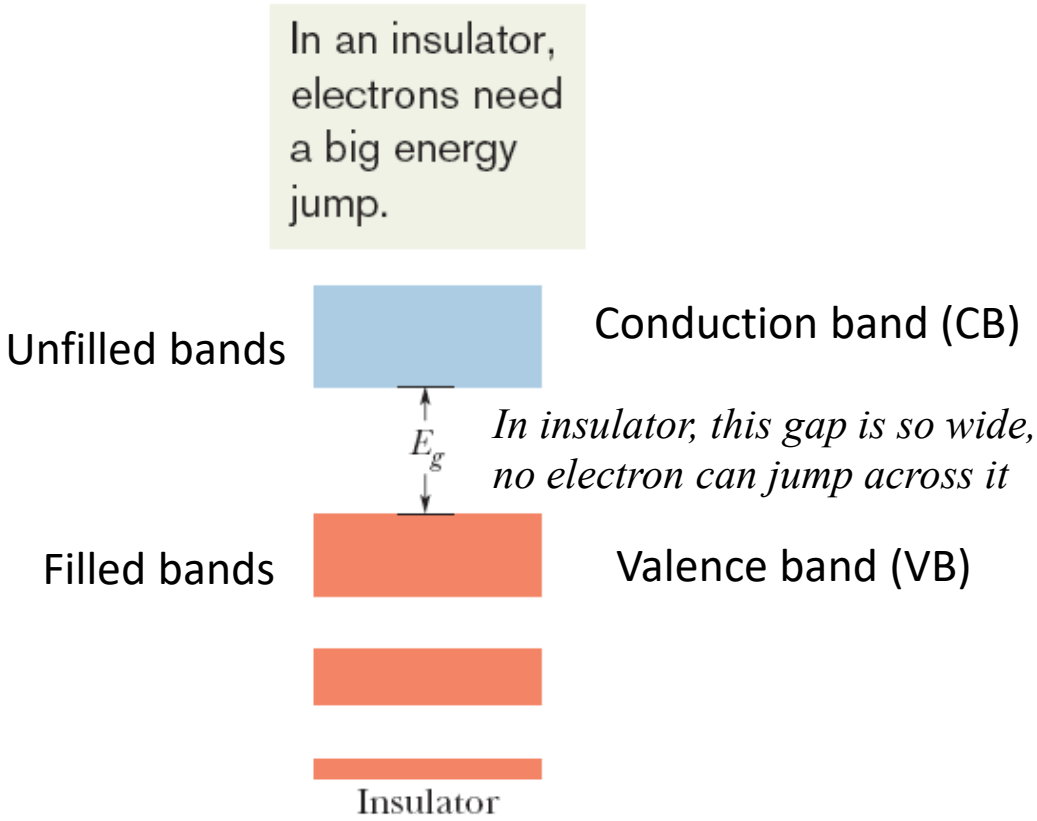


Figure 41-4 The band–gap pattern for an insulator; filled levels are shown in red and empty levels in blue.

41.5: Metals: (1 of 2)

If the electric potential energy U of a conduction electron is uniform throughout the lattice, let's set $U = 0$, so that the mechanical energy E is entirely kinetic. Then the level at the bottom of the partially filled band of Fig. 41-5 corresponds to $E = 0$. The highest occupied level in this band at absolute zero ($T = 0\ K$) is called the **Fermi level,** and the energy corresponding to it is called the **Fermi energy E_F;** for copper, E_F =7.0 eV.

The electron speed corresponding to the Fermi energy is called the **Fermi speed v_F.** For copper the Fermi speed is $= 1.6 \times 10^6 \text{m/s}$. All motion does not cease at absolute zero; at that temperature the conduction electrons are stacked up in the partially filled band of Figure 41-5 with energies that range from zero to the Fermi energy.

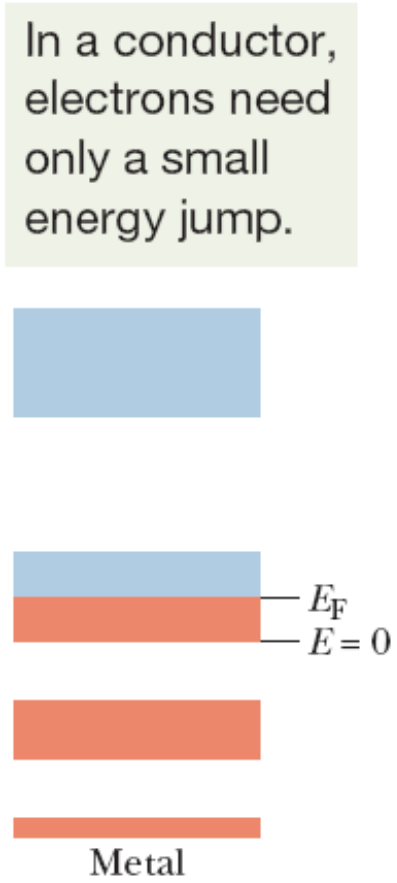


Figure 41-5 The band–gap pattern for a metal. The highest filled level, called the Fermi level, lies near the middle of a band. Since vacant levels are available within that band, electrons in the band can easily change levels, and conduction can take place.

41.5: Metals: How Many Conduction Electrons Are There?

- the total number of conduction electrons:

$$\begin{pmatrix}\text{number of conduction}\\ \text{electrons in sample}\end{pmatrix} = \begin{pmatrix}\text{number of atoms}\\ \text{in sample}\end{pmatrix}\begin{pmatrix}\text{number of valence}\\ \text{electrons per atom}\end{pmatrix}$$

- The *number density* n of conduction electrons:

$$n = \frac{\text{number of conduction electrons in sample}}{\text{sample volume } V}$$

- relate the number of atoms in a sample to various other properties:

$$\begin{pmatrix}\text{number of atoms}\\ \text{in sample}\end{pmatrix} = \frac{\text{sample mass } M_{\text{sam}}}{\text{atomic mass}} = \frac{\text{sample mass } M_{\text{sam}}}{(\text{molar mass } M)/N_{\text{A}}}$$

$$= \frac{(\text{material's density})(\text{sample volume } V)}{(\text{molar mass } M)/N_{\text{A}}},$$

where the molar mass M is the mass of one mole of the material in the sample and N_{A} is Avogadro's number ($6.02 \times 10^{23}\text{mol}^{-1}$).

41.5: Metals: The Occupancy Probability *P*(*E*):

If an energy level is available at energy E, what is the probability $P(E)$ that it is actually occupied by an electron?

$$P(E) = \frac{1}{e^{\frac{(E-E_F)}{kT}} + 1} \quad \text{(occupancy probability)}.$$

in which E_F is the Fermi energy.

Note that $P(E)$ depends not on the energy E of the level but only on the difference $E - E_F$, which may be positive or negative

41.5: Metals: The Occupancy Probability *P*(*E*):

$$P(E) = \frac{1}{e^{\frac{(E-E_F)}{kT}} + 1} \quad \text{(occupancy probability)}.$$

The Fermi energy of a given material is the energy of a quantum state that has the probability 0.5 of being occupied by an electron.

$T = 0$ K

For $E < E_F$, the exponential term in is $e^{-\infty}$, or zero; so $P(E) = 1$

For $E > E_F$, the exponential term is $e^{+\infty}$; so $P(E) = 0$

$T = 1000$ K

changes in the distribution of electrons among the available states involve only states whose energies are near the Fermi energy E_F

For $E = E_F$, $P(E) = 0.5$

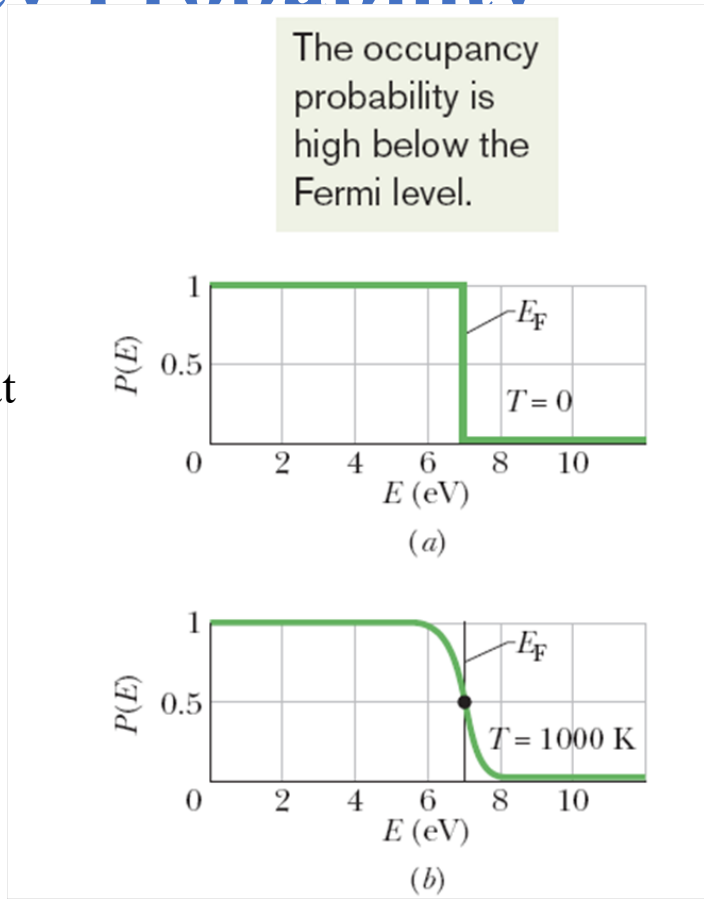


Figure 41-7 The occupancy probability $P(E)$ is the probability that an energy level will be occupied by an electron. (*a*) At $T = 0$ K, $P(E)$ is unity for levels with energies E up to the Fermi energy E_F and zero for levels with higher energies. (*b*) At $T = 1000$ K, a few electrons whose energies were slightly less than the Fermi energy at $T = 0$ K move up to states with energies slightly greater than the Fermi energy. The dot on the curve shows that, for E E_F, $P(E) = 0.5$.

41.5: Metals: The Occupancy Probability *P*(*E*):

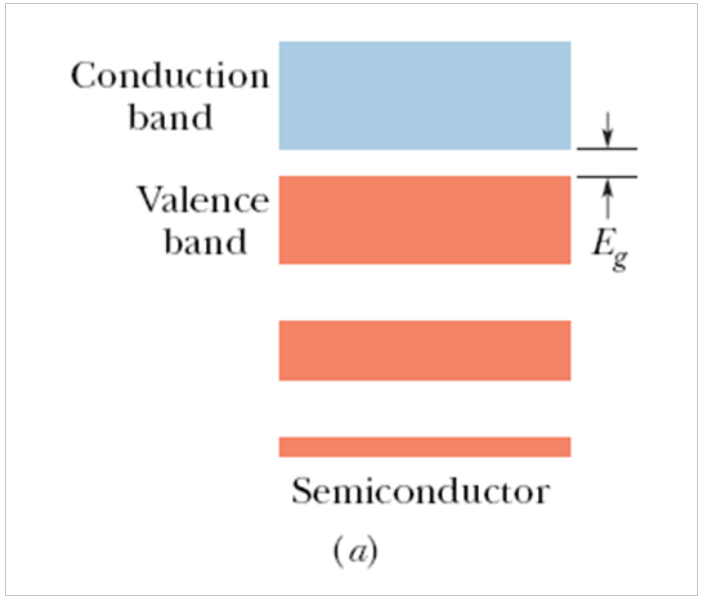
(a) What is the probability that a quantum state whose energy is 0.10 eV above the Fermi energy will be occupied? Assume a sample temperature of 800 K.

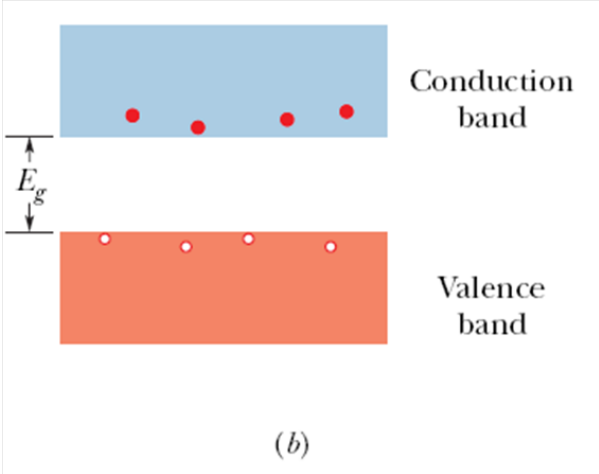
$$P(E) = \frac{1}{e^{\frac{(E-E_F)}{kT}} + 1} \quad (\text{occupancy probability}).$$

$$\frac{E - E_F}{kT} = \frac{0.10\ \text{eV}}{(8.62 \times 10^{-5}\ \text{eV/K})(800\ \text{K})} = 1.45.$$

$$P(E) = \frac{1}{e^{1.45} + 1} = 0.19 \text{ or } 19\%.$$

41.6: Semiconductors:





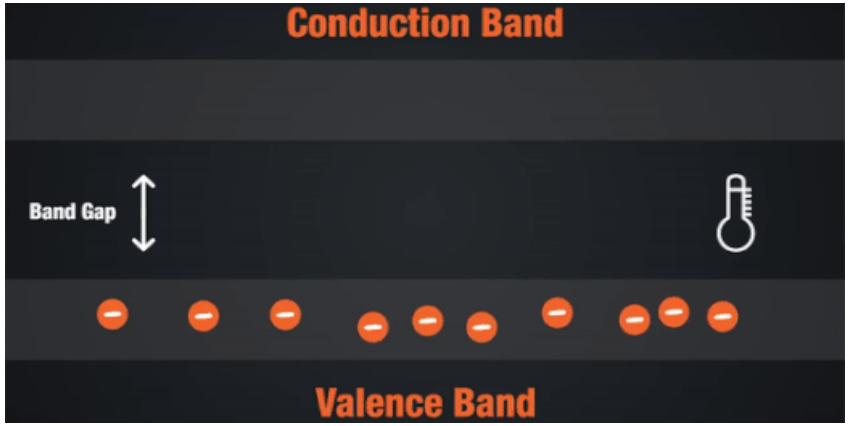


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Figure 41-9 (a) The band–gap pattern for a semiconductor. It resembles that of an insulator except that here the energy gap E_g is much smaller; thus electrons, because of their thermal agitation, have some reasonable probability of being able to jump the gap. (b) Thermal agitation has caused a few electrons to jump the gap from the valence band to the conduction band, leaving an equal number of holes in the valence band.

For example: silicon (E_g = 1.1 eV) *vs*. diamond (E_g = 5.5 eV)

there is a real possibility that thermal agitation at room temperature will cause electrons to jump the gap from valence to conduction band at silicon

41.6: Semiconductors: Temperature Coefficient of Resistivity:

$$\alpha = \frac{1}{\rho}\frac{d\rho}{dT}. \quad \text{(Here } \rho \text{ is the resistivity)} \qquad \rho = \rho_0(1 + \alpha\Delta T)$$

The resistivity of copper increases with temperature because collisions of copper's charge carriers occur more frequently at higher temperatures. This makes α positive for copper. The collision frequency also increases with temperature for silicon.

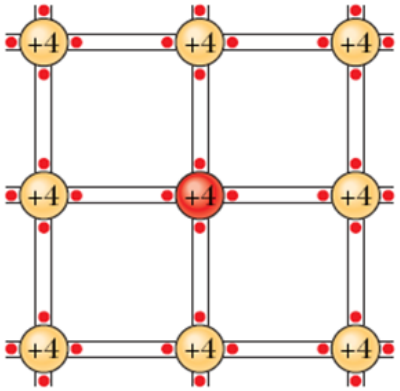
In contrast, the resistivity of silicon actually decreases with temperature since the number of charge carriers n (electrons in the conduction band and holes in the valence band) increases so rapidly with temperature. (More electrons jump the gap from the valence band to the conduction band.) Thus, the fractional change α is negative for silicon.

Table 26-1 Resistivities of Some Materials at Room Temperature (20°C)

Material	Resistivity, ρ ($\Omega \cdot$m)	Temperature Coefficient of Resistivity, α (K^{-1})
	Typical Metals	
Silver	1.62×10^{-8}	4.1×10^{-3}
Copper	1.69×10^{-8}	4.3×10^{-3}
Gold	2.35×10^{-8}	4.0×10^{-3}
Aluminum	2.75×10^{-8}	4.4×10^{-3}
Manganin[a]	4.82×10^{-8}	0.002×10^{-3}
Tungsten	5.25×10^{-8}	4.5×10^{-3}
Iron	9.68×10^{-8}	6.5×10^{-3}
Platinum	10.6×10^{-8}	3.9×10^{-3}
	Typical Semiconductors	
Silicon, pure	2.5×10^{3}	-70×10^{-3}
Silicon, *n*-type[b]	8.7×10^{-4}	
Silicon, *p*-type[c]	2.8×10^{-3}	
	Typical Insulators	
Glass	10^{10}–10^{14}	
Fused quartz	$\sim 10^{16}$	

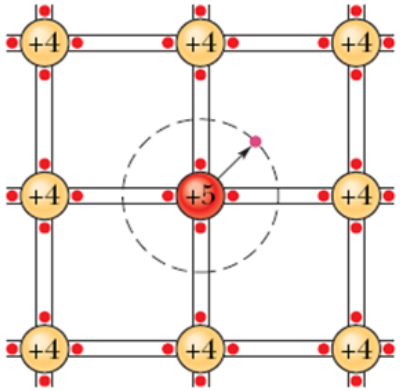
41.7: Doped Semiconductors: (1 of 3)

Introducing a small number of suitable replacement atoms (called impurities) into the semiconductor lattice—a process called **doping.**



(*a*)

pure



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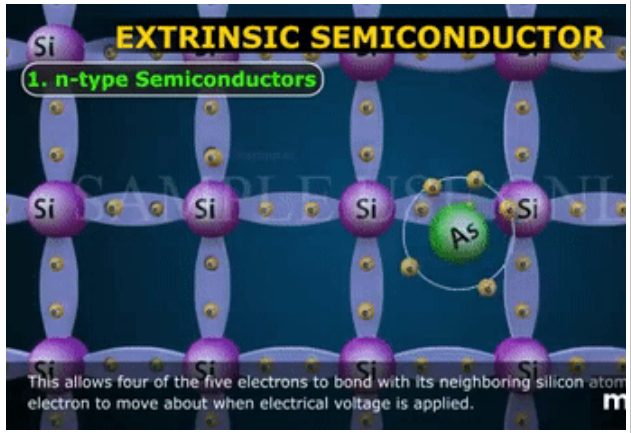
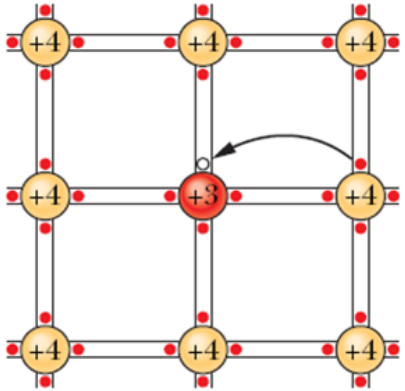
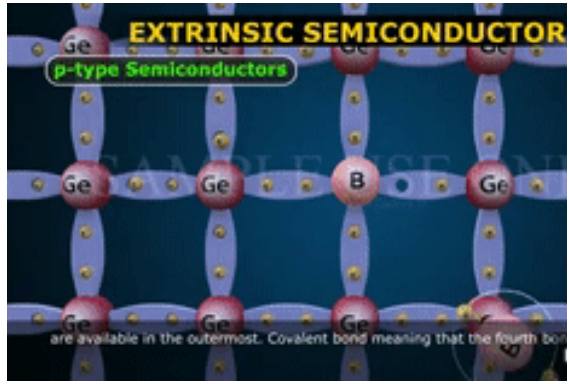


***n*-type**



(*c*)

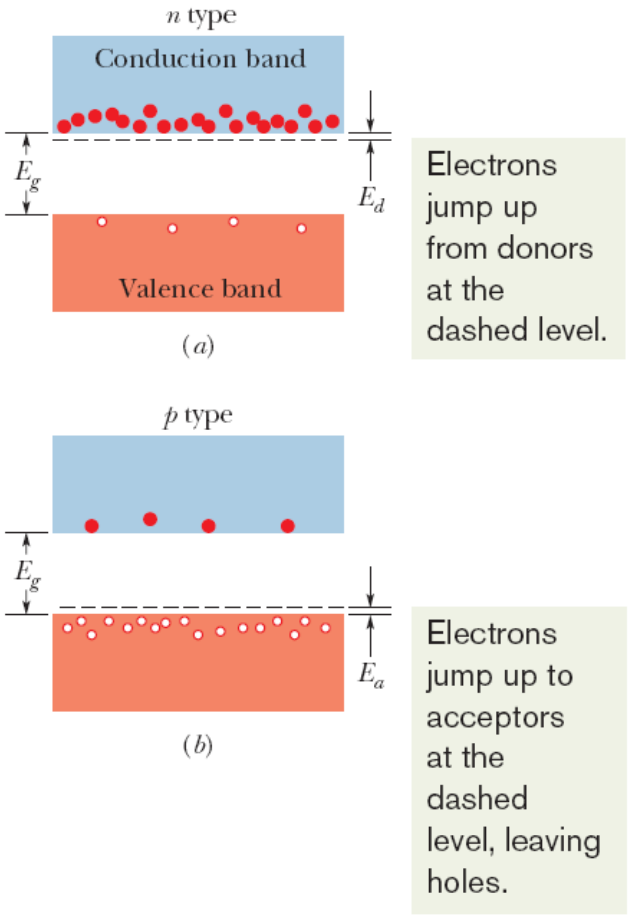


***p*-type**

Figure 41-10 (*a*) A flattened-out representation of the lattice structure of pure silicon. Each silicon ion is coupled to its four nearest neighbors by a two-electron covalent bond (represented by a pair of red dots between two parallel black lines).The electrons belong to the bond—not to the individual atoms—and form the valence band of the sample. (*b*) One silicon atom is replaced by a phosphorus atom (valence = 5). The "extra" electron is only loosely bound to its ion core and may easily be elevated to the conduction band, where it is free to wander through the volume of the lattice. (*c*) One silicon atom is replaced by an aluminum atom (valence = 3).There is now a hole in one of the covalent bonds and thus in the valence band of the sample. The hole can easily migrate through the lattice as electrons from neighboring bonds move in to fill it. Here the hole migrates rightward.

41.7: Doped Semiconductors: (2 of 3)

- In a doped *n*-type semiconductor, the energy levels of donor electrons lie a small interval E_d below the bottom of the conduction band. Because donor electrons can be easily excited to the conduction band, there are now many more electrons in that band. The valence band contains the same small number of holes as before the dopant was added.



- In a doped *p*-type semiconductor, the acceptor levels lie a small energy interval E_a above the top of the valence band. There are now many more holes in the valence band. The conduction band contains the same small number of electrons as before the dopant was added.

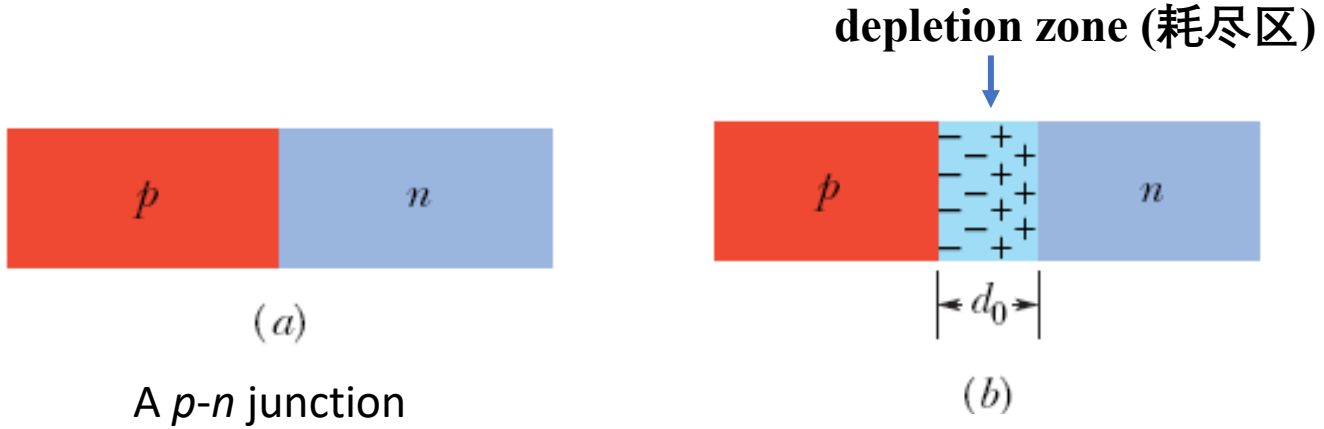
- In *n*-type semiconductors, the electrons are called the **majority carriers** and the holes are called the **minority carriers.** vice versa

41.7: Doped Semiconductors: (3 of 3)

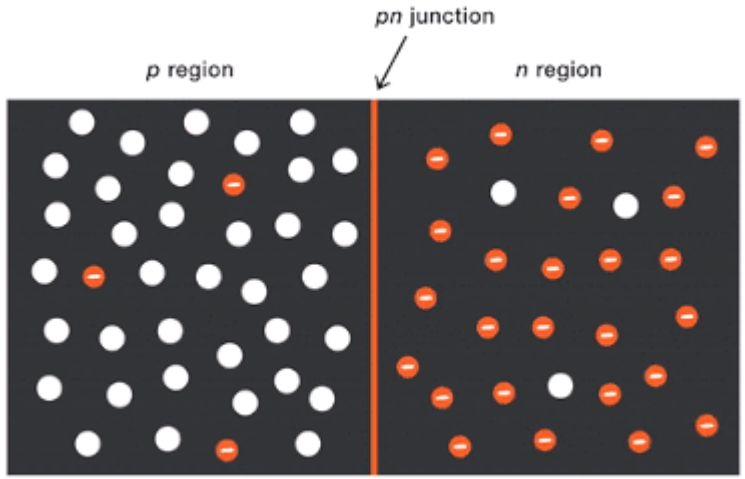
Table 41-2 Properties of Two Doped Semiconductors

Property	Type of Semiconductor	
	n	*p*
Matrix material	Silicon	Silicon
Matrix nuclear charge	$+14e$	$+14e$
Matrix energy gap	1.2 eV	1.2 eV
Dopant	Phosphorus	Aluminum
Type of dopant	Donor	Acceptor
Majority carriers	Electrons	Holes
Minority carriers	Holes	Electrons
Dopant energy gap	$E_d = 0.045$ eV	$E_a = 0.067$ eV
Dopant valence	5	3
Dopant nuclear charge	$+15e$	$+13e$
Dopant net ion charge	$+e$	$-e$

41.8: The *p*-*n* Junction:

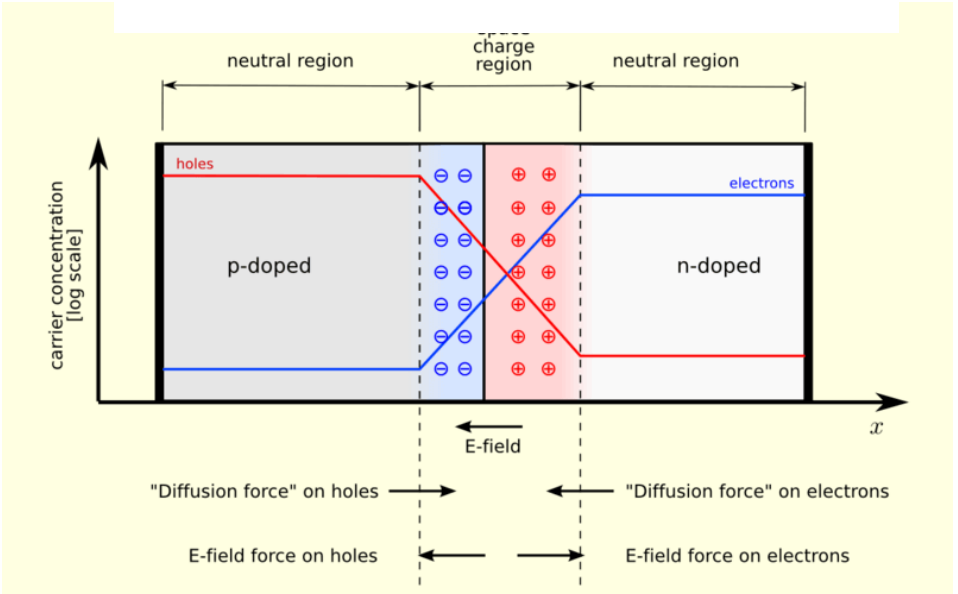


A *p*-*n* junction

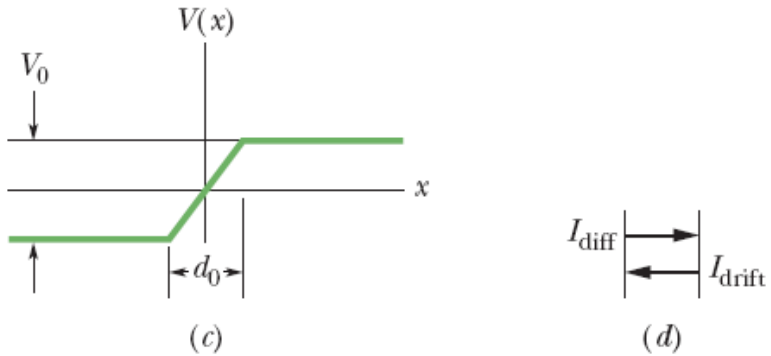


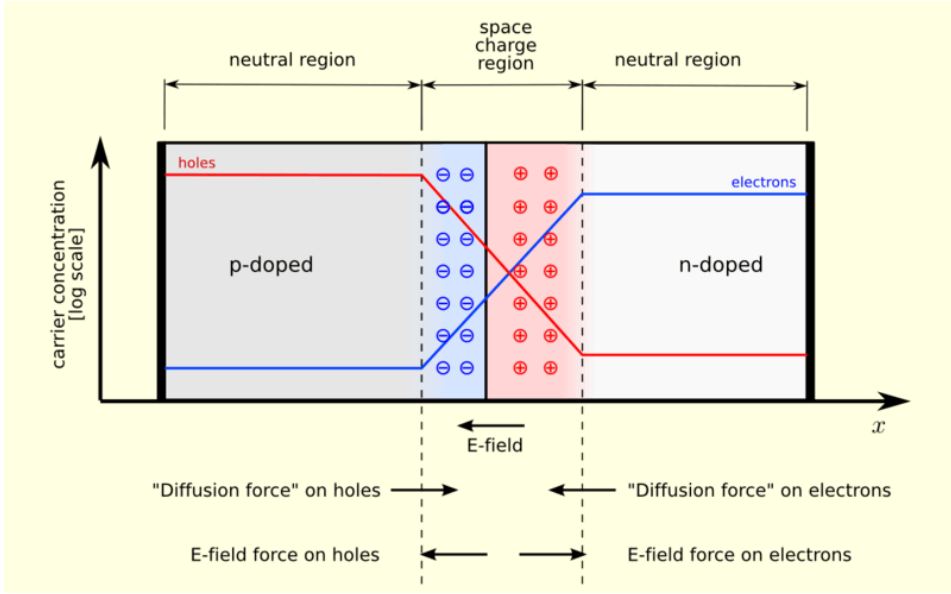
- electrons diffusing through the junction plane from right to left in result in a buildup of **space charge** on each side of the junction plane, with positive charge on the *n* side and negative charge on the *p* side.

- **depletion zone (耗尽区),** so named because it is relatively free of *mobile* charge carriers

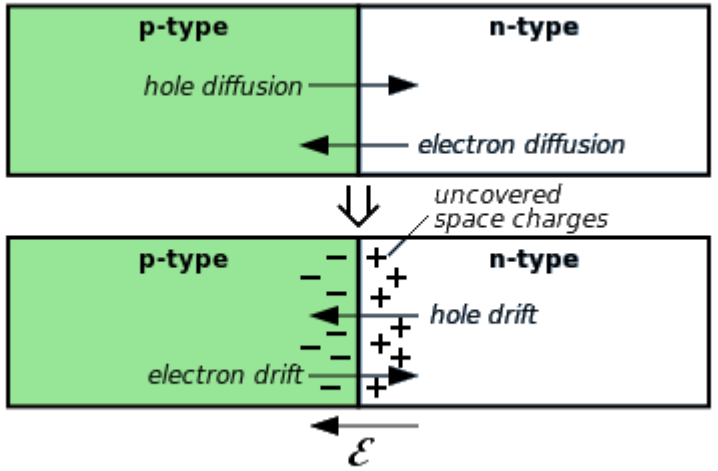


41.8: The *p-n* Junction:

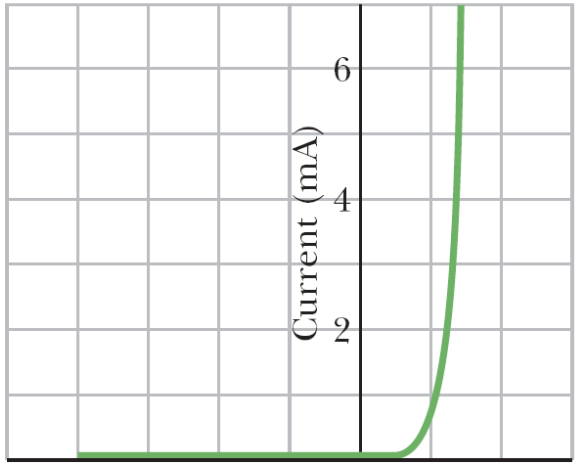




- Associated with the space charge is a contact potential difference V_0 across d_0.
- The motions of both the electrons and the holes contribute to a **diffusion current** $I_{diff,}$ conventionally directed from left to right.
- both types of minority carriers are *swept across* the junction plane by the contact potential difference and together constitute a **drift current** I_{drift} across the junction plane from right to left



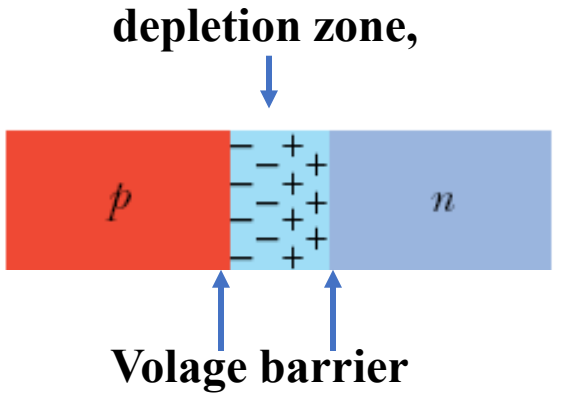
41.9: The Junction Rectifier 整流器

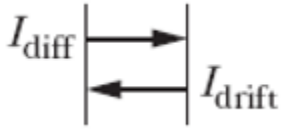


If a potential difference is applied across a *p*-*n* junction in one direction (here labeled and Forward bias"), there will be a current through the junction.

However, if the direction of the potential Difference is reversed, there will be approximately zero current through the junction.

Figure 41-13 A current–voltage plot for a *p*-*n* junction, showing that the junction is highly conducting when forward-biased and essentially nonconducting when back-biased.



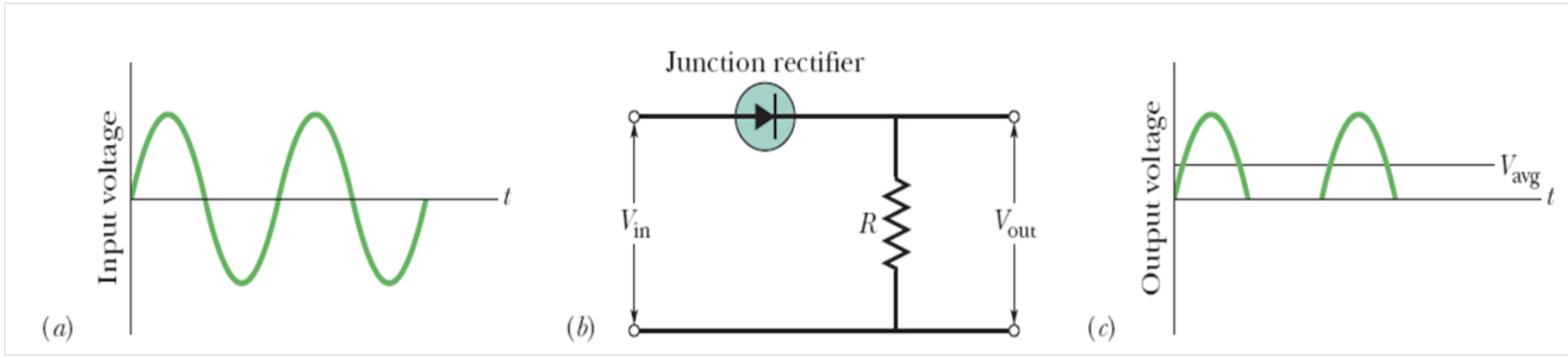


An isolated *p*-*n* junction is in an equilibrium state in which a contact potential difference V_0 exists between its ends.

At equilibrium, the average diffusion current I_{diff} that moves through the junction plane from the *p* side to the *n* side is just balanced by an average drift current I_{drift} that moves in the opposite direction.

These two currents cancel because the net current through the junction plane must be zero; otherwise charge would be transferred without limit from one end of the junction to the other.

41.9: The Junction Rectifier, An Example: (1 of 2)

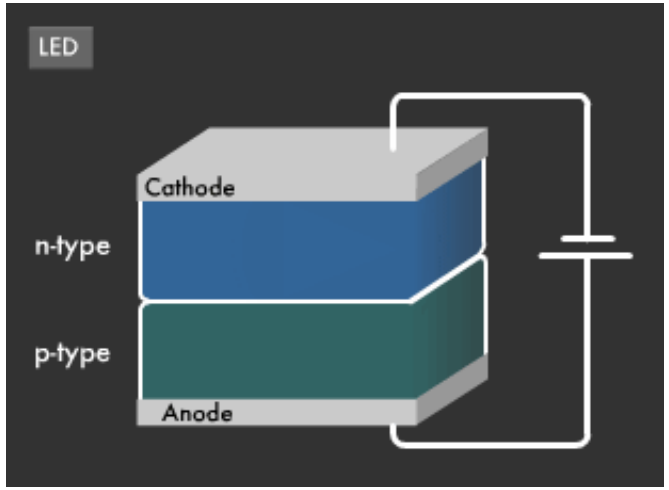


The rectifier acts as essentially a closed switch (zero resistance) for one polarity of the input potential and as essentially an open switch (infinite resistance) for the other.

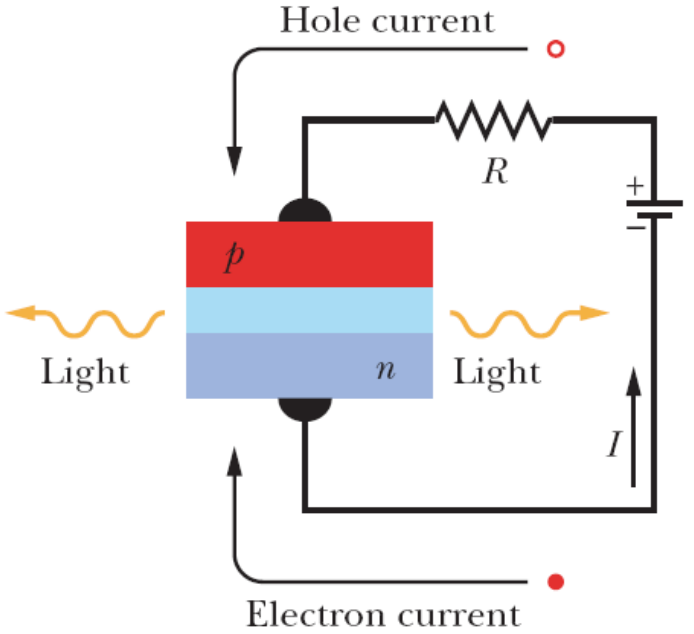
The average input voltage is zero, but the average output voltage is not.

Figure 41-14 A *p-n* junction connected as a junction rectifier. The action of the circuit in (*b*) is to pass the positive half of the input wave form in (*a*) but to suppress the negative half. The average potential of the input wave form is zero; that of the output wave form in (*c*) has a positive value V_{avg}.

41.10: The Light-Emitting Diode (LED): (1 of 5)



Source: Canon Technology



- A forward-biased *p*-*n* junction, showing electrons being injected into the *n*-type material and holes into the *p*-type material. (Holes move in the conventional direction of the current *I*, equivalent to electrons moving in the opposite direction.) Light is emitted from the narrow depletion zone each time an electron and a hole combine across that zone.
- the energy can be emitted as a photon of energy *hf* at wavelength

$$\lambda = \frac{c}{f} = \frac{c}{E_g/h} = \frac{hc}{E_g}.$$

Example, Light Emitting Diode (LED):

An LED is constructed from a *p*-*n* junction based on a certain Ga-As-P semiconducting material whose energy gap is 1.9 eV. What is the wavelength of the emitted light?

$$\lambda = \frac{c}{f} = \frac{c}{E_g/h} = \frac{hc}{E_g}.$$

$$\lambda = \frac{hc}{E_g} = \frac{\left(6.63\times10^{-34}\,\text{J}\cdot\text{s}\right)\left(3.00\times10^{8}\,\text{m/s}\right)}{\left(1.9\,\text{eV}\right)\left(1.60\times10^{-19}\,\text{J/eV}\right)}$$

$$= 6.5\times10^{-7}\,\text{m} = 650\,\text{nm}. \quad \textbf{(Answer)}$$

Light of this wavelength is red.

Review & Summary

Metals, Semiconductors, and Insulators Three electrical properties that can be used to distinguish among crystalline solids are **resistivity** ρ, **temperature coefficient of resistivity** α, and **number density of charge carriers** n. Solids can be broadly divided into **insulators** (very high ρ), **metals** (low ρ, positive and low α, large n), and **semiconductors** (high ρ, negative and high α, small n).

Energy Levels and Gaps in a Crystalline Solid An isolated atom can exist in only a discrete set of energy levels. As atoms come together to form a solid, the levels of the individual atoms merge to form the discrete energy **bands** of the solid. These energy bands are separated by energy **gaps,** each of which corresponds to a range of energies that no electron may possess.

Any energy band is made up of an enormous number of very closely spaced levels. The Pauli exclusion principle asserts that only one electron may occupy each of these levels.

Insulators In an insulator, the highest band containing electrons is completely filled and is separated from the vacant band above it by an energy gap so large that electrons can essentially never become thermally agitated enough to jump across the gap.

Review & Summary

Metals In a metal, the highest band that contains any electrons is only partially filled. The energy of the highest filled level at a temperature of 0 K is called the **Fermi energy** E_F for the metal.

The **occupancy probability** $P(E)$, the probability that a given available state will be occupied by an electron, is

$$P(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \quad \text{(occupancy probability).} \qquad (41\text{-}6)$$

Semiconductors The band structure of a semiconductor is like that of an insulator except that the gap width E_g is much smaller in the semiconductor. For silicon (a semiconductor) at room temperature, thermal agitation raises a few electrons to the **conduction band,** leaving an equal number of **holes** in the **valence band.** Both electrons and holes serve as charge carriers. The number of electrons in the conduction band of silicon can be increased greatly by doping with small amounts of phosphorus, thus forming ***n*-type material.** The number of holes in the valence band can be greatly increased by doping with aluminum, thus forming ***p*-type material.**

Review & Summary

The *p-n* Junction A ***p-n* junction** is a single semiconducting crystal with one end doped to form *p*-type material and the other end doped to form *n*-type material, the two types meeting at a **junction plane.** At thermal equilibrium, the following occurs at that plane:

The **majority carriers** (electrons on the *n* side and holes on the *p* side) diffuse across the junction plane, producing a **diffusion current** I_{diff}.

The **minority carriers** (holes on the *n* side and electrons on the *p* side) are swept across the junction plane, forming a **drift current** I_{drift}. These two currents are equal in magnitude, making the net current zero.

A **depletion zone,** consisting largely of charged donor and acceptor ions, forms across the junction plane.

A **contact potential difference** V_0 develops across the depletion zone.

Applications of the *p-n* Junction When a potential difference is applied across a *p-n* junction, the device conducts electricity more readily for one polarity of the applied potential difference than for the other. Thus, a *p-n* junction can serve as a **junction rectifier.**

When a *p-n* junction is forward biased, it can emit light, hence can serve as a **light-emitting diode** (LED). The wavelength of the emitted light is given by

$$\lambda = \frac{c}{f} = \frac{hc}{E_g}. \qquad (41\text{-}11)$$

A strongly forward-biased *p-n* junction with parallel end faces can operate as a **junction laser,** emitting light of a sharply defined wavelength.

40.2.3. The figure shows an energy level diagram for the hydrogen atom. Several transitions are shown and are labeled by letters. **Note**: *The diagram is not drawn to scale.* Which transition corresponds to the absorption of the photon with the longest wavelength?

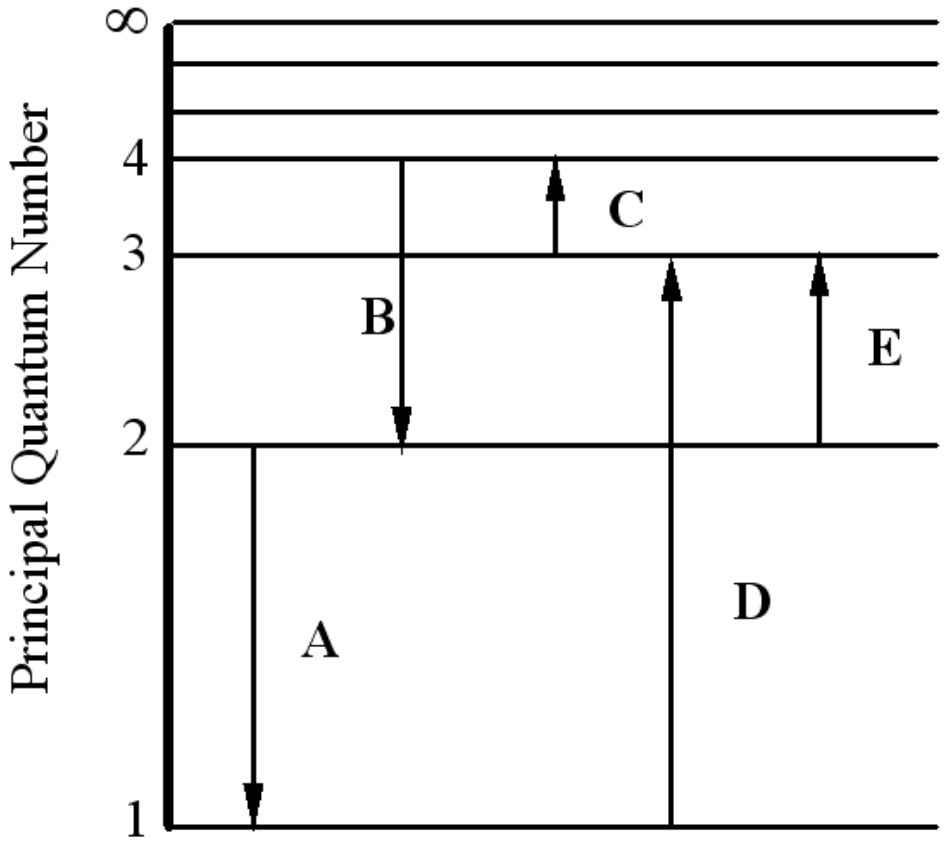
a) A

b) B

c) C

d) D

e) E



$$E_n = -\frac{13.60\ \text{eV}}{n^2}, \quad \text{for } n = 1,2,3,\ldots.$$

$$E_1 = \frac{-13.6}{1^2}eV = -13.6eV,$$

$$E_2 = \frac{-13.6}{2^2}eV = -3.4eV,$$

$$E_3 = \frac{-13.6}{3^2}eV = -1.51eV,$$

$$E_4 = \frac{-13.6}{4^2}eV = -0.85eV, E_\infty = 0.$$

40.2.3. The figure shows an energy level diagram for the hydrogen atom. Several transitions are shown and are labeled by letters. **Note**: *The diagram is not drawn to scale.* Which transition corresponds to the absorption of the photon with the longest wavelength?

a) A

b) B

c) C

d) D

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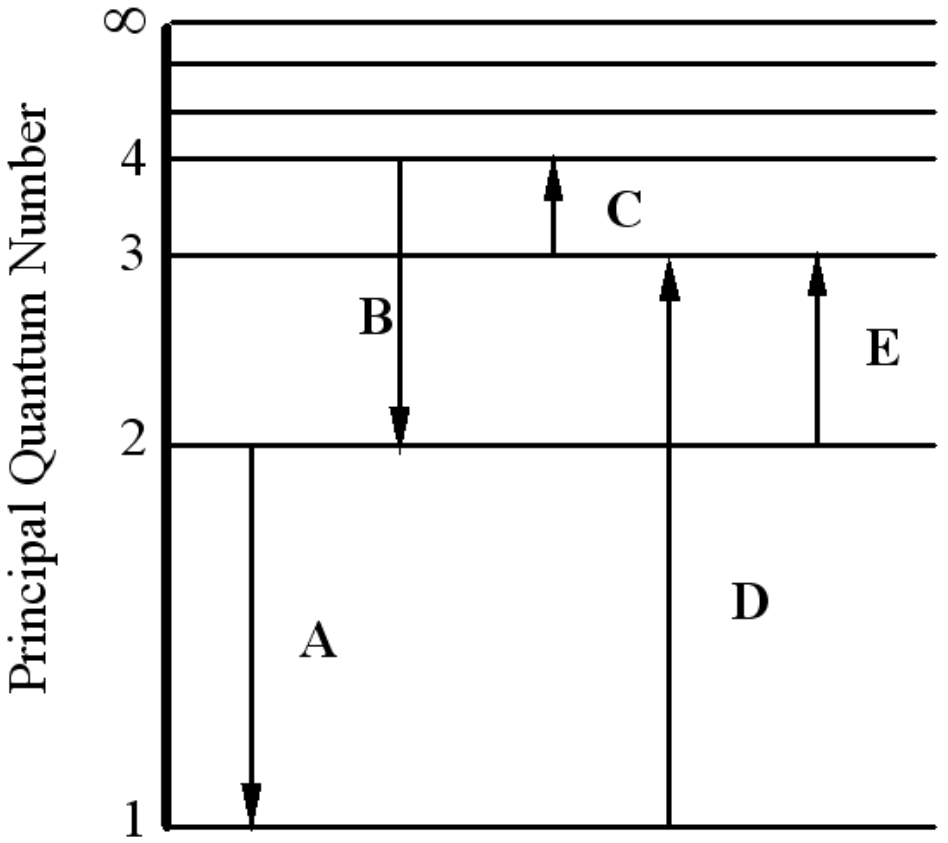

40.3.2. A hydrogen atom is in a state for which the principle quantum number is six and the magnetic quantum number is three. What are the possible values for the orbital quantum number?

a) 0 or 3 only

b) 3 or 5 only

c) 4 or 6 only

d) 3, 4, or 5 only

e) 4, 5, or 6 only

Table 40-1 Electron States for an Atom

Quantum Number	Symbol	Allowed Values	Related to
Principal	n	1,2,3, . . .	Distance from the nucleus
Orbital	ℓ	0, 1, 2, . . . , $(n-1)$	Orbital angular momentum
Orbital magnetic	m_ℓ	$0, \pm 1, \pm 2, \ldots, \pm \ell$	Orbital angular momentum (z component)
Spin	s	$\frac{1}{2}$	Spin angular momentum
Spin magnetic	m_s	$\pm \frac{1}{2}$	Spin angular momentum (z component)

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d) 3, 4, or 5 only

e) 4, 5, or 6 only

40.9.3. A neutral atom has the following electronic configuration: $1s^2 2s^2 2p^5$. How many protons are in the nucleus of this atom?

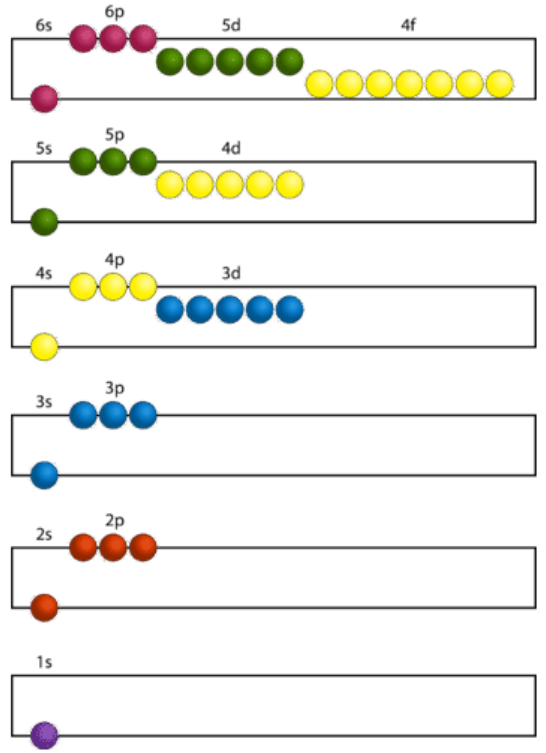
a) 3

b) 5

c) 9

d) 16

e) There is no way to tell from an electron configuration.



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c) 9

d) 16

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40.9.5. The ground state electronic configuration of a neon atom is $1s^2$ $2s^2$ $2p^6$. How many of these electrons have magnetic quantum number $m_l = 0$?

a) 2

b) 4

c) 6

d) 8

e) 10

40.9.5. The ground state electronic configuration of a neon atom is $1s^2$ $2s^2$ $2p^6$. How many of these electrons have magnetic quantum number $m_l = 0$?

a) 2

b) 4

c) 6

d) 8

e) 10

41.6.1. Which of the following features is the main difference between insulators and semiconductors?

a) The energy gap between the conduction band and the valence band is larger for insulators.

b) The energy gap between the conduction band and the valence band is smaller for insulators.

c) The width of the valence band is larger for semiconductors.

d) The width of the conduction band is larger for semiconductors.

e) The width of the conduction band is smaller for semiconductors.

41.6.1. Which of the following features is the main difference between insulators and semiconductors?

a) The energy gap between the conduction band and the valence band is larger for insulators.

b) The energy gap between the conduction band and the valence band is smaller for insulators.

c) The width of the valence band is larger for semiconductors.

d) The width of the conduction band is larger for semiconductors.

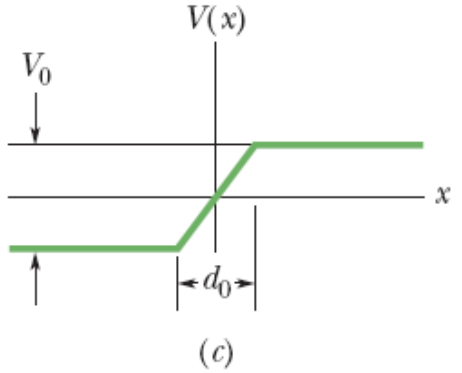
e) The width of the conduction band is smaller for semiconductors.

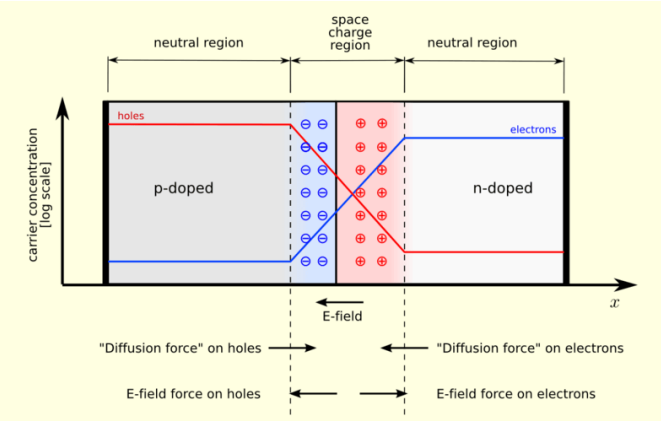
41.8.1. A junction is formed that consists of *n* type semiconducting material on the left and *p* type semiconducting material on the right. What is the direction of the electric field for this *pn*-junction, if any?

a) If the junction is not connected to a battery, there will be no electric field.

b) The direction is from left to right.

c) The direction is from right to left.





d) There is no electric field because of the presence of the depletion zone.

41.8.1. A junction is formed that consists of *n* type semiconducting material on the left and *p* type semiconducting material on the right. What is the direction of the electric field for this *pn*-junction, if any?

a) If the junction is not connected to a battery, there will be no electric field.

b) The direction is from left to right.

c) The direction is from right to left.

d) There is no electric field because of the presence of the depletion zone.

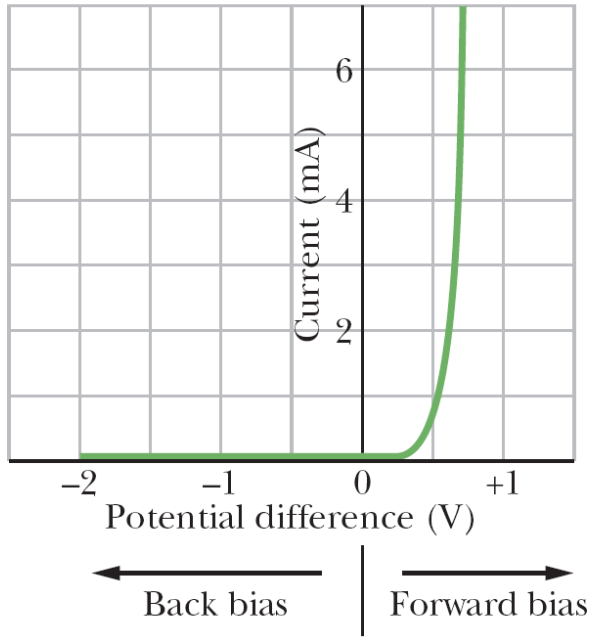
41.8.2. Does a *pn*-junction obey Ohm's law when it is forward-biased?

a) No, the current does not increase linearly with voltage for all voltages.

b) Yes, the current does increase linearly with voltage for all voltages.

c) Yes, the current does increase linearly for small voltages

d) Yes, the current does increase linearly for high voltages.



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UFUG 1504 - Honors General Physics II

Section	Instructor	No. of Students	Date	Time	Venue
L01	WU, Jiaying	9	13-Dec-2024	02:00PM - 04:00PM	Rm 122, E1
L02	LI, Haoxiang	10	13-Dec-2024	02:00PM - 04:00PM	Rm 122, E1
L03	LIN, Yuanbao	16	13-Dec-2024	02:00PM - 04:00PM	Rm 122, E1

Assessment

- In-class quiz: 20%
- End-modulus exam: 50%
- Written assignment: 20%
- Lab reports: 10%

找我（林源宝）， M2随时来查

Lab reports 有问题的找潘泽昊老师

Noted: M1 (35%) M2 (35%) M3(30%)

Final Grade	Level
Top 1 or 95+	A+
Top x or >90	A
90~80	B~A-
70~80	C~B-

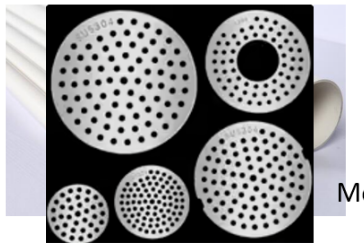
M3: 20道不难的单选题。争取90+

Assessment

26-3 Resistance and Resistivity (5 of 8)

electrical resistance $R = \dfrac{V}{i}$ (definition of R).

Resistance is a property of an object. Resistivity is a property of a material.



Thick wire → Pass quickly →small resistance

Long wire → Passs slowly →large resistance

More barriers in wire → Passs slowly →large resistance

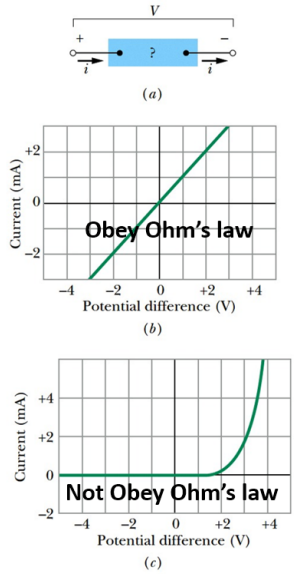
26-4 Ohm's Law (6 of 9)

Ohm's law is an assertion that the current through a device is always directly proportional to the potential difference applied to the device.

$$I \sim V \quad \text{or} \quad I = \frac{V}{R}$$

A conducting device obeys Ohm's law when the resistance of the device is independent of the magnitude and polarity of the applied potential difference.

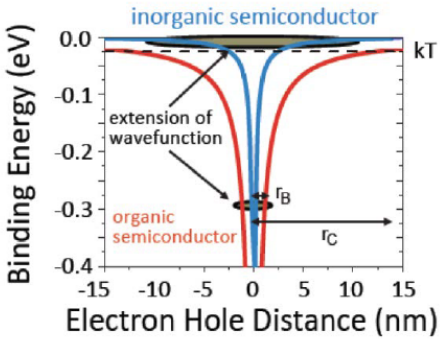
A conducting material obeys Ohm's law when the resistivity of the material is independent of the magnitude and direction of the applied electric field.



Assessment

1 Which types of excitons do you know?

Frenkel excitons (le(exciton size)<a(lattice constant)) spatially-limited to one molecule only. Energy migration happens by energy transfer via Förster or Dexter mechanisms. Frenkel excitons are frequently observed in molecular crystals and ionic crystals. **Mott-Wannier excitons** (le>>a) are highly-delocalized excited states, which typically spread over many lattice constants. exist in inorganic semi-conductors such as Si and Ge. **Charge-Transfer Excitons** (le~a) exist for example in donor-acceptor crystals, which show charge transfer transitions between the HOMO of the D and the LUMO of the A molecules. Electron and hole are spread over A and D, but have to move simultaneously like for a Frenkel-type exciton.



2 How do they differ in terms of binding energy and why? Frenkel excitons are spatially-limited to one molecule only with coulomb interaction between an electron and a hole from same cell, so the binding energy around 0.1~1 eV. Mott-Wannier excitons typically spread over many lattice constants and the rate of electron and hole hopping between different cells much exceeds the strength of their Coulomb coupling with each other, so the binding energy around is very small only 0.01 eV

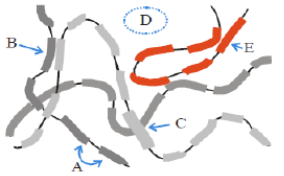
3 How do excitons diffuse in amorphous disordered organic semiconductors? In molecular crystals, exciton migration occurs mostly via energy transfer between individual molecules. It follows an **incoherent**, **statistical hopping process** in most cases. However, in highly pure single crystals and at low temperatures < 10 K, coherent excitons can also appear in organic systems.

4 Which energy transfer mechanism dominates in singlet state energy transfer and which in triplet state energy transfer and why?

the Dexter energy need the wavefunctions of D and A overlap spatially and the typical distance for Dexter energy transfer mechanism is only R= 0.5~1 nm, so for singlet state energy transfer is Förster mechanism since its R around 10 nm. For EnT of triplet states is the Dexter mechanism. Triplet state EnT is improbable by the Förster mechanism, because it requires two simultaneous dipole-dipole transitions (and corresponding spin changes) between singlet and triplet states.

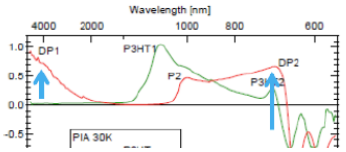
5 What's the exciton binding energy in organic materials and how is it different from inorganic materials?

an excited electron can be coulombically bound to a hole creating what is called an exciton located within the exciton band (EB), ΔE_e = CB-EB, for organic materials is around 0.3-1 eV, which is much higher than that of inorganic materials is around 0.01 eV..



A: Intrachain energy transfer B: Interchain ET
C: cross-points D: free volume E: Intra(inter)chain ET

6 Which experiments would you conduct to distinguish between weakly and strongly bound excitons? measuring the excitation spectrum of the photocurrent I_{ph} and absorption spectra, and compared the onset of absorption at $\lambda 0$ and the onset of photocurrent Iph generation at λg, if λg < λ0 the main absorption band corresponds to a strongly-bound exciton. if λg ~ λ0 Implies a band-to-band transition and generation of weakly-bound excitons.



Student Feedback Questionnaire Survey will be closed on **6 December 2024**

E1-615,
yuanbaolin@hkust-gz.edu.cn