



جلسه ۶

Energy Bands and Carrier Concentration in Thermal Equilibrium

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 - ▶ 1.3 VALENCE BONDS
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- The actual energy-momentum relationships (also called energy-band diagram) for silicon and gallium arsenide are much more complex.
- Visualized in three dimensions, the relationship between E and p is a complex surface.
- They are shown in Fig. 14 only for two crystal directions.
- Since the periodicity of most lattice is different in various directions, the energy-momentum diagram is also different for different directions.
- In the case of the diamond or zincblende lattice, the maximum in the valence band and minimum in the conduction band occur at $p = 0$ or along one of these two directions.

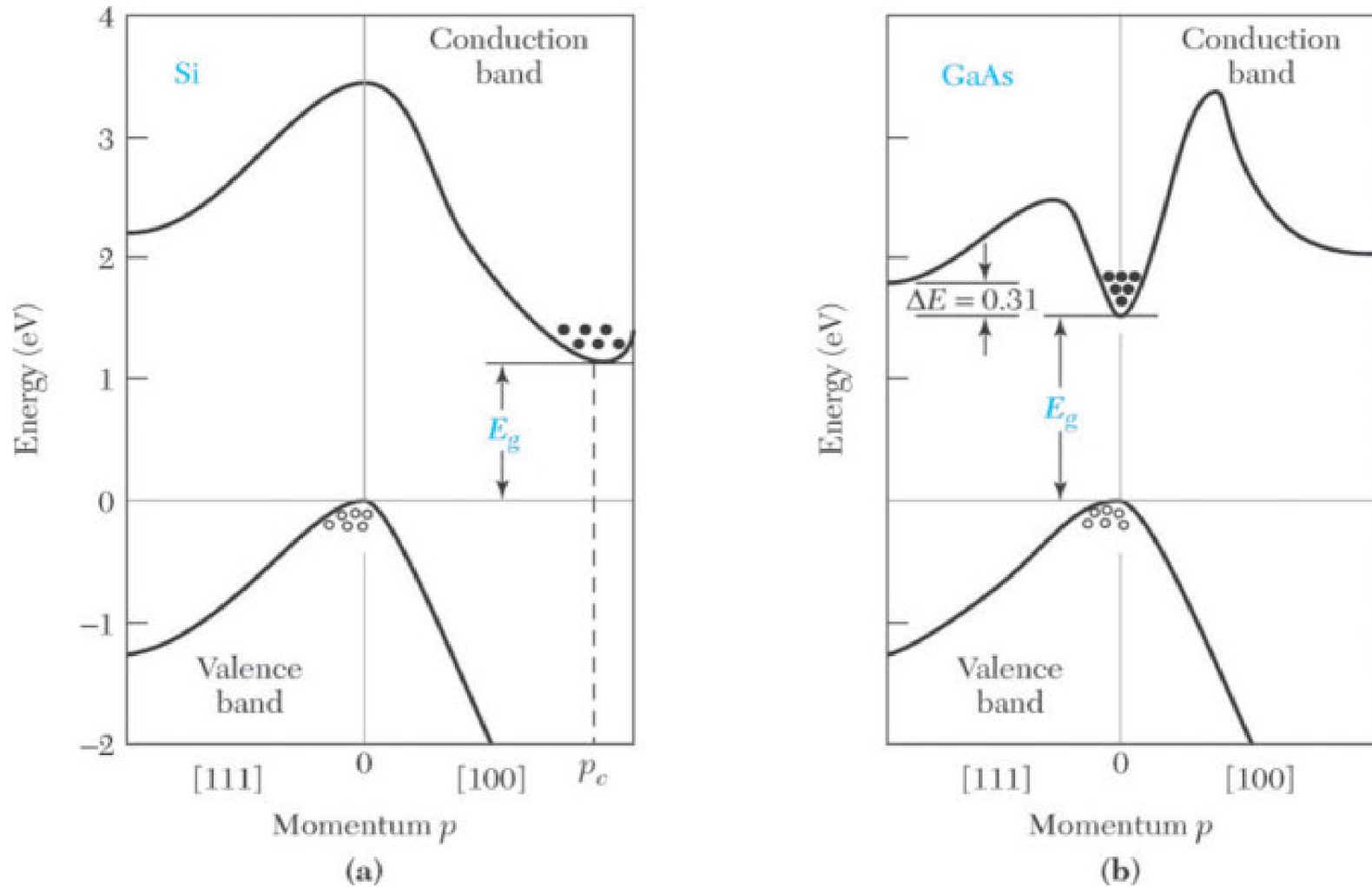


Fig. 14 Energy band structures of (a) Si and (b) GaAs. Circles (o) indicate holes in the valence bands and dots (•) indicate electrons in the conduction bands.

- If the minimum of the conduction band occurs at $p = 0$, this means the effective mass of the electrons in every direction in the crystal is the same. It also indicates that the electron motion is independent of crystal direction.
- If the minimum of the conduction band occurs at $p \neq 0$, this means that the electron behavior in every direction is not the same in the crystal.
- ↓ ➤ In general, the minimum of conduction band of polar (with partly ionic binding) semiconductors tend to be at $p = 0$.

- We note that the general features in Fig. 14 are similar to those in Fig. 13.
- First of all, the valence bands are simpler than the conduction bands. They are qualitatively similar for most semiconductors because the environments for holes moving in the covalent bonds are similar due to the similar structures in diamond and zincblende.
- There is a bandgap E_g between the bottom of the conduction band and the top of the valence band.
- Near the minimum of the conduction band or the maximum of the valence band, the E-p curves are essentially parabolic.

➤ For silicon (Fig. 14a) the maximum in the valence band occurs at $p = 0$, but the minimum in the conduction band occurs along the $[100]$ direction at $p = p_c$. Therefore, in silicon, when an electron makes a transition from the maximum point in the valence band to the minimum point in the conduction band, not only an energy change ($\geq E_g$) but also some momentum change ($\geq p_c$) is required.

➤ For gallium arsenide (Fig. 14b) the maximum in the valence band and the minimum in the conduction band occur at the same momentum ($p = 0$). Thus, an electron making a transition from the valence band to the conduction band can do so without a change in momentum.

- Gallium arsenide is called a direct semiconductor because it does not require a change in momentum for an electron transition from the valence band to the conduction band.
- Silicon is called an indirect semiconductor because a change of momentum is required in a transition.
- This difference between direct and indirect band structures is very important for light-emitting diodes and semiconductor lasers.
- These devices require direct semiconductors to generate efficiently photons (see Chapters 9 and 10).

➤ We can obtain the effective mass from Fig. 14 using Eq. 5.

$$m_n \equiv \left(\frac{d^2 E}{dp^2} \right)^{-1} . \quad (5)$$

➤ For example, for gallium arsenide with a very narrow conduction–band parabola, the electron effective mass is $0.063m_0$, while for silicon, with a wider conduction–band parabola, the electron effective mass is $0.19m_0$.

1.4.3 Conduction in Metals, Semiconductors, and Insulators

- ❖ The enormous variation in electrical conductivity of metals, semiconductors, and insulators shown in Fig. 1 may be explained qualitatively in terms of their energy bands.
- ❖ Figure 15 shows the energy band diagrams of three classes of solids—metals, semiconductors, and insulators.

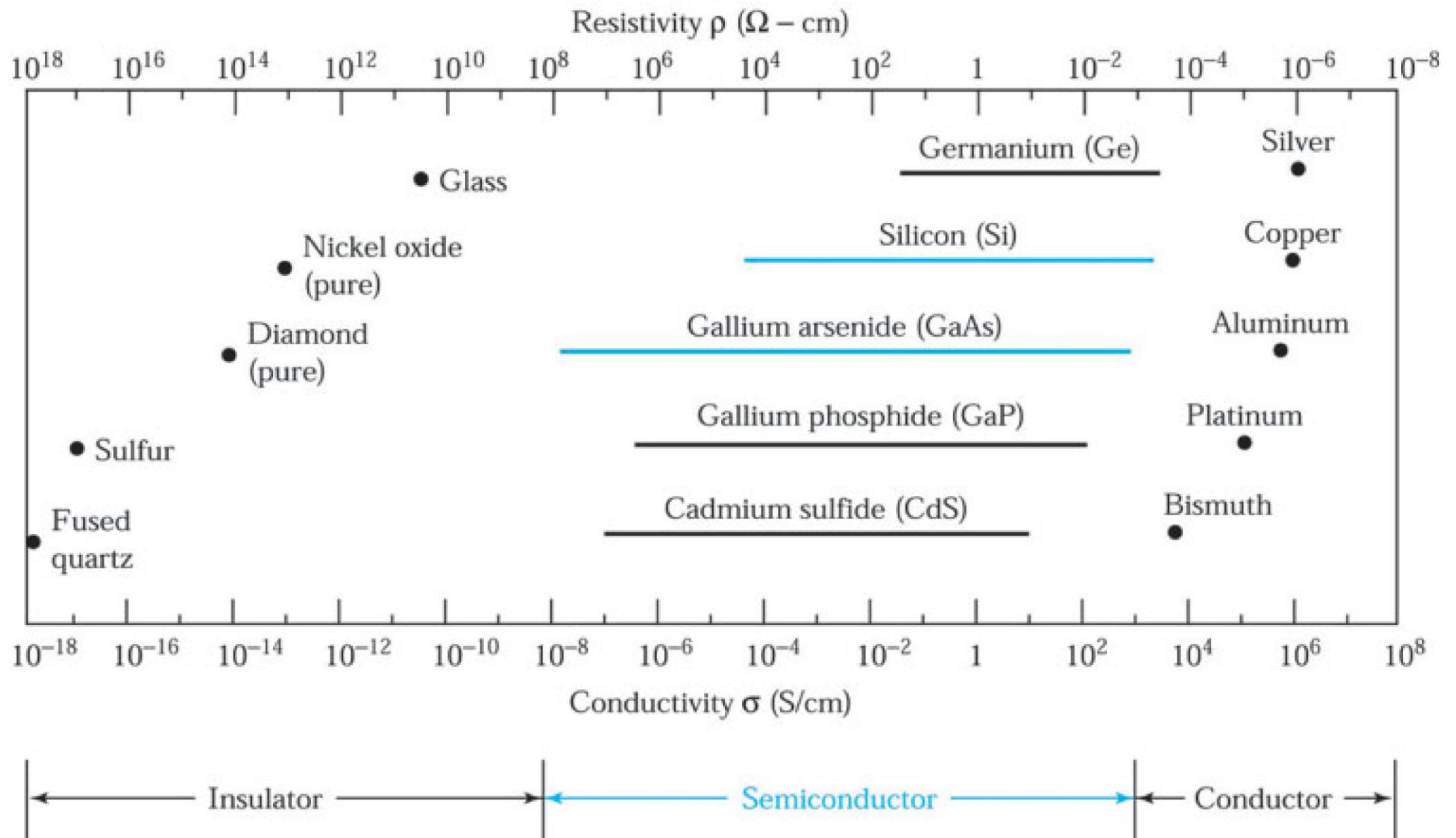


Fig. 1 Typical range of conductivities for insulators, semiconductors, and conductors.

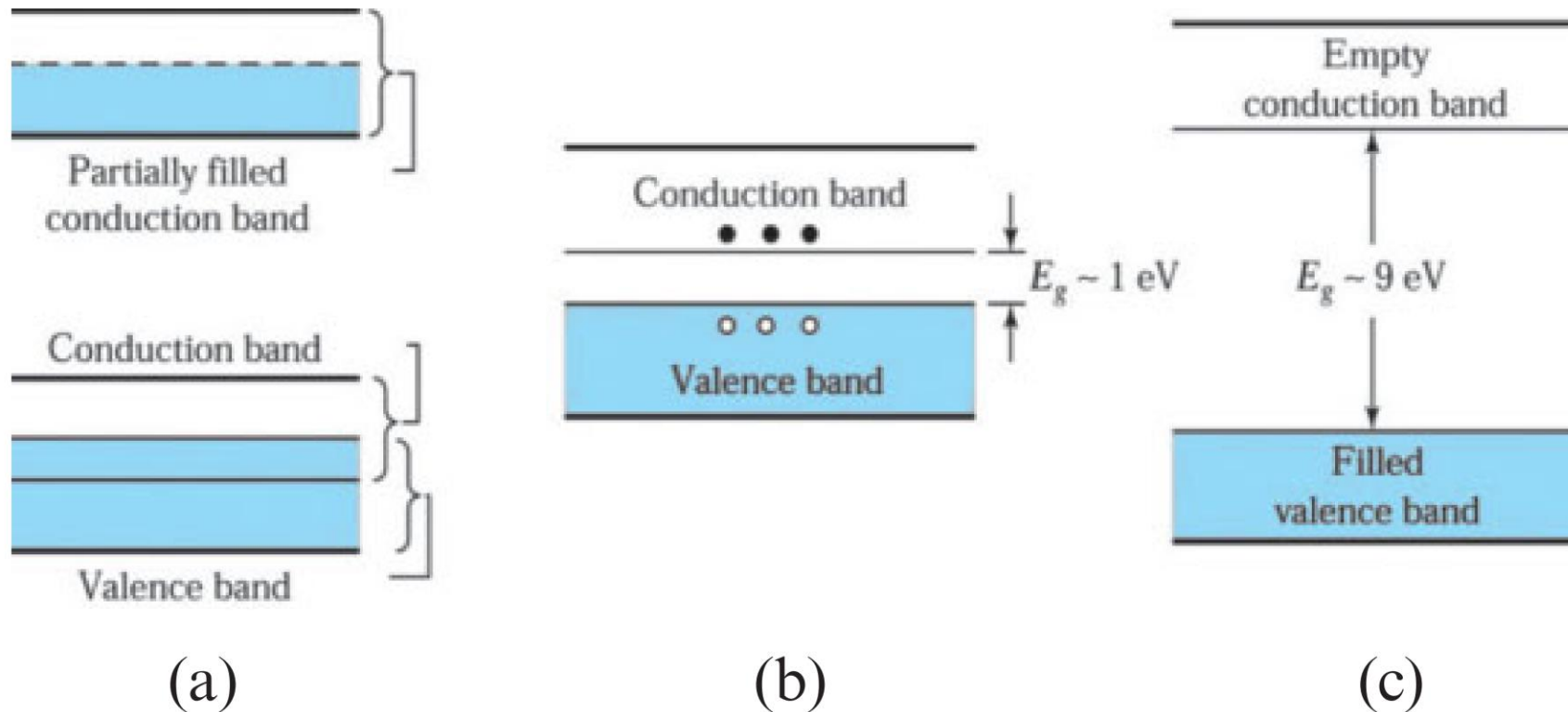


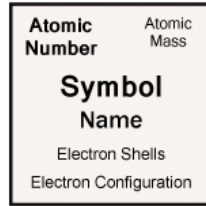
Fig. 15 Schematic energy band representations of (a) a conductor with two possibilities (either the partially filled conduction band shown at the upper portion or the overlapping bands shown at the lower portion), (b) a semiconductor, and (c) an insulator.

Metals

- ❖ The characteristics of a metal (also called a conductor) include a very low value of resistivity and a conduction band that either is partially filled (as in Cu) or overlaps the valence band (as in Zn or Pb) so that there is no bandgap, as shown in Fig. 15a.
- ❖ As a consequence, the uppermost (بالا يی) electrons in the partially filled band or electrons at the top of the valence band can move to the next higher available energy level when they gain kinetic energy (e.g., from an applied electric field).

Periodic Table of the Elements

1	1A 1A	2											13	14	15	16	17	18
1	IA 1A	2											3A 3A	4A 4A	5A 5A	6A 6A	7A 7A	VIIIA 8A
1	1	2											5	6	7	8	9	10
2	3	4											13	14	15	16	17	18
3	11	12	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
6	55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
7	87	88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118



Element symbol represents state at room temperature.

Solid, Liquid or Gas

Lanthanide Series

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
[Xe]5d ¹ 6s ²	[Xe]4f ¹ 5d ¹ 6s ²	[Xe]4f ³ 6s ²	[Xe]4f ⁴ 6s ²	[Xe]4f ⁵ 6s ²	[Xe]4f ⁶ 6s ²	[Xe]4f ⁷ 6s ²	[Xe]4f ⁷ 5d ¹ 6s ²	[Xe]4f ⁹ 6s ²	[Xe]4f ¹⁰ 6s ²	[Xe]4f ¹¹ 6s ²	[Xe]4f ¹² 6s ²	[Xe]4f ¹³ 6s ²	[Xe]4f ¹⁴ 6s ²	[Xe]4f ¹⁴ 5d ¹ 6s ²

Actinide Series

89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium
[Rn]6d ¹ 7s ²	[Rn]6d ² 7s ²	[Rn]5f ² 6d ¹ 7s ²	[Rn]5f ³ 6d ¹ 7s ²	[Rn]5f ⁴ 6d ¹ 7s ²	[Rn]5f ⁶ 6d ¹ 7s ²	[Rn]5f ⁷ 7s ²	[Rn]5f ⁷ 6d ¹ 7s ²	[Rn]5f ⁹ 7s ²	[Rn]5f ¹⁰ 7s ²	[Rn]5f ¹¹ 7s ²	[Rn]5f ¹² 7s ²	[Rn]5f ¹³ 7s ²	[Rn]5f ¹⁴ 7s ²	[Rn]5f ¹⁴ 6d ¹ 7s ²

- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Metalloid
- Nonmetal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

❖ Electrons are free to move with only a small applied field in a metal because there are many unoccupied states close to the occupied energy states. Therefore, current conduction can readily occur in conductors.

Insulators

❖ In an insulator such as silicon dioxide (SiO_2), the valence electrons form strong bonds between neighboring atoms.

❖ Since these bonds are difficult to break, there are no free electrons to participate in current conduction at near room temperature.

- ❖ As shown in the energy band diagram (Fig. 15c), insulators are characterized by a large bandgap.
- ❖ Note that electrons occupy all energy levels in the valence band and all energy levels in the conduction band are empty.
- ❖ Thermal energy[§] or the energy of an applied electric field is insufficient to raise the uppermost electron in the valence band to the conduction band.

§ The thermal energy is of the order of kT . At room temperature, kT is 0.026 eV, which is much smaller than the bandgap of an insulator.

- ❖ Thus, although an insulator has many vacant states in the conduction band that can accept electrons, so few electrons actually occupy conduction band states that the overall contribution to electrical conductivity is very small, resulting in a very high resistivity.
- ❖ Therefore, silicon dioxide is an insulator; it can not conduct current.

Semiconductors

- ❖ Now, consider a material that has a much smaller energy gap, on the order of 1 eV (Fig. 15b). Such materials are called semiconductors. At $T = 0$ K, all electrons are in the valence band, and there are no electrons in the conduction band.

- ❖ Thus, semiconductors are poor conductors at low temperatures.
- ❖ At room temperature and under normal atmospheres, values of E_g are 1.12 eV for Si and 1.42 eV for GaAs.
- ❖ The thermal energy kT at room temperature is a good fraction of E_g , and appreciable (محسوس) numbers of electrons are thermally excited from the valence band to the conduction band.
- ❖ Since there are many empty states in the conduction band, a small applied potential can easily move these electrons, resulting in a moderate current.

❖ ➤ 1.5 INTRINSIC CARRIER CONCENTRATION

- ❖ We now derive the carrier concentration in the thermal equilibrium condition, that is, the steady-state condition at a given temperature without any external excitations such as light, pressure, or an electric field.
- ❖ At a given temperature, continuous thermal agitation (برانگیختگی) results in the excitation of electrons from the valence band to the conduction band and leaves an equal number of holes in the valence band.