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Electronic Devices and Circ. Theory.

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Ch-1: Semiconductor Diodes

1. Introduction:

- miniaturization
- IC technology, 1958, Jack Kilby of TI.
- Intel Core i7 processor has 731 million transistors in a package.

1.2. Semiconductor materials: Ge, Si, GaAs

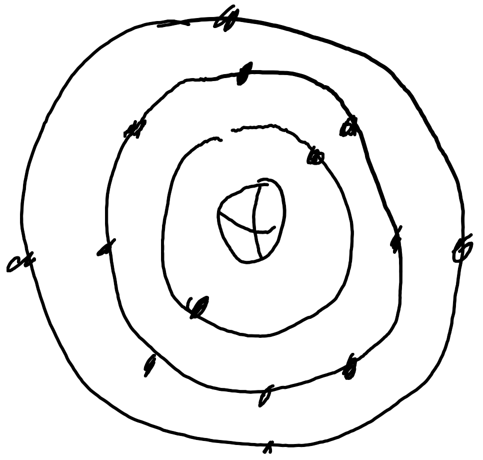
- high purity semiconductor materials needed in device making.
- Semiconductor's conductance is between a good conductor and an insulator.

Semiconductors

- Single crystal (repetitive structures): Ge, Si
- Compound (different atomic structures): GaAs, GaN, GaAsP

- Ge, Si, GaAs are three mostly used semiconductors in the construction of electronic devices.
- 1939: discovery of diode.
- 1947: " " Ge transistor.
- Ge was obtained with very high levels of purity. However, its sensitivity to temperature changes made Ge diodes/transistors unreliable.
- Si, had improved temperature sensitivities.
- 1954, first Si transistor introduced.
- Si, less temperature sensitive and most abundant materials on earth.
- Early 1970s: development of the first GaAs transistor. It address the need of 'speed'.
  → GaAs had the 5 times the speed of Si.

1.3. Covalent Bonding and Intrinsic Materials



Ge: 32 electrons (4 valence electrons)

Ga: 31 (3 valence el.)

As: 33 (5 valence el.)

Si: (14 electrons
4 valence electrons)

- valence electron: the electron orbiting in the outermost shell.

4 valence electrons (tetravalent)
3 " " (trivalent)
5 " " (pentavalent)

- Valence electrons have the least ionization energy relative to the inner shell electrons.

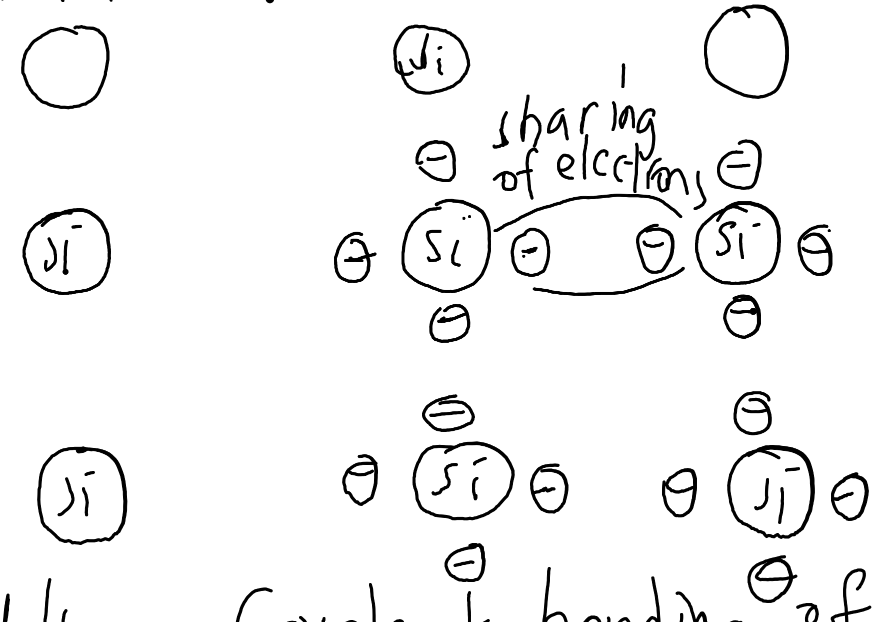
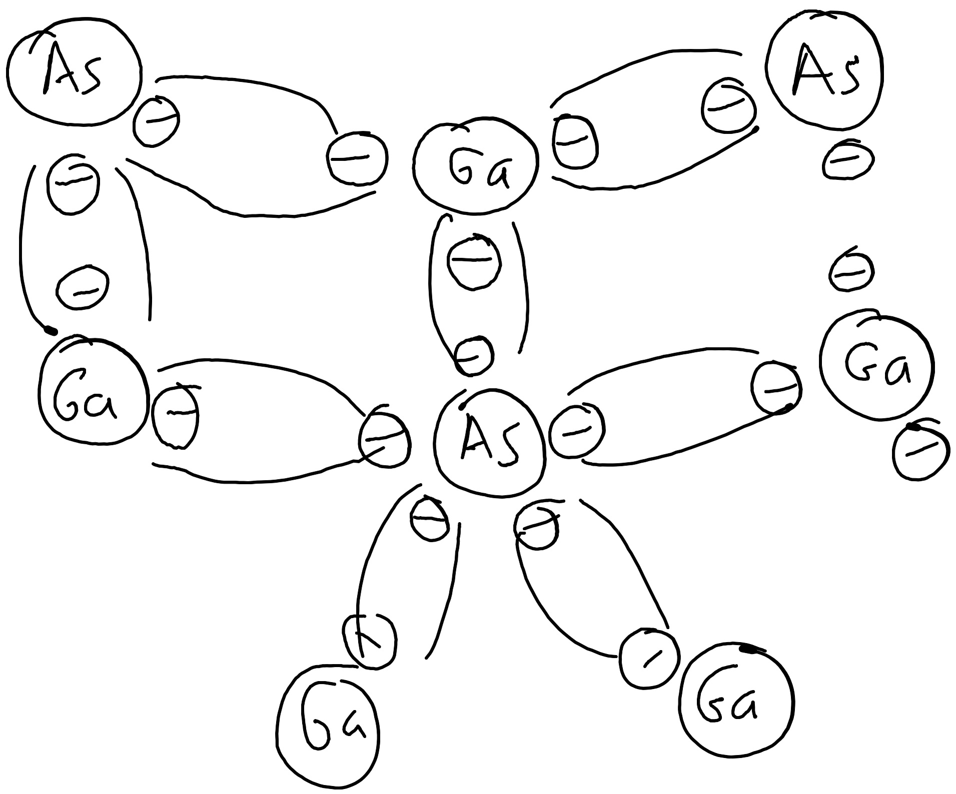


Fig. 1.4. Covalent bonding of Si atom.

- Covalent bonding: Sharing of electrons strengthens the bonding between the atoms. This is called covalent bonding.

- For GaAs (a compound semiconductor):



Ga: trivalent

As: pentavalent

Fig. 4.5. Covalent bonding of a GaAs crystal.

- electron can go to 'free' state if its covalent bond absorbs some energy of electric, heat, light etc.

- @ room temperature, there are $\sim 1.5 \times 10^{10}$ free carriers in $1\,cm^3$ of intrinsic Si.
- <u>intrinsic material</u>: purified from impurities.
- <u>intrinsic carriers</u>: the free electrons due only to external causes.

Intrinsic Carriers, n_i (per cm^3)	
GaAs	1.7×10^6
Si	1.5×10^{10}
Ge	2.5×10^{13}

Relative Mobility μ_n	
Si	1500
Ge	3900
GaAs	8500

μ_n: $(cm^2/V.s)$

- for example; GaAs is 5 times faster than Si since the mobility ratio is $\frac{8500}{1500} = 5.67$.
- High purity level is important. '1 part in 10 billion' is a common impurity level today.

- **Doping:** the ability to change the characteristics of a material through the process of adding '1 part per .....'.
- **Heat:** **Conductors:** resistance increase due to vibrational pattern of carriers that blocks the flow of carriers. These are 'positive temp. coefficient' materials.

  Semiconductors: covalent bond electrons are contributed to the number of carriers, due to their heat absorbtion. (covalent bond electrons).
  this causes the conductance increasing OR, resistance decreasing. These are called 'negative temp. coefficient' materials.

1.4. Energy levels:

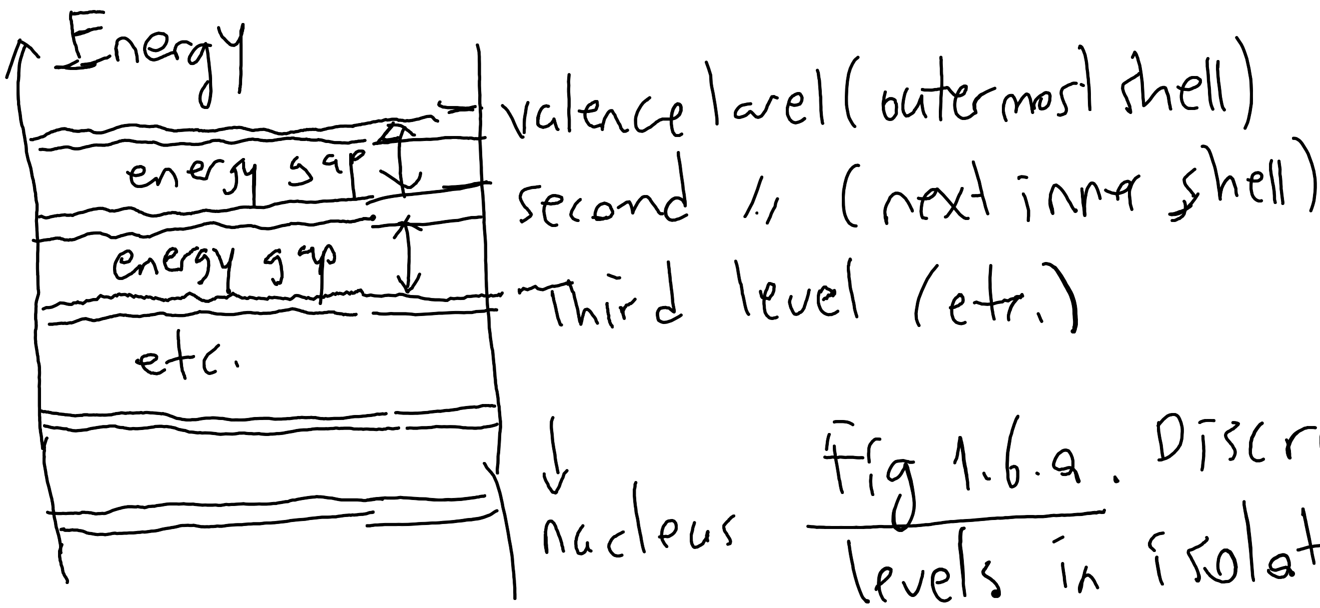


Fig 1.6.a. Discrete levels in isolated atomic structures.

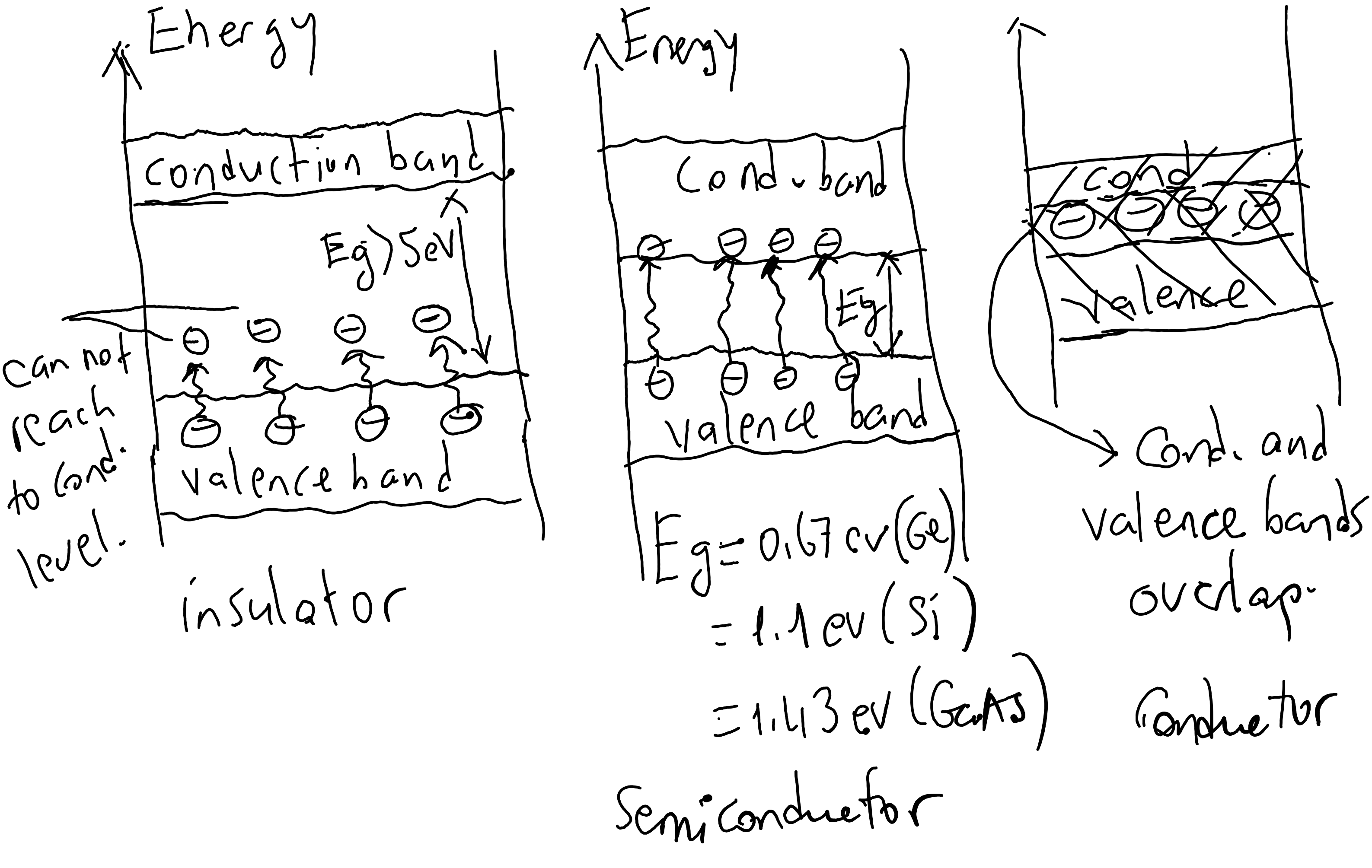
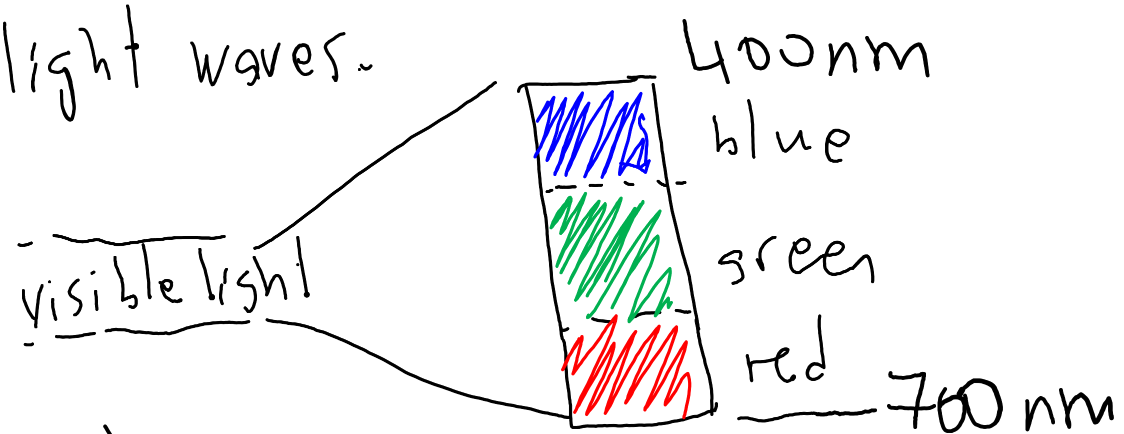


Fig 1.6.b. Conduction and valence bands of an isolator, semiconductor and conductor.

- Carriers are not permitted to reside in 'energy gaps.'
- photodetectors sensitive to light and security systems sensitive to heat appear to be an excellent area of application for Ge devices since they have a very small energy gap.
- LEDs; the wider the energy gap, the greater the possibility of energy being released in the form of <u>visible</u> or <u>invisible</u> (infrared) light waves.



$E = hf$

$c = \lambda f$

$= \lambda E / h$, where $h = 6.62 \times 10^{-34}$ Planck const.

$c = 3 \times 10^{8}$ m/s velocity of light

let $E = 1.43\,eV$ (GaAs)

$$\lambda = \frac{ch}{E} = \frac{3 \times 10^{8} \cdot 6.62 \times 10^{-34}}{(1.43)(1.6 \times 10^{-19})} = 868\,nm$$ (<u>infrared</u>)

- $V \stackrel{\Delta}{=} \frac{W}{Q}$, defining equation of voltage.

$W = QV = (1.6 \times 10^{-19} C)(1V) = 1.6 \times 10^{-19} J = \underline{1 eV}$

1.5. n-type and p-type materials:

- Addition of specific impurity atoms to the relatively pure semiconductor material, can alter the characteristics of a semi-conductor significantly.
- These impurities, although only added '1 part per 10 million', can alter the band structure.
- extrinsic material: a semiconductor material subject to the doping process. extrinsic (katkılanmış). We have two type extrinsic materials: n-type, p-type.

n-type material: created by introducing impurity atoms having 5 valence electrons (pentavalent) such as: antimony, arsenic, phosphorus.

These are 'Group V' elements in the periodic table since they have 5 valence electrons. The effect of such impurity elements is indicated in Fig 1.7.

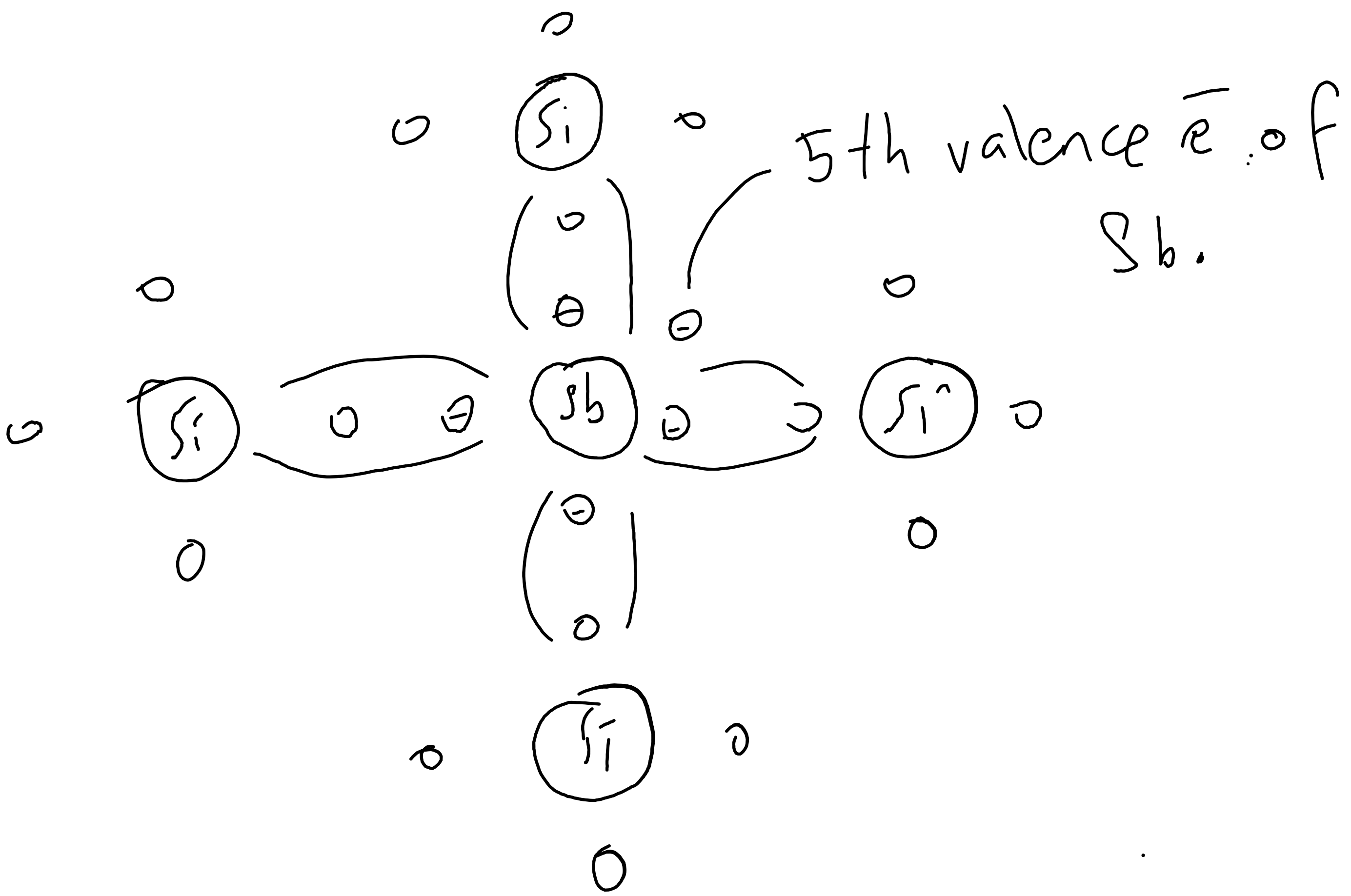
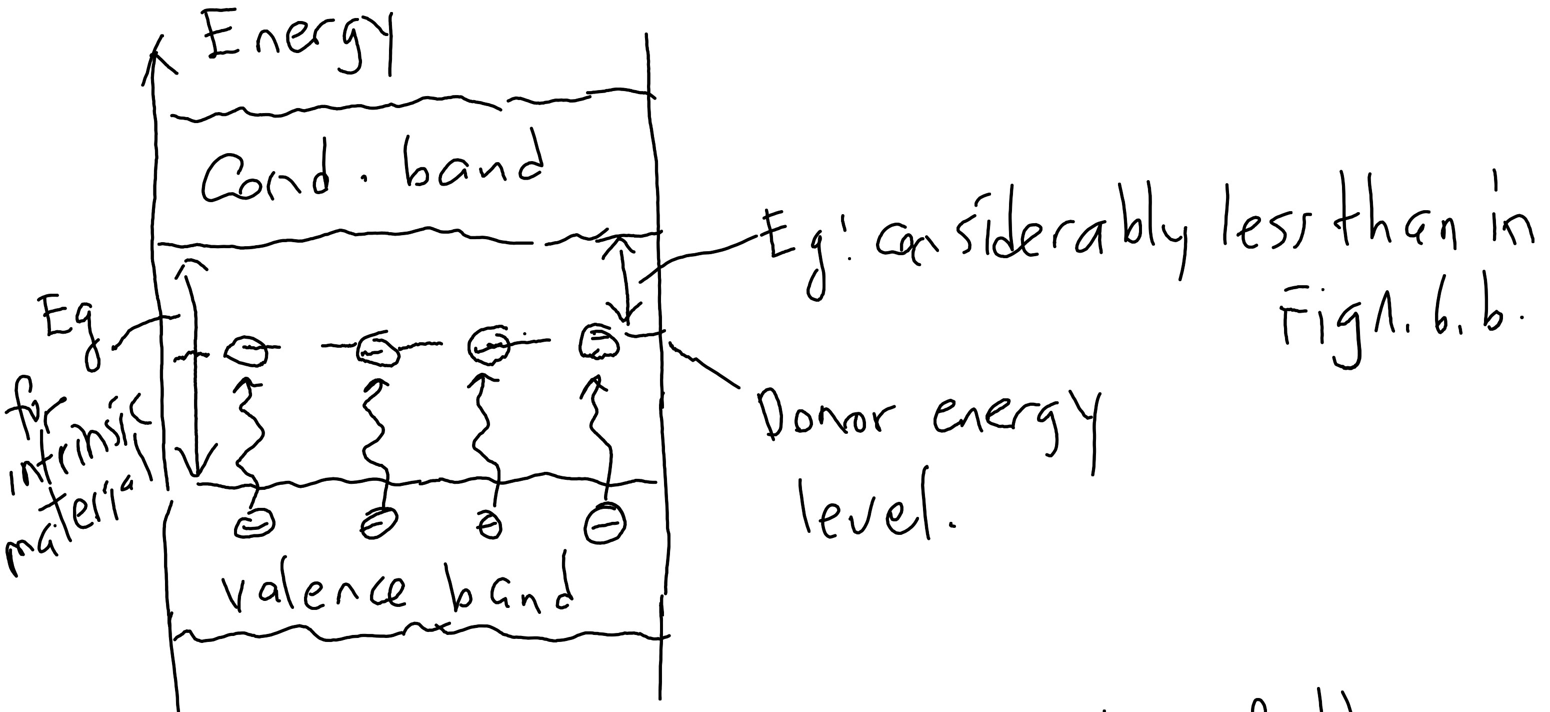


Fig 1.7. Antimony (Sb) impurity in n-type material.

— Impurities with 5 valence electrons are called donor atoms. (They donate free $\bar{e}$ to the structure).

— Notice that a large number of free carriers have been established in the n-type material. However, it is still electrically neutral since total charge is equal to zero due to $N_p^+ = N_e^-$ (p: proton, e: electron).



• Due to added impurity, conductivity of the material increases significantly, because there are a large number of carriers ($\bar{e}$) in the conduction level at room temperature.

- a room temperature in an intrinsic Si material, there is about '1 free e^- per 10^{12} atoms'. If the dosage level is 1 in 10^7, the ratio $10^{12}/10^7 = 10^5$ indicates that the carrier concentration has increased by a ratio of 100,000 : 1.

- comment (RK): the free e^- number is now '10^7 e^- per 10^{12} atoms'.

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p-type material: formed by doping a pure Ge or Si crystal with impurity atoms with 3 valence electrons. Boron, Gallium, Indium are the most frequently used elements for this purpose. They are called 'Grup III' elements in the Periodic Table.

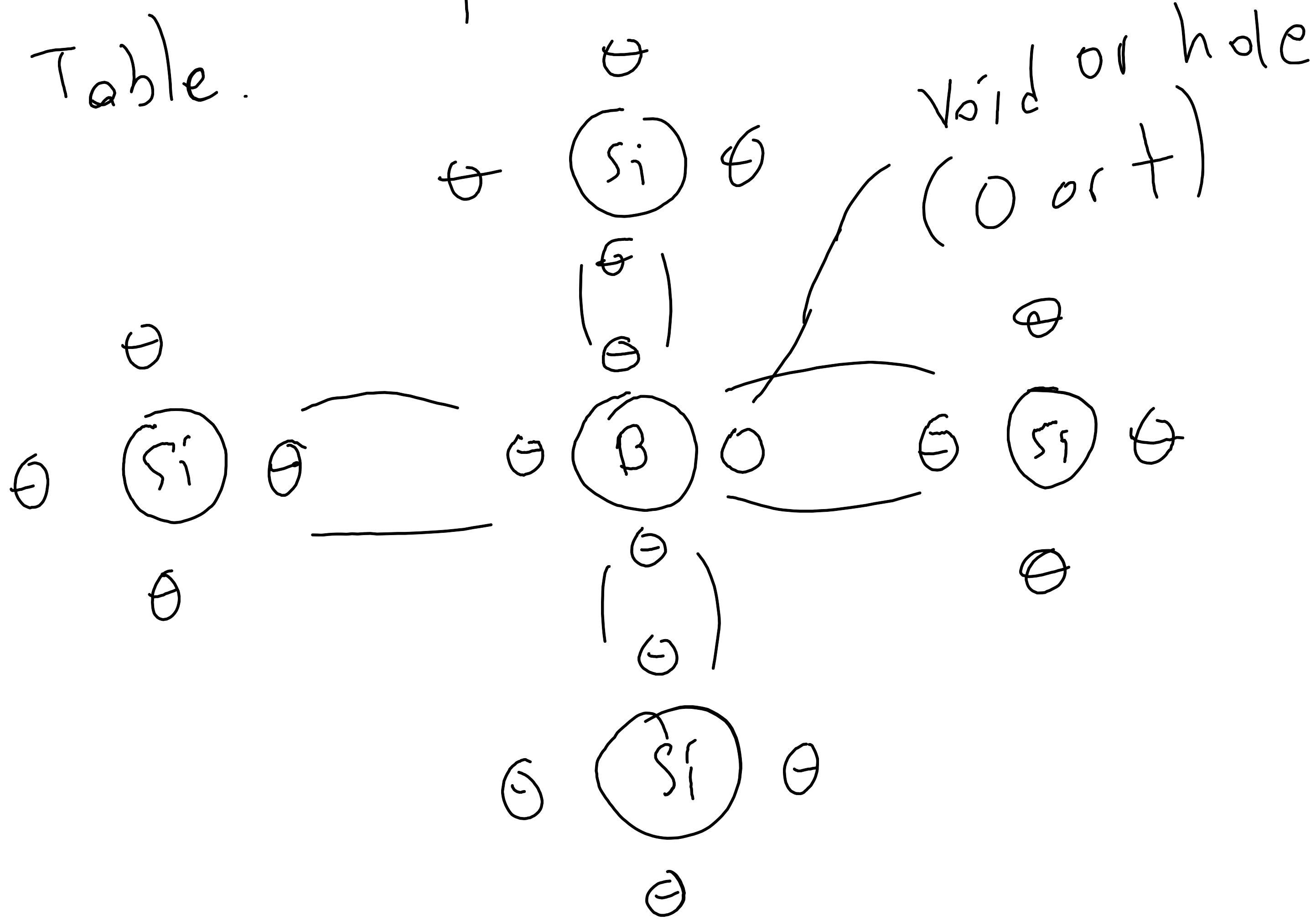


Fig 1.9. Boron impurity in p-type material.

• there is now an insufficient number of electrons to complete the covalent bonds. This vacancy is called a 'hole', represented by a O or + sign, indicating the absence of a negative charge.

- The impurities with 3 electrons are called 'acceptor' atoms. (since the vacancy accepts a free $\bar{e}$).

— the resulting p-type material is electrically neutral as in n-type one.

Electron vs Hole Flow :

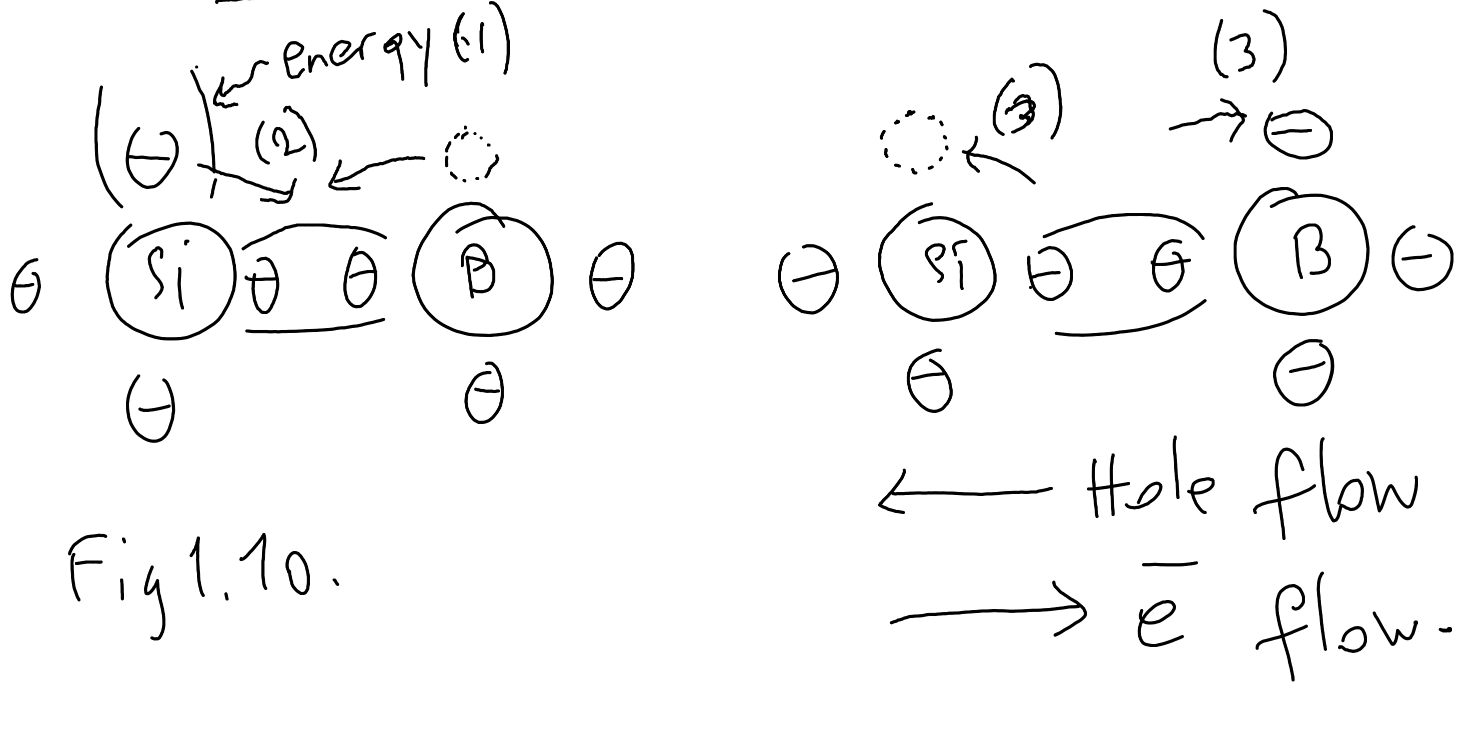
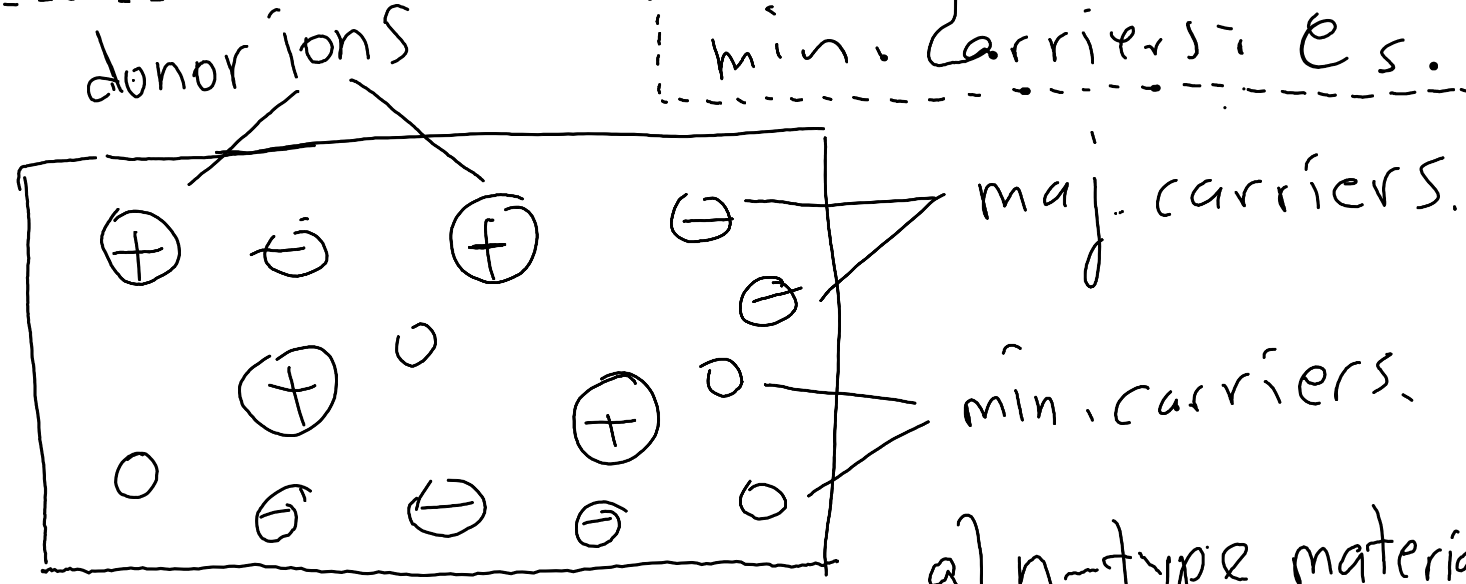


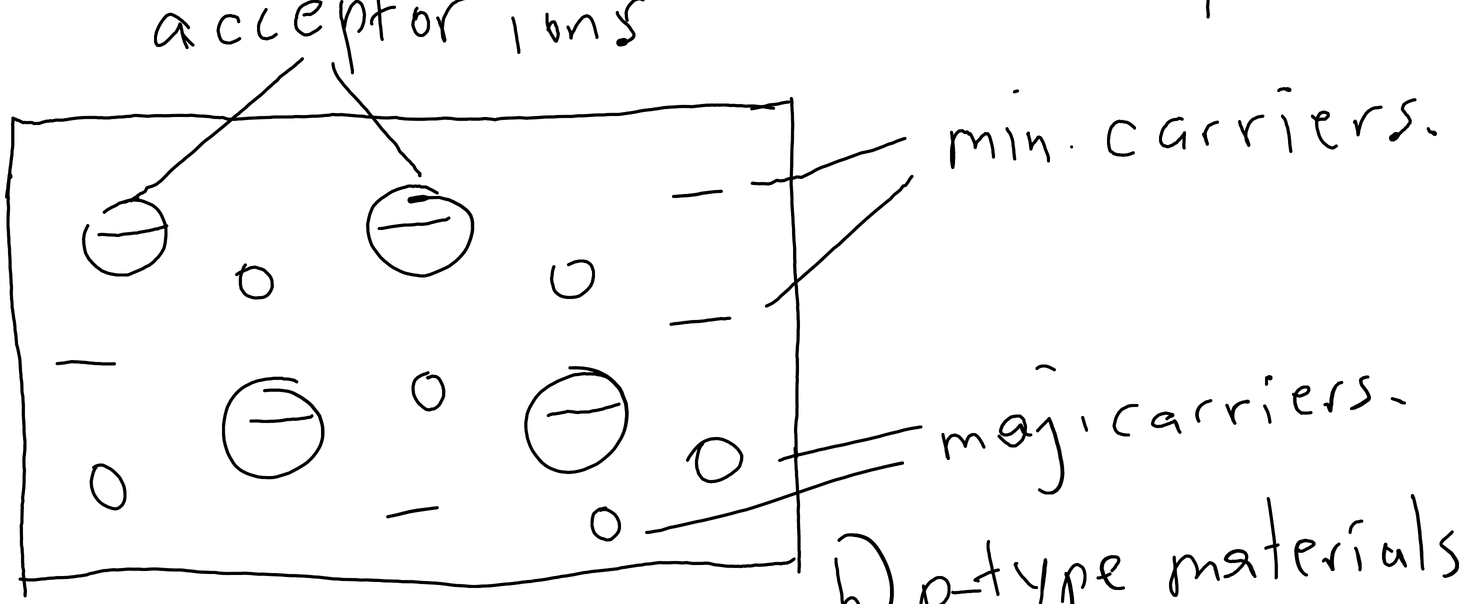
Fig 1.10.

Majority and Minority Carriers:

- In n-type material, maj. carriers: $\bar{e}$s.
  min. carriers: holes
- In p-type material, maj. carriers: holes
  min. carriers: $\bar{e}$s.



a) n-type material



b) p-type materials.

Fig 1.11.

n-type and p-type materials are the basic building blocks of semiconductor devices (such as diodes, transistors).

important!

1.6. Semiconductor diode:

No Applied Bias ($V = 0$ V)

At the instant the two materials are "joined" the electrons and the holes in the region of the junction will combine, resulting in a lack of free carriers in the region near the junction, as shown in Fig. 1.12a. Note in Fig. 1.12a that the only particles displayed in this region are the positive and the negative ions remaining once the free carriers have been absorbed.

This region of uncovered positive and negative ions is called the depletion region due to the "depletion" of free carriers in the region.

Under no-bias conditions, any minority carriers (holes) in the *n*-type material that find themselves within the depletion region for any reason whatsoever will pass quickly into the *p*-type material. The closer the minority carrier is to the junction, the greater is the attraction for the layer of negative ions and the less is the opposition offered by the positive ions in the depletion region of the *n*-type material. We will conclude, therefore, for future discussions, that any minority carriers of the *n*-type material that find themselves in the depletion region will pass directly into the *p*-type material. This carrier flow is indicated at the top of Fig. 1.12c for the minority carriers of each material.

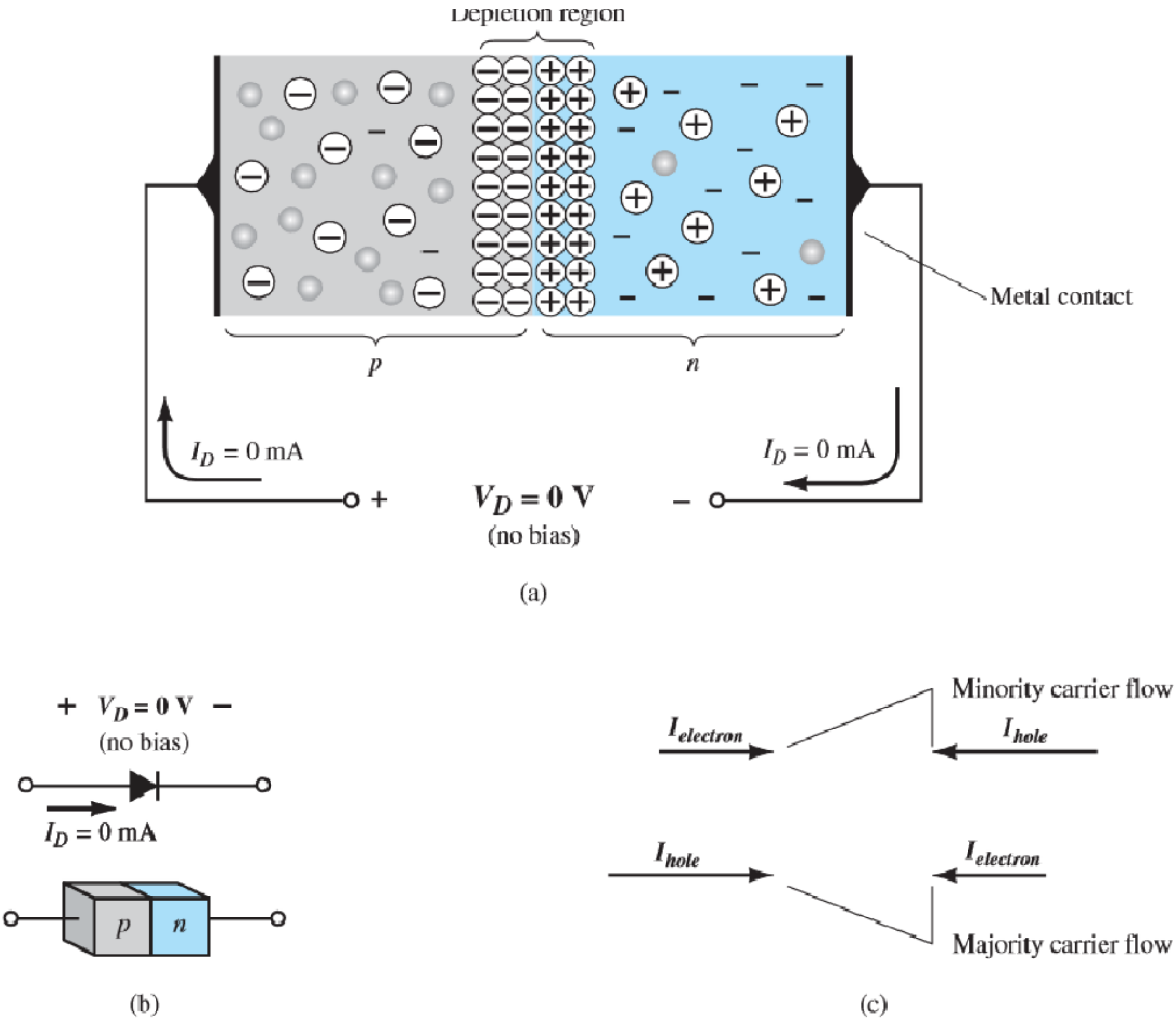


FIG. 1.12

A p–n junction with no external bias: (a) an internal distribution of charge; (b) a diode symbol, with the defined polarity and the current direction; (c) demonstration that the net carrier flow is zero at the external terminal of the device when $V_D = 0$ V.

The majority carriers (electrons) of the *n*-type material must overcome the attractive forces of the layer of positive ions in the *n*-type material and the shield of negative ions in the *p*-type material to migrate into the area beyond the depletion region of the *p*-type material. However, the number of majority carriers is so large in the *n*-type material that there will invariably be a small number of majority carriers with sufficient kinetic energy to pass through the depletion region into the *p*-type material. Again, the same type of discussion can be applied to the majority carriers (holes) of the *p*-type material. The resulting flow due to the majority carriers is shown at the bottom of Fig. 1.12c.

A close examination of Fig. 1.12c will reveal that the relative magnitudes of the flow vectors are such that the net flow in either direction is zero. This cancellation of vectors for each type of carrier flow is indicated by the crossed lines. The length of the vector representing hole flow is drawn longer than that of electron flow to demonstrate that the two magnitudes need not be the same for cancellation and that the doping levels for each material may result in an unequal carrier flow of holes and electrons. In summary, therefore:

In the absence of an applied bias across a semiconductor diode, the net flow of charge in one direction is zero.

In other words, the current under no-bias conditions is zero, as shown in Figs. 1.12a and 1.12b.

Reverse-Bias Condition ($V_D < 0$ V)

If an external potential of V volts is applied across the *p–n* junction such that the positive terminal is connected to the *n*-type material and the negative terminal is connected to the *p*-type material as shown in Fig. 1.13, the number of uncovered positive ions in the depletion region of the *n*-type material will increase due to the large number of free electrons drawn to the positive potential of the applied voltage. For similar reasons, the number of uncovered negative ions will increase in the *p*-type material. The net effect, therefore, is a

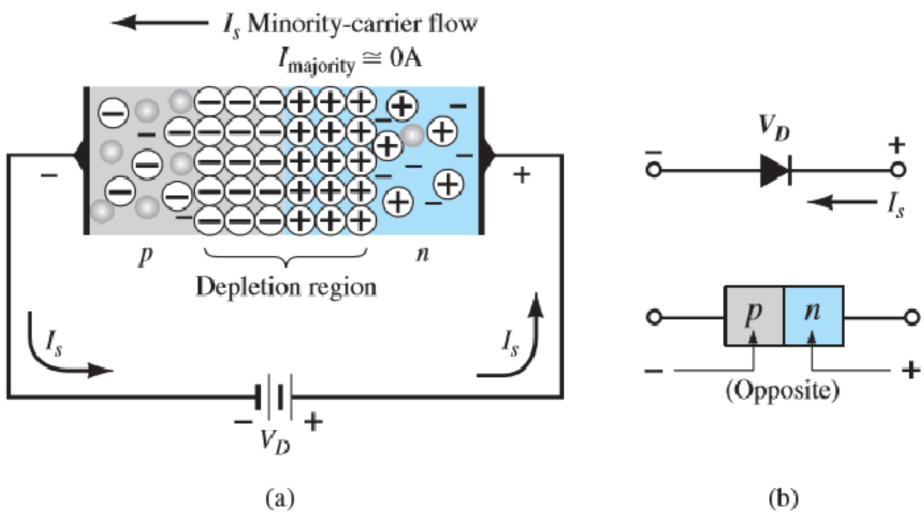


FIG. 1.13
Reverse-biased p–n junction: (a) internal distribution of charge under reverse-bias conditions; (b) reverse-bias polarity and direction of reverse saturation current.

widening of the depletion region. This widening of the depletion region will establish too great a barrier for the majority carriers to overcome, effectively reducing the majority carrier flow to zero, as shown in Fig. 1.13a.

The number of minority carriers, however, entering the depletion region will not change, resulting in minority-carrier flow vectors of the same magnitude indicated in Fig. 1.12c with no applied voltage.

The current that exists under reverse-bias conditions is called the reverse saturation current and is represented by I_s.

The reverse saturation current is seldom more than a few microamperes and typically in nA, except for high-power devices. The term *saturation* comes from the fact that it reaches its maximum level quickly and does not change significantly with increases in the reverse-bias potential, as shown on the diode characteristics of Fig. 1.15 for $V_D < 0$ V.

Forward-Bias Condition ($V_D > 0$ V)

A *forward-bias* or "on" condition is established by applying the positive potential to the *p*-type material and the negative potential to the *n*-type material as shown in Fig. 1.14.

The application of a forward-bias potential V_D will "pressure" electrons in the *n*-type material and holes in the *p*-type material to recombine with the ions near the boundary and reduce the width of the depletion region as shown in Fig. 1.14a. The resulting minority-carrier flow

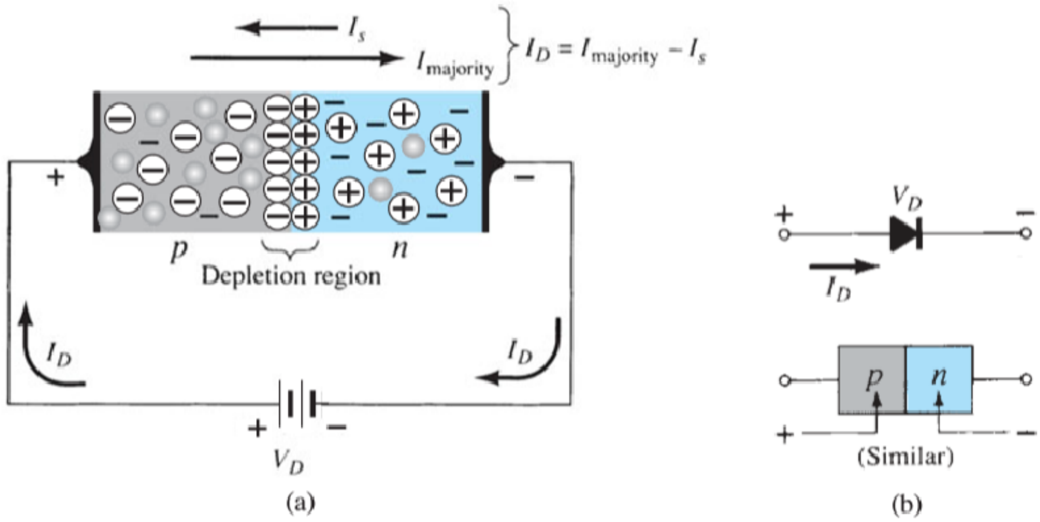


FIG. 1.14

Forward-biased p–n junction: (a) internal distribution of charge under forward-bias conditions; (b) forward-bias polarity and direction of resulting current.

of electrons from the *p*-type material to the *n*-type material (and of holes from the *n*-type material to the *p*-type material) has not changed in magnitude (since the conduction level is controlled primarily by the limited number of impurities in the material), but the reduction in the width of the depletion region has resulted in a heavy majority flow across the junction. An electron of the *n*-type material now "sees" a reduced barrier at the junction due to the reduced depletion region and a strong attraction for the positive potential applied to the *p*-type material. As the applied bias increases in magnitude, the depletion region will continue to decrease in width until a flood of electrons can pass through the junction, resulting in an exponential rise in current as shown in the forward-bias region of the characteristics of Fig. 1.15. Note that the vertical scale of Fig. 1.15 is measured in milliamperes (although some semiconductor diodes have a vertical scale measured in amperes), and the horizontal scale in the forward-bias region has a maximum of 1 V. Typically, therefore, the voltage across a forward-biased diode will be less than 1 V. Note also how quickly the current rises beyond the knee of the curve.

It can be demonstrated through the use of solid-state physics that the general characteristics of a semiconductor diode can be defined by the following equation, referred to as Shockley's equation, for the forward- and reverse-bias regions:

$$\boxed{I_D = I_s(e^{V_D/nV_T} - 1)} \quad \text{(A)} \qquad \textbf{(1.2)}$$

where I_s is the reverse saturation current
V_D is the applied forward-bias voltage across the diode
n is an ideality factor, which is a function of the operating conditions and physical construction; it has a range between 1 and 2 depending on a wide variety of factors ($n = 1$ will be assumed throughout this text unless otherwise noted).

The voltage V_T in Eq. (1.1) is called the *thermal voltage* and is determined by

$$\boxed{V_T = \frac{kT_K}{q}} \quad \text{(V)} \qquad \textbf{(1.3)}$$

where k is Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K
T_K is the absolute temperature in kelvins $= 273 +$ the temperature in °C
q is the magnitude of electronic charge $= 1.6 \times 10^{-19}$ C

EXAMPLE 1.1 At a temperature of 27°C (common temperature for components in an enclosed operating system), determine the thermal voltage V_T.

Solution: Substituting into Eq. (1.3), we obtain

$$T = 273 + {}^\circ\text{C} = 273 + 27 = 300\ \text{K}$$

$$V_T = \frac{kT_K}{q} = \frac{(1.38 \times 10^{-23}\ \text{J/K})(30\ \text{K})}{1.6 \times 10^{-19}\ \text{C}}$$

$$= 25.875\ \text{mV} \cong 26\ \text{mV}$$

The thermal voltage will become an important parameter in the analysis to follow in this chapter and a number of those to follow.

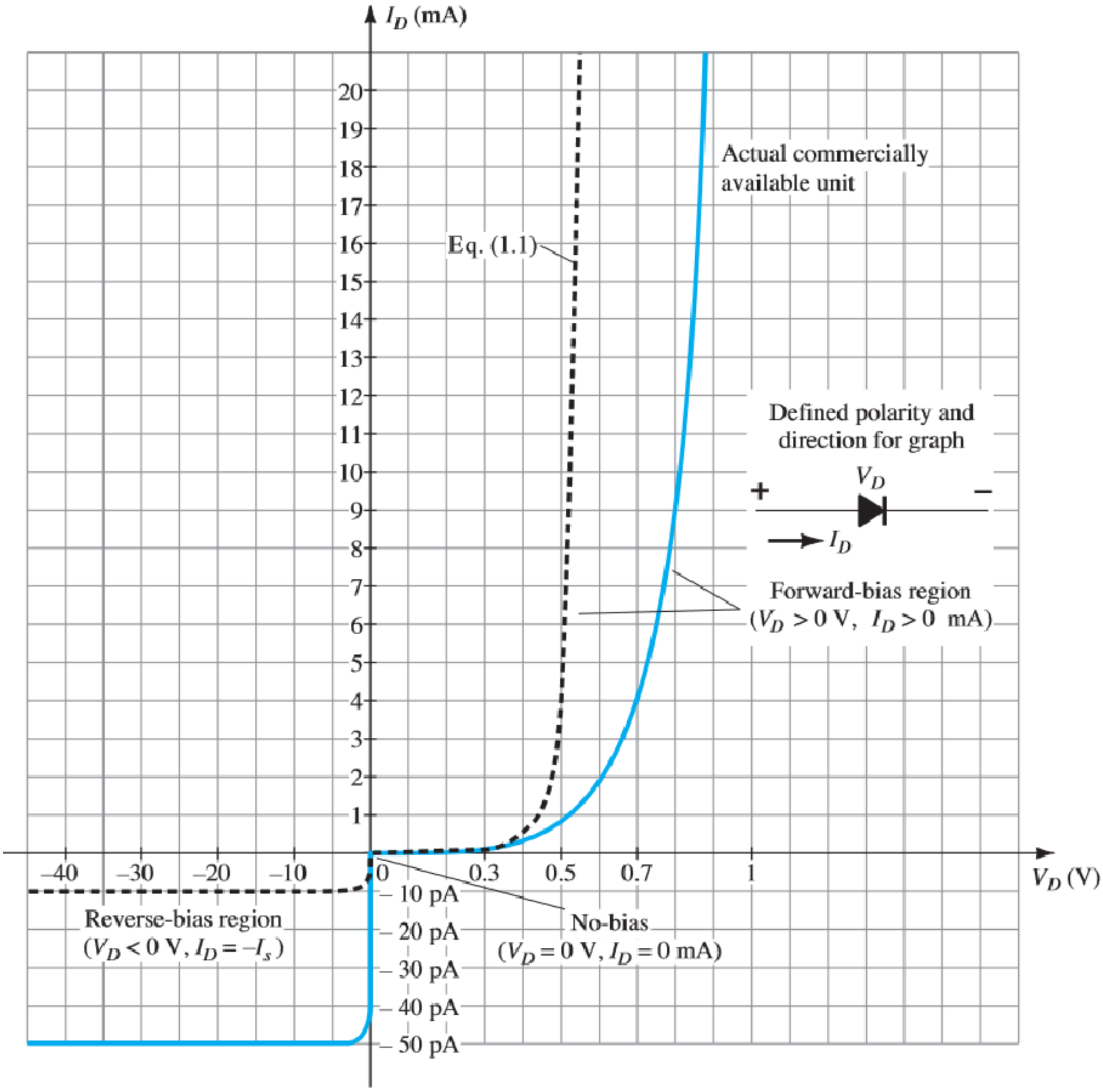


FIG. 1.15

Silicon semiconductor diode characteristics.

Breakdown Region

Even though the scale of Fig. 1.15 is in tens of volts in the negative region, there is a point where the application of too negative a voltage with the reverse polarity will result in a sharp change in the characteristics, as shown in Fig. 1.17. The current increases at a very rapid rate in a direction opposite to that of the positive voltage region. The reverse-bias potential that results in this dramatic change in characteristics is called the *breakdown potential* and is given the label V_{BV}.

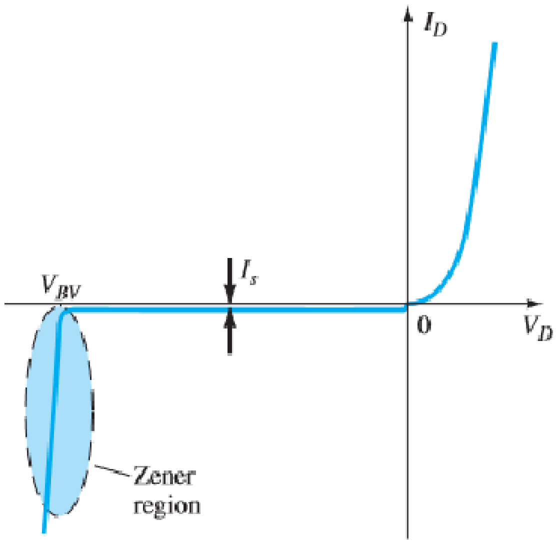


FIG. 1.17
Breakdown region.

As the voltage across the diode increases in the reverse-bias region, the velocity of the minority carriers responsible for the reverse saturation current I_s will also increase. Eventually, their velocity and associated kinetic energy ($W_K = \frac{1}{2}mv^2$) will be sufficient to release additional carriers through collisions with otherwise stable atomic structures. That is, an *ionization* process will result whereby valence electrons absorb sufficient energy to leave the parent atom. These additional carriers can then aid the ionization process to the point where a high *avalanche* current is established and the *avalanche breakdown* region determined.

The avalanche region (V_{BV}) can be brought closer to the vertical axis by increasing the doping levels in the *p*- and *n*-type materials. However, as V_{BV} decreases to very low levels, such as -5 V, another mechanism, called *Zener breakdown*, will contribute to the sharp change in the characteristic. It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and "generate" carriers. Although the Zener breakdown mechanism is a significant contributor only at lower levels of V_{BV}, this sharp change in the characteristic at any level is called the *Zener region*, and diodes employing this unique portion of the characteristic of a *p–n* junction are called *Zener diodes*. They are described in detail in Section 1.15.

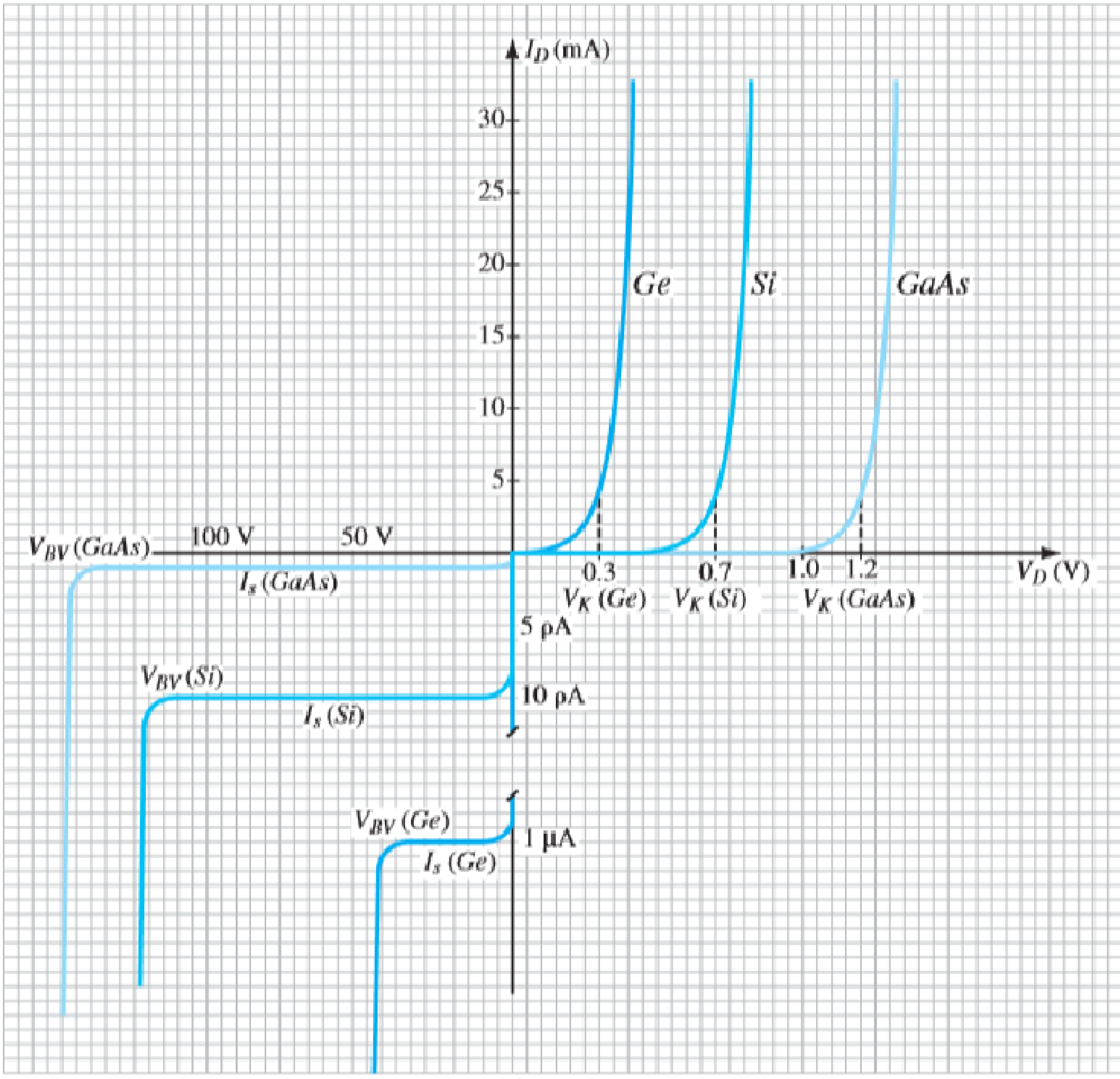


FIG. 1.18

Comparison of Ge, Si, and GaAs commercial diodes.

TABLE 1.3

Knee Voltages V_K

Semiconductor	V_K(V)
Ge	0.3
Si	0.7
GaAs	1.2

EXAMPLE 1.2 Using the curves of Fig 1.18:

a. Determine the voltage across each diode at a current of 1 mA.
b. Repeat for a current of 4 mA.
c. Repeat for a current of 30 mA.
d. Determine the average value of the diode voltage for the range of currents listed above.
e. How do the average values compare to the knee voltages listed in Table 1.3?

Solution:

a. $V_D(\text{Ge}) = 0.2\text{ V}$, $V_D(\text{Si}) = 0.6\text{ V}$, $V_D\ (\text{GaAs}) = 1.1\text{ V}$
b. $V_D(\text{Ge}) = 0.3\text{ V}$, $V_D(\text{Si}) = 0.7\text{ V}$, $V_D\ (\text{GaAs}) = 1.2\text{ V}$
c. $V_D(\text{Ge}) = 0.42\text{ V}$, $V_D(\text{Si}) = 0.82\text{ V}$, $V_D\ (\text{GaAs}) = 1.33\text{ V}$
d. Ge: $V_{av} = (0.2\text{ V} + 0.3\text{ V} + 0.42\text{ V})/3 = 0.307\text{ V}$
   Si: $V_{av} = (0.6\text{ V} + 0.7\text{ V} + 0.82\text{ V})/3 = 0.707\text{ V}$
   GaAs: $V_{av} = (1.1\text{ V} + 1.2\text{ V} + 1.33\text{ V})/3 = 1.21\text{ V}$
e. Very close correspondence. Ge: 0.307 V vs. 0.3, V, Si: 0.707 V vs. 0.7 V, GaAs: 1.21 V vs. 1.2 V.

Temperature Effects

Temperature can have a marked effect on the characteristics of a semiconductor diode, as demonstrated by the characteristics of a silicon diode shown in Fig. 1.19:

In the forward-bias region the characteristics of a silicon diode shift to the left at a rate of 2.5 mV per centigrade degree increase in temperature.

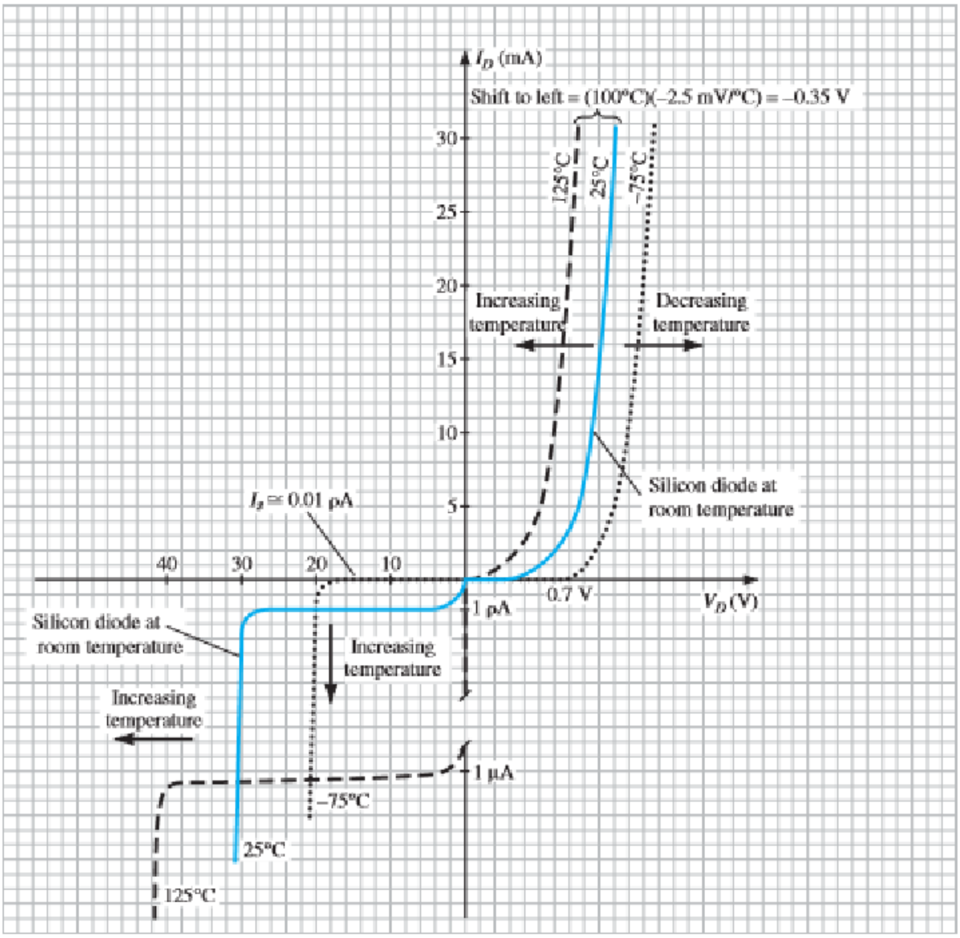


FIG. 1.19
Variation in Si diode characteristics with temperature change.

1.7 IDEAL VERSUS PRACTICAL

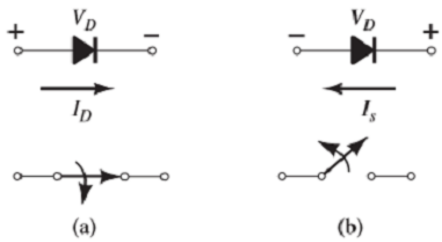


FIG. 1.21
Ideal semiconductor diode: (a) forward-biased; (b) reverse-biased.

In other words:

The semiconductor diode behaves in a manner similar to a mechanical switch in that it can control whether current will flow between its two terminals.

However, it is important to also be aware that:

The semiconductor diode is different from a mechanical switch in the sense that when the switch is closed it will only permit current to flow in one direction.

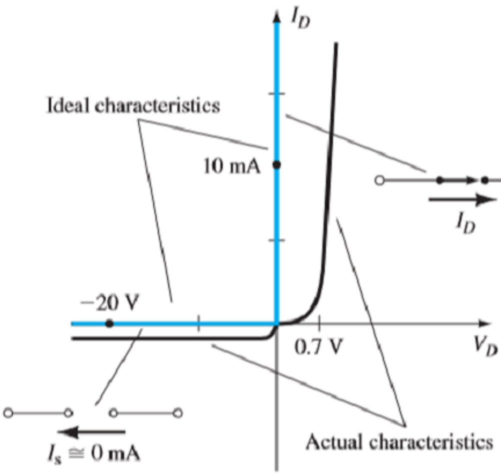


FIG. 1.22
Ideal versus actual semiconductor characteristics.

$$R_F = \frac{V_D}{I_D} = \frac{0\text{ V}}{5\text{ mA}} = \mathbf{0\ \Omega} \qquad \text{(short-circuit equivalent)}$$

In fact:

At any current level on the vertical line, the voltage across the ideal diode is 0 V and the resistance is 0 Ω.

For the horizontal section, if we again apply Ohm's law, we find

$$R_R = \frac{V_D}{I_D} = \frac{20\text{ V}}{0\text{ mA}} \cong \infty\,\Omega \qquad \text{(open-circuit equivalent)}$$

Again:

Because the current is 0 mA anywhere on the horizontal line, the resistance is considered to be infinite ohms (an open-circuit) at any point on the axis.

1.8 RESISTANCE LEVELS

DC or Static Resistance

The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time. The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D as shown in Fig. 1.23 and applying the following equation:

$$\boxed{R_D = \frac{V_D}{I_D}} \tag{1.4}$$

The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics. The resistance levels in the reverse-bias region will naturally be quite high.

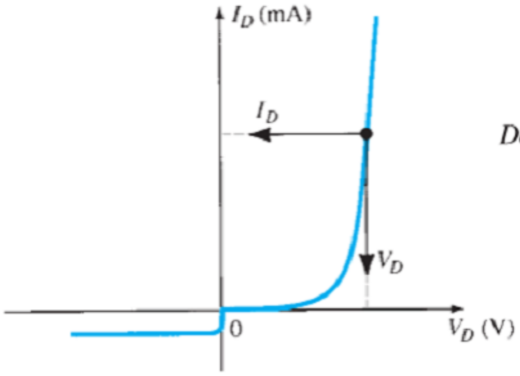


FIG. 1.23
Determining the dc resistance of a diode at a particular operating point.

In general, therefore, the higher the current through a diode, the lower is the dc resistance level.

Typically, the dc resistance of a diode in the active (most utilized) will range from about 10 Ω to 80 Ω.

EXAMPLE 1.3 Determine the dc resistance levels for the diode of Fig. 1.24 at

a. $I_D = 2$ mA (low level)
b. $I_D = 20$ mA (high level)
c. $V_D = -10$ V (reverse-biased)

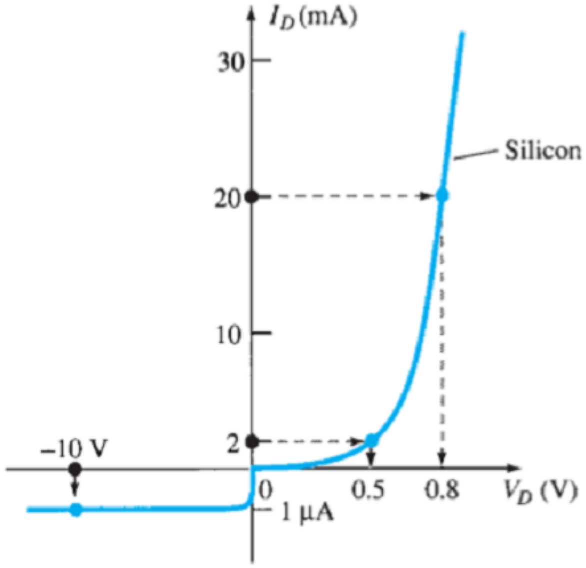


FIG. 1.24
Example 1.3.

Solution:

a. At $I_D = 2$ mA, $V_D = 0.5$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = \mathbf{250\ \Omega}$$

b. At $I_D = 20$ mA, $V_D = 0.8$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.8\text{ V}}{20\text{ mA}} = \mathbf{40\ \Omega}$$

c. At $V_D = -10$ V, $I_D = -I_s = -1\ \mu$A (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{10\text{ V}}{1\ \mu\text{A}} = \mathbf{10\ M\Omega}$$

clearly supporting some of the earlier comments regarding the dc resistance levels of a diode.

AC or Dynamic Resistance

Eq. (1.4) and Example 1.3 reveal that

the dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest.

If a sinusoidal rather than a dc input is applied, the situation will change completely. The varying input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage as shown in Fig. 1.25.

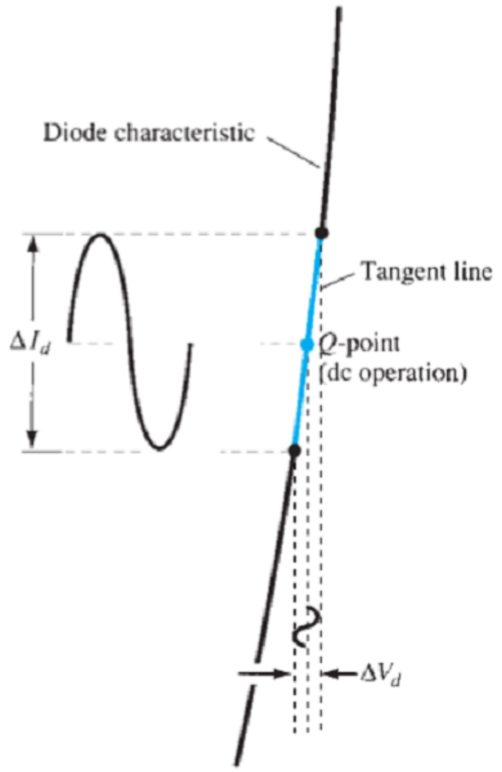


FIG. 1.25
Defining the dynamic or ac resistance.

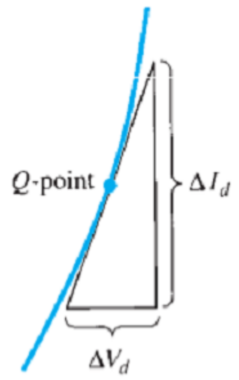


FIG. 1.26
Determining the ac resistance at a Q-point.

$$\boxed{r_d = \frac{\Delta V_d}{\Delta I_d}} \tag{1.5}$$

In general, therefore, the lower the Q-point of operation (smaller current or lower voltage), the higher is the ac resistance.

EXAMPLE 1.4 For the characteristics of Fig. 1.27:

a. Determine the ac resistance at $I_D = 2$ mA.
b. Determine the ac resistance at $I_D = 25$ mA.
c. Compare the results of parts (a) and (b) to the dc resistances at each current level.

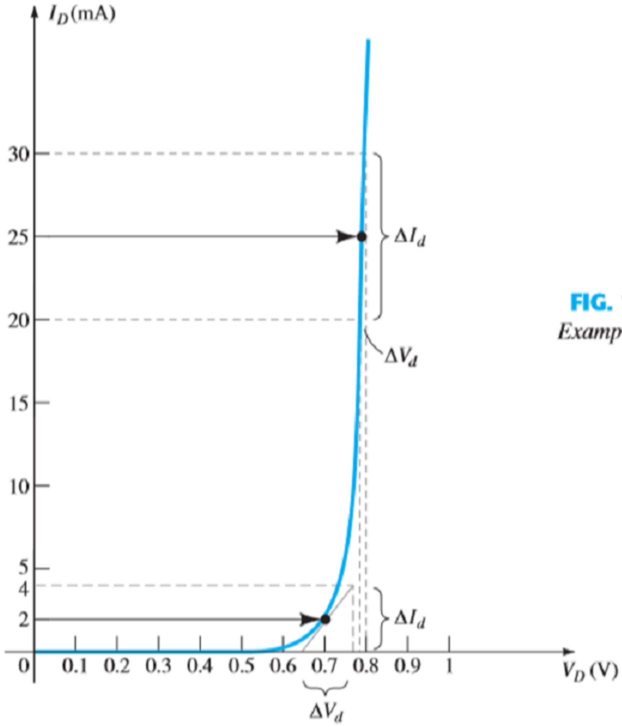


FIG. 1.27
Example 1.4.

Solution:

a.

$$\Delta I_d = 4\text{ mA} - 0\text{ mA} = 4\text{ mA}$$

and

$$\Delta V_d = 0.76\text{ V} - 0.65\text{ V} = 0.11\text{ V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.11\text{ V}}{4\text{ mA}} = \mathbf{27.5\ \Omega}$$

b.

$$\Delta I_d = 30\text{ mA} - 20\text{ mA} = 10\text{ mA}$$

and

$$\Delta V_d = 0.8\text{ V} - 0.78\text{ V} = 0.02\text{ V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.02\text{ V}}{10\text{ mA}} = \mathbf{2\ \Omega}$$

c.

$$R_D = \frac{V_D}{I_D} = \frac{0.7\text{ V}}{2\text{ mA}} = \mathbf{350\ \Omega}$$

which far exceeds the r_d of 27.5 Ω.

For $I_D = 25$ mA, $V_D = 0.79$ V and

$$R_D = \frac{V_D}{I_D} = \frac{0.79\text{ V}}{25\text{ mA}} = \mathbf{31.62\ \Omega}$$

which far exceeds the r_d of 2 Ω.

We have found the dynamic resistance graphically, but there is a basic definition in differential calculus that states:

The derivative of a function at a point is equal to the slope of the tangent line drawn at that point.

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV_D}\left[I_s(e^{V_D/nV_T} - 1)\right]$$

and

$$\frac{dI_D}{dV_D} = \frac{1}{nV_T}(I_D + I_s)$$

after we apply differential calculus. In general, $I_D \gg I_s$ in the vertical-slope section of the characteristics and

$$\frac{dI_D}{dV_D} \cong \frac{I_D}{nV_T}$$

Flipping the result to define a resistance ratio ($R = V/I$) gives

$$\frac{dV_D}{dI_D} = r_d = \frac{nV_T}{I_D}$$

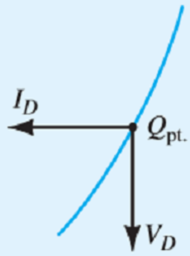
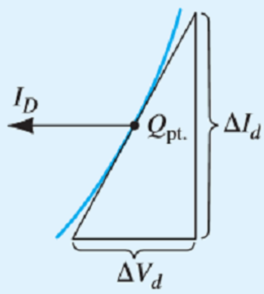
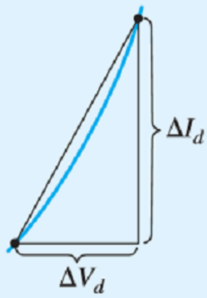
Substituting $n = 1$ and $V_T \cong 26\text{ mV}$ from Example 1.1 results in

$$\boxed{r_d = \frac{26\text{ mV}}{I_D}} \qquad \textbf{(1.6)}$$

The significance of Eq. (1.6) must be clearly understood. It implies that

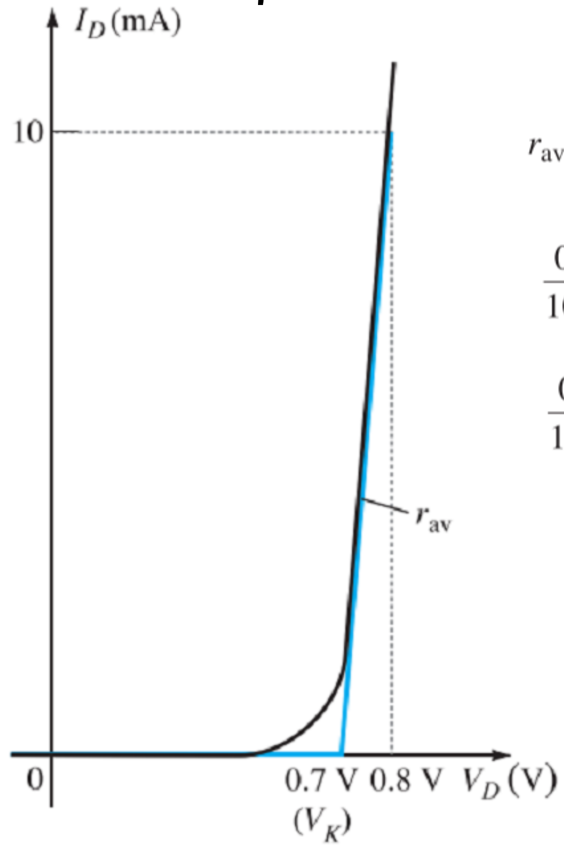
the dynamic resistance can be found simply by substituting the quiescent value of the diode current into the equation.

TABLE 1.6
Resistance Levels

Type	Equation	Special Characteristics	Graphical Determination
DC or static	$R_D = \dfrac{V_D}{I_D}$	Defined as a point on the characteristics	
AC or dynamic	$r_d = \dfrac{\Delta V_d}{\Delta I_d} = \dfrac{26\text{ mV}}{I_D}$	Defined by a tangent line at the Q-point	
Average ac	$r_{\text{av}} = \dfrac{\Delta V_d}{\Delta I_d}\Bigg\vert_{\text{pt. to pt.}}$	Defined by a straight line between limits of operation	

1.9. Diode Equivalent Circuits

1) Piece-wise Linear Equivalent Circuit:



$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}} = \frac{0.8\text{ V} - 0.7\text{ V}}{10\text{ mA} - 0\text{ mA}} = \frac{0.1\text{ V}}{10\text{ mA}} = \mathbf{10\ \Omega}$$

FIG. 1.29
Defining the piecewise-linear equivalent circuit using straight-line segments to approximate the characteristic curve.

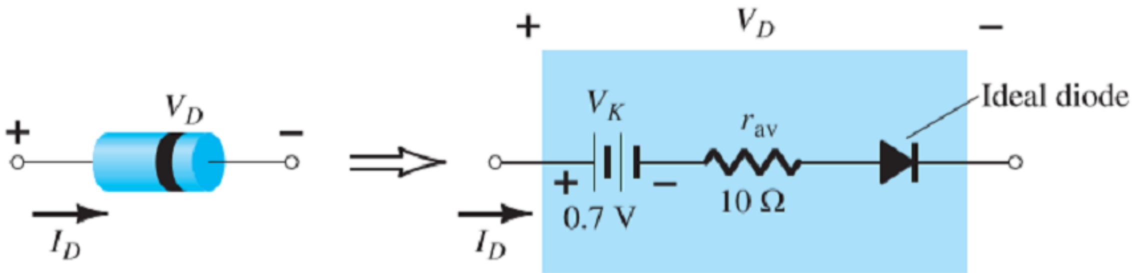


FIG. 1.30
Components of the piecewise-linear equivalent circuit.

$V_D = V_K + r_{av} \cdot I_D$, where $r_{av} = \frac{\Delta v}{\Delta i}$

example: $V_D = 0.7 + 10 \cdot (10\,mA) = \underline{0.8\,V}$.

2)

Simplified Equivalent Circuit

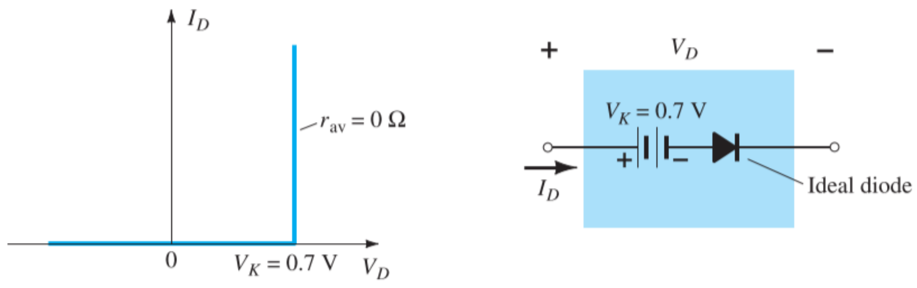


FIG. 1.31
Simplified equivalent circuit for the silicon semiconductor diode.

3)

Ideal Equivalent Circuit

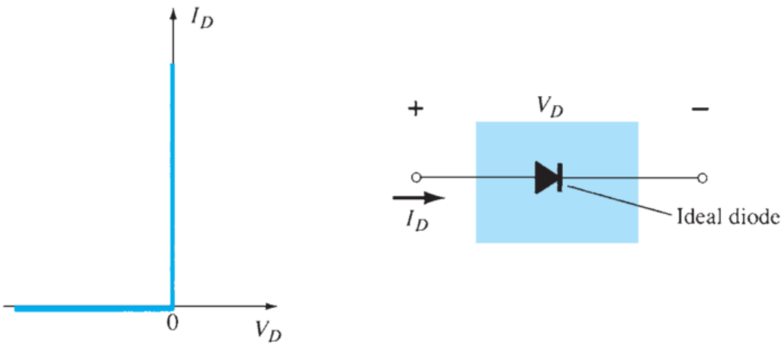
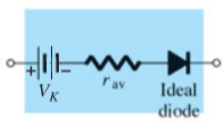
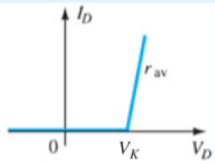
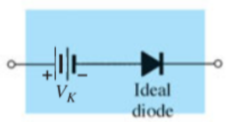
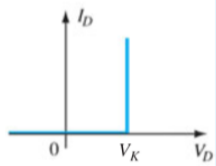
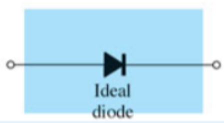
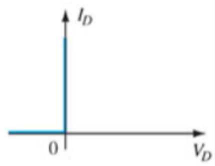


FIG. 1.32
Ideal diode and its characteristics.

TABLE 1.7
Diode Equivalent Circuits (Models)

Type	Conditions	Model	Characteristics
Piecewise-linear model			
Simplified model	$R_{network} \gg r_{av}$		
Ideal device	$R_{network} \gg r_{av}$ $E_{network} \gg V_K$		

1.15. Zener Diodes

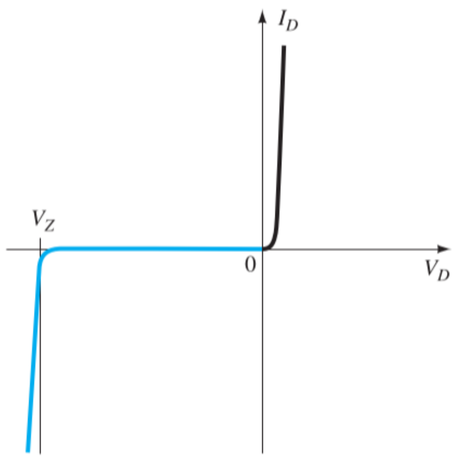


FIG. 1.45
Reviewing the Zener region.

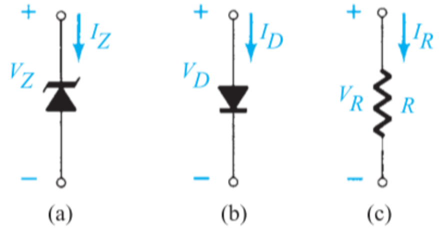


FIG. 1.46
Conduction direction: (a) Zener diode; (b) semiconductor diode; (c) resistive element.

The location of the Zener region can be controlled by varying the doping levels. An increase in doping that produces an increase in the number of added impurities, will decrease the Zener potential. Zener diodes are available having Zener potentials of 1.8 V to 200 V with power ratings from ¼ W to 50 W. Because of its excellent temperature and current capabilities, silicon is the preferred material in the manufacture of Zener diodes.

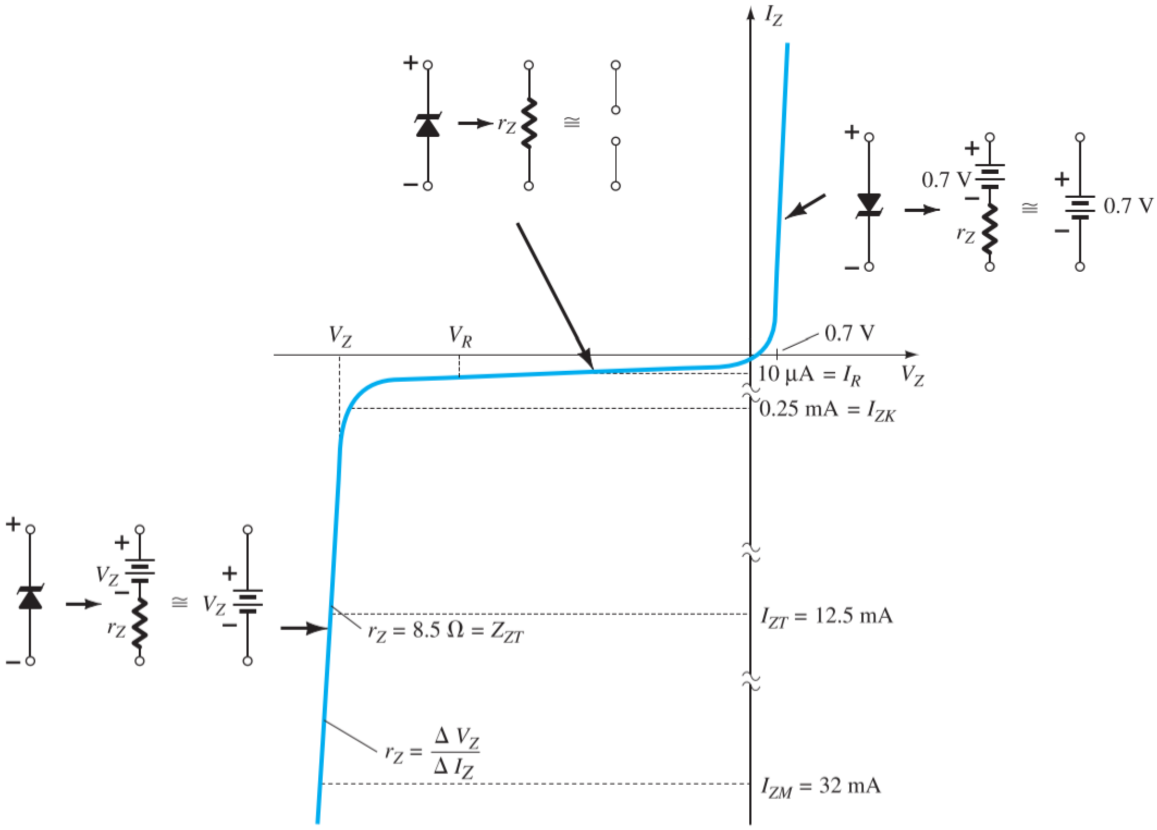


FIG. 1.47
Zener diode characteristics with the equivalent model for each region.

1.16. LED (Light-Emitting Diode)

1.16 LIGHT-EMITTING DIODES

As the name implies, the light-emitting diode is a diode that gives off visible or invisible (infrared) light when energized. In any forward-biased *p–n* junction there is, within the structure and primarily close to the junction, a recombination of holes and electrons. This recombination requires that the energy possessed by the unbound free electrons be transferred to another state. In all semiconductor *p–n* junctions some of this energy is given off in the form of heat and some in the form of photons.

In Si and Ge diodes the greater percentage of the energy converted during recombination at the junction is dissipated in the form of heat within the structure, and the emitted light is insignificant.

For this reason, silicon and germanium are not used in the construction of LED devices. On the other hand:

Diodes constructed of GaAs emit light in the infrared (invisible) zone during the recombination process at the p–n junction.

TABLE 1.9
Light-Emitting Diodes

Color	Construction	Typical Forward Voltage (V)
Amber	AlInGaP	2.1
Blue	GaN	5.0
Green	GaP	2.2
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

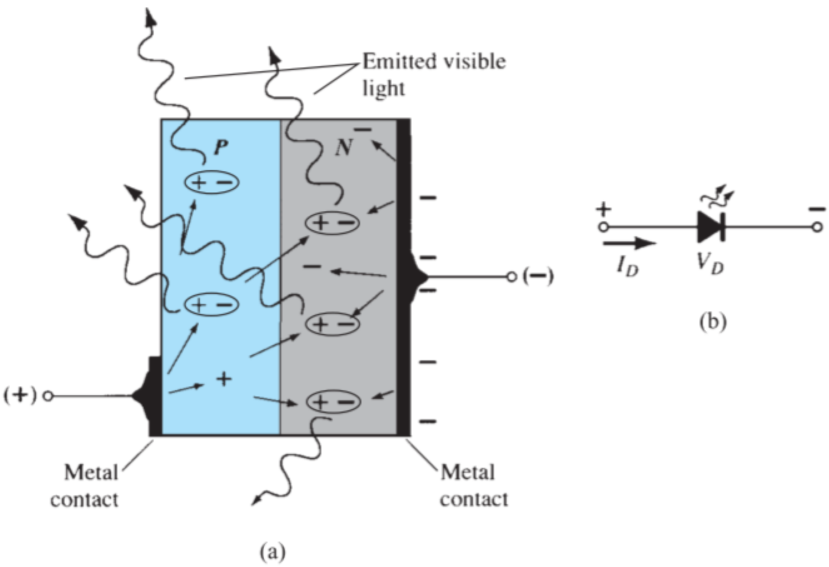


FIG. 1.50
(a) Process of electroluminescence in the LED; (b) graphic symbol.

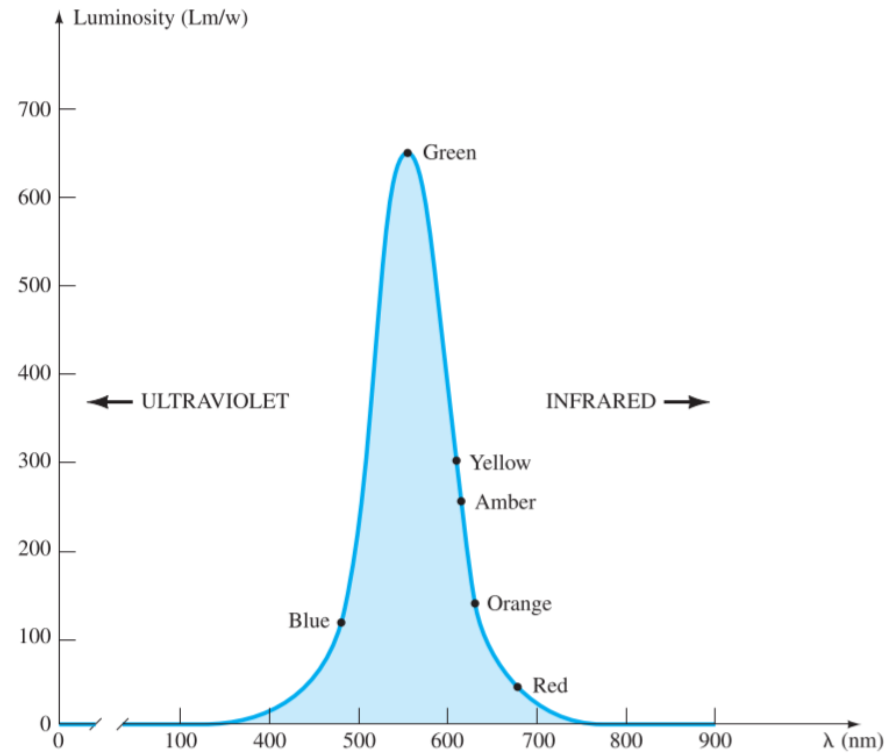


FIG. 1.51

Standard response curve of the human eye, showing the eye's response to light energy peaks at green and falls off for blue and red.

$$\boxed{E_g = \frac{hc}{\lambda}} \tag{1.16}$$

with E_g = joules (J) [1 eV = 1.6×10^{-19} J]
h = Planck's constant = 6.626×10^{-34} J·s.
$c = 3 \times 10^8$ m/s
λ = wavelength in meters

If we substitute the energy gap level of 1.43 eV for GaAs into the equation, we obtain the following wavelength:

$$1.43\ \cancel{\text{eV}}\left[\frac{1.6 \times 10^{-19}\ \text{J}}{1\ \cancel{\text{eV}}}\right] = 2.288 \times 10^{-19}\ \text{J}$$

and
$$\lambda = \frac{hc}{E_g} = \frac{(6.626 \times 10^{-34}\ \text{J}\cdot\text{s})(3 \times 10^8\ \text{m/s})}{2.288 \times 10^{-19}\ \text{J}}$$
$$= 869\ \mathbf{nm}$$

For silicon, with $E_g = 1.1$ eV

$$\lambda = \mathbf{1130\ nm}$$

which is well beyond the visible range of Fig. 1.51.

The wavelength of 869 nm places GaAs in the wavelength zone typically used in infrared devices. For a compound material such as GaAsP with a band gap of 1.9 eV the resulting wavelength is 654 nm, which is in the center of the red zone, making it an excellent compound semiconductor for LED production. In general, therefore:

The wavelength and frequency of light of a specific color are directly related to the energy band gap of the material.