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CHAPTER 1: SEMICONDUCTOR DIODES

Topics/Suggestions:

Theory:

1. Definition and concept: Semiconductor, Semiconductor materials
2. Definition and concept: Covalent Bonding, Energy levels
3. Definition: Extrinsic material: n type, p type, donor atoms, acceptor atoms, majority carriers, minority carriers.
4. No applied bias, Reverse bias, Forward bias condition
5. Shockley's equation and Thermal Voltage
6. Breakdown Region
7. Ideal vs Actual Semiconductor characteristics, Difference between Semiconductor diode and mechanical switch
8. DC or Static vs AC or Dynamic vs Average AC
9. Piecewise-linear equivalent circuit
10. Simplified vs Ideal vs Piecewise-linear equivalent circuit
11. Reverse recovery time
12. LED

Math:

13. Example 1.1
14. Example 1.3
15. Example 1.5
16. Example 1.6

SEMICONDUCTOR MATERIALS:

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.

The three semiconductors used most frequently in the construction of electronic devices are Ge, Si, and GaAs.

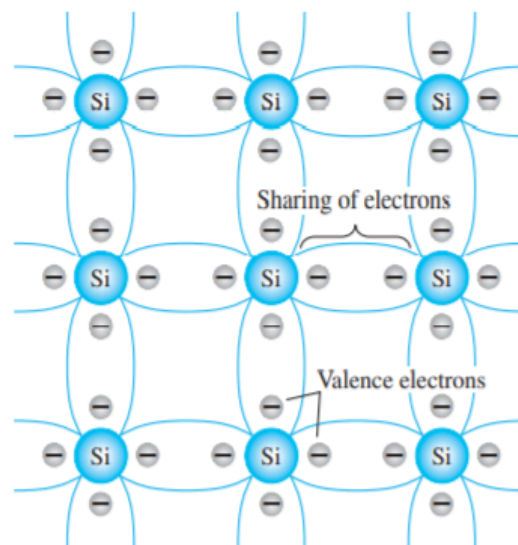


FIG. 1.4
Covalent bonding of the silicon atom.

COVALENT BONDING:

This bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding.

ENERGY LEVELS:

The farther an electron is from the nucleus, the higher is the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.

SEMICONDUCTOR DIODES

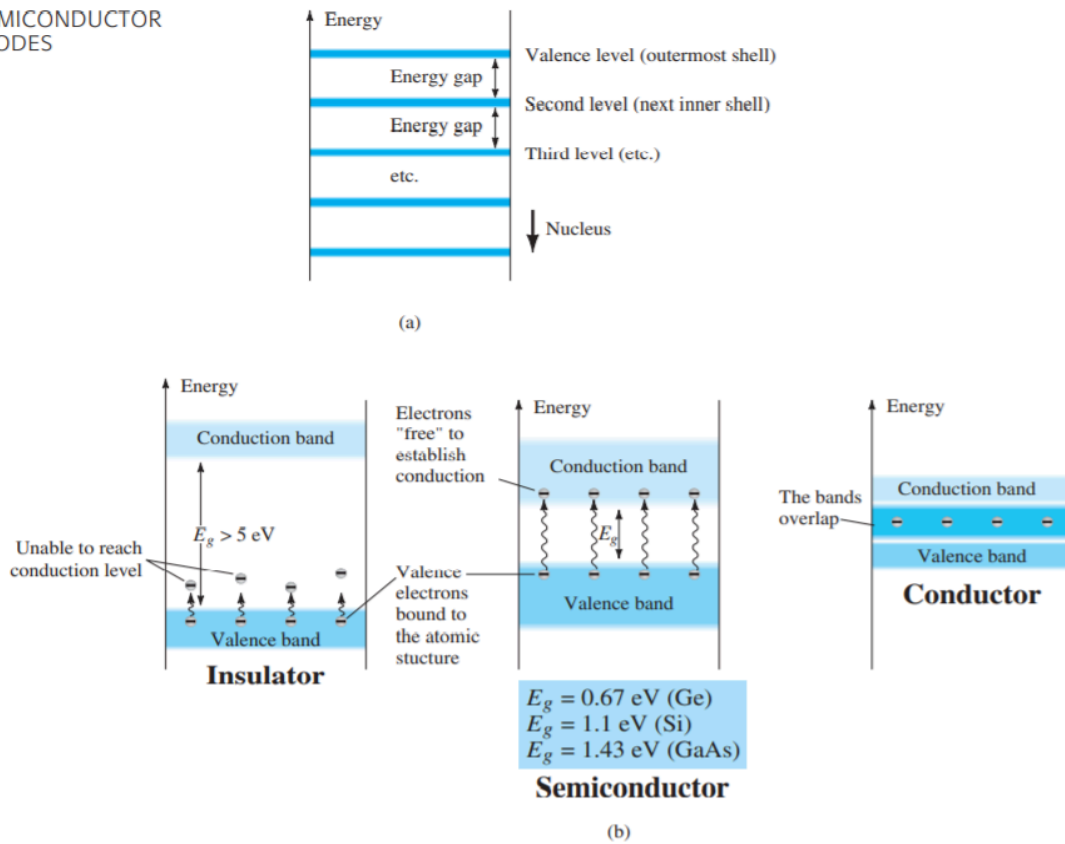


FIG. 1.6

Energy levels: (a) discrete levels in isolated atomic structures; (b) conduction and valence bands of an insulator, a semiconductor, and a conductor.

In Fig. 1.6 the units of measurement are electron volts (eV). The unit of measure is appropriate because W (energy) = QV (as derived from the defining equation for voltage: $V = W / Q$). Substituting the charge of one electron and a potential difference of 1 V results in an energy level referred to as one electron volt .

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

$$= 1.6 \times 10^{-19} \text{ J}$$

$$\text{and } 1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

EXTRINSIC MATERIAL:

A semiconductor material that has been subjected to the doping process is called an extrinsic material. There are two extrinsic materials of immeasurable importance to semiconductor device fabrication: n-type and p-type materials.

n -Type Material:

An n -type material is created by introducing impurity elements that have five valence electrons (pentavalent), such as antimony , arsenic , and phosphorus.

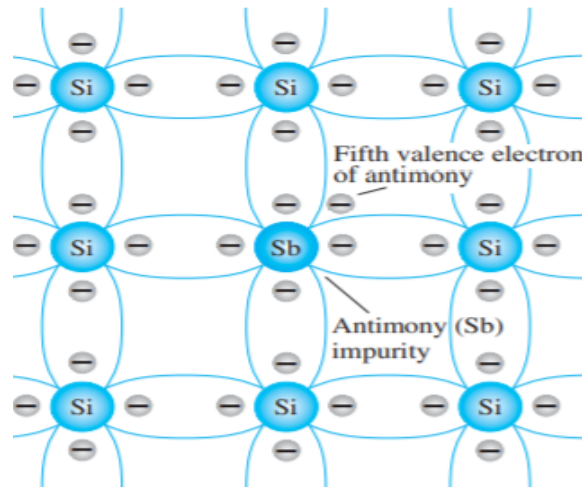


FIG. 1.7

Antimony impurity in n-type material.

Each is a member of a subset group of elements in the Periodic Table of Elements referred to as Group V because each has five valence electrons.

Diffused impurities with five valence electrons are called donor atoms.

p -Type Material:

The p -type material is formed by doping a pure germanium or silicon crystal with impurity atoms having three valence electrons. The elements most frequently used for this purpose are boron , gallium , and indium . Each is a member of a subset group of elements in the Periodic Table of Elements referred to as Group III because each has three valence electrons.

The diffused impurities with three valence electrons are called acceptor atoms.

Majority and Minority Carriers:

In an n-type material (Fig. 1.11a) the electron is called the majority carrier and the hole the minority carrier.

For the p-type material the number of holes far outweighs the number of electrons, as shown in Fig. 1.11b . Therefore: In a p-type material the hole is the majority carrier and the electron is the minority carrier.

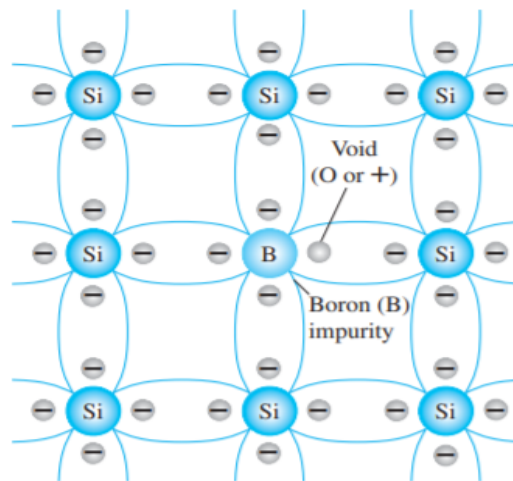


FIG. 1.9
Boron impurity in p-type material.

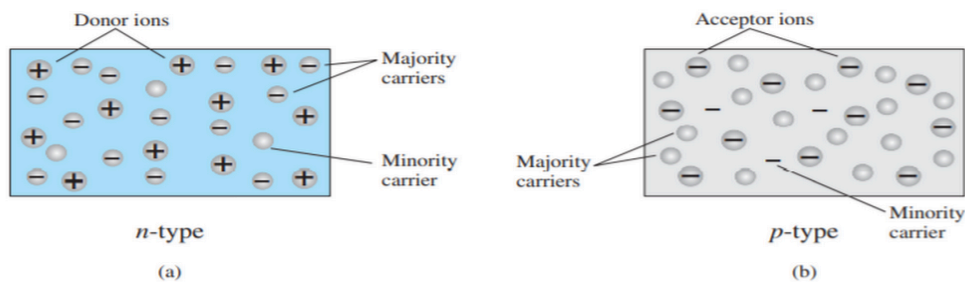


FIG. 1.11
(a) n-type material; (b) p-type material.

No Applied Bias ($V=0$ V):

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

If leads are connected to the ends of each material, a two-terminal device, three options then become available: no bias , forward bias , and reverse bias .

The condition shown in Figs. 1.12a and 1.12b is the no-bias situation because there is no external voltage applied.

If a voltage applied across the diode has the same polarity across the diode as in Fig. 1.12b, it will be considered a positive voltage. If the reverse, it is a negative voltage.

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 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

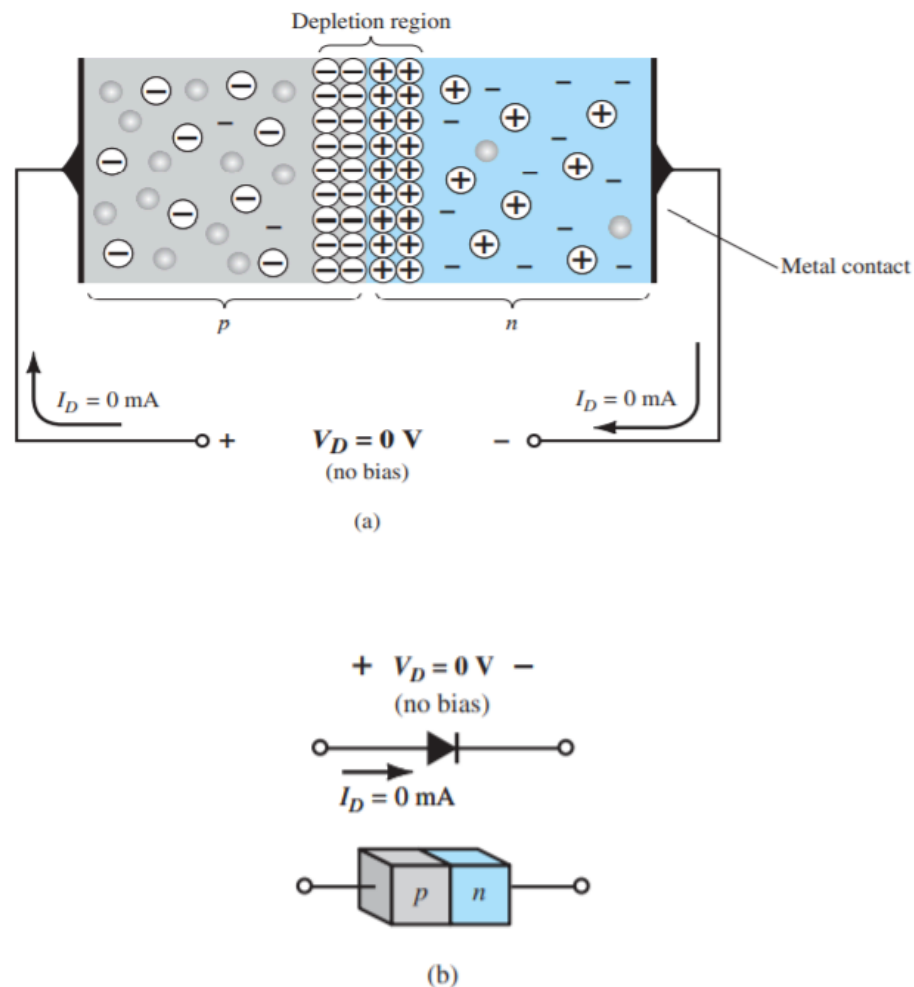


Fig: 1.12

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.

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

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 widening of the depletion region.

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

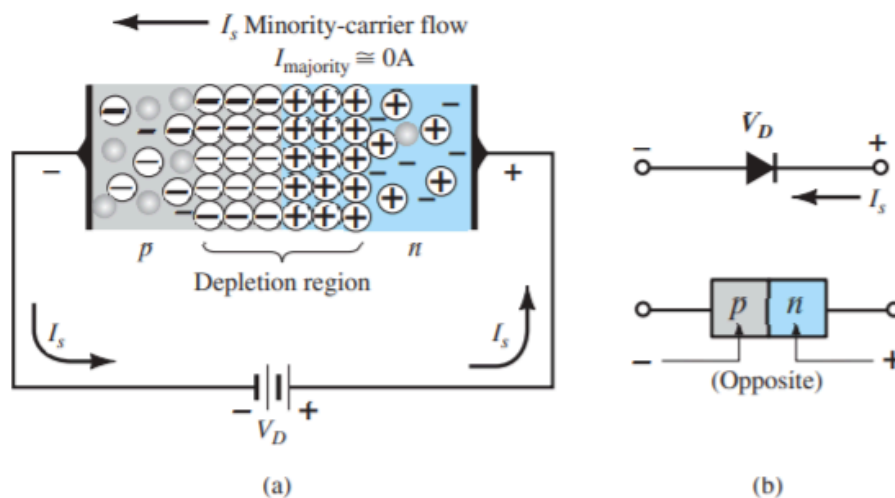


FIG. 1.13

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

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 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,

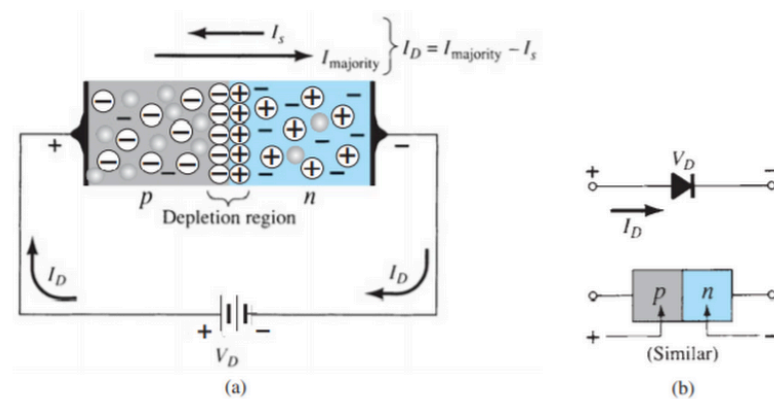


FIG. 1.14

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

SHOCKLEY'S EQUATION AND THERMAL VOLTAGE:

Shockley's equation, for the forward- and reverse-bias regions:

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

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

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

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

Example 1.1:

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

$$\begin{aligned} T &= 273 + ^{\circ}\text{C} = 273 + 27 = 300 \text{ K} \\ V_T &= \frac{kT_K}{q} = \frac{(1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})}{1.6 \times 10^{-19} \text{ C}} \\ &= 25.875 \text{ mV} \cong 26 \text{ mV} \end{aligned}$$

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

BREAKDOWN REGION:

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.

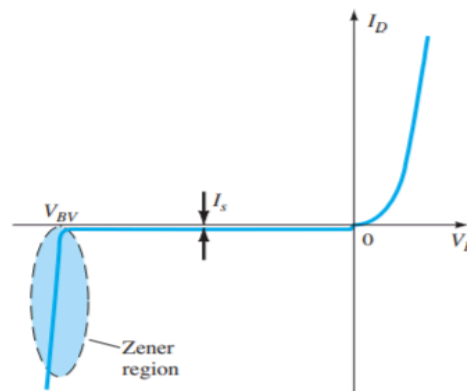


FIG. 1.17
Breakdown region.

IDEAL VERSUS PRACTICAL :

When a switch is closed the resistance between the contacts is assumed to be 0. At the plot point chosen on the vertical axis the diode current is 5 mA and the voltage across the diode is 0 V. Substituting into Ohm's law results in

$$R_F = \frac{V}{I} = \frac{0 \text{ V}}{5 \text{ mA}} = 0 \Omega \text{ (short circuit equivalent)}$$

At any current level on the vertical line, the voltage across the ideal diode is 0 V and the resistance is 0 . For the horizontal section, if we again apply Ohm's law, we find

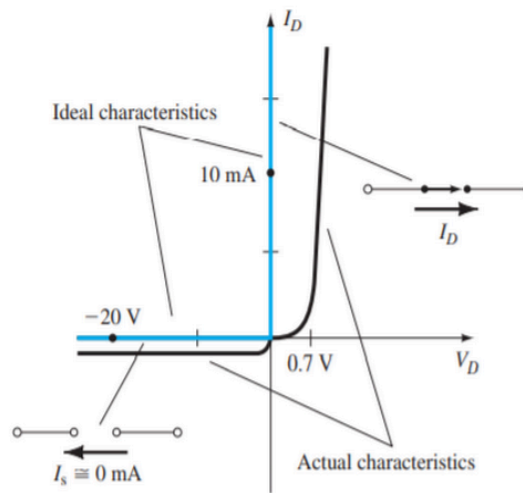


FIG. 1.22

Ideal versus actual semiconductor characteristics.

$$R_R = \frac{V}{I} = \frac{20 \text{ V}}{0 \text{ mA}} = \infty \Omega \text{ (open circuit equivalent)}$$

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.

Difference between Semiconductor Diode and Mechanical Switch:

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.

Example 1.3

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

- $I_D = 2 \text{ mA}$ (low level)
- $I_D = 20 \text{ mA}$ (high level)
- $V_D = -10 \text{ V}$ (reverse-biased)

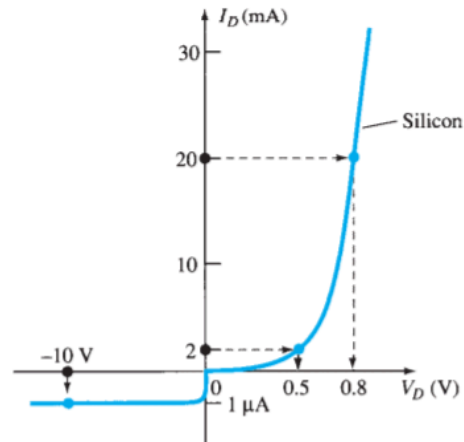


FIG. 1.24
Example 1.3.

Solution:

- a. At $I_D = 2 \text{ mA}$, $V_D = 0.5 \text{ V}$ (from the curve) and

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

- b. At $I_D = 20 \text{ mA}$, $V_D = 0.8 \text{ V}$ (from the curve) and

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

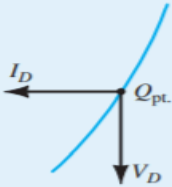
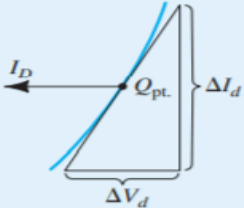
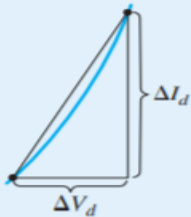
- c. At $V_D = -10 \text{ V}$, $I_D = -I_s = -1 \mu\text{A}$ (from the curve) and

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

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

DC or Static vs AC or Dynamic vs Average AC:

TABLE 1.6
Resistance Levels

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

Piecewise-Linear Equivalent Circuit :

One technique for obtaining an equivalent circuit for a diode is to approximate the characteristics of the device by straight-line segments, as shown in Fig. 1.29 . The resulting equivalent circuit is called a piecewise-linear equivalent circuit. It should be obvious from Fig. 1.29 that the straight-line segments do not result in an exact duplication of the actual characteristics, especially in the knee region. However, the resulting segments are sufficiently close to the actual curve to establish an equivalent circuit that will provide an excellent first approximation to the actual behavior of the device.

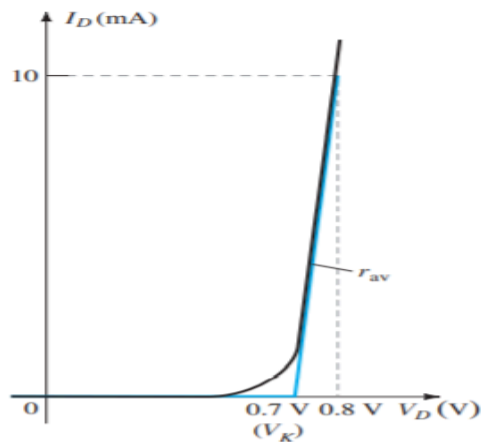


FIG. 1.29

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

Simplified vs Ideal vs Piecewise-linear equivalent circuit:

TABLE 1.7

Diode Equivalent Circuits (Models)

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

REVERSE RECOVERY TIME :

Because of the large number of minority carriers in each material, the diode current will simply reverse as shown in Fig. 1.35 and stay at this measurable level for the period of time t_s (storage time) required for the minority carriers to return to their majority-carrier state in the opposite material. In essence, the diode will remain in the short-circuit state with a current $I_{reverse}$ determined by the network parameters. Eventually, when this storage phase has passed, the current will be reduced in level to that associated with the non conducting state. This second period of time is denoted by t_t (transition interval).

The reverse recovery time is the sum of these two intervals: $t_{rr} = t_s + t_t$

Reverse Recovery Time= storage time + transition interval

This is an important consideration in high-speed switching applications.

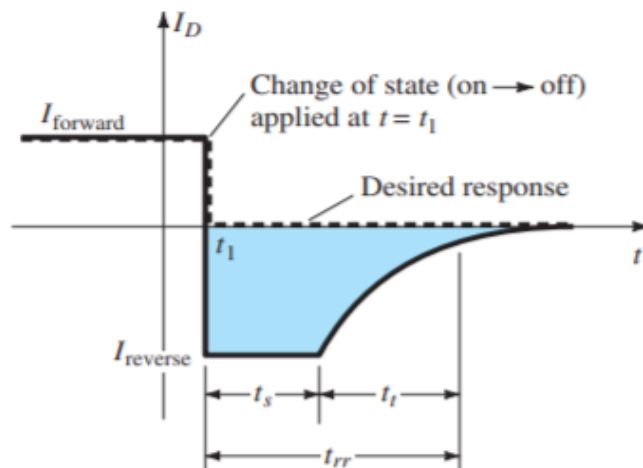


FIG. 1.35

Defining the reverse recovery time.

Example 1.5

The temperature coefficient can be used to find the change in Zener potential due to a change in temperature using the following equation:

$$T_C = \frac{\Delta V_Z / V_Z}{T_1 - T_0} \times 100\% / ^\circ\text{C} \quad (1.14)$$

where T_1 is the new temperature level
 T_0 is room temperature in an enclosed cabinet (25°C)
 T_C is the temperature coefficient
and V_Z is the nominal Zener potential at 25°C .

To demonstrate the effect of the temperature coefficient on the Zener potential, consider the following example.

EXAMPLE 1.5 Analyze the 10-V Zener diode described by Table 1.7 if the temperature is increased to 100°C (the boiling point of water).

Solution: Substituting into Eq. (1.14), we obtain

$$\begin{aligned} \Delta V_Z &= \frac{T_C V_Z}{100\%} (T_1 - T_0) \\ &= \frac{(0.072\% / ^\circ\text{C})(10 \text{ V})}{100\%} (100^\circ\text{C} - 25^\circ\text{C}) \end{aligned}$$

and $\Delta V_Z = 0.54 \text{ V}$

The resulting Zener potential is now

$$V_Z' = V_Z + 0.54 \text{ V} = \mathbf{10.54 \text{ V}}$$

which is not an insignificant change.

LIGHT-EMITTING DIODES:

A 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.

Security systems, industrial processing, optical coupling, safety controls such as on garage door openers, and in home entertainment centers are some applications of LED.

The basic construction of an LED appears in Fig. 1.50 :

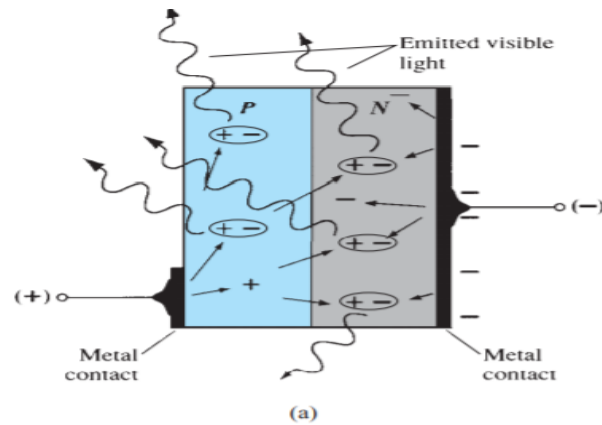


FIG. 1.50

(a) Process of electroluminescence in the LED;

Example 1.6

$$\lambda = \frac{c}{f} \quad (\text{m}) \quad (1.15)$$

where $c = 3 \times 10^8$ m/s (the speed of light in a vacuum)
 f = frequency in Hertz
 λ = wavelength in meters.

LIGHT-EMITTING DIODES

EXAMPLE 1.6 Using Eq. (1.15), find the range of wavelength for the frequency range of visible light (400 THz–750 THz).

Solution:

$$\begin{aligned} c &= 3 \times 10^8 \frac{\text{m}}{\text{s}} \left[\frac{10^9 \text{ nm}}{\text{m}} \right] = 3 \times 10^{17} \text{ nm/s} \\ \lambda &= \frac{c}{f} = \frac{3 \times 10^{17} \text{ nm/s}}{400 \text{ THz}} = \frac{3 \times 10^{17} \text{ nm/s}}{400 \times 10^{12} \text{ Hz}} = 750 \text{ nm} \\ \lambda &= \frac{c}{f} = \frac{3 \times 10^{17} \text{ nm/s}}{750 \text{ THz}} = \frac{3 \times 10^{17} \text{ nm/s}}{750 \times 10^{12} \text{ Hz}} = 400 \text{ nm} \end{aligned}$$

400 nm to 750 nm

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Published Papers

[1] Ali Adib Arnab, Sheikh Sadia Afrin, F.M. Fahad, Hasan U. Zaman, "A cost effective way to build a web controlled search and CO detector rover," [DOI:10.1109/CCWC.2017.7868451](https://doi.org/10.1109/CCWC.2017.7868451) (Received the track Best Paper Award), Proceedings of the 7th IEEE Annual Computing and Communication Workshop and Conference (IEEE CCWC 2017), Las Vegas, USA, 9-11 January, 2017, Publisher: IEEE

[2] Ali Adib Arnab, Sheikh Md. Razibul Hasan Raj, John Schormans, Sultana Jahan Mukta, Nafi Ahmad "Analysis of the Cost of Varying Levels of User Perceived Quality for Internet Access," https://doi.org/10.1007/978-3-030-68154-8_36, Proceedings of the 3rd International Conference on Intelligent Computing & Optimization – ICO 2020, Hua Hin, Thailand, 22-23 April, 2021, Publisher: Springer

- **Research and Teaching Interests:**
- Wireless and Mobile Communication
- Telecommunication Engineering
- Communication Theory
- Electronics
- Internet of Things
- Digital Electronics
- Renewable Energy
- VLSI