TECHNICAL UNIVERSITY OF KOŠICE

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATICS

DEPARTMENT OF ELECTRONICS AND MULTIMEDIA COMMUNICATIONS

BASIC OF ELECTRONICS

Lecture 1

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Applied Informatics

Contents

Lecture 1:

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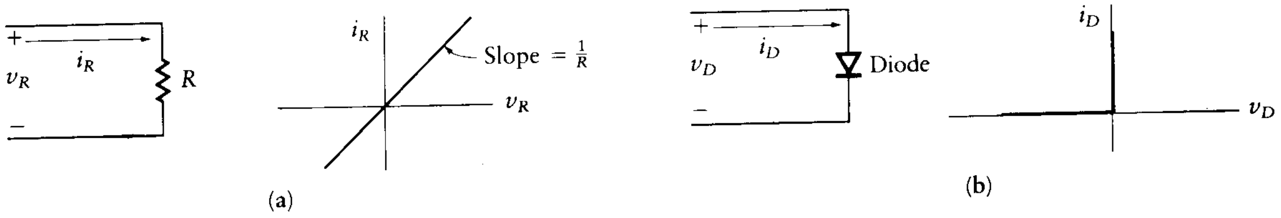
1.2 Semiconductor Diodes

The simplest linear circuit element is the resistor. The voltage across this element is related to current through it by Ohm's law. This relationship is graphically depicted by a straight line, as shown in Figure 1.9(a). The slope of the line is the conductance of the resistor, i.e., the ratio of current to voltage. The reciprocal of this slope is the resistance in ohms. If the resistor is connected in any circuit, the operating point must fall somewhere on this curve.

The ideal diode is a nonlinear device with a current versus voltage characteristic, as shown in Figure 1.9(b). This characteristic is referred to as *piecewise linear,* since the curve is constructed from segments of straight lines. Note that as we attempt to impose a positive (or forward) voltage on the diode, we are not successful and the voltage is limited to zero. The slope of the curve is infinity. Therefore, under this condition the resistance is zero and the diode behaves as a short circuit. If we place a negative (or reverse) voltage across the diode, the current is zero and the slope of the curve is zero. Thus, the diode is now behaving as an infinite resistance, or open circuit.

Figure 1.9 Operating curves for resistor and ideal diode.



1.2.1 *Diode Construction*

Figure 1.10 shows a *p*-type material and an *n*-type material placed together to form a junction. This represents a simplified model of diode construction. The model ignores gradual changes in concentration of the impurities in the material. Practical diodes are constructed as a single piece of semiconductor material, where one side is doped with *p*-type material and the other side with *n*-type material.

Also shown in Figure 1.10 is the schematic symbol of the diode. Note that the "arrow" in this symbol points from the *p*- to the *n*-type material.

Three different materials are commonly used in the construction of diodes: germanium, silicon, and gallium arsenide. Silicon has generally replaced germanium for diodes because its larger energy gap allows higher temperature operation, and the material costs are much lower. Gallium arsenide is particularly useful in microwave and high-frequency applications. However, gallium arsenide is more expensive than silicon and the manufacture of gallium arsenide diodes is difficult.

The precise distance over which the change from *p*- to *n*-type material occurs within the crystal varies with the fabrication technique. The essential feature of the *pn* junction is that the change in impurity concentration must occur in a relatively short distance. Otherwise, the junction will not behave as a diode. There are cases where the *pn* junction cannot be treated as an abrupt change in material type, notably when the diode is formed by diffusion. This causes the doping near the junction to be *graded*—that is, the donor and acceptor concentrations are a function of distance across the junction [2, 14, 36, 37, 44, 53, 57, 61].

A *depletion region* will exist in the vicinity of the junction, as shown in Figure 1.11(a). This phenomenon is due to a combination of electrons and holes where the materials join. This depletion region will have few carriers. The minority carriers on each side of the depletion region (electrons in the *p*-region and holes in the *n*-region) will migrate to the other side and combine with ions in that material. Likewise, the majority carriers (electrons in the *n*-region and holes in the *p*-region) will migrate across the junction.

However, the two components of the current formed by the hole and electron movements across the junction add together to form the diffusion current, I_D. The direction of this current is from the *p*-side to the *n*-side. In addition to the diffusion current, a current exists due to the minority carrier drift across the junction, and this is referred to as I_S. Some of the thermally generated holes in the *n*-type material diffuse through the *n*-type material to the edge of the depletion region. There they experience the electric field and are swept across the depletion region into the *p*-type side. The electrons react in the same manner. The components of these actions combine to form the drift current, I_S.

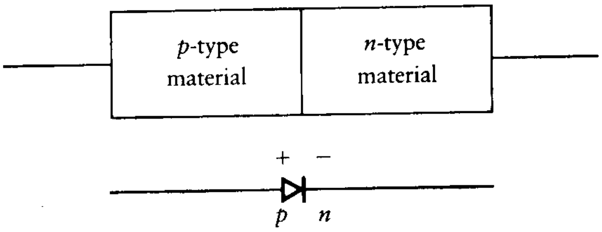


Figure 1.10
Simplified diode model.

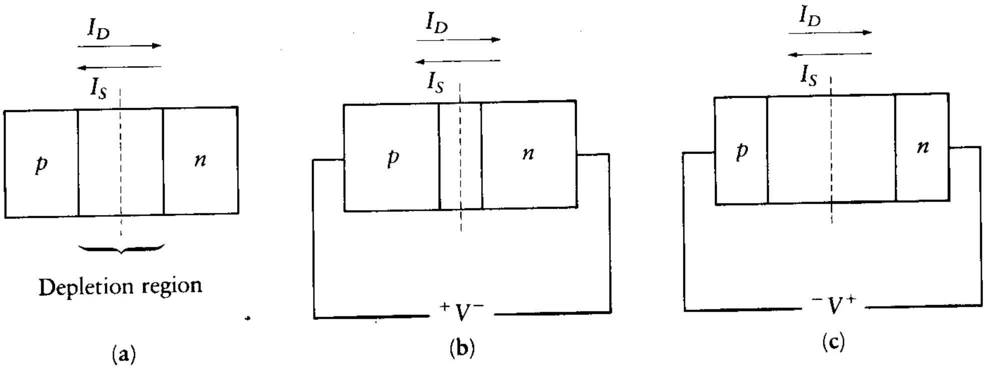


Figure 1.11
Depletion regions.

During open-circuit conditions, the diffusion current is equal to the drift current (at equilibrium).

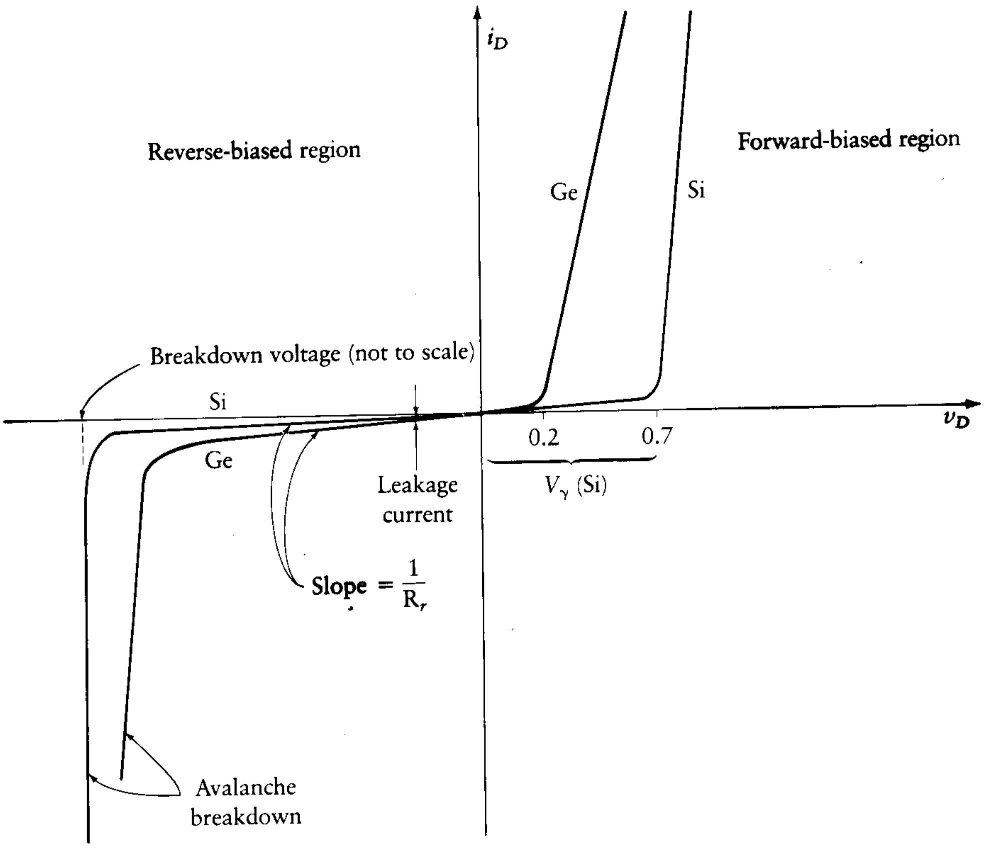
If we now apply a positive potential to the *p*-material relative to the *n*-material, as shown in Figure 1.11(b), the diode is said to be *forward-biased.* The depletion region shrinks in size due to the attraction of majority carriers to the opposite side. That is, the negative potential at the right attracts holes in the *p*-region, and vice-versa. With a smaller depletion region, current can flow more readily. When forward-biased, $I_D - I_S = I$ after equilibrium is achieved, where I is the current through the junction.

Alternatively, if the applied voltage is as shown in Figure 1.11(c), the diode is *reverse-biased.* Free electrons are drawn from the *n*-material toward the right, and, similarly, holes are drawn to the left. The depletion region gets wider and the diode acts as an insulator. When reverse-biased, $I_S - I_D = I$ after equilibrium is achieved, where I is the current through the junction.

1.2.2 *Diode Operation*

Figure 1.12 illustrates the operating characteristics of a *practical* diode. This curve differs from the ideal characteristic of Figure 1.9(b) in the following ways: As the forward voltage increases beyond zero, current does not immediately start to flow. It takes a minimum voltage, denoted by $V\gamma$, to obtain any noticeable current. As the voltage tries to exceed $V\gamma$, the current increases

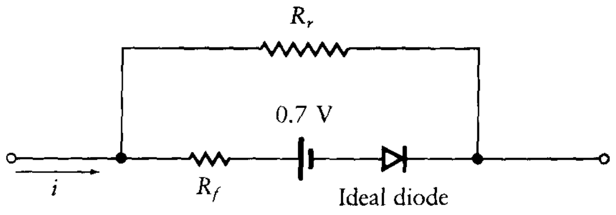
Figure 1.12
Diode operating characteristics.



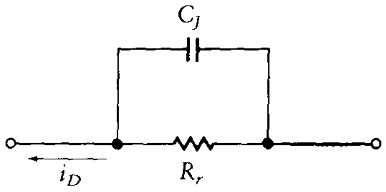
rapidly. The slope of the characteristic curve is large but not infinite, as is the case with the ideal diode. The minimum voltage required to obtain noticeable current, $V\gamma$, is approximately 0.7 V for silicon semiconductors (at room temperature) and 0.2 V for germanium semiconductors. The difference between the voltage for silicon and germanium stems from the atomic structure of the materials. For gallium arsenide diodes, $V\gamma$ is approximately 1.2 V.

When the diode is reverse-biased, there is some small leakage current. This current occurs provided that the reverse voltage is less than the voltage required to break down the junction. The leakage current is much greater for germanium diodes than it is for silicon or gallium arsenide diodes. If the negative voltage becomes large enough to be in the breakdown region, a normal diode may be destroyed. This breakdown voltage is defined as the *peak inverse voltage* (PIV) in manufacturers' specifications (Appendix D shows representative specification sheets. We refer to these often in this text, so you should take a minute to locate them at this time). The curve of Figure 1.12 is not to scale in the reverse region as the avalanche breakdown is usually at a large negative voltage (typically 50 V or more). The damage to the normal diode at breakdown is due to the avalanche of electrons, which flow across the junction with little increase in voltage. The large current can cause destruction of the diode if excessive

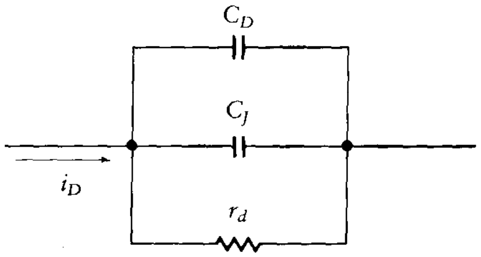
Figure 1.13
Diode models.



(a) dc model (both forward and reverse)



(b) Simple ac model for reverse-biased diode



(c) ac model for forward-biased diode

heat builds up. This breakdown is sometimes referred to as the diode voltage breakdown (V_{BR}).

Diodes can be constructed to utilize the breakdown voltage to simulate a voltage-control device. The result is a zener diode, which is discussed in Section 1.6.

1.2.3 *Diode Equivalent Circuit Models*

The circuit shown in Figure 1.13(a) represents a simplified model of the silicon diode under both forward and reverse *dc* operating conditions. The relationships for this model approximate the diode operating curve of Figure 1.12. The resistor R_r represents the reverse-bias resistance of the diode and is usually of the order of megohms. The resistor R_f represents the contact and bulk resistance of the diode and is usually less than 50 Ω. When forward-biased, the ideal diode is a short circuit, or zero resistance. The circuit resistance of the practical diode modeled in Figure 1.13(a) is

$$R_r \parallel R_f \approx R_f$$

Under reverse-bias conditions, the ideal diode has infinite resistance (open circuit), and the circuit resistance of the practical model is R_r. The ideal diode that is part of the model of Figure 1.13(a) is forward-biased when the terminal voltage exceeds 0.7 V.

The *ac* circuit models are more complex because the diode operation depends upon frequency. A simple ac model for a reverse-biased diode is shown in Figure 1.13(b). The capacitor, C_J, represents the junction capacitance. Figure 1.13(c) shows the ac equivalent circuit for a forward-biased diode. The model includes two capacitors, the *diffusion capacitor,* C_D, and the *junction capacitor,* C_J. The diffusion capacitance, C_D, approaches zero for reverse-biased diodes. The *dynamic resistance* is r_d and it is given by the slope of the voltage-current characteristic. At low frequencies, the capacitive effects are small and r_d is the only significant element.

1.3 Physics of Solid-State Diodes

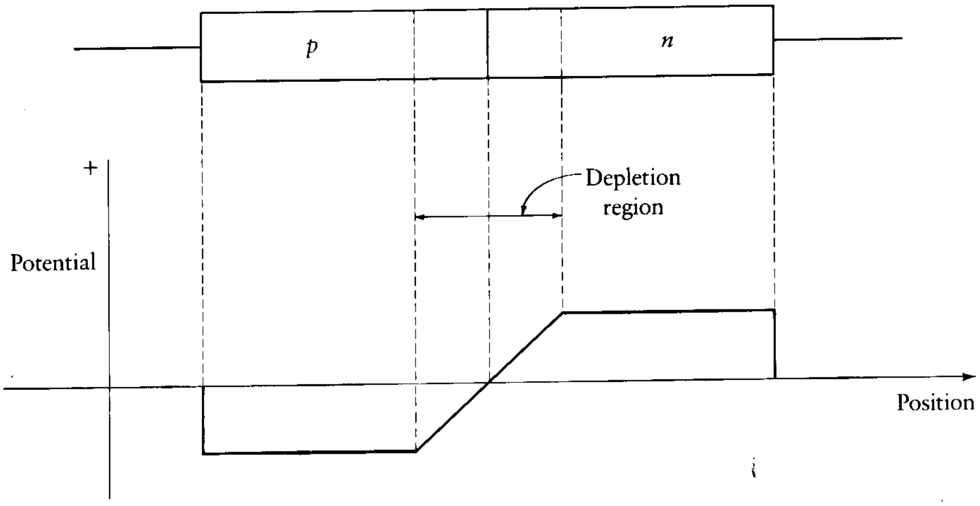
Now that we have discussed diode construction and have had a brief introduction to practical diode models, we shall explore some of the more detailed aspects of the differences between practical and ideal diodes. Additional detail is presented in Appendix B.

1.3.1 *Charge Distribution*

Diodes can be visualized as a combination of an *n*-type semiconductor connected to a *p*-type semiconductor. However, in actual production, a single crystal of a semiconductor is formed with part of the crystal doped with *n*-type material and the other part doped with *p*-type material.

When the *p*- and *n*-type materials exist together in a crystal, a charge redistribution occurs. Some of the free electrons from the *n*-material migrate across the junction and combine with the free holes in the *p*-material. Similarly some of the free holes from the *p*-material migrate across the junction and combine with free electrons in the *n*-material. As a result of this charge redistribution, the *p*-material acquires a net negative charge and the *n*-material acquires a net positive charge. These charges create an electric field and a potential difference between the two types of material that will inhibit any further charge movement. The result is to reduce the number of current carriers near the junction. This happens in an area known as the *depletion region.* The resulting electric field provides a *potential barrier,* or *hill,* in a direction that inhibits the migration of carriers across the junction. This is shown in Figure

Figure 1.14
Barrier potentials.



1.14. In order to produce a current across the junction, we must reduce the potential barrier, or hill, by applying a voltage of the proper polarity across the diode.

1.3.2 *Relationship Between Diode Current and Diode Voltage*

An exponential relationship exists between diode current and applied potential. It is possible to write a single expression for the current that applies for both the forward- and reverse-bias conditions. The expression applies as long as the voltage does not exceed the breakdown voltage. The relationship is described by equation (1.1).

$$i_D = I_o\left[\exp\left(\frac{qv_D}{nkT}\right) - 1\right] \tag{1.1}$$

The terms in equation (1.1) are defined as follows:

i_D = current in the diode
v_D = potential difference across the diode
I_o = leakage current
q = electron charge: 1.6×10^{-19} coulombs (C)
k = Boltzmann's constant: 1.38×10^{-23} J/°K
T = absolute temperature in degrees Kelvin
n = empirical constant between 1 and 2, sometimes referred to as the *exponential ideality factor*

Equation (1.1) can be simplied by defining

$$V_T = \frac{\mathrm{k}T}{q}$$

This yields

$$i_D = I_o\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \tag{1.2}$$

If we operate at room temperature (25°C) and only in the forward-bias region ($v_D > 0$), then the first term in parenthesis predominates and the current is approximately given by

$$i_D = I_o\exp\left(\frac{v_D}{nV_T}\right) \tag{1.3}$$

These equations are illustrated in Figure 1.15.

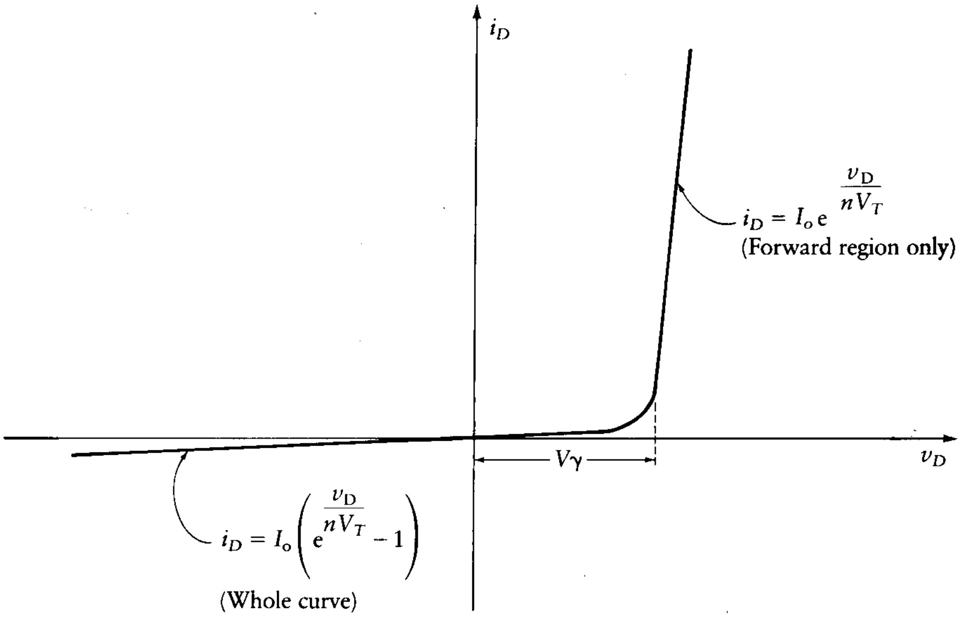
The reverse saturation current, I_o, is a function of the material purity, doping, and geometry of the diode. The empirical constant, n, is a number that is a property of the diode construction. It can vary in accordance with the voltage and current levels. However, some diodes may operate over a considerable voltage range with a fairly constant n. If $n = 1$, the value of nV_T is 26 mV at 25°C. When $n = 2$, nV_T becomes 52 mV. For germanium diodes, n is usually considered to be 1. For silicon diodes, the Sah-Noyce-Shockley (SNS) theory [47] predicts that n should equal 2. Although the value of 2 is predicted, most silicon diodes operate in the range $n = 1.3$ to 1.6. The value of n can vary somewhat even in a particular production run due to manufacturing tolerance, material purity, and doping levels ([36], Section 1.2).

We now have the necessary information to evaluate the relationship between current and voltage at an operating point Q. Although the curves for the forward region shown in Figure 1.15 resemble a straight line, we know the line is not straight, as it has to follow the exponential relationship. This means that the slope of the line is changing as i_D changes. We can differentiate the expression of equation (1.3) to find the slope at any fixed i_D:

$$\frac{di_D}{dv_D} = \frac{I_o\left[\exp\left(\frac{v_D}{nV_T}\right)\right]}{nV_T} \tag{1.4}$$

In order to eliminate the exponential function, we solve equation (1.2) to get

Figure 1.15
Diode voltage-current relationship.



$$\exp\left(\frac{v_D}{nV_T}\right) = \frac{i_D}{I_o} + 1$$

Then, substituting this expression into equation (1.4) yields

$$\frac{di_D}{dv_D} = \frac{(i_D + I_o)}{nV_T}$$

The dynamic resistance, r_d, is the reciprocal of this expression, or

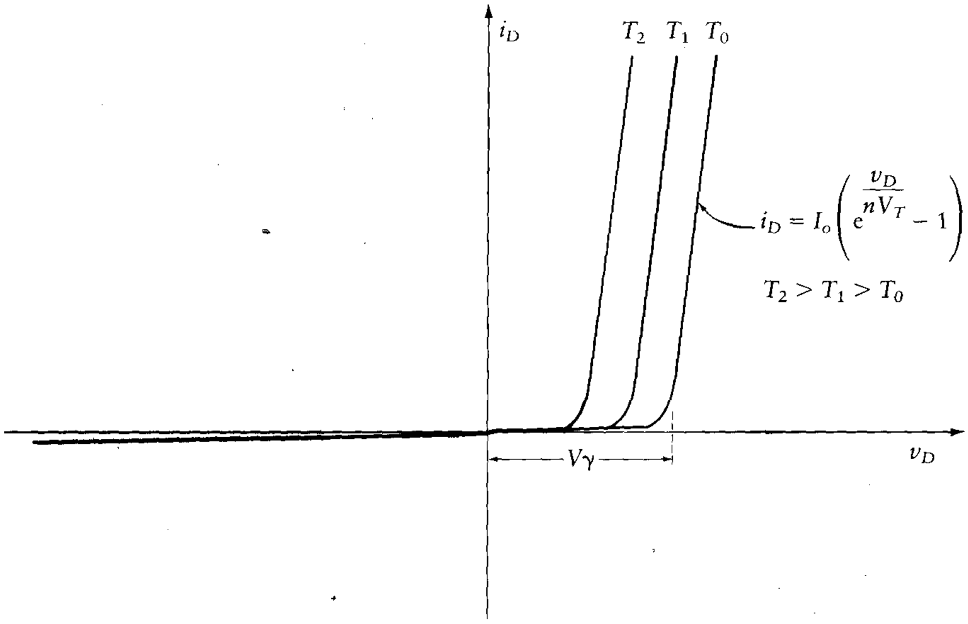
$$r_d = \frac{nV_T}{(i_D + I_o)} \approx \frac{nV_T}{i_D}$$

Although we know r_d changes when i_D changes, we can assume it is fixed for a specific operating range. We use the term R_f to denote diode forward resistance, which is composed of r_d and the contact resistance.

1.3.3 Temperature Effects

Temperature plays an important role in determining operational characteristics of diodes. Changes in the diode characteristics caused by changing temperature may require adjustments in the design and packaging of circuits.

Figure 1.16
Dependence of I_D upon temperature.



As temperature increases, the turn-on voltage, $V\gamma$, decreases. Alternatively, a decrease in temperature results in an increase in $V\gamma$. This is illustrated in Figure 1.16. Here $V\gamma$ varies linearly with temperature according to the following equation (we assume that the diode current, i_D, is held constant):

$$V\gamma(T_1) - V\gamma(T_o) = k(T_1 - T_o)$$

where

T_o = room temperature, or 25°C
T_1 = new temperature of diode in °C
$V\gamma(T_o)$ = diode voltage at room temperature (**ambient**)
$V\gamma(T_1)$ = diode voltage at new temperature
k = temperature coefficient in V/°C

Although k does in fact vary with changing operating parameters, standard engineering practice permits assuming that it is constant. Values of k for the various types of diodes are given as follows ([50], Section 1.11):

$k = -2.5$ mV/°C	for germanium diodes
$k = -2.0$ mV/°C	for silicon diodes
$k = -1.5$ mV/°C	for Schottky diodes

$V\gamma(T_o)$ is equal to the value given below.

silicon diodes:	0.7 V

germanium diodes:	0.2 V
Schottky diodes:	0.3 V
gallium arsenide diodes:	1.2 V

The reverse saturation current, I_o, is another diode parameter that depends upon temperature. It increases approximately 7.2%/°C for both silicon and germanium diodes. In other words, I_o approximately doubles for every 10°C increase in temperature. The expression for the reverse saturation current as a function of temperature is

$$I_o(T_2) = I_o(T_1)\exp[k_i(T_2 - T_1)]$$

where

$$k_i = 0.072/°\mathrm{C}$$

and T_1 and T_2 are two different temperatures. This expression can be simplified and rewritten as follows:

$$I_o(T_2) = I_o(T_1)2^{(T_2 - T_1)/10} \tag{1.5}$$

This simplification is possible because

$$e^{0.72} \approx 2$$

Drill Problems

D1.1 When a silicon diode is conducting at a temperature of 25°C, a 0.7 V drop exists across its terminals. What is the voltage, $V\gamma$, across the diode at 100°C?

Ans: $V\gamma = 0.55$ V

D1.2 The diode described in Problem D1.1 is cooled to −100°C. What is the voltage required across the diode to establish a noticeable current at the new temperature?

Ans: $V\gamma = 0.95$ V

1.3.4 *Diode Load Lines*

Since the diode is a nonlinear device, standard circuit-analysis techniques must be modified. We cannot simply write equations and solve for the variables, since the equations only hold within a particular operating region.