8

Semiconductor Diode

Bogdan M. Wilamowski
Auburn University

The *pn* semiconductor junctions exhibit nonlinear current–voltage characteristics and they are used to rectify and shape electrical signals. Exponential current–voltage characteristics are sometimes used to build logarithmic amplifiers. The thickness of the depletion layer depends on applied reverse voltage, and the voltage-dependent capacitance can be used to tune frequency characteristics of electronic circuits. There are over 20 different types of diodes using different properties of *pn* junctions or metal–semiconductor junction properties. Some of these special diodes are described in Section 8.6.

8.1 Nonlinear Static *I–V* Characteristics

Typical *I–V* diode characteristics are shown in Figure 8.1. In case of common silicon diode the forward direction current increases exponentially at first, and then it is limited by an ohmic resistance of the structure. A very small current in the reverse direction at first increases slightly with applied voltage and then starts to multiply near the breakdown voltage The current at the breakdown is limited by the ohmic resistances of the structure. In germanium (small energy gap) diodes, the recombination-generation component of the current is much smaller than the diffusion components, and in a wide range of reverse voltages the current is almost constant. In the case of silicon diodes (larger energy gap), the diffusion component of the reverse current is negligibly small, and the reverse current is caused by the recombination-generation phenomena, and the current is proportional to the size of the depletion layer (which increases slightly with the voltage). The diode equation (8.6) is not valid for silicon diodes in the reverse direction. Typical reverse characteristics of germanium and silicon diodes are shown in Figure 8.2.

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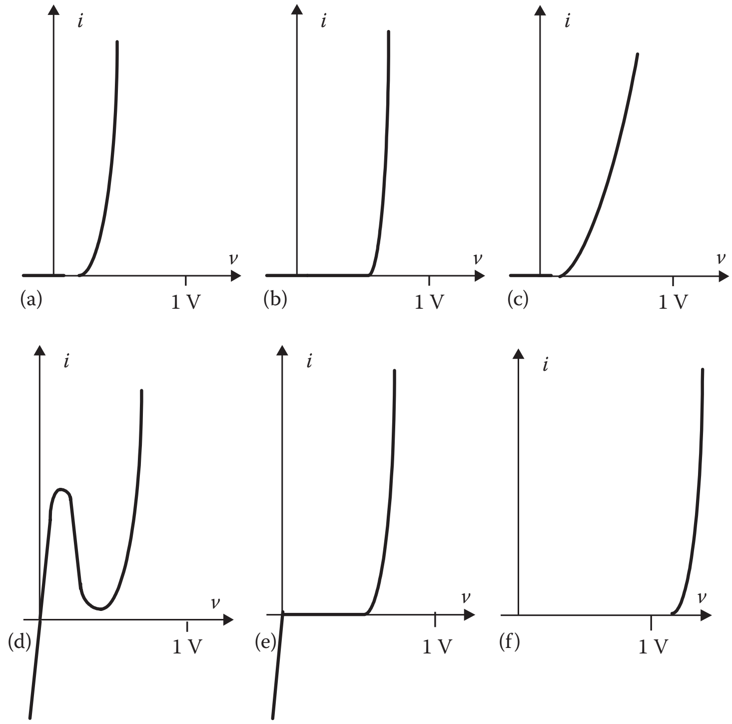

FIGURE 8.1 Forward current–voltage characteristics of various types of diodes: (a) germanium diode, (b) silicon diode, (c) Schottky diode, (d) tunnel diode, (e) backward diode, and (f) LED.

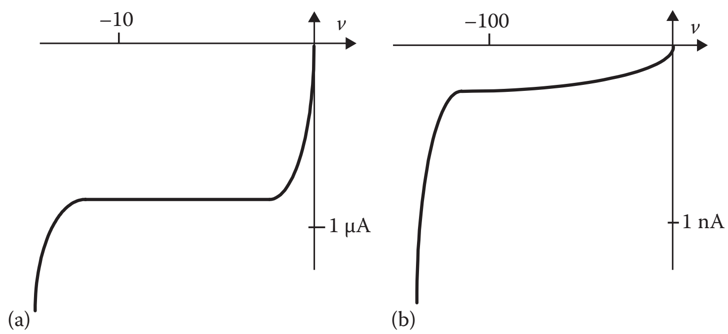

FIGURE 8.2 Reverse current–voltage characteristics: (a) germanium diode, (b) silicon diode.

8.1.1 *pn* Junction Equation

The *n*-type semiconductor material has a positive impurity charge attached to the crystal lattice structure. This fixed positive charge is compensated by free moving electrons with negative charges. Similarly, the *p*-type semiconductor material has a lattice with a negative charge, which is compensated by free moving holes, as is shown in Figure 8.3. The number of majority carriers (electrons in *p*-type and holes in *n*-type materials) are approximately equal to the donor or acceptor impurity concentrations, i.e., $n_n = N_D$ and $p_p = N_A$. The number of minority carriers (electrons in *p*-type and holes in *n*-type) can be found using the equations

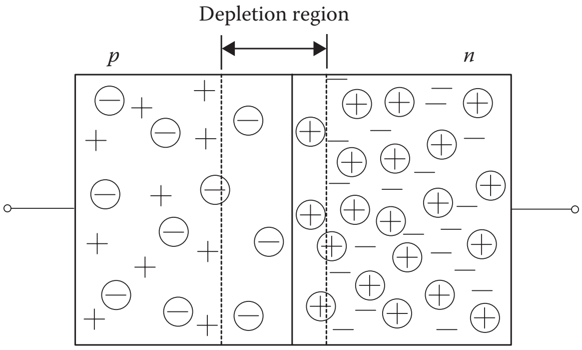

FIGURE 8.3 Illustration of the *pn* junction.

$$n_p = \frac{n_i^2}{p_p} \approx \frac{n_i^2}{N_A} \qquad p_n = \frac{n_i^2}{n_n} \approx \frac{n_i^2}{N_D} \tag{8.1}$$

The intrinsic carrier concentration, n_i, is given by

$$n_i^2 = \xi T^3 \exp\left(-\frac{V_g}{V_T}\right); \quad V_T = \frac{kT}{q} \tag{8.2}$$

where
- $V_T = kT/q$ is the thermal potential ($V_T = 25.9\,\text{mV}$ at 300 K)
- T is the absolute temperature in K
- $q = 1.6 \times 10^{-16}$ C is the electron charge
- $k = 8.62 \times 10^{-5}$ eV/K is the Boltzmann's constant
- V_g is the potential gap ($V_g = 1.1$ V for silicon)
- ξ is a material constant

For silicon intrinsic concentration n_i is given by AQ1

$$n_i = 3.88 \times 10^{16} T^{3/2} \exp\left(-\frac{7000}{T}\right) \tag{8.3}$$

For silicon at 300 K, $n_i = 1.5 \times 10^{10}\,\text{cm}^{-2}$.

When a *pn* junction is formed, the fixed electrostatic lattice charges form an electrical field at the junction. Electrons are pushed by electrostatic forces deeper into the *n*-type region and holes into the *p*-type region, as illustrated in Figure 8.4. Between *n*-type and *p*-type regions there is a depletion layer with a built-in potential that is a function of impurity doping level and intrinsic concentration n_i:

$$V_{pn} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = V_T \ln\left(\frac{n_n p_p}{n_i^2}\right) = V_T \ln\left(\frac{n_n}{n_p}\right) = V_T \ln\left(\frac{p_p}{p_n}\right) \tag{8.4}$$

The junction current as a function of biasing voltage is described by the diode equation

$$i = I_s \left[\exp\left(\frac{v}{V_T}\right) - 1\right] \tag{8.5}$$

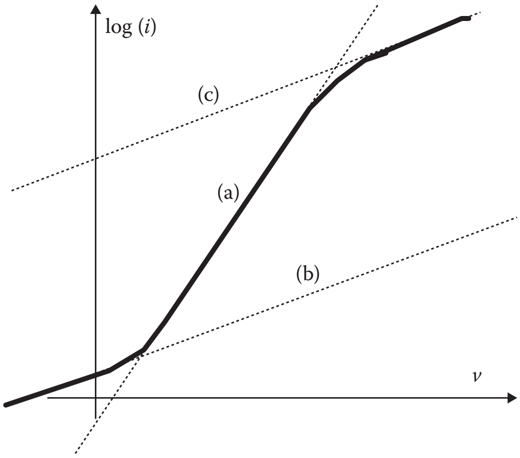

FIGURE 8.4 Current–voltage characteristics of the *pn* junction in forward direction: (a) diffusion current, (b) recombination current, and (c) high-level injection current.

where

$$I_s = Aqn_i^2V_T\left(\frac{\mu_p}{\int_0^{L_p} n_n dx} + \frac{\mu_n}{\int_0^{L_n} p_p dx}\right) \tag{8.6}$$

where
- $n_n \approx N_D$
- $p_p \approx N_A$
- μ_n and μ_p are the mobility of electrons and holes
- L_n and L_p are the diffusion length for electron and holes
- A is the device area

In the case of diodes made of silicon or other semiconductor material with a high energy gap, the reverse-biasing current cannot be calculated from the diode equation (8.5). This is due to the carrier generation-recombination phenomenon. Lattice imperfection and most impurities are acting as generation-recombination centers. Therefore, the more imperfections there are in the structure, the larger the deviation from ideal characteristics.

8.1.2 Forward *I–V* Diode Characteristics

The diode equation (8.5) was derived with an assumption that injected carriers are recombining on the other side of the junction. The recombination within the depletion layer was neglected. In forward-biased diode, electrons and holes are injected through the depletion region, and they may recombine there. The recombination component of the forward-biased diode is given by

$$i_{rec} = qwA\frac{n_i}{2\tau_0}\exp\left(\frac{v}{2V_T}\right) = I_{ro}\exp\left(\frac{v}{2V_T}\right) \tag{8.7}$$

where
- w is the depletion layer thickness
- τ_0 is the carrier lifetime in depletion region

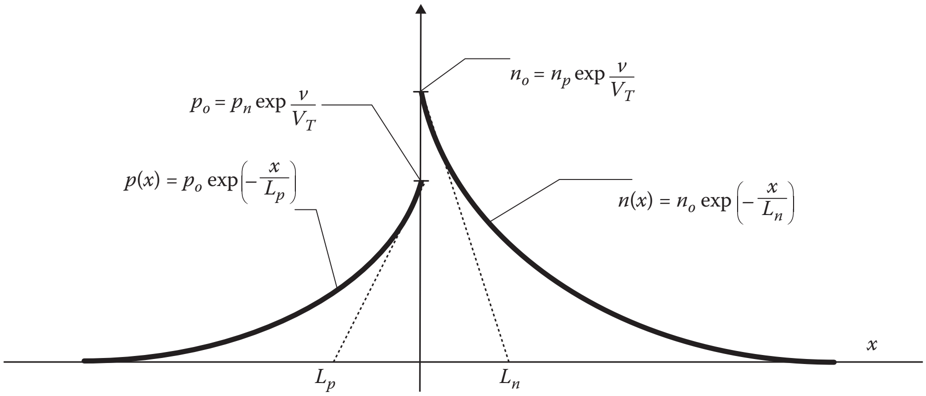

FIGURE 8.5 Minority carrier distribution in the vicinity of the *pn* junction biased in forward direction.

The total diode current $i_T = i_D + i_{rec}$, where i_D and i_{rec} are defined by Equations 8.5 and 8.7. The recombination component dominates at low current levels, as Figure 8.5 illustrates.

Also, in very high current levels the diode equation (8.5) is not valid. Two phenomena cause this deviation. First, there is always an ohmic resistance that plays an important role for large current values. The second deviation is due to high concentration of injected minority carriers. For very high current levels, the injected minority carrier concentrations may approach, or even become larger than, the impurity concentration. An assumption of the quasi-charge neutrality leads to an increase of the majority carrier concentration. Therefore, the effective diode current is lower, as it can be seen from Equation 8.6. The high current level in the diode follows the relation

$$i_h = I_{ho} \exp\left(\frac{v}{2V_T}\right) \tag{8.8}$$

Figure 8.4 shows the diode *I–V* characteristics, which include generation-recombination, diffusion, and high current phenomena. For modeling purposes, the forward diode current can be approximated by

$$i_D = I_o \exp\left(\frac{v}{\eta V_T}\right) \tag{8.9}$$

where η has a value between 1.0 and 2.0. Note that the η coefficient is a function of current, as shown in Figure 8.5. It has a larger value for small and large current regions and it is close to unity in the medium current region.

8.1.3 Reverse *I–V* Characteristics

The reverse leakage current in silicon diodes is mainly caused by the electron-hole generation in the depletion layer. This current is proportional to the number of generation-recombination centers. These centers are formed either by a crystal imperfection or deep impurities, which create energy states near the center of the energy gap. Once the reverse voltage is applied, the size of the depletion region and the number of generation-recombination centers increase. Thus, the leakage current is proportional to the thickness of the depletion layer $w(v)$. For a step-abrupt junction

$$w = \sqrt{\frac{2\varepsilon\varepsilon_o\left(V_{pn} - v\right)}{qN_{eff}}} \tag{8.10}$$

For other impurity profiles w can be approximated by

$$w = K\left(V_{pn} - v\right)^{1/m} \tag{8.11}$$

The reverse diode current for small and medium voltages can therefore be approximated by

$$i_{rev} = Aw(v)\frac{qn_i}{2\tau_o} \tag{8.12}$$

where n_i is given by Equation 8.2 and w by Equation 8.10 or 8.11. The reverse current increases rapidly near the breakdown voltage. This is due to the avalanche multiplication phenomenon. The multiplication factor is often approximated by

$$M = \frac{1}{1-\left(v/BV\right)^m} \tag{8.13}$$

where

BV stands for the breakdown voltage

m is an exponent chosen experimentally

Note that for the reverse biasing, both v and BV have negative values and the multiplication factor M reaches an infinite value for $v = BV$.

8.2 Diode Capacitances

Two types of capacitances are associated with a diode junction. One capacitance, known as diffusion capacitance, is proportional to the diode current. This capacitance exists only for the forward-biased condition and has the dominant effect there. Second capacitance, known as the depletion capacitance, is a weak function of the applied voltage.

8.2.1 Diffusion Capacitance

In a forward-biased diode, minority carriers are injected into opposite sides of the junction. Those minority carriers diffuse from the junction and recombine with the majority carriers. Figure 8.6 shows the distribution of minority carriers in the vicinity of the junction of uniformly doped n-type and p-type regions. The electron charge stored in the p-region corresponds to the area under the curve, and it is equal to $Q_n = qn_oL_n$. Similarly, the charge of stored holes $Q_p = qp_oL_p$. The storage charge can be also expressed as $Q_n = I_n\tau_n$ and $Q_p = I_p\tau_p$, where I_n and I_p are electron and hole currents at the junction, τ_n and τ_p are the lifetimes for minority carriers. Assuming $\tau = \tau_n = \tau_p$ and knowing that $I = I_p + I_n$ the total storage charge at the junction is $Q = I\tau$. The diffusion capacitance can then be computed as

$$C_{dif} = \frac{dQ}{dv} = \frac{d}{dv}\left[\tau I_o \exp\left(\frac{v}{\eta V_T}\right)\right] = \frac{\tau I_B}{\eta V_T} \tag{8.14}$$

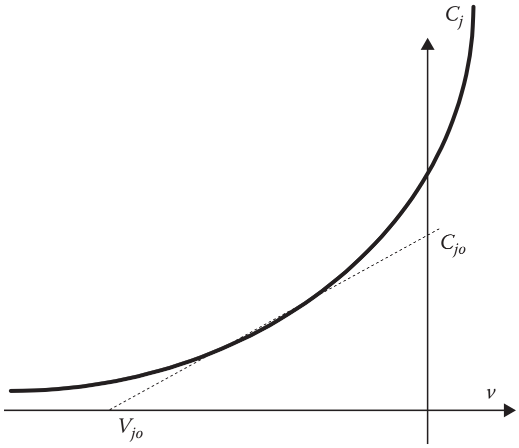

FIGURE 8.6 Capacitance–voltage characteristics for reverse-biased junction.

As one can see, the diffusion capacitance C_{dif} is proportional to the storage time τ and to the diode biasing current I_B. Note that the diffusion capacitance does not depend on the junction area, but it only depends on the diode current. The diffusion capacitances may have very large values. For example, for 100 mA current and $\tau = 1\,\mu s$, the junction diffusion capacitance is about $4\,\mu F$. Fortunately, this diffusion capacitance is connected in parallel to the small-signal junction resistance $r = \eta V_T / I_B$, and the time constant rC_{dif} is equal to the storage time τ.

8.2.2 Depletion Capacitance

The reversed-biased diode looks like a capacitor with two "plates" formed of p-type and n-type regions and the dielectric layer (depletion region) between them. The capacitance of a reversed-biased junction can then be written as

$$C_{dep} = A\frac{\varepsilon}{w} \tag{8.15}$$

where

A is a junction area
ε is the dielectric permittivity of semiconductor material
w is the thickness of the depletion layer

The depletion layer thickness w is a weak function of the applied reverse-biasing voltage. In the simplest case, with step-abrupt junction, the depletion capacitance is

$$C_j = \sqrt{\frac{qN_{eff}\varepsilon\varepsilon_o}{2(V_{pn} - v)}};\quad \frac{1}{N_{eff}} = \frac{1}{N_D} + \frac{1}{N_A} \tag{8.16}$$

The steepest capacitance–voltage characteristics are in pn^+n diodes with the impurity profiles shown in Figure 8.1f. In general, for various impurity profiles at the junction, the depletion capacitance C_j can be approximated by

$$C_j = C_{jo}\left(V_{pn} - v\right)^{1/m} \tag{8.17}$$

or using linear approximation, as shown in Figure 8.6

$$C_j = C_{jo}\left(1 - \frac{v}{V_{jo}}\right) \tag{8.18}$$

8.3 Diode as a Switch

The switching time of the *pn* junction is limited mainly by the storage charge of injected minority carriers into the vicinity of the junction (electrons injected in *p*-type region and holes injected in *n*-type region). When a diode is switched from forward to reverse direction, these carriers may move freely through the junction. Some of the minority carriers recombine with time. Others are moved away to the other side of the junction. The diode cannot recover its blocking capability as long as a large number of the minority carriers exist and can flow through the junction. An example of the current–time characteristics of a diode switching from forward to reverse direction is shown in Figure 8.7. Few characteristics that are shown in the figure are for the same forward current and different reverse currents. Just after switching, these reverse currents are limited only by external circuitry. In this example, shown in Figure 8.7, most of the minority carriers are moved to the other side of the junction by the reverse current and the recombination mechanism is negligible. Note, that the larger the reverse current flows after switching, the shorter time is required to recover the blocking capability. This type of behavior is typical for commonly used high voltage diodes.

In order to shorten the switching time, diodes sometimes are doped with gold or other deep-level impurities to create more generation centers and to increase the carrier recombination. This way, the minority carrier lifetimes of such switching diodes are significantly reduced. The switching time is significantly shorter, but it is almost independent of the reverse diode current after switching, as Figure 8.8 shows.

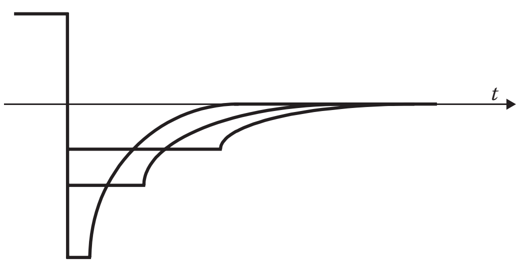

FIGURE 8.7 Currents in diode with large minority carrier lifetimes after switching from forward to reverse direction.

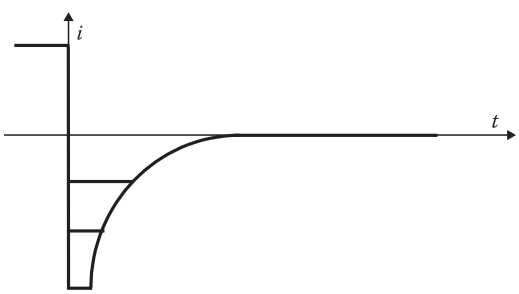

FIGURE 8.8 Currents in diode with small minority carrier lifetimes after switching from forward to reverse direction.

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This method of artificially increasing recombination rates has some severe disadvantages. Such switching diodes are characterized by very large reverse leakage current and small breakdown voltages.

The best switching diodes utilize metal–semiconductor contacts. They are known as the Schottky diodes. In such diodes there is no minority carrier injection phenomenon, therefore, these diodes recover the blocking capability instantaneously. The Schottky diodes are also characterized by a relatively small (0.2–0.3 V) voltage drop in the forward direction. However, their reverse leakage current is larger, and the breakdown voltage rarely exceeds 20–30 V. Lowering the impurity concentration in the semiconductor material leads to slightly larger breakdown voltages, but at the same time, the series diode resistances increase significantly.

8.4 Temperature Properties

Both forward and reverse diode characteristics are temperature dependent. These temperature properties are very important for correct circuit design. The temperature properties of the diode can be used to compensate for the thermal effects of electronic circuits. Diodes can be used also as accurate temperature sensors. The major temperature effect in a diode is caused by the strong temperature dependence of the intrinsic concentration n_i (Equations 8.2 and 8.3) and by the exponential temperature relationship of the diode equation (8.7). By combining Equations 8.2 and 8.7 and assuming the temperature dependence of carrier mobilities, the voltage drop on the forward-biased diode can be written as

$$v = \eta\left[V_T \ln\left(\frac{i}{\xi T^{\alpha}}\right) + V_g\right] \tag{8.19}$$

or diode current

$$i = I_o\left(\frac{T}{T_o}\right)^{\alpha} \exp\left(\frac{T_o}{T}\frac{(v/\eta) - V_g}{V_{To}}\right) \tag{8.20}$$

where

V_g is the potential gap in semiconductor material
$V_g = 1.1$ V for silicon and $V_g = 1.4$ V for GaAs
α is a material coefficient ranging between 2.5 and 4.0

The temperature dependence of the diode voltage drop dv/dT can be obtained by calculating the derivative of Equation 8.19

$$\frac{dv}{dT} = \frac{v - \eta\left(V_g + \alpha V_T\right)}{T} \tag{8.21}$$

For example, in the case of the silicon diode with a 0.6 V drop and assuming $\eta = 1.1$, $\alpha = 3.0$, and $T = 300$ K, the $dV/dT = 1.87$ mV/°C.

The reverse diode current is a very strong function of the temperature. For diodes made of the semiconductor materials with a small potential gap, such as germanium, the diffusion component dominates. In this case, the reverse current is proportional to

$$i_{rev} \propto T^{\alpha} \exp\left(-\frac{qV_g}{kT}\right) \tag{8.22}$$

For diodes made of silicon and semiconductors with a higher energy gap, the recombination is the dominant mechanism. In this case, reverse leakage current is proportional to

$$i_{rev} \propto T^{\alpha/2} \exp\left(-\frac{qV_g}{2kT}\right) \tag{8.23}$$

Using Equation 8.23, one may calculate that for silicon diodes at room temperatures, the reverse leakage current doubles for about every 10°C.

ἀ e breakdown voltage is also temperature dependent. ἀ e tunneling effect dominates in diodes with small breakdown voltages. ἀ is effect is often known in literature as the Zener breakdown. In such diodes the breakdown voltage decreases with the temperature. ἀ e avalanche breakdown dominates in diodes with large breakdown voltages. When the avalanche mechanism prevails then the breakdown voltage increases 0.06%–0.1% per °C. For medium range breakdown voltages, one phenomenon compensates the other, and the temperature-independent breakdown voltage can be observed. ἀ is zero temperature coefficient exists for diodes with breakdown voltages equal to about $5V_g$. In the case of the silicon diode, this breakdown voltage, with a zero temperature coefficient, is equal to about 5.6 V.

8.5 Piecewise Linear Model

ἀ e nonlinear diode characteristics are often approximated by the piecewise linear model. ἀ ere are a few possible approaches to linearize the diode characteristics, as shown in Figure 8.9. ἀ e parameters of the most accurate linearized diode model are shown in Figure 8.10a, and the linearized diode equivalent circuit is shown in Figure 8.10b

ἀ e modified diode equation (8.9) also can be written as

$$v = \eta V_T \ln\left(\frac{i}{I_o}\right) \tag{8.24}$$

For the biasing point V_B and I_B, the small-signal diode resistance dv/di can be computed from Equation 8.24 as

$$r = \frac{dv}{di} = \frac{\eta V_T}{I_B}; \quad V_{tho} = V_B - V_T \tag{8.25}$$

and it is only the function of the thermal potential V_T and the biasing current I_B. Note that the small-signal diode resistance is almost independent on the diode construction or semiconductor material used. If one requires that this linearized diode have the I_B current for the V_B voltage, then the piecewise diode characteristics should be as in Figure 8.10. ἀ e equivalent ἀ evenin and Norton circuits are

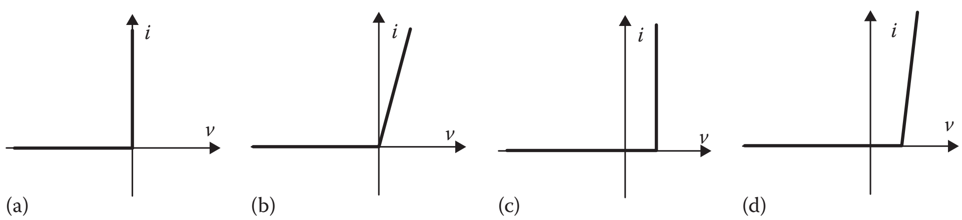

FIGURE 8.9 Various ways of linearizing diode characteristics.

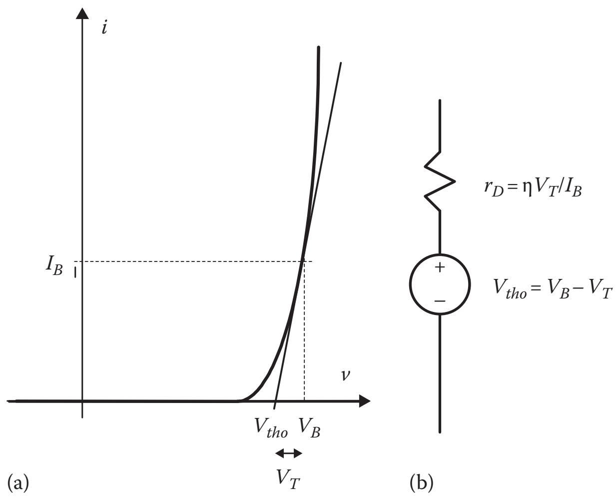

FIGURE 8.10 Linearization of the diode: (a) diode characteristics, (b) equivalent diagram.

shown in Figure 8.11. In a case of large signal operation, the diode can be approximated by shifting the characteristics to the left by ΔV. In this case, the threshold voltage becomes $V_{tho} = V_B - 2V_T$ instead of $V_{tho} = V_B - V_T$.

8.6 Different Types of Diodes

Using different phenomena in semiconductors, it is possible to develop many different types of diodes with specific characteristics. Different diodes have different symbols, as shown in Figure 8.11. Various types of diodes are briefly described in this section.

8.6.1 Switching Diodes

Switching diodes are usually small-power *pn* junction diodes that are designed for fast switching. In order to reduce the storage time (and diffusion capacitances), the lifetime of electron and holes were purposely reduced by introducing deep-level impurities such as gold or platinum.

8.6.2 Zener Diodes

Zener diodes use the reverse-breakdown voltage to stabilize voltages in electronic circuits. ἀ e breakdown voltage of *pn* junction decreases with an increase of the impurity level. When junction is heavy

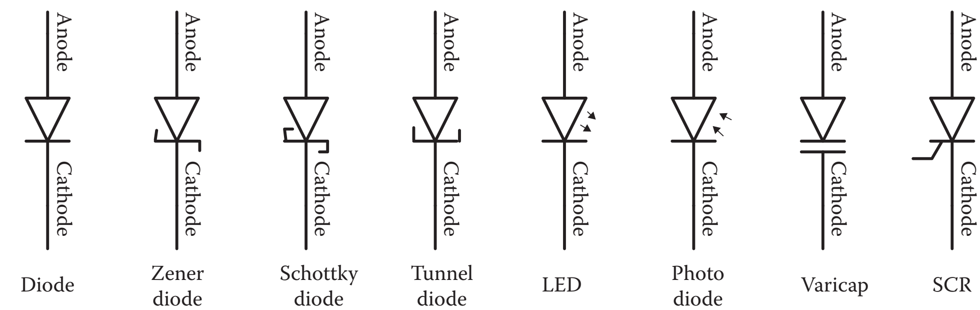

FIGURE 8.11 Commonly used symbols for various diodes.

doped, the breakdown voltage is controlled by the tunneling mechanism, and its decrease with temperature. With lightly doped junction and high breakdown voltages, the avalanche breakdown is the dominant mechanism and the breakdown voltage increases with temperature. In other words, Zener diodes for small voltages have negative temperature coefficient, and Zener diodes for large voltages have positive temperature coefficient. It is worth noticing that for voltages equal about 5 energy gaps (about 5.6 V for silicon) Zener diodes have close to zero temperature coefficients. Such temperature-compensated Zener diodes are known as reference diodes.

8.6.3 Tunnel Diodes (Esaki Diodes)

When both sides of the junction are very heavily doped, then for small forward-biasing voltages (0.1–0.3 V) a large tunneling current may occur. For larger forward voltages (0.4–0.5 V) this tunneling current vanishes. This way, the current–voltage characteristic has a negative resistance region somewhere between 0.2 and 0.4 V (Figure 8.1d). The germanium and other than silicon semiconductors are used to fabricate tunnel diodes.

8.6.4 Backward Diode

The backward diode has slightly lower impurity concentrations than the tunnel diode, and the tunneling current in forward direction does not occur (Figure 8.1e). The backward diode is characterized by a very sharp knee near 0 V, and it is used for detection (rectifications) of signals with very small magnitudes.

8.6.5 PIN Diodes

Diodes with high breakdown voltage have the *pin* structure with an impurity profile shown in Figure 8.12d. A similar *pin* structure is also used in microwave circuits as a switch or as an attenuating resistor. For reverse biasing, such microwave *pin* diode represents an open circuit with a small parasitic junction capacitance. In the forward direction this diode operates as a resistor whose conductance is proportional to the biasing current. At very high frequencies electrons and holes will oscillate rather than flow. Therefore, the microwave *pin* diode exhibits linear characteristics even for large modulating voltages.

8.6.6 Schottky Diodes

The switching time of a *pn* junction from forward to reverse direction is limited by the storage time of minority carriers injected into the vicinity of the junction. Much faster operation is possible in the Schottky diode, where minority carrier injection does not exist. Another advantage of the Schottky diode is that the forward voltage drop is smaller (0.2–0.3 V) than in the silicon *pn* junction. This diode uses the metal–semiconductor contact for its operation. Schottky diodes are characterized by relatively small reverse-breakdown voltage, rarely exceeding 50 V.

8.6.7 Super Barrier Diodes

The major drawback of Schottky diodes is their low breakdown voltage. By combining *pn* junctions with Schottky contact, it is possible to make super barrier diodes where voltage drop in forward direction is determined by Schottky contact, but for reverse direction, specially profiled *pn* junction [9] lower electrical field Schottky contact, resulting in much larger breakdown voltages.

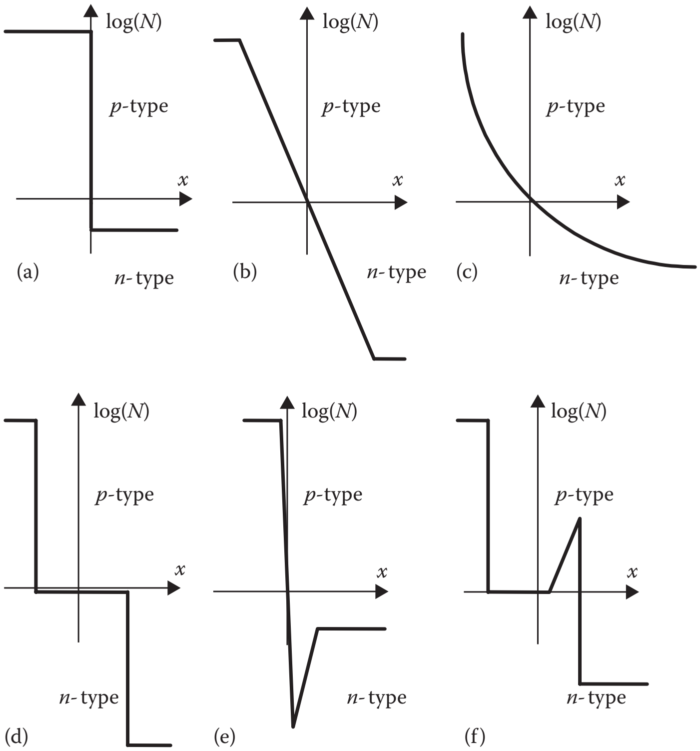

FIGURE 8.12 Impurity profiles for various diodes: (a) step junction, (b) linear junction, (c) diffusion junction, (d) pin junction, (e) hyperabrupt junction, and (f) *pipn* junction.

8.6.8 Step-Recovery Diodes

When *pn* junction is biased in forward detection, then minority carriers are injected to both sides of the junction. Electrons are injected into *n*-type region and electrons are injected into *p*-type region. When AQ2 diode switches in reverse directions, injected minority carriers flow back through the junction creating large temporary reverse current. This current decays with time as the number of minority carriers decreases with time. The step-recovery diodes have such impurity profile that the built-in potentials push minority carriers away from the junction, so large reverse current flows only for a very short time after switching and then this current drops very rapidly generating very sharp current pulse. When RF signal is applied to this diode, many higher harmonic frequencies are generated. These step-recovery diodes are used for frequency multiplication.

8.6.9 Avalanche Diodes

The destructive thermal breakdown in high-power diodes occur when the leakage current, which is an exponential function of the temperature, starts to increase. Locally, larger current creates large local heat dissipation, which leads to further temperature increase and, as a consequence, the destructive thermal breakdown. When the breakdown is controlled by avalanche mechanism, the breakdown voltage increases locally with temperature. In the hotter part of the diode, the breakdown voltage increases, the current stops to flow in this region, and the region cools down. Therefore, high-power avalanche diodes can sustain large reverse currents without destruction. The avalanche mechanism is also used to generate truly random noise and, of course, these are low-power avalanche diodes.

8.6.10 Varicaps

The thickness of the depletion layer in *pn* junction depends on the applied voltage, and this phenomenon can be used as voltage-controlled capacitor to tune high-frequency electronic circuits. Capacitance–voltage relationship depends on the impurity profile of the junction. In a typical junction with an impurity profile as shown in Figure 8.12a or b, capacitance does not change much; but with the hyperabrupt junction, as shown in Figure 8.12e, the value of capacitance may change several times.

8.6.11 Solar Batteries

The semiconductor *pn* junction illuminated by light will generate a voltage on its terminals. Such a diode is known as a solar battery or photovoltaic cell. The maximum voltage of a solar cell is limited by forward *pn* junction characteristics.

8.6.12 Photodiodes

If *pn* junction is eliminated with light, then the reverse junction current is proportional to the light intensity at the junction. This phenomenon is used in photodiodes. If the reversely biased collector junction is illuminated with light, then this photocurrent is amplified beta times by the transistor and as a result phototransistor is beta times more sensitive than the photodiode. Phototransistors are slower than photodiodes, and as a result only photodiodes are used in optical communications.

8.6.13 LEDs

If a diode is biased in the forward direction, it may emit light. In order to obtain high emission efficiency, the light emitting diode (LED) should be made out of a semiconductor material with a direct energy band structure. This way electrons and holes can recombine directly between valence and conduction bands. The silicon diodes do not emit light because the silicon has indirect band structure and the probability of a direct band-to-band recombination is very small. Typically, LEDs are fabricated using various compositions of $Ga_yAl_{1-y}As_xP_{1-x}$. The wavelength of generated light is inversely proportional to the potential gap of junction material.

8.6.14 Laser Diodes

When in LEDs the light intensity is enhanced by the addition of micromirrors, then laser action may occur. Laser diodes have a better efficiency and they generate coherent light.

8.6.15 Gun Diodes

These are other microwave diodes that generate microwave signals. The gun diode uses material like gallium arsenide, where for certain electrical field electron velocity decreases with electrical field. This phenomenon leads to grouping moving electrons in packs and to the generation of microwave frequencies on its terminals.

8.6.16 IMPATT Diodes

Another interesting "diode" structure has the impurity profile shown in Figure 8.12f. When reverse biasing exceeds the breakdown voltage, this element generates a microwave signal with a frequency related to the electron transient time through structure. Such a diode is known as an IMPATT (IMPact Avalanche Transit Time) diode.

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8.6.17 Peltier Diodes

Moving electrons and holes are also carrying thermal energy. In order to efficiently transfer heat, the semiconductor material must have large mobility and as small as possible thermal conductivity. Peltier diodes are composed of *p*-type and *n*-type bars connected in such a way that currents through *p*-type and *n*-type bars flow in opposite directions. Since holes move in the same direction as current, and electrons move in the opposite direction of current, the majority of carriers (both electron and holes) move in the same direction in different bars carrying heat. Peltier diodes are used for thermoelectric cooling.

There are many other two-terminal bulk semiconductor devices that can be considered diodes. Thermistors are made out of semiconductors with small energy gap (0.2–0.3 eV), and their conductance increases exponentially with temperature. Photoresistors are made from semiconductors with large minority carrier lifetime and their resistances change with illumination. Photoresistors have very slow response. Piezoresistors are sensitive to the induced stress. They can be over 100 times more sensitive than thin film tensometers. Magnetoresistors change their resistance with magnetic field. The most popular magnetoresistor structure is the Corbino ring.

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