CHAPTER 10
High-Frequency and High-Power Devices

OBJECTIVES

1. Understand how tunneling, transit time effects, and electron transfer can lead to NDR
2. Understand SCRs
3. Describe how IGFETs switch power

We have discussed a number of devices that are useful in microwave circuits, such as the varactor and specially designed high-frequency transistors, which can provide amplification and other functions at microwave frequencies up to 10^{11} Hz. However, transit time and other effects limit the application of transistors beyond the 10^{11}-Hz range. Therefore, other devices are required to perform electronic functions such as switching and d-c-to-microwave power conversion at higher frequencies.

Several important devices for high-frequency applications use the instabilities that occur in semiconductors. An important type of instability involves *negative conductance*. Here we shall concentrate on three of the most commonly used negative conductance devices: *Esaki* or *tunnel* diodes, which depend on quantum-mechanical tunneling; transit-time diodes, which depend on a combination of carrier injection and transit-time effects; and *Gunn* diodes, which depend on the transfer of electrons from a high-mobility state to a low-mobility state. Each is a two-terminal device that can be operated in a negative conductance mode to provide amplification or oscillation at microwave frequencies in a proper circuit.

10.1 TUNNEL DIODES

The tunnel diode is a p-n junction device that operates in certain regions of its I–V characteristic by the quantum mechanical tunneling of electrons through the potential barrier of the junction. (See Sections 2.4.4 and 5.4.1.) The tunneling process for reverse current is essentially the Zener effect, although negligible reverse bias is needed to initiate the process in tunnel diodes. As we shall see in this section, the tunnel diode (often called the Esaki diode after L. Esaki, who received the Nobel Prize in 1973 for his work on the effect) exhibits the important feature of *negative resistance* over a portion of its I–V characteristic.

10.1.1 Degenerate Semiconductors

Thus far, we have discussed the properties of relatively pure semiconductors; any impurity doping represented a small fraction of the total atomic density of the material. Since the few impurity atoms were so widely spaced throughout the sample, we could be confident that no charge transport could take place within the donor or acceptor levels themselves. At high doping, the impurities are so close together that we can no longer consider the donor level as being composed of discrete, noninteracting energy states. Instead, the donor states form a band, which may overlap the bottom of the conduction band. If the conduction-band electron concentration n exceeds the effective density of states N_c, the Fermi level is no longer within the band gap, but lies within the conduction band. When this occurs, the material is called *degenerate* n-type. The analogous case of degenerate p-type material occurs when the acceptor concentration is very high and the Fermi level lies in the valence band. We recall that the energy states below E_F are mostly filled and states above E_F are empty, except for a small distribution dictated by the Fermi statistics. Thus, in a degenerate n-type sample, the region between E_c and E_F is for the most part filled with electrons, and in a degenerate p-type sample, the region between E_v and E_F is almost completely filled with holes.

A p-n junction between two degenerate semiconductors is illustrated in terms of energy bands in Fig. 10-1a. This is the equilibrium condition, for which the Fermi level is constant throughout the junction. We notice that E_{Fp} lies below the valence-band edge on the p side, and E_{Fn} is above the conduction-band edge on the n side. Thus, the bands must overlap on the energy scale in order for E_F to be constant. This overlapping of bands is very important; it means that, with a small forward or reverse bias, filled states and empty states appear opposite each other, separated by essentially the width of the depletion region. If the metallurgical junction is sharp, the depletion region will be very narrow for such high-doping concentrations, and the electric field at the junction will be quite large. Hence, the conditions for electron tunneling are met: filled and empty states separated by a narrow potential barrier of finite height. In Fig. 10-1, the bands are shown filled to the Fermi level for convenience of illustration, with the understanding that a distribution is implied.

Since the bands overlap under equilibrium conditions, a small reverse bias (Fig. 10-1b) allows electron tunneling from the filled valence-band states below E_{Fp} to the empty conduction-band states above E_{Fn}. This condition is similar to the Zener effect, except that no bias is required to create the condition of overlapping bands. As the reverse bias is increased, E_{Fn} continues to move down the energy scale with respect to E_{Fp}, placing more filled states on the p side opposite empty states on the n side. Thus, the tunneling of electrons from p to n increases with increasing reverse bias. The resulting conventional current is opposite to the electron flow—that is, from n to p. At

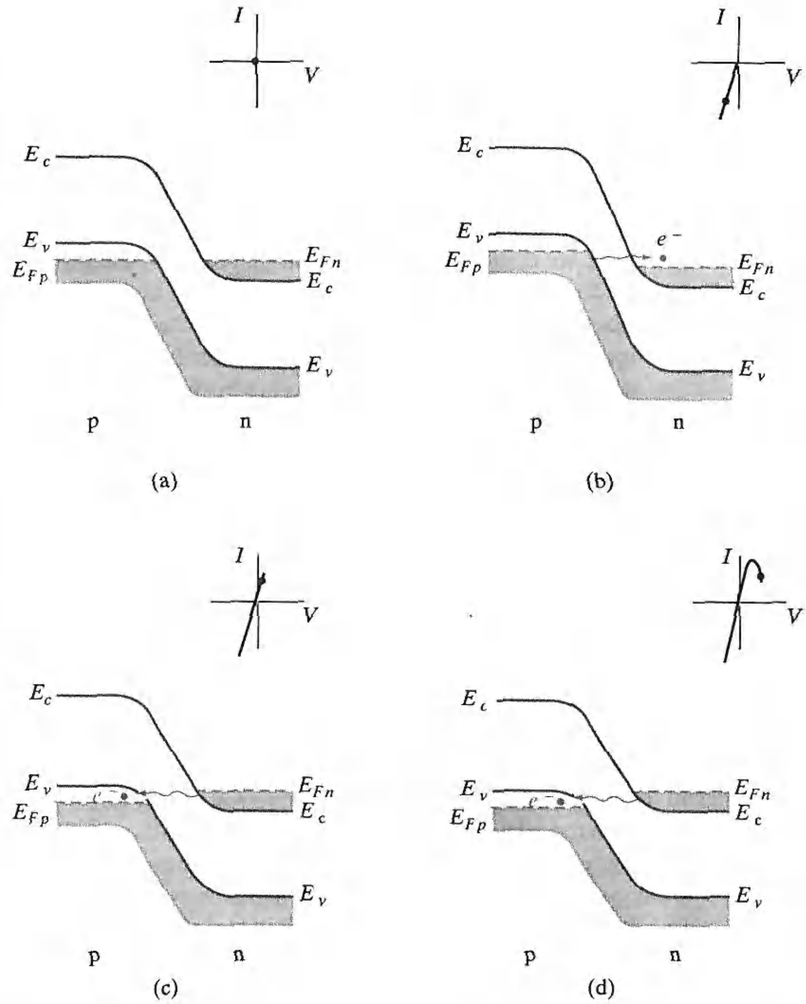

Figure 10–1 Tunnel diode band diagrams and *I–V* characteristics for various biasing conditions: (a) equilibrium (zero bias) condition, no net tunneling; (b) small reverse bias, electron tunneling from p to n; (c) small forward bias, electron tunneling from n to p; (d) increased forward bias, electron tunneling from n to p decreases as bands pass by each other

equilibrium (Fig. 10–1a), there is equal tunneling from n to p and from p to n, given a zero net current.

When a small forward bias is applied (Fig. 10–1c), E_{Fn} moves up in energy with respect to E_{Fp} by the amount qV. Thus, electrons below E_{Fn} on the n side are placed opposite empty states above E_{Fp} on the p side. Electron tunneling occurs from n to p as shown, with the resulting conventional current from p to n. This forward-tunneling current continues to increase with increased bias as more filled states are placed opposite empty states. However, as E_{Fn} continues to move up with respect to E_{Fp}, a point is reached at which the bands begin to pass by each other. When this occurs, the number of filled states opposite empty states decreases. The resulting decrease in tunneling current is illustrated in Fig. 10–1d. This region of the *I–V* characteristic is important in that the *decrease* in tunneling current with *increased* bias produces

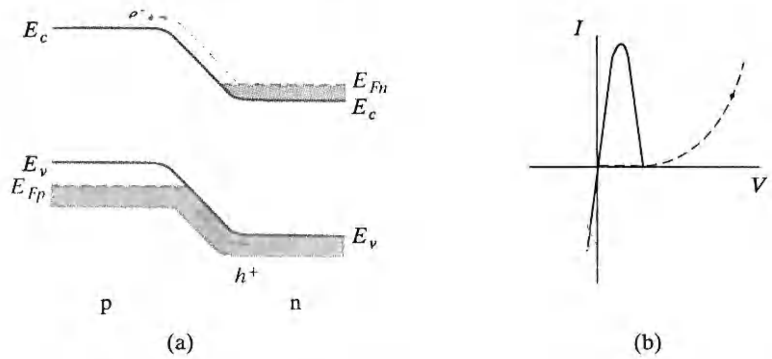

Figure 10–2 Band diagram (a) and *I–V* characteristic (b) for the tunnel diode beyond the tunnel current region. In (b), the tunneling component of current is shown by the solid curve and the diffusion current component is dashed.

a region of negative slope; that is, the *dynamic resistance dV/dI* is negative. This negative-resistance region is useful in oscillators.

If the forward bias is increased beyond the negative-resistance region, the current begins to increase again (Fig. 10-2). Once the bands have passed each other, the characteristic resembles that of a conventional diode. The forward current is now dominated by the diffusion current—electrons surmounting their potential barrier from n to p and holes surmounting their potential barrier from p to n. Of course, the diffusion current is present in the forward tunneling region, but it is negligible compared with the tunneling current.

The total tunnel diode characteristic (Fig. 10-3) has the general shape of an N (if a little imagination is applied); therefore, it is common to refer to this characteristic as exhibiting a *type-N negative resistance*. It is also called a *voltage-controlled negative resistance*, meaning that the current decreases rapidly at some critical voltage (in this case, the *peak voltage* V_p, taken at the point of maximum forward tunneling).

The values of *peak tunneling current* I_p and *valley current* I_v (Fig. 10-3) determine the magnitude of the negative-resistance slope for a diode of given material. For this reason, their ratio I_p/I_v is often used as a figure of merit for

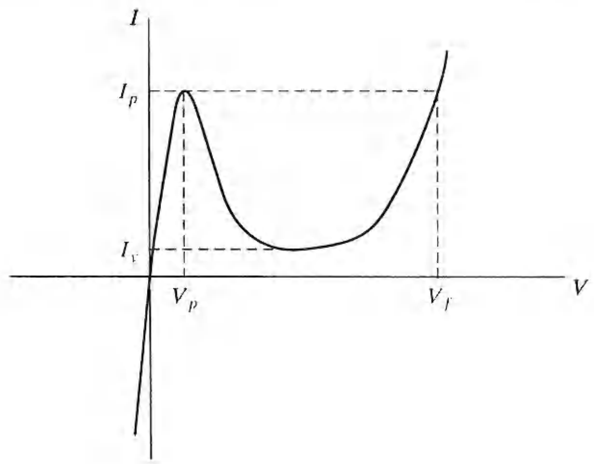

Figure 10–3 Total tunnel diode characteristic.

the tunnel diode. Similarly, the ratio V_p/V_f is a measure of the voltage spread between the two positive-resistance regions.

The negative resistance of the tunnel diode can be used in a number of ways to achieve oscillation and other circuit functions. The fact that the tunneling process does not present the time delays of drift and diffusion makes the tunnel diode a natural choice for certain high-speed circuits. However, the tunnel diode has not achieved widespread application, because of its relatively low current operation and competition from other devices.

10.2 THE IMPATT DIODE

In this section, we describe a type of microwave negative-conductance device that operates by a combination of carrier injection and transit-time effects. Diodes with simple p-n junction structure, or with variations on that structure, are biased to achieve tunneling or avalanche breakdown, with an a-c voltage superimposed on the d-c bias. The carriers generated by the injection process are swept through a drift region to the terminals of the device. We shall see that the a-c component of the resulting current can be approximately 180° out of phase with the applied voltage under proper conditions of bias and device configuration, giving rise to negative conductance and oscillation in a resonant circuit. Transit-time devices can convert d-c to microwave a-c signals with high efficiency and are very useful in the generation of microwave power for many applications.

The original suggestion for a microwave device employing transit-time effects was made by W. T. Read and involved an n^+-p-i-p^+ structure such as that shown in Fig. 10-4. This device operates by injecting carriers into the drift region and is called an *impact avalanche transit-time (IMPATT)* diode. Although IMPATT operation can be obtained in simpler structures, the Read diode is best suited for illustration of the basic principles. The device consists essentially of two regions: (1) the n^+-p region, at which avalanche multiplication occurs, and (2) the i (essentially intrinsic) region, through which generated holes must drift in moving to the p^+ contact. Similar devices can be built in the p^+-n-i-n^+ configuration, in which electrons resulting from

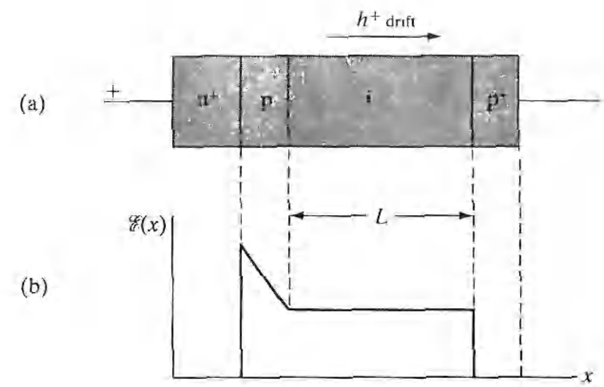

Figure 10–4 The Read diode: (a) basic device configuration; (b) electric field distribution in the device under reverse bias.