5-3 MICROWAVE TUNNEL DIODES

After the publication of Esaki's classic paper on tunnel diodes in 1958, the potential of tunnel diodes for microwave applications was quickly established. Prior to 1958 the anomalous characteristics of some *p-n* junctions were observed by many scientists, but the irregularities were rejected immediately because they did not follow the "classic" diode equation. Esaki, however, described this anomalous phenomenon by applying a quantum tunneling theory. The tunneling phenomenon is a majority carrier effect. The tunneling time of carriers through the potential energy barrier is not governed by the classic transit-time concept—that the transit time is equal to the barrier width divided by the carrier velocity—but rather by the quantum transition probability per unit time. Tunnel diodes are useful in many circuit applications in microwave amplification, microwave oscillation, and binary memory because of their low cost, light weight, high speed, low-power operation, low noise, and high peak-current to valley-current ratio.

5-3-1 Principles of Operation

The tunnel diode is a negative-resistance semiconductor *p-n* junction diode. The negative resistance is created by the tunnel effect of electrons in the *p-n* junction. The doping of both the *p* and *n* regions of the tunnel diode is very high—impurity concentrations of 10^{19} to 10^{20} atoms/cm^3 are used—and the depletion-layer barrier at the junction is very thin, on the order of 100 Å or 10^{-6} cm. Classically, it is possible for those particles to pass over the barrier if and only if they have an energy equal to or greater than the height of the potential barrier. Quantum mechanically, however, if the barrier is less than 3 Å there is an appreciable probability that particles will tunnel through the potential barrier even though they do not have enough kinetic energy to pass over the same barrier. In addition to the barrier thinness, there must also be filled energy states on the side from which particles will tunnel and allowed empty states on the other side into which particles penetrate through at the same energy level. In order to understand the tunnel effects fully, let us analyze the energy-band pictures of a heavily doped *p-n* diode. Figure 5-3-1 shows energy-band diagrams of a tunnel diode.

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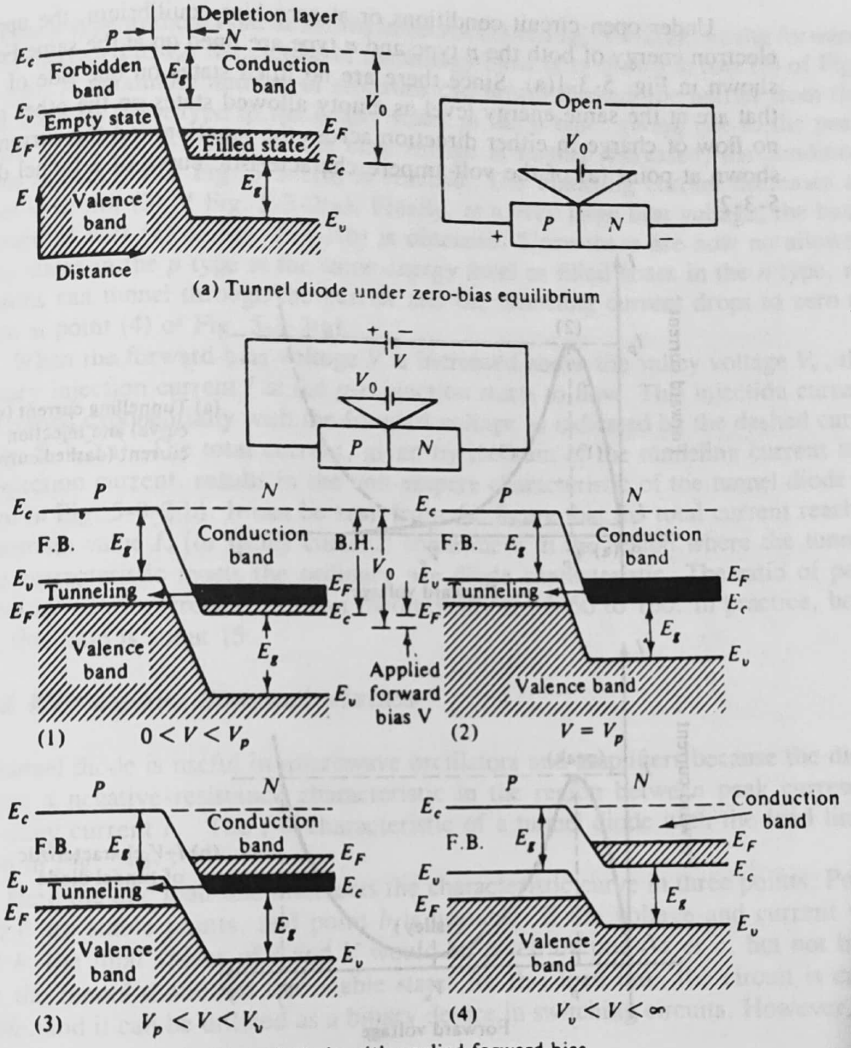

E_F is the Fermi level representing the energy state with 50% probability of being filled if no forbidden band exists
V_0 is the potential barrier of the junction
E_g is the energy required to break a covalent bond, which is 0.72 eV for germanium and 1.10 eV for silicon
E_c is the lowest energy in the conduction band
E_v is the maximum energy in the valence band
V is the applied forward bias
F.B. stands for the forbidden band
B.H. represents the barrier height

Figure 5-3-1 Energy-band diagrams of tunnel diode

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Under open-circuit conditions or at zero-bias equilibrium, the upper levels of electron energy of both the p type and n type are lined up at the same Fermi level as shown in Fig. 5-3-1(a). Since there are no filled states on one side of the junction that are at the same energy level as empty allowed states on the other side, there is no flow of charge in either direction across the junction and the current is zero, as shown at point (a) of the volt-ampere characteristic curve of a tunnel diode in Fig. 5-3-2.

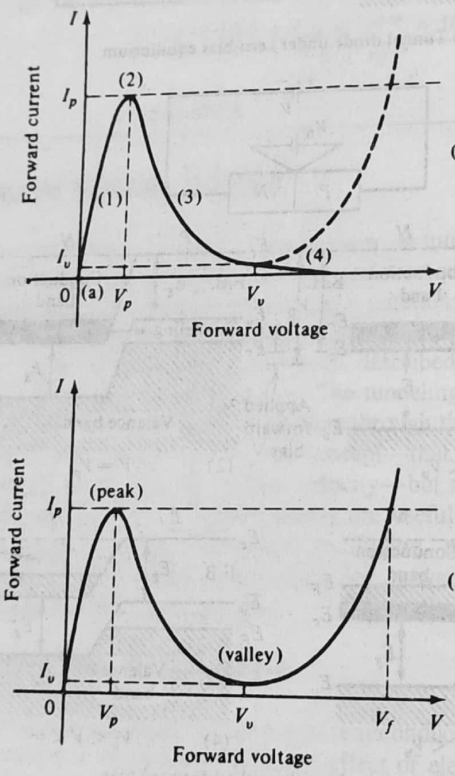

Figure 5-3-2 Ampere-voltage characteristics of tunnel diode.

In ordinary diodes the Fermi level exists in the forbidden band. Since the tunnel diode is heavily doped, the Fermi level exists in the valence band in p-type and in the conduction band in n-type semiconductors. When the tunnel diode is forward-biased by a voltage between zero and the value that would produce peak tunneling current $I_p (0 < V < V_p)$, the energy diagram is shown in part (1) of Fig. 5-3-1(b). Accordingly, the potential barrier is decreased by the magnitude of the applied forward-bias voltage. A difference in Fermi levels in both sides is created. Since there are filled states in the conduction band of the n type at the same energy level as allowed empty states in the valence band of the p type, the electrons tunnel through the barrier from the n type to the p type, giving rise to a forward tunneling current

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from the p type to the n type as shown in sector (1) of Fig. 5-3-2(a). As the forward bias is increased to V_p, the picture of the energy band is as shown in part (2) of Fig. 5-3-1(b). A maximum number of electrons can tunnel through the barrier from the filled states in the n type to the empty states in the p type, giving rise to the peak current I_p in Fig. 5-3-2(a). If the bias voltage is further increased, the condition shown in part (3) of Fig. 5-3-1(b) is reached. The tunneling current decreases as shown in sector (3) of Fig. 5-3-2(a). Finally, at a very large bias voltage, the band structure of part (4) of Fig. 5-3-1(b) is obtained. Since there are now no allowed empty states in the p type at the same energy level as filled states in the n type, no electrons can tunnel through the barrier and the tunneling current drops to zero as shown at point (4) of Fig. 5-3-2(a).

When the forward-bias voltage V is increased above the valley voltage V_v, the ordinary injection current I at the p-n junction starts to flow. This injection current is increased exponentially with the forward voltage as indicated by the dashed curve of Fig. 5-3-2(a). The total current, given by the sum of the tunneling current and the injection current, results in the volt-ampere characteristic of the tunnel diode as shown in Fig. 5-3-2(b). It can be seen from the figure that the total current reaches a minimum value I_v (or valley current) somewhere in the region where the tunnel-diode characteristic meets the ordinary p-n diode characteristic. The ratio of peak current to valley current (I_p/I_v) can theoretically reach 50 to 100. In practice, however, this ratio is about 15.

5-3-2 Microwave Characteristics

The tunnel diode is useful in microwave oscillators and amplifiers because the diode exhibits a negative-resistance characteristic in the region between peak current I_p and valley current I_v. The I-V characteristic of a tunnel diode with the load line is shown in Fig. 5-3-3.

Here the abc load line intersects the characteristic curve in three points. Points a and c are stable points, and point b is unstable. If the voltage and current vary about b, the final values of I and V would be given by point a or c, but not by b. Since the tunnel diode has two stable states for this load line, the circuit is called *bistable*, and it can be utilized as a binary device in switching circuits. However, mi-

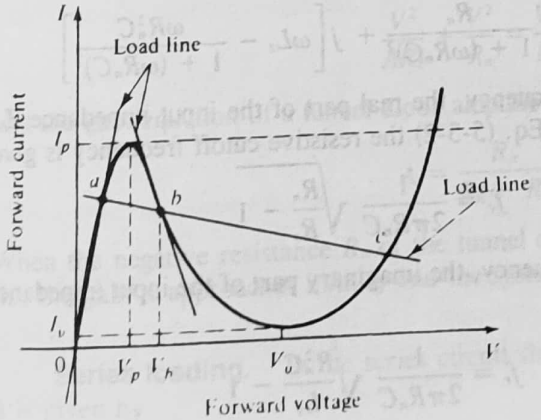

Figure 5-3-3 I-V characteristic of tunnel diode with load line.

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crowave oscillation or amplification generated by the tunnel diode is our major concern in this section. The second load line intersects the *I-V* curve at point *b* only. This point is stable and shows a dynamic negative conductance that enables the tunnel diode to function as a microwave amplifier or oscillator. The circuit with a load line crossing point *b* in the negative-resistance region is called *astable*. Another load line crossing point *a* in the positive-resistance region indicates a *monostable* circuit. The negative conductance in Fig. 5-3-3 is given by

$$-g = \left.\frac{\partial i}{\partial v}\right|_{v_b} = \frac{1}{-R_n} \tag{5-3-1}$$

where R_n is the magnitude of negative resistance.

For a small variation of the forward voltage about V_b, the negative resistance is constant and the diode circuit behavior is stable. A small-signal equivalent circuit for the tunnel diode operated in the negative-resistance region is shown in Fig. 5-3-4. Here R_s and L_s denote the inductance and resistance of the packaging circuit of a tunnel diode. The junction capacitance C of the diode is usually measured at the valley point; R_n is the negative resistance of the diode. Typical values of these parameters for a tunnel diode having a peak current I_p of 10 mA are

$$-R_n = -30\ \Omega \qquad R_s = 1\ \Omega \qquad L_s = 5\ \text{nH} \qquad C = 20\ \text{pF}$$

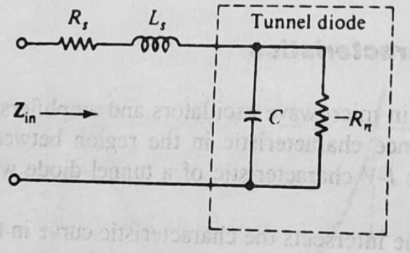

Figure 5-3-4 Equivalent circuit of tunnel diode.

The input impedance $\mathbf{Z}_{in}$ of the equivalent circuit shown in Fig. 5-3-4 is given by

$$\mathbf{Z}_{in} = R_s + j\omega L_s + \frac{R_n[\,j/(\omega C)]}{-R_n - j/(\omega C)}$$

$$\mathbf{Z}_{in} = R_s - \frac{R_n}{1 + (\omega R_n C)^2} + j\left[\omega L_s - \frac{\omega R_n^2 C}{1 + (\omega R_n C)^2}\right] \tag{5-3-2}$$

For the resistive cutoff frequency, the real part of the input impedance $\mathbf{Z}_{in}$ must be zero. Consequently, from Eq. (5-3-2) the resistive cutoff frequency is given by

$$f_c = \frac{1}{2\pi R_n C}\sqrt{\frac{R_n}{R_s} - 1} \tag{5-3-3}$$

For the self-resonance frequency, the imaginary part of the input impedance must be zero. Thus,

$$f_r = \frac{1}{2\pi R_n C}\sqrt{\frac{R_n^2 C}{L_s} - 1} \tag{5-3-4}$$

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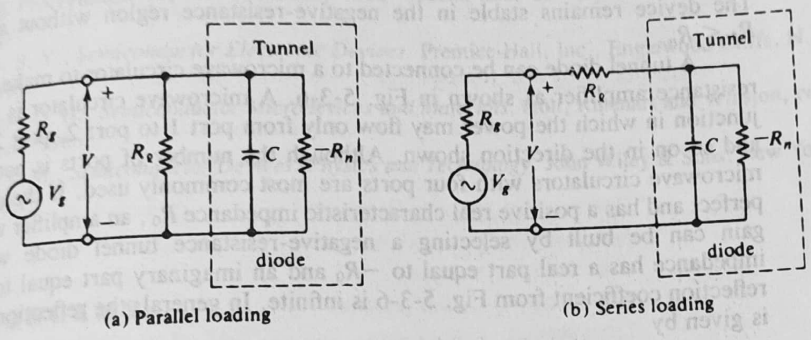
The tunnel diode can be connected either in parallel or in series with a resistive load as an amplifier; its equivalent circuits are shown in Fig. 5-3-5.



(a) Parallel loading (b) Series loading

Figure 5-3-5 Equivalent circuits of tunnel diodes.

Parallel loading. It can be seen from Fig. 5-3-5(a) that the output power in the load resistance is given by

$$P_{out} = \frac{V^2}{R_\ell} \tag{5-3-5}$$

One part of this output power is generated by the small input power through the tunnel diode amplifier with a gain of A, and this part can be written

$$P_{in} = \frac{V^2}{AR_\ell} \tag{5-3-6}$$

Another part of the output power is generated by the negative resistance, and it is expressed as

$$P_n = \frac{V^2}{R_n} \tag{5-3-7}$$

Therefore

$$\frac{V^2}{AR_\ell} + \frac{V^2}{R_n} = \frac{V^2}{R_\ell} \tag{5-3-8}$$

and the gain equation of a tunnel diode amplifier is given by

$$A = \frac{R_n}{R_n - R_\ell} \tag{5-3-9}$$

When the negative resistance R_n of the tunnel diode approaches the load resistance R_ℓ, the gain A approaches infinity and the system goes into oscillation.

Series loading. In the series circuit shown in Fig. 5-3-5(b) the power gain A is given by

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$$A = \frac{R_\ell}{R_\ell - R_n} = \frac{1}{1 - R_n/R_\ell} \tag{5-3-10}$$

The device remains stable in the negative-resistance region without switching if $R_\ell < R_n$.

A tunnel diode can be connected to a microwave circulator to make a negative-resistance amplifier as shown in Fig. 5-3-6. A microwave circulator is a multiport junction in which the power may flow only from port 1 to port 2, port 2 to port 3, and so on in the direction shown. Although the number of ports is not restricted, microwave circulators with four ports are most commonly used. If the circulator is perfect and has a positive real characteristic impedance R_0, an amplifier with infinite gain can be built by selecting a negative-resistance tunnel diode whose input impedance has a real part equal to $-R_0$ and an imaginary part equal to zero. The reflection coefficient from Fig. 5-3-6 is infinite. In general, the reflection coefficient is given by

$$\Gamma = \frac{-R_n - R_0}{-R_n + R_0} \tag{5-3-11}$$

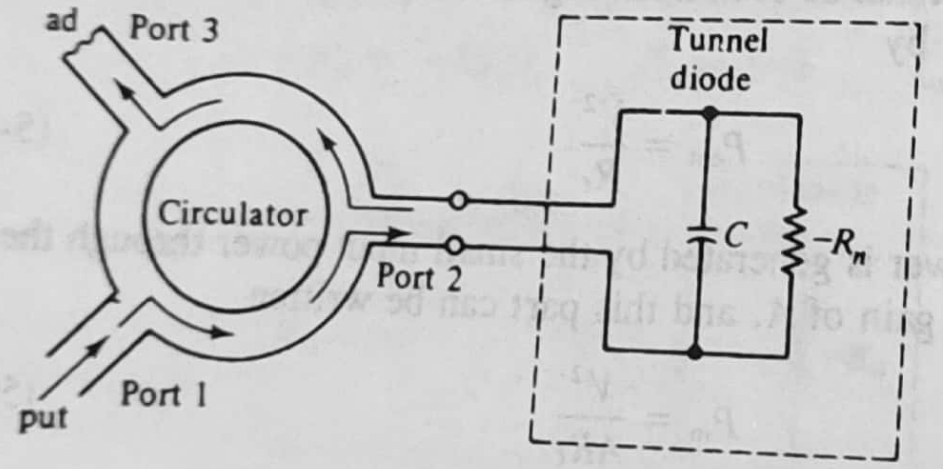

Figure 5-3-6 Tunnel diode connected to circulator.

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