20-4 Thermistors

The word *thermistor* is a combination of *thermal* and *resistor*. A thermistor is a resistor with definite thermal characteristics. Most thermistors have a *negative temperature coefficient* (NTC), but *positive temperature coefficient* (PTC) devices are also available. Thermistors are widely applied for *temperature compensation*, i.e., canceling the effects of temperature on other electronic devices. They are also employed for measurement and control of temperature, liquid level, gas flow, etc.

Silicon and germanium are not normally used for thermistor manufacture, because larger and more predictable temperature coefficients are available with metallic oxides. Various mixtures of manganese, nickel, cobalt, copper, iron, and uranium are pressed into desired shapes and sintered (or baked) at high temperature to form thermistors. Electrical connections are made either by including fine wires during the shaping process or by silvering the surfaces after sintering. Thermistors are made in the shape of beads, probes, discs, washers, etc. (Fig. 20-13). Beads may be glass coated or enclosed in evacuated or gas-filled envelopes for protection against corrosion. Washer-shaped thermistors can be bolted together for series or parallel connection. Tiny thin-film thermistors, formed by sintering metal oxide coatings onto a ceramic or foil substrate, are also available.

A typical thermistor resistance / temperature characteristic is shown in Fig. 20-14. It is seen that the device resistance decreases by approximately 500 times when heated through 150°C. Current through a thermistor causes power dissipation which raises the device temperature. Thus, the device resistance is

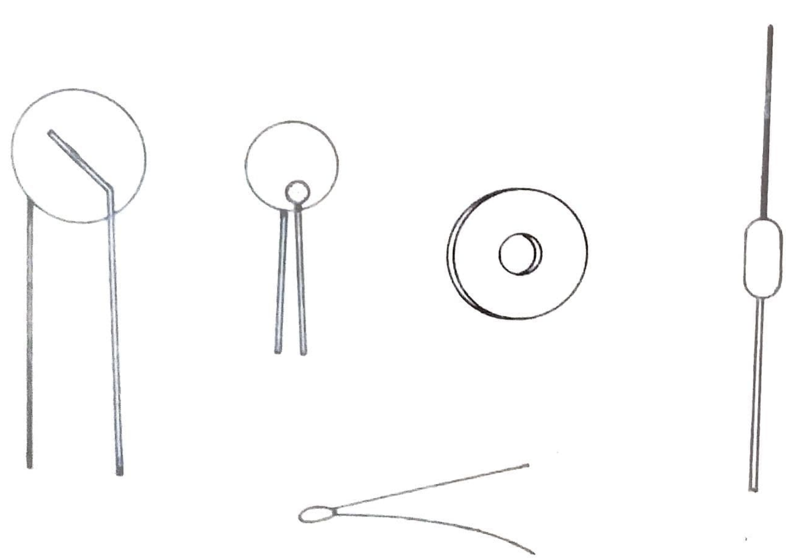


Figure 20-13 Thermistors are produced in a variety of shapes for various applications.

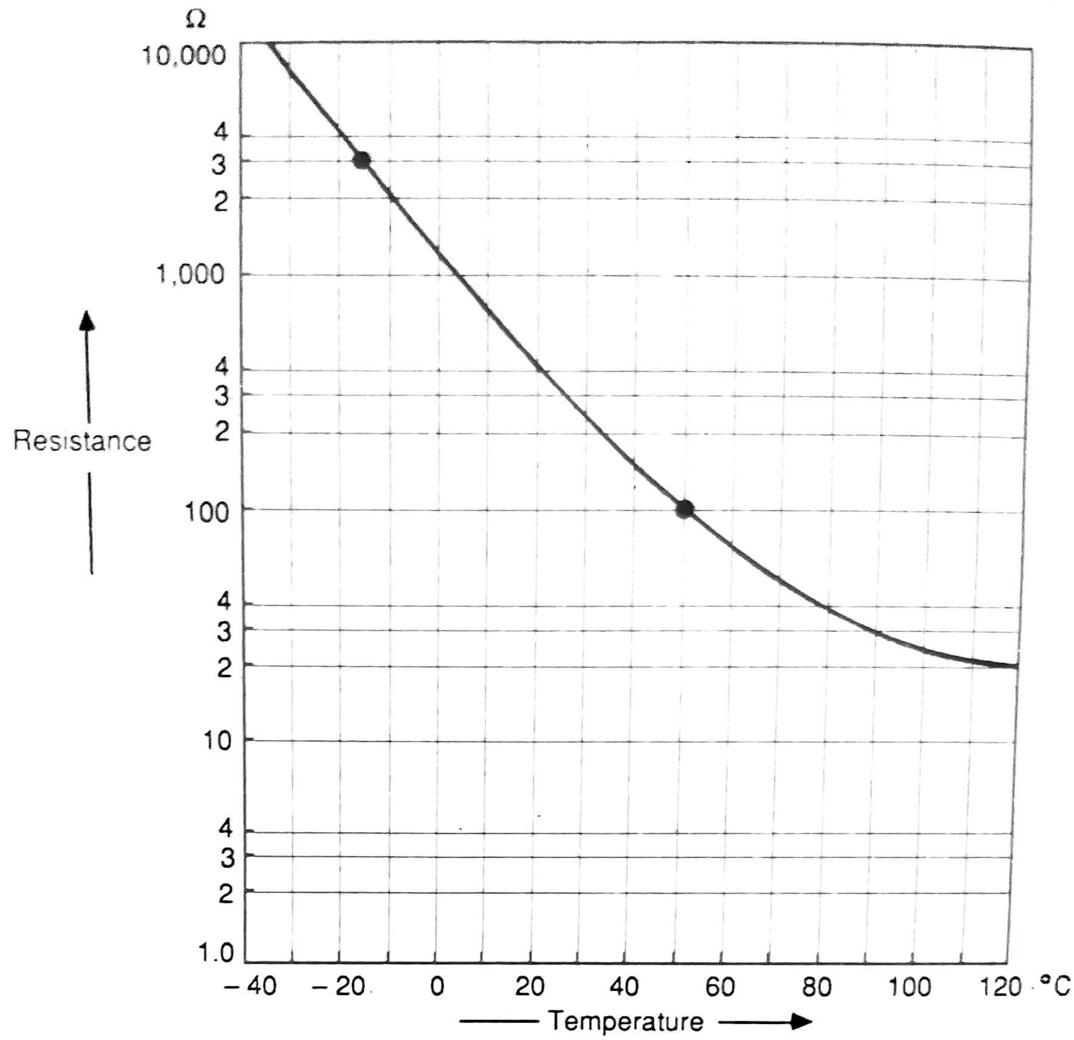


Figure 20-14 The typical resistance/temperature characteristic for a thermistor shows a wide variation in device resistance with change in temperature.

dependent upon ambient temperature and self-heating. For a fixed ambient temperature, the thermistor resistance is dependent upon its own power dissipation. Very small currents have no effect, so that a plot of voltage versus current (Fig. 20-15) shows the device behaving initially as a constant-value resistance. As the current increases, a peak is reached at which the heating effect of the current begins to significantly change the thermistor resistance. Further increase in current causes a progressive reduction in resistance and consequently produces a reduction in voltage across the device.

Example 20-3

A thermistor with the resistance/temperature characteristic in Fig. 20-14 is employed in the circuit of Fig. 20-16. The relay coil has a resistance of 5 kΩ at −15°C, and 6.5 kΩ at 50°C. If the relay is energized by a current of 1 mA, calculate the required value of R_1 at −15°C and at 50°C (a) with the thermistor and R_2 *not* in the circuit; (b) with the thermistor in circuit; (c) with the thermistor and R_2 in the circuit

Solution

(a) Without the thermistor and R_2,

$$I = \frac{E}{R_1 + R_C}$$

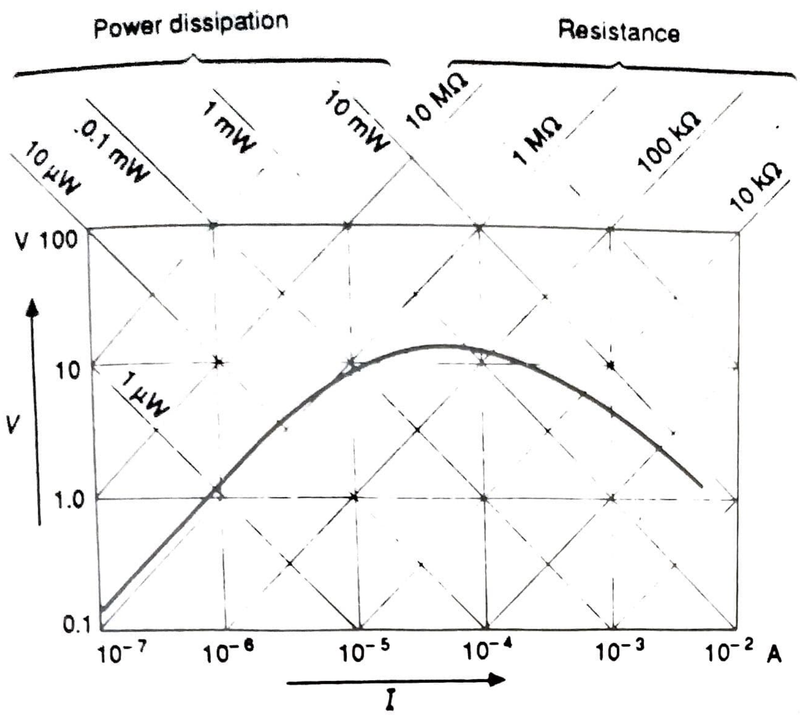


Figure 20-15 The static voltage / current characteristic for a thermistor shows that the device resistance remains constant until the power dissipation is large enough to produce self-heating. When the device self-heats, the resistance falls off.

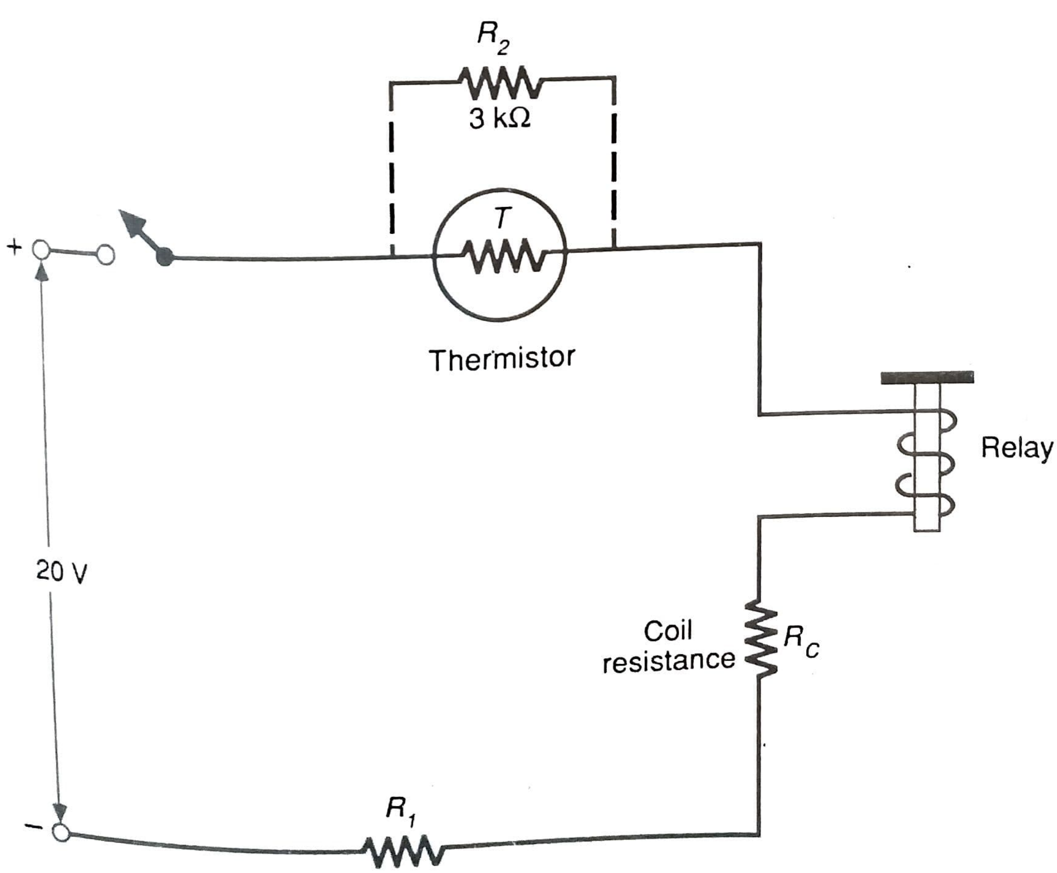


Figure 20-16 A thermistor may be used to compensate for an increase in coil resistance with increasing temperature.

or,

$$R_1 = \frac{E}{I} - R_C$$

At −15°C,

$$R_1 = \frac{20\ \text{V}}{1\ \text{mA}} - 5\ \text{k}\Omega = 15\ \text{k}\Omega$$

At 50° C,

$$R_1 = \frac{20\ \text{V}}{1\ \text{mA}} - 6.5\ \text{k}\Omega = 13.5\ \text{k}\Omega$$

(b) With the thermistor,

$$I = \frac{E}{R_1 + R_T + R_C}$$

$$R_1 = \frac{E}{I} - R_T - R_C$$

From Fig. 20-14, $R_T \approx 3\ \text{k}\Omega$ at −15°C and 100 Ω at 50°C. So *at −15°C,*

$$R_1 = \frac{20\ \text{V}}{1\ \text{mA}} - 3\ \text{k}\Omega - 5\ \text{k}\Omega = 12\ \text{k}\Omega$$

At 50°C,

$$R_1 = \frac{20\ \text{V}}{1\ \text{mA}} - 100\ \Omega - 6.5\ \text{k}\Omega = 13.4\ \text{k}\Omega$$

(c) With R_2 and the thermistor,

$$I = \frac{E}{R_1 + (R_T \| R_2) + R_C}$$

or

$$R_1 = \frac{E}{I} - (R_T \| R_2) - R_C$$

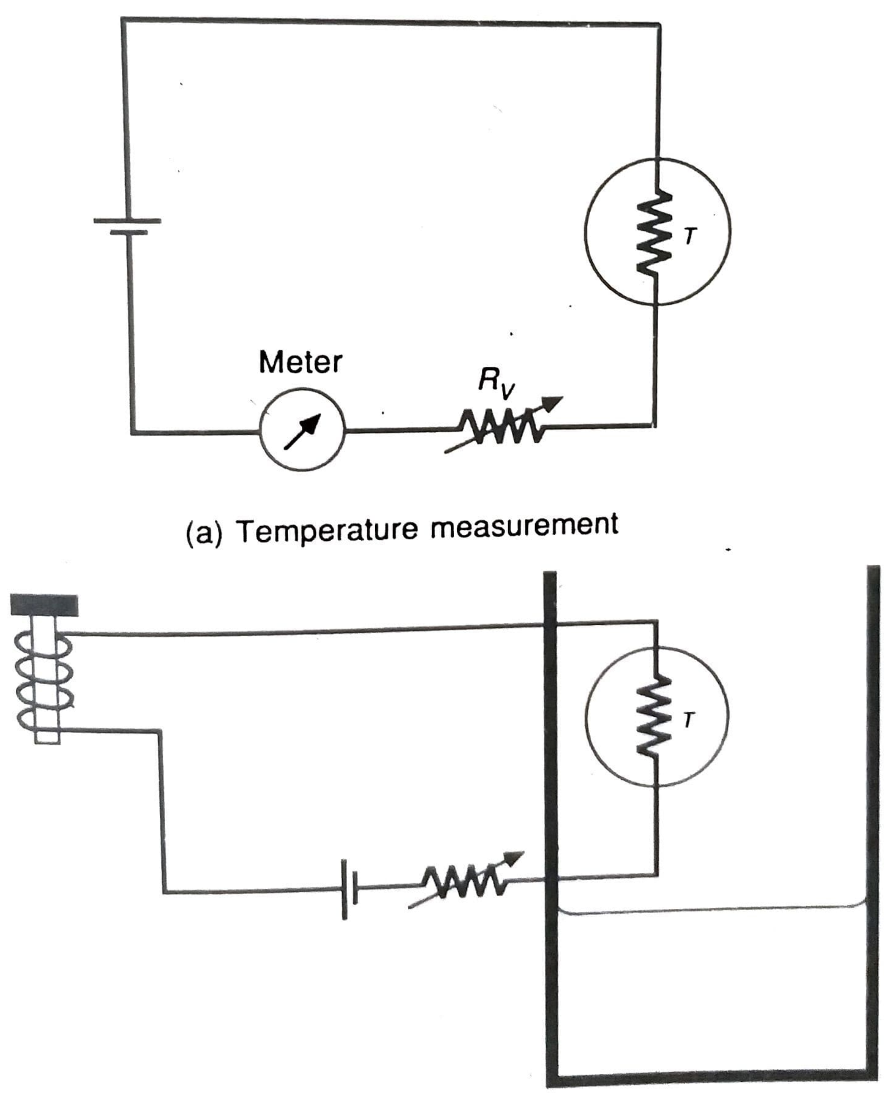
At −15°C,

$$R_1 = \frac{20\ \text{V}}{1\ \text{mA}} - (3\ \text{k}\Omega \| 3\ \text{k}\Omega) - 5\ \text{k}\Omega = 13.5\ \text{k}\Omega$$

At 50°C,

$$R_1 = \frac{20\ \text{V}}{1\ \text{mA}} - (3\ \text{k}\Omega \| 100\ \Omega) - 6.5\ \text{k}\Omega = 13.4\ \text{k}\Omega$$

From Example 20-3 it is seen that, without the thermistor in the circuit, R_1 must be *reduced* from 15 kΩ to 13.5 kΩ when the ambient temperature is increased from −15°C to 50°C. This reduction is necessary to allow the 1 mA energizing current to flow through the relay coil. With the unshunted thermistor in the circuit, R_l must be *increased* from 12 kΩ to 13.4 kΩ when the temperature goes from −15°C to 50°C. This means that the thermistor is *overcompensating* for the change in coil resistance. Finally, when the thermistor and 3 kΩ shunt are included in the circuit, virtually no adjustment of R_l is necessary at the temperature extremes. Thus, the shunted thermistor completely compensates for the coil resistance changes with temperature. Two points should be noted about Example 20-3. One is that only the temperature extremes were looked at, and obviously the adequacy of compensation between the extremes should be considered. The other point is that the heating effect of the current through the thermistor was assumed negligible. Other thermistor applications are illustrated in Fig. 20-17.



(b) Liquid level detection

Figure 20-17 Thermistors can be employed for temperature measurement and for liquid level detection.

20-5 Tunnel Diodes

A *tunnel diode* (sometimes called an *Esaki diode* after its inventor, Leo Esaki) is a two-terminal *negative resistance* device which can be employed as an amplifier, an oscillator, or a switch. Because of its very fast response to inputs, it is almost exclusively a high-frequency component. Tunnel diodes require smaller bias voltages and lower load resistances than most other electronic devices.

Depletion Region and Energy Band Diagrams

Recall from Chapter 1 that the width of the depletion region at a *pn*-junction depends upon the doping density of the semiconductor material. Lightly doped material has a wide depletion region, while heavily doped material has a narrow region. In the case of the tunnel diode, the junction is formed of very heavily doped material, and consequently the depletion region is very narrow.

The depletion region is an insulator since it lacks charge carriers, and usually charge carriers can cross it only when the external bias is large enough to overcome the barrier potential. However, because the depletion region in a tunnel diode is extremely narrow, it does not constitute much of a barrier to electron flow. Consequently, a small forward or reverse bias (not large enough to overcome the barrier potential) can give charge carriers sufficient energy to cross the depletion region. When this occurs, the charge carriers are said to be *tunneling* through the barrier.

Consider the silicon energy band diagrams shown in Fig. 20-18. If the material is normally doped (either *n*-type or *p*-type), electrons fill all the holes in the valence band of energy levels and the conduction band is empty [Fig. 20-18(a)]. When semiconductor material is very heavily doped with holes (i.e., *p*-type), there is a shortage of electrons and the valence band cannot be regarded as filled. The result is that at the top of the valence band there is a layer of empty energy levels. This situation is illustrated in Fig. 20-18(b). With very heavily doped *n*-type material, there is an abundance of electrons. Consequently, electrons fill the valence band and create a layer of filled energy levels at the bottom of the conduction band [Fig. 20-18(c)].

Reverse Biased Tunnel Diode

The energy band diagram for a heavily doped unbiased *pn*-junction is shown in Fig. 20-19. Note that the depletion region is very narrow and that the filled levels on the *n*-side are exactly opposite those on the *p*-side. In this condition, no tunneling occurs because there are no empty lower energy levels to which electrons from either side might cross the depletion region. Note also that the conduction and valence bands on the *p*-side are (negatively) higher than those on the *n*-side. This is a result of the depletion region and barrier potential

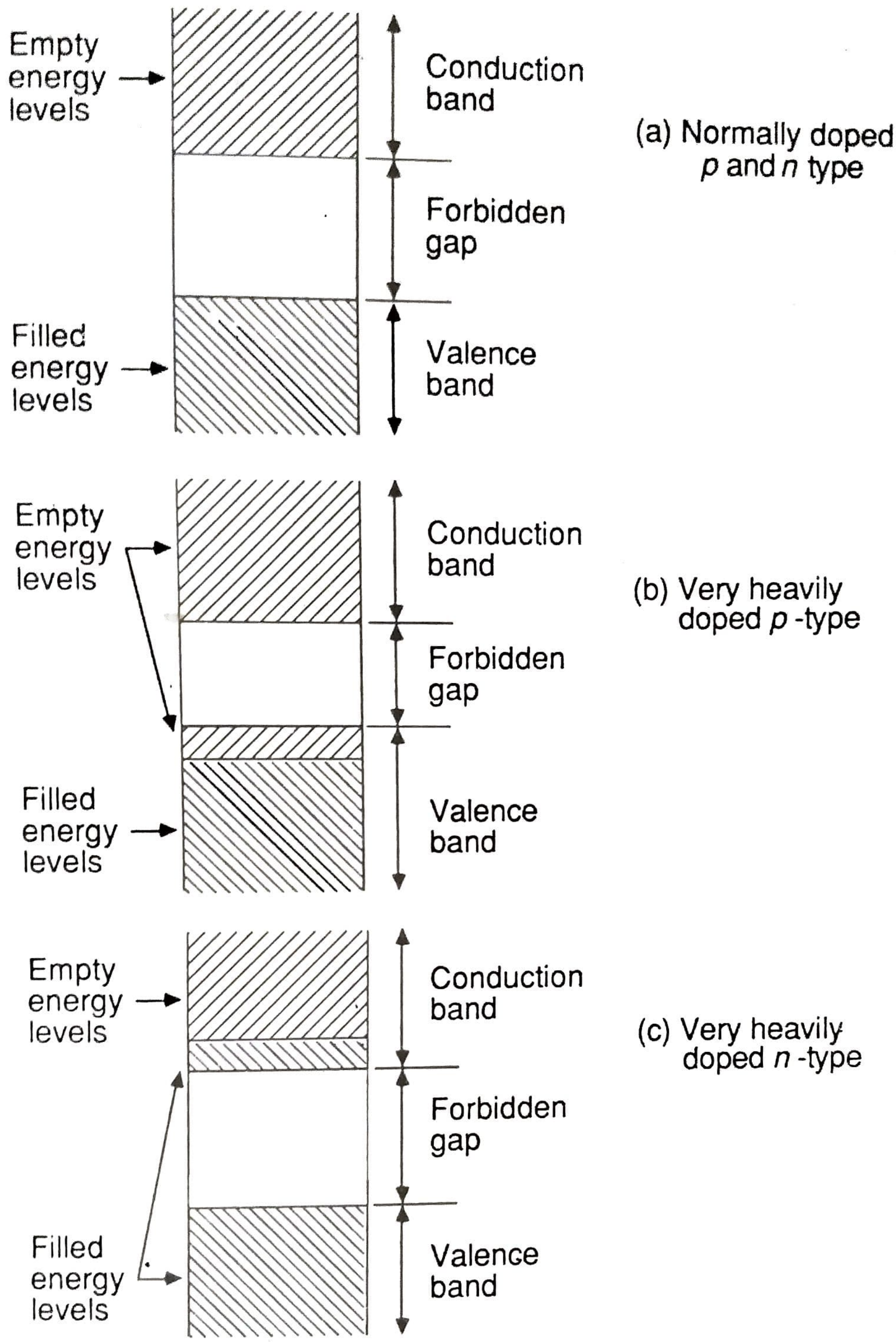


Figure 20-18 Energy band diagrams for normally doped and for very heavily doped semiconductor material.

being created by electrons crossing from the n-side to the p-side. The n-side has lost negative charges and the p-side has gained them.

When the junction is reverse biased (negative on the p-side, positive on the n-side), the p-side moves up with respect to the n-side in Fig. 20-19. Consequently, filled energy levels on the p-side become opposite empty energy levels on the n-side. The result is that electrons tunnel through the barrier from the higher energy levels on the p-side to the lower levels on the n-side. Despite the fact that the junction is reverse biased, substantial current flows.

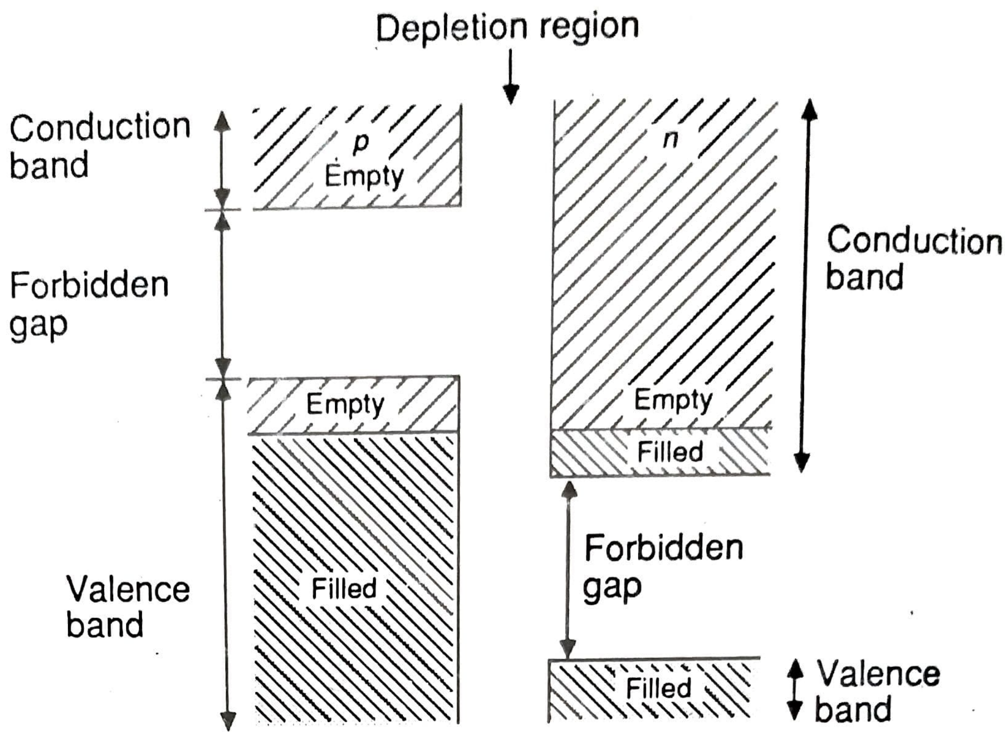


Figure 20-19 Energy band diagrams for a tunnel diode. Reverse current flows when a reverse bias is applied. Forward current flow increases to a peak level when the forward voltage is increased from zero. After the peak point, I_F decreases as E_F is increased.

With increasing reverse bias, more electrons tunnel from the *p*-side to the *n*-side and a greater current flows. Therefore, the reverse characteristic of a tunnel diode is linear, just like that of a resistor.

Forward Biased Tunnel Diode

When the tunnel diode is forward biased, its initial behavior is similar to that when it is reverse biased. In this case, some of the filled levels on the *n*-side are raised to a higher energy level than empty levels on the *p*-side (see Fig. 20-19). Electron tunneling now occurs from the *n*-side to the *p*-side. When the forward bias is increased, more and more of the electrons on the *n*-side are raised to a higher level than the empty levels on the *p*-side, resulting in more tunneling of electrons from the *n*-side to the *p*-side. Eventually, however, a maximum level of tunneling is reached when the band of filled energy levels at the bottom of the conduction band on the *n*-side is directly opposite the band of empty energy levels at the top of the valence band on the *p*-side. With further increase in forward bias, part of the band of filled levels on the *n*-side is raised to an energy level corresponding to the forbidden gap on the *p*-side. Electrons cannot tunnel to a forbidden energy level; thus, the current flow due to tunneling is reduced. With continued increase in forward bias, the tunneling continues to be reduced. When all of the band of filled levels at the bottom of the conduction band on the n-side is raised to a level corresponding to the forbidden gap on the p-side, the current flow due to tunneling is reduced to a minimum. Now, however, the normal process of current flow across a forward biased junction begins to take over, as the bias becomes large enough to overcome the barrier potential. Current now increases as the voltage increases, and the final portion of the tunnel diode forward characteristics is similar to that for an ordinary pn-junction.

Characteristics and Parameters

A typical tunnel diode characteristic is shown in Fig. 20-20, along with frequently employed symbols for the device. The *peak current* I_p and *valley current* I_v are easily identified on the characteristic as the maximum and minimum levels, repectively, of I_F prior to the device being completely forward biased. The *peak voltage* V_p is the E_D level corresponding to I_p, and the *valley voltage* V_v is the E_D level at I_v. V_F is the *forward voltage drop* when the device is completely forward biased. The broken line on Fig. 20-20(a) shows the characteristic for an ordinary forward biased diode. It is seen that this joins the tunnel diode characteristic as V_F is approached.

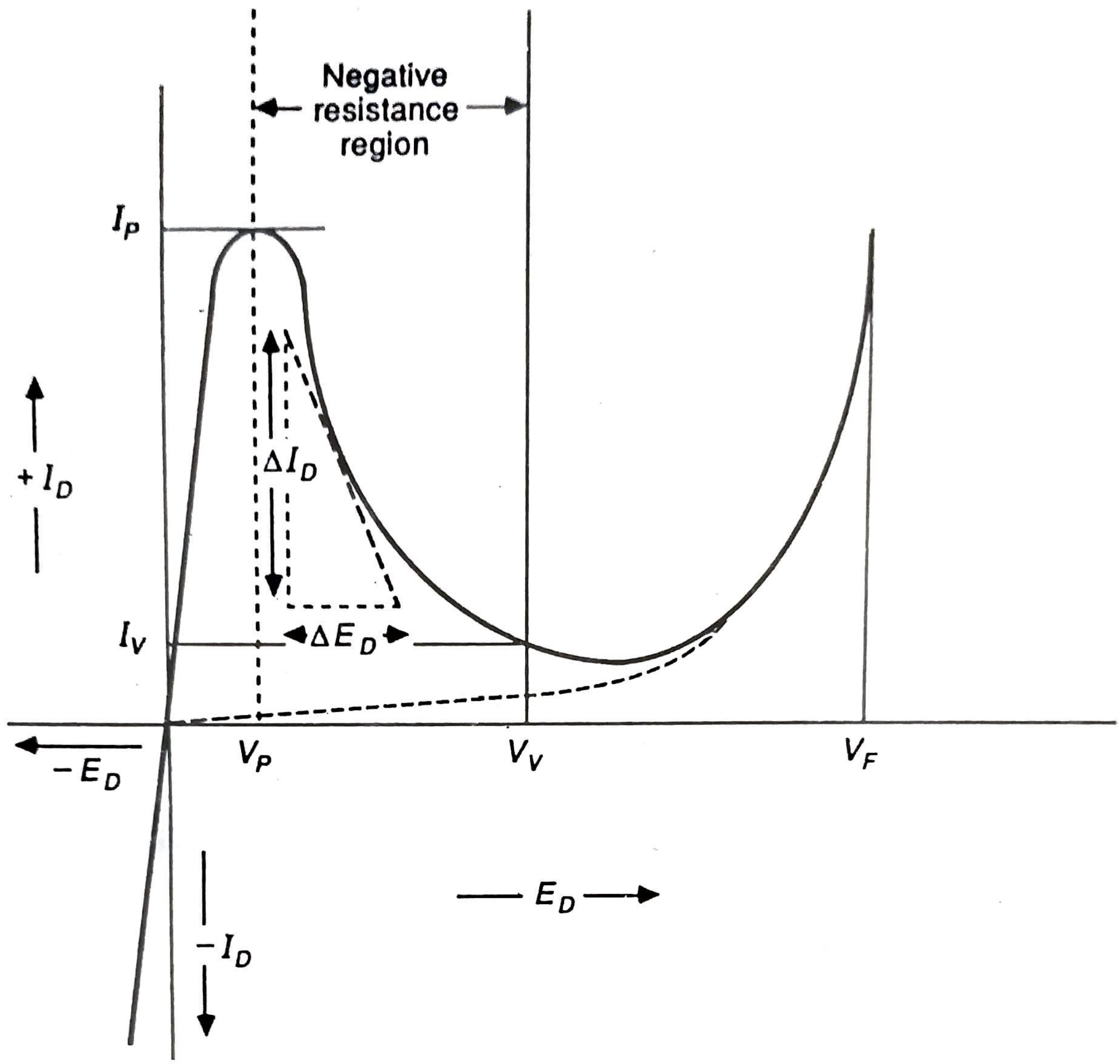
When a voltage is applied to a resistance, the current normally increases as the applied voltage is increased. Between I_p and I_v on the tunnel diode characteristic, I_D actually *decreases* as E_D is increased. This region of the characteristic is named the *negative resistance region*, and the *negative resistance* R_D of the tunnel diode is its most important property.

The value of the negative resistance may be determined by calculating the reciprocal of the slope of the characteristic in the negative resistance region. From Fig. 20-20(a), the negative resistance $R_D = \Delta E_D / \Delta I_D$, and the negative conductance $G_D = \Delta I_D / \Delta E_D$.

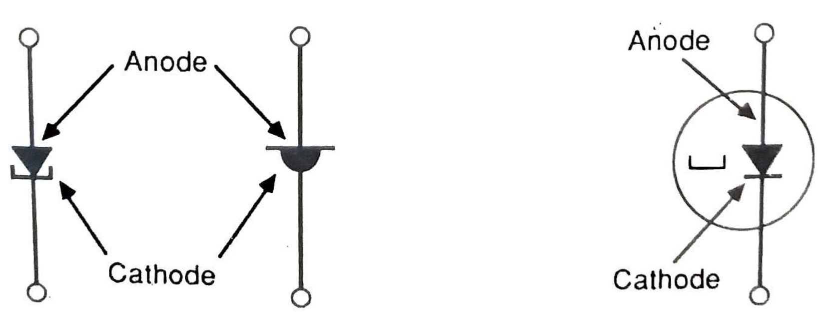
If R_D is measured at different points on the negative resistance portion of the characteristic, slightly different values will be obtained because the slope is not constant. Therefore, R_D is usually specified at the center of the negative resistance region.

Typical tunnel diode parameters are as follows:

Peak current I_p	$= 1$ mA to 100 mA
Peak voltage V_p	$= 50$ mV to 200 mV
Valley current I_v	$= 0.1$ mA to 5 mA
Valley voltage V_v	$= 350$ mV to 500 mV
Forward voltage V_F	$= 0.5$ V to 1 V
Negative resistance R_D	$= -10\ \Omega$ to $-200\ \Omega$



(a) Characteristics



(b) Symbols

Figure 20-20 Tunnel diode characteristic and symbol. The characteristic has a negative resistance region.

In Chapter 2 it was shown that a straight-line approximation of diode characteristics can sometimes be conveniently employed. This is true also of the tunnel diode; for which the *piecewise linear characteristics* can be constructed from the data provided by the device manufacturer.

Example 20-4

Construct the piecewise linear characteristics and determine R_D for the 1N3712 from the following data: $I_p = 1$ mA, $I_v = 0.12$ mA, $V_p = 65$ mV, $V_v = 350$ mV, and $V_F = 500$ mV (at $I_F = I_P$).

Solution

Refer to Fig. 20-21. Point 1 is first plotted at $I_p = 1$ mA and $V_p = 65$ mV. Point 2 is plotted at $I_v = 0.12$ mA and $V_v = 350$ mV. The origin and point 1 are joined by a straight line to give the initial portion of the forward characteristic. A straight line is now drawn between points 1 and 2 to give the negative resistance region. Point 3 is plotted at $V_F = 500$ mV and $I_F = I_P$, and the forward voltage portion of the characteristic is drawn at the same slope as the line between 0 and point 1. (Sometimes a second value of V_F at $\frac{1}{4} I_P$ is given

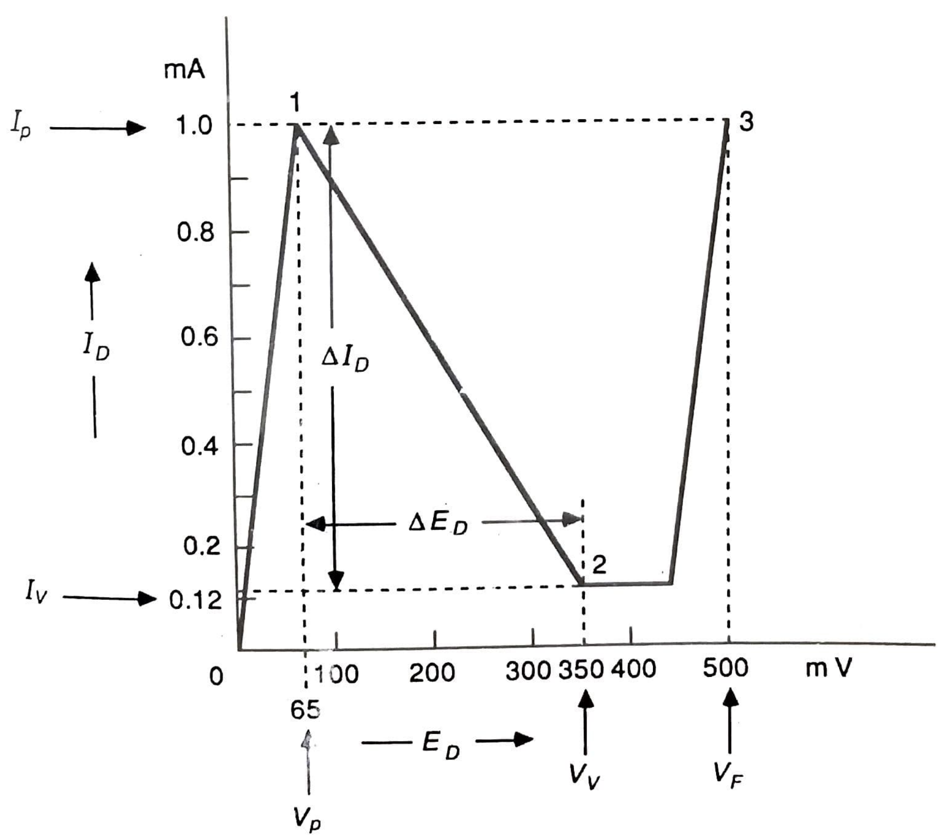


Figure 20-21 The tunnel diode piecewise linear characteristics can be drawn from information on the device data sheet.

so that the forward region can be plotted more accurately.) A horizontal line is then drawn from point 2 to this line to represent the valley region of the characteristic.

R_D is determined by calculating the reciprocal of the slope of the negative resistance region of the characteristic:

$$R_D = \frac{\Delta E_D}{-\Delta I_D} = \frac{350 \text{ mV} - 65 \text{ mV}}{-(1 \text{ mA} - 0.12 \text{ mA})} = -324\ \Omega$$

20-6 Tunnel Diode Circuits

Equivalent Circuit

The equivalent circuit shown in Fig. 20-22 is for a tunnel diode biased in the negative resistance region. Therefore, it consists of the negative resistance R_D shunted by the junction capacitance C_D. Values of C_D range from 5 to 100 pF. R_S represents the resistance of the connecting leads and the semiconductor material, and is of the order of 1 Ω. L_S, which is typically 0.5 nH, is the inductance of the connecting leads to the tunnel diode.

Because of the presence of L_S and C_D in the equivalent circuit, the tunnel diode has a *self-resonance frequency* f_{xo}, which may range from 700 MHz to

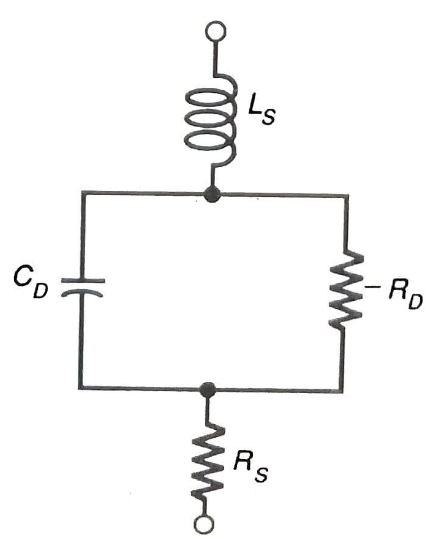


Figure 20-22 The tunnel diode equivalent circuit consists of a negative resistance $-R_D$ shunted by the junction capacitance C_D. Connecting lead resistance R_S and inductance L_S must also be included.

43194

4 GHz. The negative resistance determined from the characteristic does not allow for the effects of C_D shunting R_D at high frequencies. Thus, the *effective negative resistance* becomes progressively smaller as operating frequency increases, and there is a frequency at which the effective R_D becomes zero. This frequency is known as the *resistive cutoff frequency* f_{ro}. Values of f_{ro} range from 1.6 GHz to about 3.3 GHz.

Parallel Amplifier

For operation as an amplifier, a tunnel diode must be biased to the center of its negative resistance region. Figure 20-23(a) shows the basic circuit of a parallel amplifier. Load resistor R_L is connected in parallel with diode D_1 and supplied with current from battery voltage E_B and signal e_S. Figure 20-23(b) shows the dc conditions of the diode when the signal voltage $e_S = 0$ and when $e_S = \pm 100$ mV. Operation of the circuit is explained by the following example.

Example 20-5

Assuming that E_B and e_S have zero source resistance, calculate the current gain, voltage gain, and power gain for the tunnel diode parallel amplifier circuit in Fig. 20-23(a).

Solution

When $e_S = 0$,

$$E_D = E_B + e_S = 200\text{ mV} + 0$$
$$= 200\text{ mV}$$

From point Q on the characteristic in Fig. 20-23(b), $I_D = 2$ mA and $E_R = (E_B + e_S) = 200$ mV. Therefore,

$$I_L = \frac{E_R}{R_L} = \frac{200\text{ mV}}{80\ \Omega} = 2.5\text{ mA}$$

$$I_B = I_D + I_L = 4.5\text{ mA}$$

When $e_S = +100$ *mV*,

$$E_B + e_S = 200\text{ mV} + 100\text{ mV} = 300\text{ mV}$$

and

$$E_D = E_R = 300\text{ mV}$$

From point A on the characteristic, $I_D = 1$ mA and

$$I_L = 300\text{ mV}/80\ \Omega = 3.75\text{ mA}$$
$$I_B = 1\text{ mA} + 3.75\text{ mA} = 4.75\text{ mA}$$