5-9 The Schottky Diode

As frequency increases, the action of small-signal rectifier diodes begins to deteriorate. They are no longer able to switch off fast enough to produce a well-defined half-wave signal. The solution to this problem is the *Schottky diode.* Before describing this special-purpose diode, let us look at the problem that arises with ordinary small-signal diodes.

GOOD TO KNOW

Schottky diodes are relatively high-current devices, capable of switching quickly while providing forward currents in the neighborhood of 50 A! It is also worth noting that Schottky diodes normally have lower breakdown voltage ratings as compared to conventional *pn* junction rectifier diodes.

Charge Storage

Figure 5-27*a* shows a small-signal diode, and Fig. 5-27*b* illustrates its energy bands. As you can see, conduction-band electrons have diffused across the junction and traveled into the *p* region before recombining (path *A*). Similarly, holes have crossed the junction and traveled into the *n* region before recombination occurs (path *B*). The greater the lifetime, the farther the charges can travel before recombination occurs.

For instance, if the lifetime equals 1 μs, free electrons and holes exist for an average of 1 μs before recombination takes place. This allows the free electrons to penetrate deeply into the *p* region, where they remain temporarily stored at the higher energy band. Similarly, the holes penetrate deeply into the *n* region, where they are temporarily stored in the lower energy band.

The greater the forward current, the larger the number of charges that have crossed the junction. The greater the lifetime, the deeper the penetration of these charges and the longer the charges remain in the high and low energy bands. The temporary storage of free electrons in the upper energy band and holes in the lower energy band is referred to as *charge storage.*

Charge Storage Produces Reverse Current

When you try to switch a diode from on to off, charge storage creates a problem. Why? Because if you suddenly reverse-bias a diode, the stored charges will flow in the reverse direction for a while. The greater the lifetime, the longer these charges can contribute to reverse current.

For example, suppose a forward-biased diode is suddenly reverse-biased, as shown in Fig. 5-28*a*. Then a large reverse current can exist for a while because of the flow of stored charges in Fig. 5-28*b*. Until the stored charges either cross the junction or recombine, the reverse current will continue.

Figure 5-27 Charge storage. (*a*) Forward bias creates stored charges; (*b*) stored charges in high- and low-energy bands.

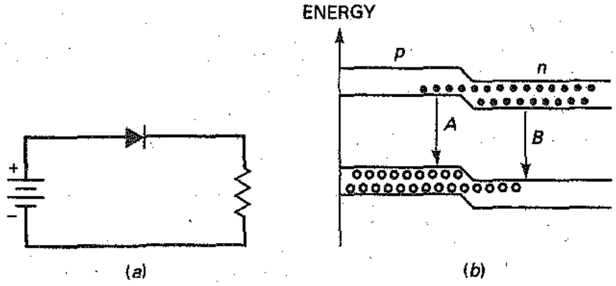
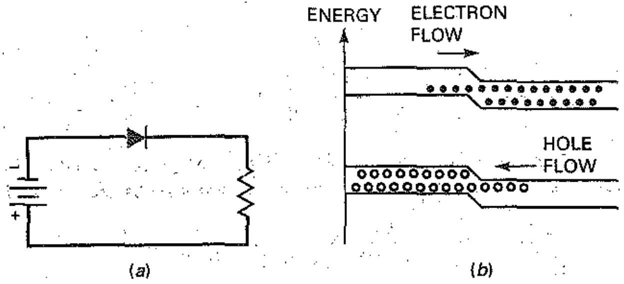


Figure 5-28 Stored charges allow a brief reverse current. (*a*) Sudden reversal of source voltage; (*b*) flow of stored charges in reverse direction.



Reverse Recovery Time

The time it takes to turn off a forward-biased diode is called the *reverse recovery time* t_{rr}. The conditions for measuring t_{rr} vary from one manufacturer to the next. As a guide, t_{rr} is the time it takes for the reverse current to drop to 10 percent of the forward current.

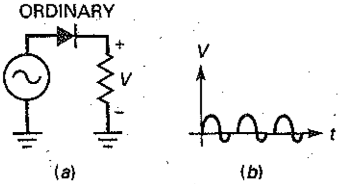
For instance, the 1N4148 has a t_{rr} of 4 ns. If this diode has a forward current of 10 mA and it is suddenly reverse-biased, it will take approximately 4 ns for the reverse current to decrease to 1 mA. Reverse recovery time is so short in small-signal diodes that you don't even notice its effect at frequencies below 10 MHz or so. It's only when you get well above 10 MHz that you have to take t_{rr} into account.

Poor Rectification at High Frequencies

What effect does reverse recovery time have on rectification? Take a look at the half-wave rectifier shown in Fig. 5-29*a*. At low frequencies the output is a half-wave rectified signal. As the frequency increases well into megahertz, however, the output signal begins to deviate from the half-wave shape, as shown in Fig. 5-29*b*. Some reverse conduction (called *tails*) is noticeable near the beginning of the reverse half cycle.

The problem is that the reverse recovery time has become a significant part of the period, allowing conduction during the early part of the negative half cycle. For instance, if $t_{rr} = 4$ ns and the period is 50 ns, the early part of the reverse half cycle will have tails similar to those shown in Fig. 5-29*b*. As the frequency continues to increase, the rectifier becomes useless.

Figure 5-29 Stored charges degrade rectifier behavior at high frequencies. (*a*) Rectifier circuit with ordinary small-signal diode; (*b*) tails appear on negative half cycles at higher frequencies.



Eliminating Charge Storage

The solution to the problem of tails is a special-purpose device called a **Schottky diode.** This kind of diode uses a metal such as gold, silver, or platinum on one side of the junction and doped silicon (typically *n*-type) on the other side. Because of the metal on one side of the junction, the Schottky diode has no depletion layer. The lack of a depletion layer means that there are *no stored charges at the junction.*

When a Schottky diode is unbiased, free electrons on the *n* side are in smaller orbits than are the free electrons on the metal side. This difference in orbit size is called the *Schottky barrier,* approximately 0.25 V. When the diode is forward biased, free electrons on the *n* side can gain enough energy to travel in larger orbits. Because of this, free electrons can cross the junction and enter the metal, producing a large forward current. Since the metal has no holes, there is no charge storage and no reverse recovery time.

Hot-Carrier Diode

The Schottky diode is sometimes called a *hot-carrier diode.* This name came about as follows. Forward bias increases the energy of the electrons on the *n* side to a higher level than that of the electrons on the metal side of the junction. This increase in energy inspired the name *hot carrier* for the *n*-side electrons. As soon as these high-energy electrons cross the junction, they fall into the metal, which has a lower-energy conduction band.

High-Speed Turnoff

The lack of charge storage means that the Schottky diode can switch off faster than an ordinary diode can. In fact, a Schottky diode can easily rectify frequencies above 300 MHz. When it is used in a circuit like Fig. 5-30*a*, the Schottky diode produces a perfect half-wave signal like Fig. 5-30*b* even at frequencies above 300 MHz.

Figure 5-30*a* shows the schematic symbol of a Schottky diode. Notice the cathode side. The lines look like a rectangular *S*, which stands for *Schottky.* This is how you can remember the schematic symbol.

Applications

The most important application of Schottky diodes is in digital computers. The speed of computers depends on how fast their diodes and transistors can turn on and off. This is where the Schottky diode comes in. Because it has no charge storage, the Schottky diode has become the backbone of low-power Schottky TTLs, a group of widely used digital devices.

A final point. Since a Schottky diode has a barrier potential of only 0.25 V, you may occasionally see it used in low-voltage bridge rectifiers because you subtract only 0.25 V instead of the usual 0.7 V for each diode when using the second approximation. In a low-voltage supply, this lower diode voltage drop is an advantage.

Figure 5-30 Schottky diodes eliminate tails at high frequencies. (*a*) Circuit with Schottky diode; (*b*) half-wave signal at 300 MHz.

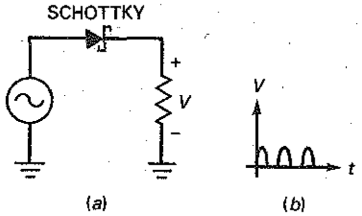
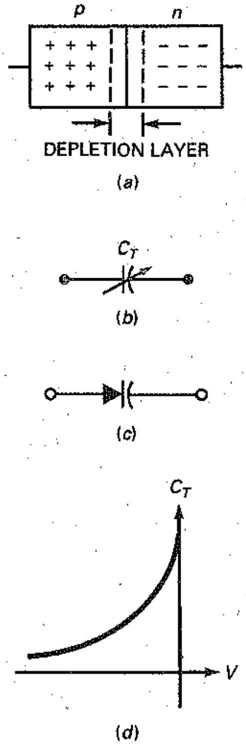


Figure 5-31 Varactor. (*a*) Doped regions are like capacitor plates separated by a dielectric; (*b*) ac equivalent circuit; (*c*) schematic symbol; (*d*) graph of capacitance versus reverse voltage.



5-10 The Varactor

The **varactor** (also called the *voltage-variable capacitance, varicap, epicap,* and *tuning diode*) is widely used in television receivers, FM receivers, and other communications equipment because it can be used for electronic tuning.

Basic Idea

In Fig. 5-31*a*, the depletion layer is between the *p* region and the *n* region. The *p* and *n* regions are like the plates of a capacitor, and the depletion layer is like the dielectric. When a diode is reverse-biased, the width of the depletion layer increases with the reverse voltage. Since the depletion layer gets wider with more reverse voltage, the capacitance becomes smaller. It's as though you moved apart the plates of a capacitor. The key idea is that capacitance is controlled by reverse voltage.

Equivalent Circuit and Symbol

Figure 5-31*b* shows the ac equivalent circuit for a reverse-biased diode. In other words, as far as an ac signal is concerned, the varactor acts the same as a variable capacitance. Figure 5-31*c* shows the schematic symbol for a varactor. The inclusion of a capacitor in series with the diode is a reminder that a varactor is a device that has been optimized for its variable-capacitance properties.

Capacitance Decreases at Higher Reverse Voltages

Figure 5-31*d* shows how the capacitance varies with reverse voltage. This graph shows that the capacitance gets smaller when the reverse voltage gets larger. The really important idea here is that reverse dc voltage controls capacitance.

How is a varactor used? It is connected in parallel with an inductor to form a parallel resonant circuit. This circuit has only one frequency at which maximum impedance occurs. This frequency is called the *resonant frequency*. If the dc reverse voltage to the varactor is changed, the resonant frequency is also changed. This is the principle behind electronic tuning of a radio station, a TV channel, and so on.

Varactor Characteristics

Because the capacitance is voltage-controlled, varactors have replaced mechanically tuned capacitors in many applications such as television receivers and automobile radios. Data sheets for varactors list a reference value of capacitance measured at a specific reverse voltage, typically −3 V to −4 V. Figure 5-32 shows a partial data sheet for a MV209 varactor diode. It lists a reference capacitance C_t of 29 pF at −3 V.

In addition to providing the reference value of capacitance, data sheets normally list a capacitance ratio, C_R, or tuning range associated with a voltage range. For example, along with the reference value of 29 pF, the data sheet of a MV209 shows a minimum capacitance ratio of 5:1 for a voltage range of −3 V to −25 V. This means that the capacitance, or tuning range, decreases from 29 to 6 pF when the voltage varies from −3 V to −25 V.

The tuning range of a varactor depends on the doping level. For instance, Fig. 5-33*a* shows the doping profile for an abrupt-junction diode (the ordinary type of diode). The profile shows that the doping is uniform on both sides of the junction. The tuning range of an abrupt-junction diode is between 3:1 and 4:1.

Figure 5-32 MV209 Partial Data Sheet. (Copyright of Semiconductor Components Industries, LLC. Used by Permission.)

	C_t, Diode Capacitance V_R = 3.0 Vdc, f = 1.0 MHz pF			Q, Figure of Merit V_R = 3.0 Vdc f = 50 MHz	C_R, Capacitance Ratio C_3/C_{25} f = 1.0 MHz (Note 1)	
Device	**Min**	**Nom**	**Max**	**Min**	**Min**	**Max**
MMBV109LT1, MV209	26	29	32	200	5.0	6.5

1. C_R is the ratio of C_t measured at 3 Vdc divided by C_t measured at 25 Vdc.

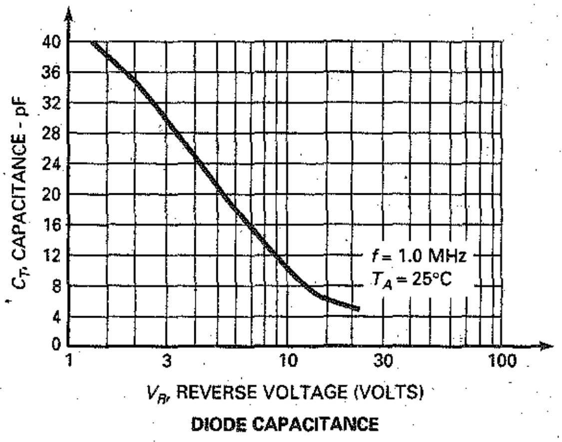
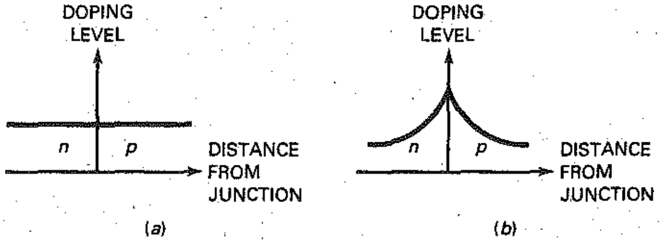


Figure 5-33 Doping profiles. (*a*) Abrupt junction; (*b*) hyperabrupt junction.



To get larger tuning ranges, some varactors have a *hyperabrupt junction*, one whose doping profile looks like Fig. 5-33*b*. This profile tells us that the doping level increases as we approach the junction. The heavier doping produces a narrower depletion layer and a larger capacitance. Furthermore, changes in reverse voltage have more pronounced effects on capacitance. A hyperabrupt varactor has a tuning range of about 10:1, enough to tune an AM radio through its frequency range of 535 to 1605 kHz. (Note: You need a 10:1 range because the resonant frequency is inversely proportional to the square root of capacitance.)

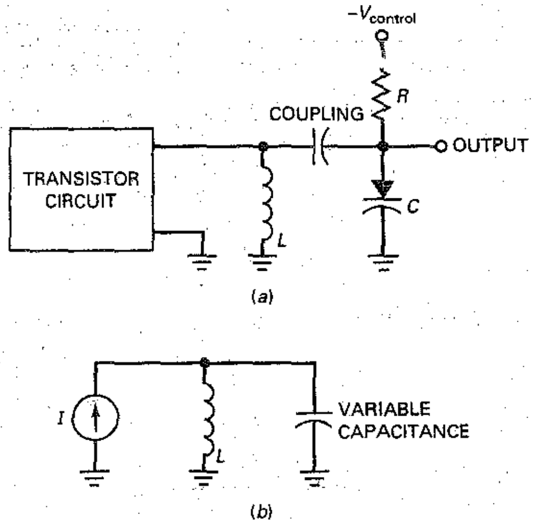
Example 5-17

What does the circuit of Fig. 5-34*a* do?

SOLUTION As mentioned in Chap. 1, a transistor is a semiconductor device that acts like a current source. In Fig. 5-34*a*, the transistor pumps a fixed number of milliamperes into the resonant *LC* tank circuit. A negative dc voltage reverse-biases the varactor. By varying this dc control voltage, we can vary the resonant frequency of the *LC* circuit.

As far as the ac signal is concerned, we can use the equivalent circuit shown in Fig. 5-34*b*. The coupling capacitor acts like a short circuit. An ac current source drives a resonant *LC* tank circuit. The varactor acts like variable capacitance, which means that we can change the resonant frequency by changing the dc control voltage. This is the basic idea behind the tuning of radio and television receivers.

Figure 5-34 Varactors can tune resonant circuits. (*a*) Transistor (current source) drives tuned *LC* tank; (*b*) ac equivalent circuit.



5-11 Other Diodes

Besides the special-purpose diodes discussed so far, there are others you should know about. Because they are so specialized, only a brief description follows.

Varistors

Lightning, power-line faults, and transients can pollute the ac line voltage by superimposing dips and spikes on the normal 120 V rms. *Dips* are severe voltage drops lasting microseconds or less. *Spikes* are very brief overvoltages up to 2000 V