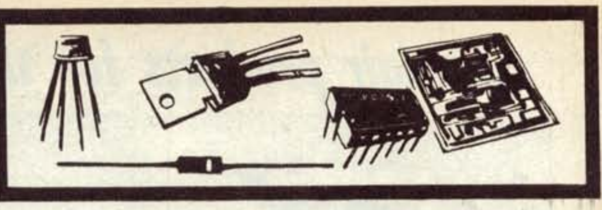
Fundamentals of SOLID STATE



Chapter 5

by Jamieson Rowe

Diodes and semiconductor materials — reverse bias current — temperature effects — forward bias characteristics — high temperature operation — power rating — surge current rating — reverse breakdown — peak inverse voltage rating — switching speed — package capacitance — junction capacitance — charge storage — diode applications.

The basic P-N junction, whose behaviour was described in the preceding chapter, effectively forms the functional "heart" of almost every type of semiconductor diode. However, as the reader may already be aware, practical semiconductor diodes are encountered with widely differing electrical ratings. They are also found in circuits performing a variety of rather different tasks, and seen in an almost bewildering array of different physical forms.

In order to provide the reader with a satisfying explanation of these wide divergences between practical semiconductor diodes, it is necessary to expand the concepts of basic P-N junction operation already developed, and this will be attempted in the present chapter and in that which follows it. The present chapter will deal with what may be called "orthodox" diodes — that is, those devices which are designed to take advantage mainly of the unidirectional conduction properties of the P-N junction. Such diodes include those commonly encountered in circuits performing rectification, signal detection, mixing, switching, gating and clipping.

Chapter six will deal in turn with those diode devices which are designed to take advantage of aspects of P-N junction behaviour other than that of unidirectional conduction. Examples of this type of device are diodes used as voltage regulators and coupling elements, variable capacitors, oscillators and amplifiers, light detectors and energy converters.

Perhaps the first thing to be noted regarding practical semiconductor diodes is that, as one might perhaps expect, they are made from a number of different semiconductors. A very large majority of diodes in use at the present time are made from either germanium or silicon; the latter having been used to a lesser extent in the early days of semiconductor technology because of manufacturing difficulties, but now used very extensively and possibly to a greater extent than germanium. Other semiconductor materials which are becoming used for diodes include gallium arsenide, gallium phosphide and gallium antimonide.

The electrical behaviour and the ratings of a diode are both influenced significantly by the semiconductor material from which it is made. As we shall see, the semiconductor concerned plays a significant part, along with the doping level, in determining the voltage-current characteristics of a diode for both forward and reverse bias. It also determines the extent to which this behaviour varies with temperature, and the power which the device is capable of dissipating before this behaviour is permanently altered.

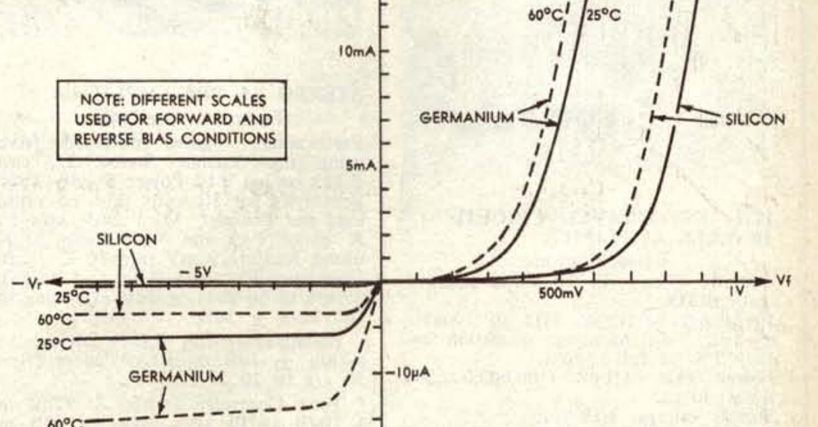


Figure 5.1

As we saw in chapter 2, all crystalline semiconductors are alike in the sense that, in the ground state, they behave as electrical insulators. The valence electron energy band is completely filled, while the empty conduction band is isolated from it by the "forbidden energy" gap. From an electrical viewpoint the essential differences between the various semiconductors arise mainly because this forbidden energy gap has a different width in each case.

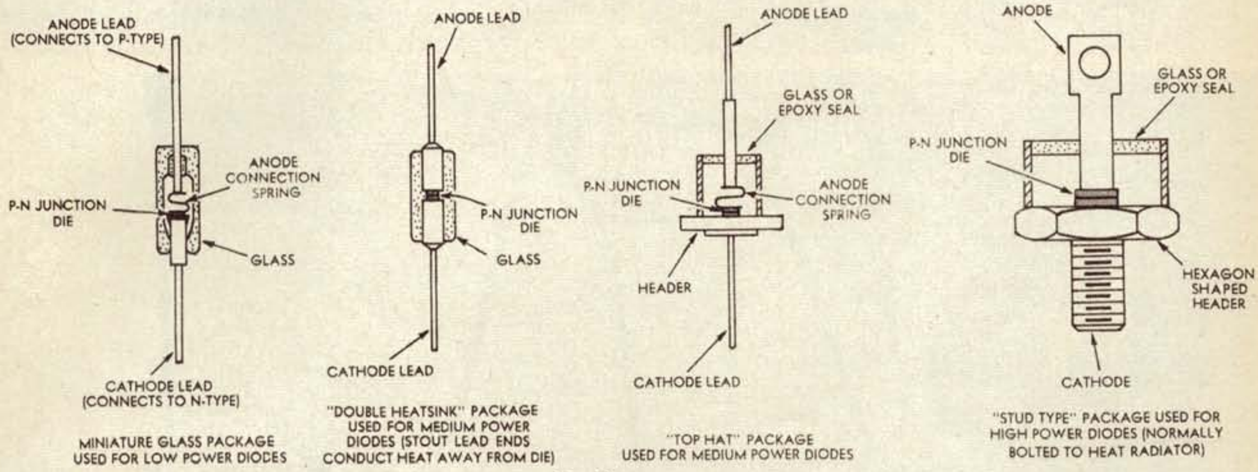
Germanium, it may be remembered, has a forbidden energy gap width of 0.72eV (electron-volts), while silicon has a somewhat larger gap width of 1.11eV. The compound semiconductor gallium arsenide has a gap width which is even larger again at 1.39eV.

The width of the forbidden energy gap was shown earlier to control the conductivity of intrinsic semiconductor material, by determining the excitation energy required for electrons to be transferred to the conduction band. From this, and knowing that the generation of minority carriers in an impurity semiconductor material takes place by the same "intrinsic" mechanism, it should be fairly clear that the gap width also determines the number of minority carriers generated in an impurity semiconductor at any given excitation and doping level.

However, it is also true that the width of the energy gap controls, in a minor, but inverse manner, the relationship between minority carrier level and excitation level. Thus, although material with a wide energy gap tends initially to have a smaller number of minority carriers than material with a narrower gap, for the same excitation, its minority carrier population tends to multiply slightly more rapidly with increasing excitation.

Hence, while silicon impurity semiconductor material tends to have a considerably smaller minority carrier population than germanium material, at room temperatures, it also exhibits a slightly increased tendency for this population to grow as the temperature is increased. Despite this the minority carrier population of typical silicon material does not even approach that of germanium until very high temperatures are reached, both because germanium has a larger initial population, and because this population itself increases significantly with temperature.

What effect do these differences have on the behaviour of practical P-N diodes? They have a significant effect upon the reverse-bias saturation currents, because it may be recalled that these currents are directly proportional to the minority carrier populations on either side of the junction.



MINIATURE GLASS PACKAGE USED FOR LOW POWER DIODES

"DOUBLE HEATSINK" PACKAGE USED FOR MEDIUM POWER DIODES (STOUT LEAD ENDS CONDUCT HEAT AWAY FROM DIE)

"TOP HAT" PACKAGE USED FOR MEDIUM POWER DIODES

"STUD TYPE" PACKAGE USED FOR HIGH POWER DIODES (NORMALLY BOLTED TO HEAT RADIATOR)

Figure 5.2

In short, diodes made from a semiconductor material having a relatively wide forbidden energy gap, such as silicon or gallium arsenide, tend to have a very low reverse bias saturation current at normal temperatures. In comparison diodes made from a semiconductor material such as germanium, which has a relatively narrow energy gap, tend to have a somewhat larger saturation current at the same temperature. This despite the fact that in the former case the saturation current will tend to increase slightly more rapidly with temperature.

It is true that the total reverse bias current drawn by a practical semiconductor diode is not composed of the minority carrier saturation currents alone. It is very difficult, during the manufacture of practical diodes, to ensure that the surface of the semiconductor crystal element or "die" does not become contaminated in some way, and such contamination tends to result in additional reverse bias currents, which are commonly referred to as **leakage** currents.

Early in the history of semiconductor device development, these leakage currents were typically of the same order of magnitude as the saturation currents. However, in recent years, manufacturing techniques have been considerably improved, and leakage currents can typically be held to a very small fraction of the saturation currents. Hence, with modern semiconductor diodes and other devices, the reverse bias current drawn by an independent P-N junction is almost entirely composed of the minority carrier saturation currents.

In quantitative terms, the total reverse bias current of a typical modern silicon diode is of the order of a few hundred nA (nanoamps), at room temperature. Comparable germanium diodes typically have reverse bias currents of something like 100 times this figure, i.e., a few tens of uA (microamps). Because of the influence of excitation upon minority carrier generation these figures both increase as the temperature is raised, the silicon device current increasing slightly more rapidly.

Typically the reverse bias current of a germanium diode approximately doubles for every 8°C rise in temperature, while that of a silicon diode approximately doubles for every 5°C rise.

An illustration of the reverse-bias aspect of diode performance is provided by the left-hand portion of figure 5.1, which shows the reverse-bias currents of typical silicon and germanium diodes compared at room temperature (25°C) and at 60°C. It may be seen that at both temperatures the silicon diode has a considerably lower saturation current, even though the proportional increase may be larger over the temperature range concerned.

From the foregoing one might be tempted to infer that, because silicon diodes have lower reverse bias currents than germanium diodes under similar conditions, they would consequently be preferable for any application requiring a device whose performance should approach that of an "ideal" unidirectional conducting element. However, while this is true where reverse bias is concerned, unfortunately the reverse is the case under forward bias conditions. Here it is found that germanium diodes are somewhat closer to the ideal.

The reason for this is that, in addition to its influence upon minority carrier generation, and consequently upon saturation currents, the forbidden energy gap width of a semiconductor also plays an important part in determining the magnitude of the "inbuilt" drift field and potential barrier set up across a P-N junction in equilibrium. As a result the gap width also has a controlling influence upon the forward bias characteristic of such a junction, because it may be remembered that the forward bias current consists of excess majority carrier diffusion currents, which develop as the inbuilt potential barrier is surmounted.

For a semiconductor with a relatively wide forbidden energy gap, there will be a large energy difference between the Fermi levels of P-type and N-type material. Because of this, the potential barrier set up across a P-N junction made from the material will be relatively large under equilibrium conditions, compared with that across a junction made from a semiconductor having a relatively narrow energy gap. In turn this will mean that a relatively high external forward bias will be required before the internal barrier is surmounted.

Hence, because of the wider energy gap of silicon, a diode made from this material tends to require a higher applied forward bias than a comparable germanium diode for the same total forward conduction current. This is illustrated by the right-hand portion of figure 5.1, which shows the forward conduction characteristics of typical silicon and germanium diodes compared as before at 25°C and 60°C. It may be seen that the silicon diode is "harder to turn on" than the germanium device, and also that it has a higher voltage drop when in forward conduction.

It should be noted that both types of device "turn on" at a lower voltage, and have a lower conducting voltage drop, at the elevated temperature. The reason for this should become clear if it is recalled that the Fermi level of an impurity semiconductor moves toward the forbidden energy gap midpoint with increasing excitation, due to the increase in minority carriers. This means that the energy difference between the Fermi levels of the P-type and N-type materials becomes less as the temperature is raised, and accordingly the junction barrier potential also decreases. Forward conduction thus takes place at a lower applied voltage.

At this stage it should be fairly clear that when both forward and reverse characteristics are considered, neither silicon nor germanium diodes have a clear advantage. The silicon diode tends to have a somewhat lower reverse bias current, and therefore, more closely approximates the "ideal" diode in the reverse bias condition, but the germanium diode has a lower forward bias voltage requirement and thus represents the closer approximation to the ideal in the forward bias condition.

In terms of characteristics, then, the choice of the semiconductor material from which a diode is made depends largely upon the ultimate application and its requirements. If the application is one in which low reverse bias current is necessary or desirable, then a diode made from a wide energy-gap material such as silicon or gallium arsenide would be most appropriate.

Conversely if the prime requirement of the application concerned is for turn-on at a low voltage and minimum forward voltage drop in conduction, then the choice would favour a diode made from a narrow energy-gap semiconductor such as germanium. It is true that if either both forward and reverse bias behaviour were critical, or both were not unduly critical, the choice would be less straightforward. In such cases the decision might well be made on the basis of other factors, one of which would probably be operating temperature capability.

Generally a diode made from a semiconductor having a wide energy gap is more suitable for high temperature operation than a diode made from a semiconductor having a narrow energy gap. This is partly because of the somewhat lower reverse bias current at higher temperatures. However, a further reason is that the energy gap of a semiconductor plays a part in determining both the temperature at which the electrical structure of the device begins to alter permanently, due to thermal diffusion of the actual impurity atoms and ions, and also the crystal melting point. The wider the energy gap, the higher these temperatures tend to occur.

In practice the manufacturer of a semiconductor diode or other device usually rates his product in terms of the maximum allowable **junction temperature.** This is done in order to take into account the fact that both the ambient temperature and the power dissipated by the device contribute to its internal operating temperature.

Typically, germanium devices are given a maximum junction temperature rating of around 80-90°C, while silicon devices are usually given a somewhat higher rating of between 150-180°C. A silicon device would, therefore, be the logical choice for most applications involving high temperatures and/or very high power dissipation.

In order to allow the user to ensure that a device is operated within its maximum junction temperature rating at all ambient temperatures, the manufacturer must also normally provide information regarding the typical temperature rise of the device junction(s) with power dissipation. This informaton is usually given in terms of the **thermal resistance** of the device, expressed in units of (degrees C/watt dissipation).

Naturally the thermal resistance of a particular device depends upon both the size of the semiconductor crystal die itself, and the physical "package" in which it is mounted. Hence a device intended for very low power applications may have a very small die and be mounted in a small glass or plastic package having a fairly high thermal resistance, while a device for high power use will normally have a relatively large die and will be mounted in a large metal package of low thermal resistance.

In addition to thermal resistance, a crystal die and its package also possess thermal "capacitance" or inertia. Because of this, heating and cooling of the device involve definite thermal time-constants. Hence the heating of the die tends to be proportional not to the instantaneous power dissipation, but to the average dissipation taken over a short time interval — the interval length depending upon the crystal die itself, and on the package and its thermal time-constant.

As a result of this averaging effect, a diode is typically able to withstand short bursts or "surges" of power dissipation which may be considerably higher than its continuous or "steady-state" dissipation rating. This short-term capability is often expressed in terms of the forward conduction **surge current rating** of the device, which may be given a number of values for different time periods.

Depending upon the device itself and also upon the time period for which a surge rating is given, it may represent from about five times to more than 50 times the forward current corresponding to the continuous power rating of the device. The shorter the time involved, naturally enough, the higher tends to be the figure; however devices may be produced with the ability to withstand quite long surges of high amplitude, by appropriate thermal design.

Further discussion of thermal considerations will be given in a later chapter. However, from the foregoing it should be apparent that power dissipation requirements provide at least a partial explanation for the variety of packages in which semiconductor devices are found. Figures 5.2 and 5.3 show the basic construction of some of the diode packages in common use.

In general each of the various sizes and packages in which "orthodox" diodes of both the germanium and silicon type are made available are further subdivided into many individual device types differing from one another mainly in terms of two other important parameters. These are the reverse breakdown characteristic, and the switching speed, each of which will now be briefly discussed.

It may be remembered that if the reverse bias voltage applied to a P-N junction is increased, a point is eventually reached where the junction current rises rapidly from its low saturation value, and the junction is then said to have entered **"breakdown."** One of two main mechanisms is usually responsible for this behaviour, one being called field emission or Zener breakdown, and the other avalanche breakdown.

As was explained in the preceding chapter, the phenomenon of junction reverse breakdown does not involve inherent damage. However, it does constitute a potentially high-dissipation mode of operation, because under breakdown conditions a junction tends to maintain a relatively large voltage drop while at the same time being capable of heavy conduction.

It is also true that with practical P-N junctions, in diodes and other semiconductor devices, breakdown tends to occur unevenly and in a localised manner at some specific point on the crystal die. As a result, the increased current which flows is concentrated in a small area, and localised overheating and damage can occur with great rapidity at power levels considerably lower than the forward conduction continuous power rating of the device.

By exercising extreme control over

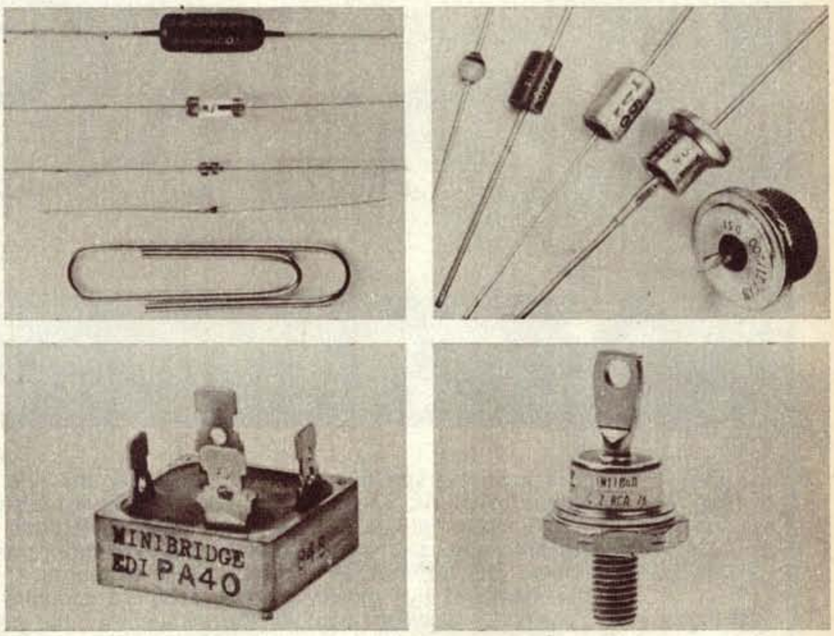


Figure 5.3. Typical semiconductor diodes. At upper left are various low-power or "signal" diodes, compared in size with a common paper clip. At upper right are four medium-power diodes as used in many receiver and amplifier power supplies, together with a power diode used in the rectifier within an automotive alternator. At lower left is an assembly containing four high-power silicon diodes, connected for bridge rectification. At lower right is a single stud-mounting high power silicon diode capable of handling an average current of 40 amps. All devices are shown approximately normal size.

cleanliness and such factors as doping uniformity during the various fabrication processes, device manufacturers have recently been able to effect a considerable reduction in this tendency for localised breakdown. However, the "transient protected" devices which have resulted from this effort are necessarily more costly than devices fabricated under less stringent conditions; and, of course, such devices still enter breakdown eventually, albeit in a uniform and evenly distributed manner.

Junction breakdown thus represents a condition which at the very least involves potential device damage. It should also be evident that quite apart from this, the rise in reverse current, which tends to occur at breakdown, represents in itself a significant departure from the ideal diode characteristic.

For a practical diode, therefore, the reverse breakdown characteristic is of considerable importance. It must be considered not only with relevance to the protection of the device itself, but also because of its possible consequences in the circuitry into which the device is connected.

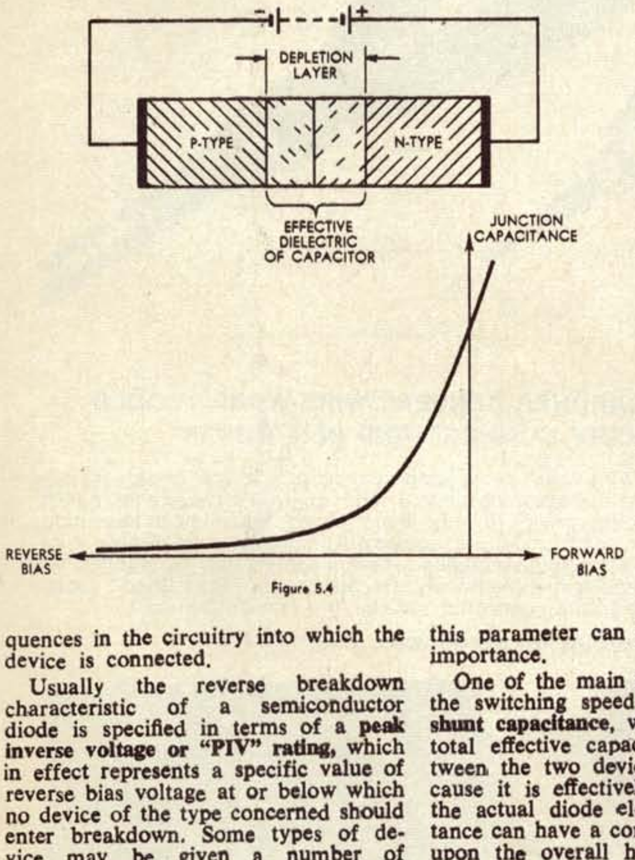


Figure 5.4

Usually the reverse breakdown characteristic of a semiconductor diode is specified in terms of a **peak inverse voltage or "PIV" rating,** which in effect represents a specific value of reverse bias voltage at or below which no device of the type concerned should enter breakdown. Some types of device may be given a number of different PIV ratings, to cover both steady-state and various reverse transient conditions. The "transient protected" diodes mentioned earlier are examples of devices normally given such multiple ratings.

Both silicon and germanium diodes may be manufactured to exhibit a wide range of breakdown voltages. However, devices required to have a very high breakdown voltage rating are usually made from silicon or some other semiconductor having a similarly wide energy gap. This is because the relatively high reverse saturation current of a narrow-gap semi-conductor such as germanium tends to make it very difficult to delay the onset of avalanche breakdown.

Germanium diodes are typically available with PIV ratings ranging from less than a volt to about 150V. Silicon diodes are available with PIV ratings ranging from about 3V to more than 1500V. Still higher PIV ratings can be produced by connecting a number of individual silicon dice in series; devices with PIV ratings in excess of 50KV have been produced using this technique.

As noted earlier, a further important general parameter of practical semiconductor diode behaviour is **switching speed.** This basically describes the ability, or otherwise, of a device to rapidly follow any changes in external circuit conditions. As diodes are often found in circuits involving rapid reversal of the bias voltages applied to the device, this parameter can be of considerable importance.

One of the main factors determining the switching speed of a diode is its **shunt capacitance**, which is simply the total effective capacitance present between the two device electrodes. Because it is effectively in parallel with the actual diode element, this capacitance can have a considerable influence upon the overall high-speed performance. For example, it tends to draw a current component which is purely proportional to the rate of change of applied voltage, regardless of polarity; behaviour which fairly obviously represents a significant departure from that of an ideal diode.

Naturally enough the diode package alone will contribute to the total shunt capacitance, as some finite package capacitance is unavoidable with practical devices. However, by careful design manufacturers have been able to produce packages with very low shunt capacitance, and these are normally employed for those devices intended for extremely high speed operation.

Quite apart from the package capacitance, however, an important component of the total shunt capacitance is provided by the inherent capacitance of the diode P-N junction itself. This capacitance is known as the "depletion layer capacitance," "barrier capacitance," "space charge capacitance," "junction capacitance," or "transition capacitance."

Although it may seem surprising at first that the P-N junction itself acts as a capacitor, the reason for this should become evident after a moment's consideration. Essentially, a capacitor consists of two conductors separated by a dielectric, and in the P-N junction we have, after all, two quite high conductivity semiconductor regions separated by a low conductivity depletion layer region. The latter is largely devoid of carriers, yet provided with the facility for charge storage in the form of ionised impurity atoms; small wonder, therefore, that it acts as a very effective dielectric.

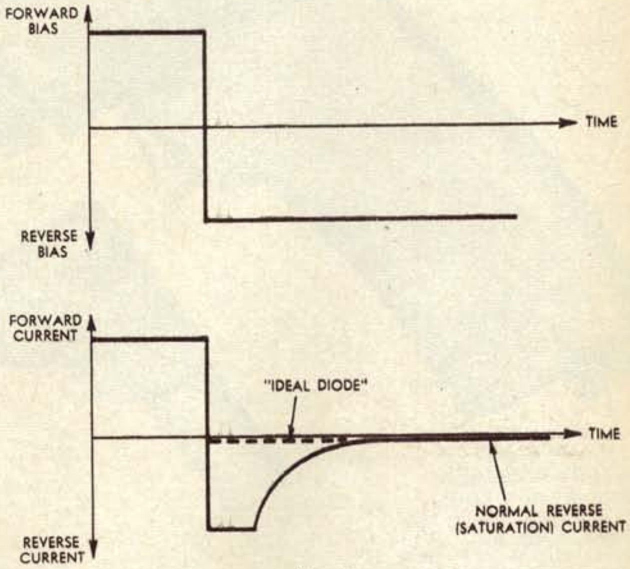


Figure 5.5

Of course the width of the depletion layer varies with applied voltage, as we have seen. Under equilibrium conditions, with zero applied bias, it has a width determined by the semiconductor concerned and by the doping levels. If reverse bias is applied, the depletion layer widens to uncover more impurity ions, and conversely if forward bias is applied it narrows to reduce the number of uncovered ions.

Because of this width variation, the junction capacitance is not static but also varies with applied voltage. This is illustrated in figure 5.4, where it may be seen that the junction capacitance of a typical diode varies inversely with reverse bias voltage, and directly with forward bias voltage.

The junction capacitance of a device may be minimised by using the smallest crystal die capable of handling the required power, and by using low doping levels to result in a relatively wide depletion layer. Naturally the latter technique involves a compromise, as low doping levels also increase the resistivity of the material and hence tend to increase the forward voltage drop and consequently lower efficiency.

As will be discussed in the next chapter, some semiconductor diodes are expressly designed to exhibit a very high junction capacitance. Such diodes are intended not for use as unidirectional circut elements, but rather as voltage-controlled variable capacitors.

Yet another important factor which influences the switching speed of a semiconductor diode is the phenomenon known as **charge storage** or **minority carrier storage.** This is particularly relevant where a diode is required to switch rapidly between the forward conducting or "on" state and the reverse-biased "off" state.

When a P-N junction is conducting due to forward bias, it may be remembered, excess majority carrier diffusion currents are flowing in both directions across the junction. At the same time the depletion layer has a width somewhat less than that for equilibrium conditions, and the potential barrier a somewhat lower value.

If the voltage applied to the device is changed, these conditions must also change to achieve a new dynamic balance. Thus if the forward bias is increased, additional carriers must be swept across the junction to set up higher diffusion current levels, while at the same time some of the previously ionised impurity atoms must be neutralised to reduce the depletion layer width and reduce the potential barrier.

Conversely, if the bias is reduced or reversed in polarity, the number of carriers crossing the junction must fall, while additional impurity atoms must be ionised to widen the depletion layer and increase the potential barrier.

In both cases, significant time must elapse before the new conditions stabilise. The depletion layer changes involve movement of carriers through a finite volume of material, and this necessarily takes time. Hence there is an inevitable delay involved before the new balance conditions are reached, and during the delay period the behaviour of the device may differ considerably from that of an ideal diode.

For example, figure 5.5 shows what tends to happen if the polarity of the applied voltage is suddenly switched from a forward bias value to a reverse bias value. Ideally when this occurs the diode current would drop immediately to its very low reverse saturation current value; however, it can be seen that what in fact happens is that the current swings rapidly to a high reverse value, and only subsequently falls back exponentially to its saturation value.

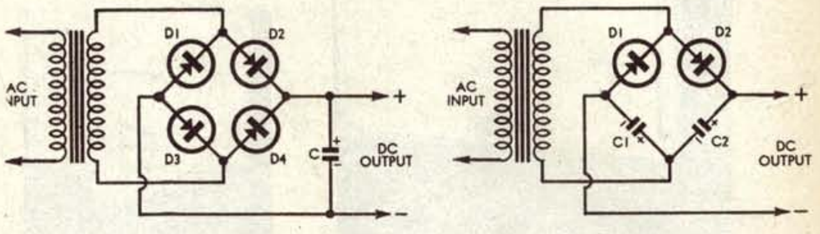
The reason for this is that at the instant of bias reversal, a considerable number of carriers of both types are stored or "trapped," in the depletion layer region and also in the adjacent P-type and N-type material as injected minority carriers. Before normal reverse-bias operation can be achieved, these carriers must all be removed, generally by being swept back across the junction in both directions. It is the removal of these stored carriers which results in the temporary high reverse current.

The charge-storage mechanism can be controlled to a considerable extent by special techniques involving non-uniform doping and careful choice of impurities. The rather specialised diodes produced by such techniques include those called "step-recovery diodes," "snap-off diodes," "avalanche switching diodes" and "PIN diodes."

To conclude this discussion of "orthodox" semiconductor diodes, brief descriptions will be given of a small, but representative selection of the great many applications of these devices.

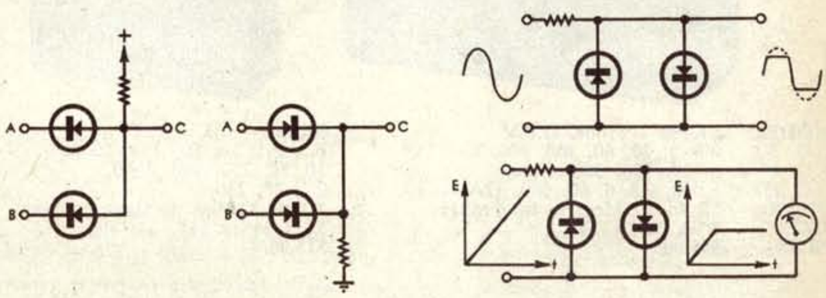
Probably the most familiar application of semiconductor diodes is in circuits used for the rectification of alternating current into unidirectional current. In fact they are particularly well suited for this task, because, despite the limitations discussed in this chapter, they still represent the closest available approximation to an ideal diode element.

There are numerous different rectifier circuit configurations, each of which has certain distinct advantages in specific situations. Two of the most common configurations are illustrated in figure 5.6 (a) and (b).



(a) BRIDGE RECTIFIER

(b) VOLTAGE-DOUBLING RECTIFIER



(c) LOGIC GATING

(d) CLIPPING, NON-LINEAR SHUNTING

Figure 5.6

The first of these is the so-called "bridge" circuit, which employs four diode elements as a commutating switch which effectively reverses the output connections to the AC source on alternate half-cycles. The second configuration is the so-called "full-wave voltage doubler" circuit, which during alternate half-cycles charges two storage or reservoir capacitors which are effectively connected in additive series with respect to the DC output circuit.

In both of these circuits (but not necessarily in other rectifiers) the diodes used should normally have a dissipation rating sufficient to allow them to carry the full load current for 50% of the time. This is because each element conducts on alternate half-cycles only, but can under some circumstances conduct for the full half-cycle.

In the voltage-doubling circuit, and in the bridge circuit if a reservoir capacitor is used (shown dashed), the diodes must also be capable of handling the surge currents which will flow when the capacitor(s) are fully discharged. The amplitude of such surges is limited primarily by the effective secondary impedance of the transformer, but can be reduced if necessary to suit particular diode devices, by the addition of a low-value high-dissipation resistor in series with the transformer secondary.

The PIV rating of the diodes used in a bridge rectifier must be greater than the **peak** value of the transformer secondary voltage, as each diode when non-conducting is effectively connected directly across the winding. In contrast, the PIV rating of the diodes used in a voltage-doubler circuit must be greater than the **peak-to-peak** value of the transformer secondary voltage, because when non-conducting each diode is effectively connected across both the winding and a charged reservoir capacitor in series.

It should be noted that in both cases the minimum diode PIV rating corresponds to the no-load DC output voltage. This relationship is not universal among rectifier circuits; in fact it is relatively uncommon. Many rectifier circuits require the use of diodes having a PIV rating of more than double the no-load DC output.

Many "rectifier" circuit configurations are in basic form suitable not only for power rectification, but also for detection—the process of extracting modulation information from a high frequency carrier signal. Hence signal detection circuits form another important application of semiconductor diodes, and account for many of the diodes found in radio and television receivers and test equipment. Few detector circuits are based upon the bridge or voltage-doubling circuits of figure 5.6, however, most being based upon either the "full-wave" or "half-wave" configurations.

A rapidly growing application for semiconductor diodes is in circuitry involved in logic gating and signal switching. Here the unidirectional properties of the device are used to effectively connect or disconnect circuit points in response to their relative voltage polarities.

Simple circuit configurations of this type are shown in figure 5.6(c). In the left-hand circuit, it may be seen that point "C" will assume a significant positive potential if, and only if, both points "A" and "B" are raised to a positive potential. If either "A" or "B" is connected to earth (reference potential), "C" will also be held at approximately earth potential by the corresponding diode.

In logical terms the circuit thus performs the "AND" operation, because it can be said that if point "C" is positive, then **both** points "A" **and** "B" must also be positive.

In contrast with this behaviour is that of the right-hand circuit of figure 5.6(c). Here, because of the changed diode connections, the point "C" will go positive if either point "A" or "B" is taken positive. In this case the circuit can be said to perform the logical "OR" operation, because if point "C" is positive, then **either** point "A" **or** point "B" (or both) must be positive also.

Another important class of applications for semiconductor diodes includes circuits which take advantage of the fact that the forward characteristic of such devices is non-linear, representing a high initial resistance and subsequently a low resistance when the device reaches full conduction. Figure 5.6(d) illustrates two of the many types of circuit which exploit this behaviour.

In the left-hand circuit, it may be seen that two diodes are connected in inverse parallel across a source of sinewave signals, a resistor being used to limit diode current. During each half-cycle of the signal, one of the two diodes conducts; however because of the non-linearity of the forward bias characteristic, this conduction is effectively confined to that part of the half-cycle during which the signal amplitude exceeds the turn-on "knee." Hence the effect of the diodes is to effectively "clip" the signal to a known peak-to-peak amplitude.

The second circuit of figure 5.6(d) shows how a similar diode configuration may be used to protect a delicate meter movement from damage due to overload. Here the non-linearity of the diodes effectively prevents the voltage applied to the movement from rising above the turn-on knee voltage, in either direction. Silicon diodes are normally used in this type of application, because their higher turn-on voltage and lower saturation current both ensure that normal meter operation is not disturbed.

While the foregoing discussion of semiconductor applications has been necessarily very brief, it is hoped that it will serve to give the reader some insight into the vast number of applications to which these devices are being applied.

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RELIABILITY IN TERMS OF M.T.B.F.

How long should any piece of electronic equipment operate before it is likely to give trouble? It seems a bit like the classic question "How long is a piece of string?" but in fact reliability engineers have methods of reducing the complex question of equipment reliability to simple statistics.

TYPICAL COMPONENT FAILURE RATES

COMPONENT	FAILURE RATE (% per 1000 hrs.)
Resistor, composition	0.001
Resistor, film	0.002
Capacitor, paper	0.01
Capacitor, moulded mica	0.003
Capacitor, ceramic	0.001
Capacitor, electrolytic	0.03
Choke	0.2
Transformer	0.2
Potentiometer, composition	0.2
Transistor	0.04
Semiconductor diode	0.02
Valve	5.0

After you build a project, do you have any idea of how long it will operate before it needs repair? Do you have any idea how long your kitchen radio will play before it starts giving trouble? Or your TV set? Have you ever wondered why transistor radios seem to work forever (unless you drop them or start fiddling with the insides) while valve sets seem to go on the blink regularly?

It all has to do, of course, with what we call reliability — and what reliability engineers call "mean time between failure" or M.T.B.F. A numerical value, in hours for M.T.B.F. can be calculated for any given piece of equipment by using a simple mathematical expression. Although the value thus determined is not infallible since there are too many variables (temperature, voltage variations, humidity, shock and vibration, etc.), experience has shown that a reasonable amount of faith can be placed on M.T.B.F. calculations.

A fundamental assumption used in M.T.B.F. calculations is that failure of one part causes failure of the entire system — otherwise why have that particular part at all? Thus, to determine the M.T.B.F. of an electronic system, we first need to know the failure rate of each of the parts that make up the system.

Failure rates for the most important electronic components in use today are shown in the table. These values were arrived at through extensive testing by various component and system manufacturers.

The use of the table in calculating M.T.B.F. can best be shown through an example. Assume we have a transistor radio containing 10 transistors, 11 resistors, 1 potentiometer, 6 inductors (including chokes and transformers), 12 paper capacitors, 6 ceramic capacitors, and 5 electrolytic capacitors.

First find the failure rate for each type of component from the table. Multiply the failure rate by the number of components of that type and add all of the resulting figures. Thus:

Transistors: 10 x 0.04 = 0.400
Resistors: 11 x 0.001 = 0.011
Potentiometers: 1 x 0.2 = 0.200
Inductors: 6 x 0.2 = 1.200
Paper capacitors: 12 x 0.01 = 0.120
Cer. capacitors: 6 x 0.001 = 0.006
Elec. capacitors: 5 x 0.03 = 0.150
2.087

So the total failure rate is 2.087 per cent per 1000 hours. To find the M.T.B.F., divide the total failure rate into 100,000.

M.T.B.F. = 100,000/2.087
= 48,000 hours (approx.)

Once this is known, establish how many hours a day the device will be used, and you can then calculate how many days, weeks, months, or years, the system will probably operate.

If we were to determine the M.T.B.F. for the same radio with five valves instead of the 10 transistors, we would come out with about 3700 hours. Now you know why transistor radios last longer.

How can you improve the reliability of a piece of electronic equipment? You can start by derating the components you use. If physical size is not too big a problem, use resistors with a higher wattage rating or capacitors with higher voltage ratings. The use of premium valves, high-quality components, heat sinks for valves and transistors, and cooling fans can also improve reliability. A good rule of thumb is to derate all components by 50 per cent and use them in a cool environment. (Reproduced from "Popular Electronics," August, 1969, by arrangement.) ■

Notes and Errata

IMPROVED VERSION OF PARLOUR GAME, Reader Built It, August, 1969, page 109. On Bank No. 2, the contact representing "one counter remaining" (No. 6 counting anti-clockwise) should be joined to the three adjacent contacts, Nos. 7, 8 and 9. On Bank No. 3, the connection from the battery positive line to the centre contact of S1b should connect, instead, to the right-hand contact.

CRYSTAL DRIVE CLOCK UNIT, Part Two, July, 1969, page 40. We have been advised by the Postmaster-General's Department that a new schedule of VNG time signals came into operation recently.

MHz (DSB)	Transmission Times E.A.S.T.
4.500	1945 - 0730
7.500	0845 - 0830
12.000	0745 - 1930

Also, the power of all transmissions has increased from 1KW to 10KW. ■