

APPENDIX A

High Voltage Rectifiers

High Voltage! The sight of this familiar warning jars the senses and triggers caution in even the most experienced engineer. High voltage is a relative term, however, as warnings are similar whether applied to 100 volts or 100 kilovolts.

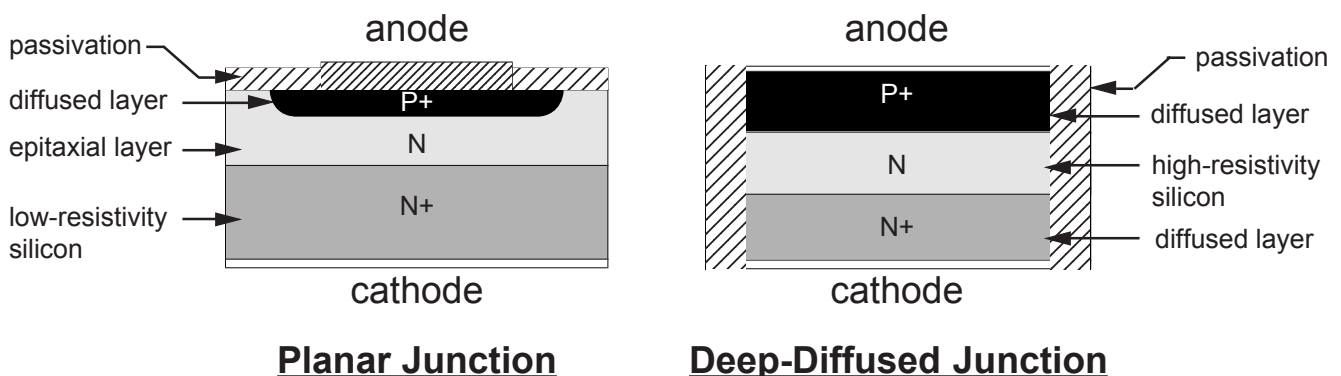
High-voltage rectification is also a relative term. As it surrounds our lives in CRT supplies, TWT supplies, X-Ray supplies and a host of other devices; the concept of high-voltage rectification must be clearly defined.

Ideally a high voltage rectifier is a single-junction diode, which blocks the required voltage quickly without leaking reverse current, or generating heat from power losses in the process. However in reality, high-voltage rectifiers offer complex trade-offs. To begin, a choice must be made between multi-junction, high-voltage, silicon diodes and strings of single-junction, silicon diodes.

Before a decision between single and multiple-junction diodes can be made, it is necessary to examine the fundamental characteristics of PN junctions. Two common techniques for fabricating high-voltage PN junctions come into play. They are **planar junction fabrication** and **deep-diffused junction fabrication** as depicted in Figure 1. Many variations of each technique exist. Severe angles, for example, are often present on a deep-diffused junction, creating a "mesa" appearance. Also, epitaxially-grown silicon may be used in either technique and a variety of dopants may be used.

FIGURE 1

Cross-sections of typical planar and deep-diffused diode junctions



Appendix A: High Voltage Rectifiers

Reverse Voltage and the Depletion Region

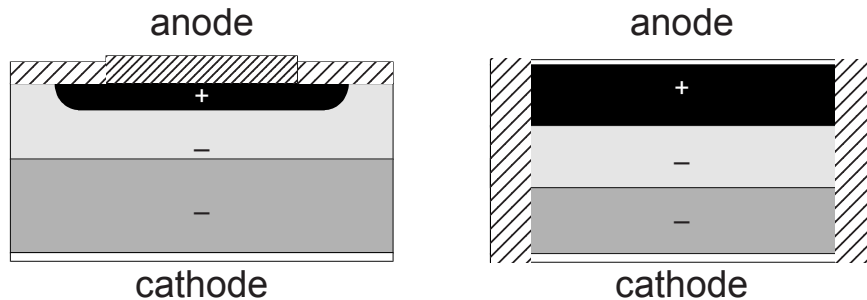
The depletion region increases, in the direction of the weakest field (area of highest resistivity), as reverse voltage is applied. As the reverse voltage is increased, this expansion continues until the field stress threshold is reached.

Epitaxially-grown layers have very abrupt differences in the depletion-region movement. Deep diffusion results in depletion-region movement in the N+ and P+ directions. During which, abrupt junctions develop in depletion-region expansion, primarily toward the N+ layer.

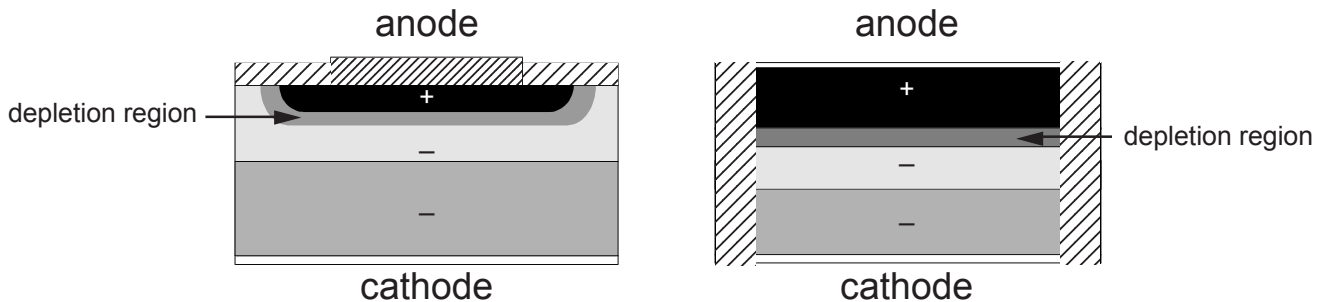
FIGURE 2

Depletion region as a function of reverse bias in typical planar (left) and deep-diffused (right) diode junctions

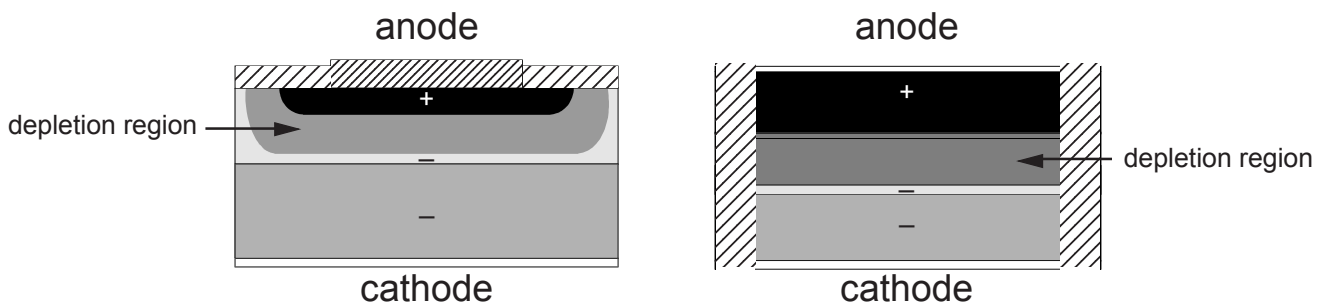
No Reverse Bias: No Depleted Region:



Slight Reverse Bias: Increased Depleted Region:



Full Reverse Bias: High-resistivity Layer Fully Depleted:



Appendix A: High Voltage Rectifiers

Reverse Breakdown Voltage (V_{BR})

Semiconductors have practical reverse-voltage limitations. The reverse breakdown voltage (V_{BR}) of silicon is determined primarily by three factors; the resistivity of the silicon (avalanche), the depletion region width (punch-through or reach-through) and the surface stress at the junction/passivation (zener) interface.

Reverse breakdown occurs when the voltage stress across one of these three areas exceeds the withstanding threshold, triggering a high reverse current across the entire junction area as shown in Figure 3. This condition is non-destructive in a properly designed device, provided the reverse current is limited to a level that minimizes thermal dissipation. This phenomenon should be seen as "water flowing over a spillway" and not as a failure of the dielectric material.

Zener diodes routinely operate in this mode and are designed for breakdown to be initiated by resistivity limitations rather than punch-through or avalanche. It should be noted, however, that high voltage zener diodes are less practical. This is because the higher-resistivity silicon and deeper diffusion depths required to achieve the higher voltage ratings make it difficult to predict the voltage at which breakdown occurs.

Three non-destructive breakdown mechanisms:

<u>Breakdown By</u>	<u>Descriptive Term</u>
depletion region	punch through or reach through
junction/passivation interface	avalanche
resistivity	zener

In the past, the term "controlled avalanche diodes" referred to those diodes which exhibited "sharp" breakdown characteristics. They must additionally survive over-voltage with controlled reverse current. The term "non-controlled avalanche diodes" typically referred to those diodes which possessed very high reverse currents at considerably lower than breakdown voltages. This high reverse current leads to overheating and very round breakdown curves.

Appendix A: High Voltage Rectifiers

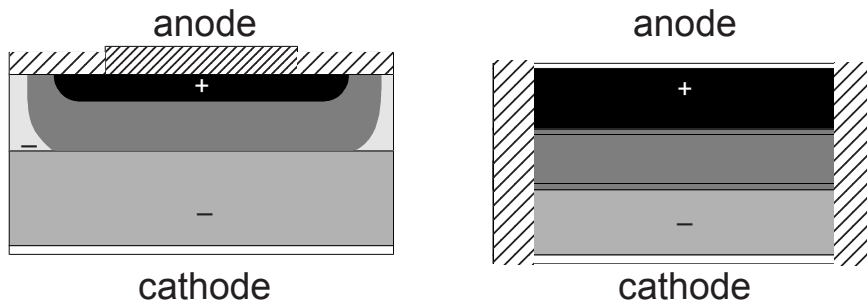
Reverse Breakdown Voltage (continued)

Rectifiers are generally subjected to a peak inverse voltage (PIV) test to identify their breakdown characteristics. This test is performed by applying 60-hertz half-wave reverse voltage at a sufficient amplitude to initiate breakdown. During the test, the reverse current is usually limited to 50 micro-amps. The resulting waveform is observed on an oscilloscope to determine the sharpness of the "knee" at the point of breakdown. Both planar and deep-diffusion processes yield controlled avalanches under PIV test conditions.

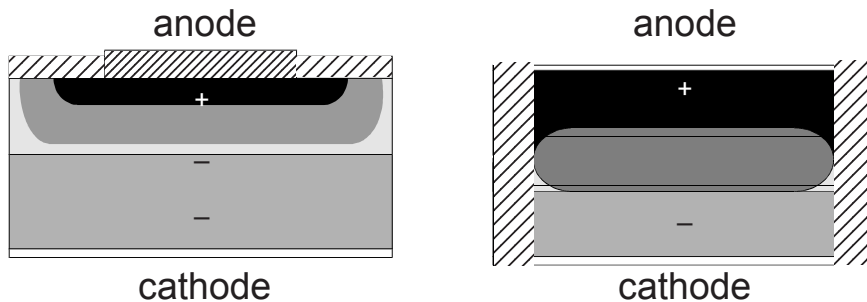
FIGURE 3

Reverse breakdown mechanisms for typical planar (left) and deep-diffused (right) diode junctions

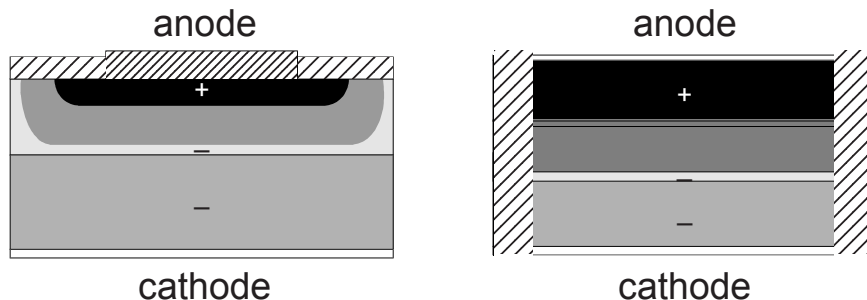
Punch through: *depletion region extends into low-resistivity area; surface strength > reverse voltage*



Avalanche: *depletion region strength > surface strength*



Zener: *N region does not sustain reverse voltage depletion region into N+*



Appendix A: High Voltage Rectifiers

Reverse Leakage

Reverse current (I_R) flows through the diode junction when reverse voltage is applied.

Factors Influencing the Amplitude of the Reverse Current Include:

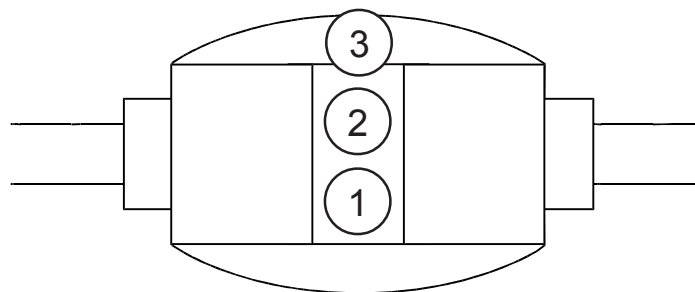
- a) thickness of the silicon
- b) amplitude of the reverse voltage
- c) junction temperature
- d) cross-sectional area of the junction
- e) exposure of the junction to light
- f) dopants used
- g) amount of radiation impinging on the junction

A common approximation is to assume that I_R doubles every 10°C . However, the actual value of the reverse current is the sum of three distinct current flows:

- 1) current due to diffusion
- 2) current due to surface leakage
- 3) current due to charge generation.

FIGURE 4

leakage current paths



High-voltage junctions differ from their low-voltage counterparts in that, at room temperature, the dominant leakage path is usually along the surface. Current, due to junction capacitance, is much lower in amplitude. For this reason, it is important to pay careful attention to the leakage source.

Appendix A: High Voltage Rectifiers

Reverse Leakage (continued)

For example, it is common to match the reverse current measurements of diodes connected in a string at 25°C. The string is then subjected to elevated temperatures. In such a scenario, it is probable that, at even slightly elevated temperatures, the reverse current flowing through the diodes would change significantly, resulting in a severe mismatch. This, in turn, would result in an over-voltage condition on some of the diodes.

To appreciate how this can happen, consider a situation in which two diodes exhibit exactly the same reverse current at 25°C.

Example:

	$T_A = +25^\circ\text{C}$	$T_A = +100^\circ\text{C}$
Diode 1	I_R (diffusion) = 10nA + I_R (surface) = 500nA <hr/> I_R (total) = 510nA	I_R (diffusion) = 15μA + I_R (surface) = 500nA <hr/> I_R (total) = 15.5μA
Diode 2	I_R (diffusion) = 500nA + I_R (surface) = 10nA <hr/> I_R (total) = 510nA	I_R (diffusion) = 75μA + I_R (surface) = 10nA <hr/> I_R (total) = 75.1μA

Thus a pair of diodes, which were perfectly matched at a temperature of 25°C, would be terribly mismatched at higher temperatures.

Forward Voltage:

V_F varies with:

- resistivity
- thickness of silicon
- level of dopant concentration
- type of dopant
- temperature
- current density

Forward drop is not usually as important an issue, in a high voltage rectifier, as it is in low-voltage applications. Consider, for example, a 1000-watt, 5-volt power

Appendix A: High Voltage Rectifiers

Reverse Leakage (continued)

supply. If its rectifiers exhibit a 0.7-volt forward drop, the power loss, with 20 amps flowing, would be 140 watts. That is, 14 percent of the power being handled. In contrast, the rectifier's forward drop, in a typical 1000-watt, 1000-volt supply, ranges between 1 and 1.5 volts. At full output, the current is 1 amp. With a 1.5-volt forward drop, this translates to a 1.5-watt power loss. This represents less than two-tenths of one percent of the power being passed through the rectifier.

Reverse Recovery Time:

- T_{RR} varies with:
- a) resistivity
 - b) dopant concentration
 - c) type of dopant
 - d) junction width
 - e) forward current
 - f) temperature
 - g) change in reverse current with time (di/dt)

In applications, these factors cause high voltage junctions to exhibit slower recovery times than similarly doped low voltage junctions. As a result, high-voltage junctions typically contain considerably higher concentrations of dopants, like platinum or gold, than their similar-speed, low-voltage junction counterparts. The higher dopant concentrations cause higher forward voltage drops and reverse leakage currents.

Appendix A: High Voltage Rectifiers

Creating High-Voltage Rectifiers

There are three differing approaches to creating high-voltage rectifiers. Two of these involve connecting a number of low-voltage, single-junction diodes in series. The simplest series, called a high-voltage stick, consists of tying the required number of diodes end-to-end.

This connection method requires consideration of such factors as voltage sharing, junction temperature, and matching reverse-recovery characteristics. To account for these factors, compensation networks of resistor/capacitor strings are frequently employed. The resulting network, called an R/C-compensated diode string, is usually employed in applications exceeding 30 watts of power.

At lower power levels, such as those encountered in CRT power supplies, multi-junction diodes are used. Deep-diffused junctions are ideal for high-voltage, multi-junction designs. The greatest advantage of the multi-junction process is the capability of stacking diodes during the wafer stage. This allows high-temperature bonding, reducing metallization to almost zero. In addition, fabricating all the diode junctions on the same wafer provides a simple method of matching junction characteristics.

Multi-Junction Reverse Recovery Time

Deep-diffused, multi-junction diodes ideally address the problem of mismatched reverse recovery times between individual diodes. The question is, how does one prevent the faster diode from reacting to the combined reverse voltage while the slower diodes are recovering? As stated earlier, reverse recovery time varies with temperature, resistivity, and dopant concentrations. The concentric use of matched wafers ensures closely matched dice, which, with temperature, track much better than discrete diodes. Also, each die can survive, while operating in the reverse avalanche mode, in the event that one chip recovers more quickly than another.

The worst-case temperature of the center junction is often perceived as an uncontrollable problem, when it is, in fact, controlled through thermal management.

Appendix A: High Voltage Rectifiers

Multi-Junction Reverse Recovery Time (continued)

Silicon is a very good thermal conductor, comparing favorably with some aluminum alloys. As a result, it provides an efficient thermal path, through the multi-junction stack, to the leads.

An important factor in any high-voltage application is corona. A partial discharge resulting from air ionization in a voltage-stressed gap, the presence of corona destroys insulation over time. It is particularly destructive in trapped-air voids near high-voltage sources. As the multi-junction, deep-diffused diode is cylindrical and free of voids, it addresses the corona issue geometrically. Additionally, the elimination of unnecessary air traps; through encapsulation in a dielectric material, and the use of multi-junction diodes; often leads to fewer corona problems in potted assemblies.

Conclusion

High-voltage rectification presents unique challenges to the designer. Careful examination of the application requirements is essential when selecting the best solution for size, cost and reliability. Diode parameters are interdependent and the decision of whether to employ high or low voltage diodes require a completely different thought process.

Stray parameters become major influences with voltage. Diodes become more temperature-dependent and mismatches increase in significance. As a result of these factors, deep-diffused, multi-junction diodes offer solutions to many high-voltage rectification problems.