

# APPENDIX B

## Diode Thermal Analysis

Controlling junction temperature is key to reliable semiconductor package design. High voltage diodes present unique junction temperature problems which must be addressed. In high voltage diodes, heat is generated primarily by:

- 1) Forward Voltage
- 2) Reverse Leakage Current
- 3) Reverse Recovery Losses

Each of these factors change differently and must be considered carefully over the intended operating range. The following examples depict the typical relative change in heat sources:

### Diode Losses vs. Temperature:

Diode= 1N6515  
 $T_{RR}$ = 70ns  
PIV= 3000V  
 $V_F$ = 4.0V @ 0.5A

### Circuit Conditions:

Operating Frequency = 50kHz  
Voltage Rise Time = 100ns  
Average Rectified Current = 0.5A per diode  
Reverse Voltage = 2000V Peak

T <sub>J</sub> = +25°C Heat Source		T <sub>J</sub> = +75°C Heat Source		T <sub>J</sub> = +125°C Heat Source	
V <sub>F</sub>	2.000 watts	V <sub>F</sub>	1.850 watts	V <sub>F</sub>	1.600 watts
I <sub>R</sub>	0.002 watts	I <sub>R</sub>	0.030 watts	I <sub>R</sub>	0.080 watts
T <sub>RR</sub>	<u>0.100 watts</u>	T <sub>RR</sub>	<u>0.250 watts</u>	T <sub>RR</sub>	<u>2.500 watts</u>
Total	2.102 watts	Total	2.130 watts	Total	4.180 watts

# ***Appendix B: Diode Thermal Analysis***

## ***Controlling Junction Temperature***

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In the previous example, the junction temperature would exceed +150°C, if the package thermal impedance exceeds 6.25°C/watt. Thus, total heat source consideration is necessary. The deceptive difference, in high voltage application recovery losses, is primarily a result of the high voltage bias, as applied while the diode is recovering from forward bias to a blocking mode. The problem presented can be addressed by:

- a) decreasing the forward voltage
- b) decreasing the reverse recovery losses
- c) improving the thermal impedance
- d) operating over a reduced temperature range

Both forward voltage and reverse recovery losses are dependent on the diode used in the circuit, as well as the circuit characteristics. In many cases, there are trade-offs to any change made in diode characteristics. For instance, decreasing the reverse recovery time in a diode will generally cause its forward voltage to increase. However, reducing a diode's reverse blocking voltage in order to facilitate a reduction in its forward voltage may increase the risk of exceeding the voltage rating on the part.

Once a diode has been selected for an application, it is necessary to optimize the thermal impedance of the diode package. Rectifier thermal impedance is the resistance against heat energy movement, from the rectifier junction to a heat sink or heat dissipation reservoir. The thermal path for the rectifier will vary depending on the part's packaging configuration. The remainder of Appendix B will list some typical rectifier packaging schemes to address these issues.

## ***Reverse Recovery Power Loss Measurement***

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In high voltage, high frequency diode applications, reverse recovery losses can significantly contribute to the power dissipated in the diodes. Reverse recovery losses occur during the transition from forward current to reverse voltage. When reverse voltage is applied to a diode, it will conduct in the reverse direction for a short time (the reverse recovery time). While the diode is conducting in the reverse direction, the power dissipated is equal to the reverse recovery

# Appendix B: Diode Thermal Analysis

## Reverse Recovery Power Loss Measurement (continued)

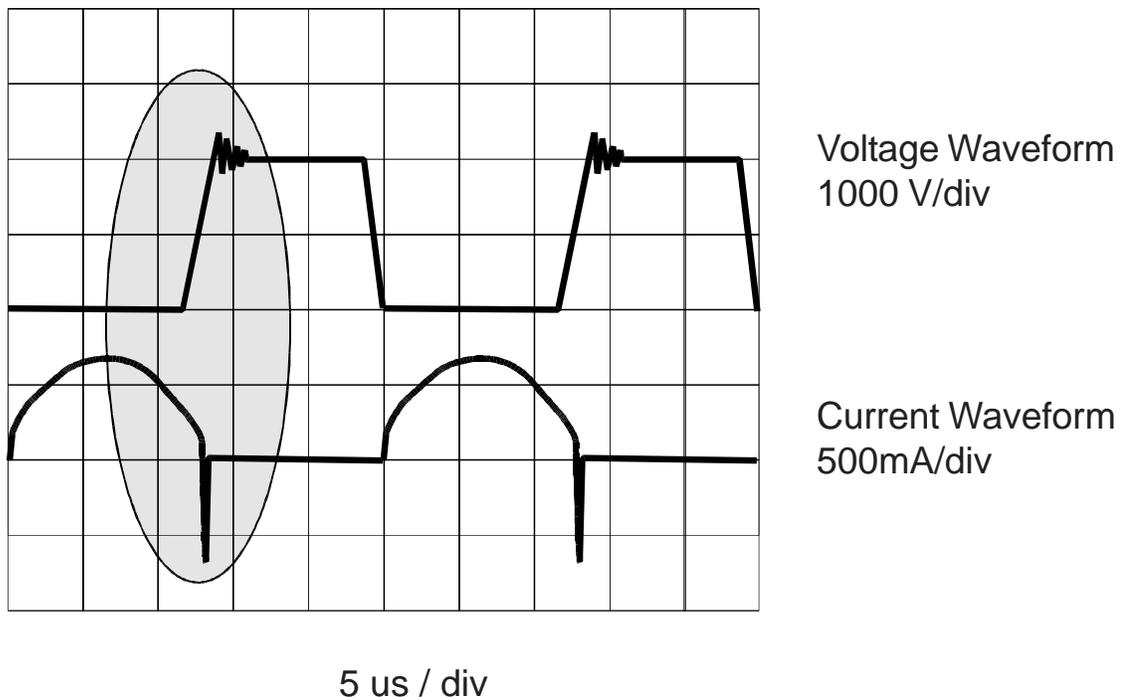
current multiplied by the reverse voltage.

Unfortunately, it is not possible to determine the reverse recovery losses for a diode in a circuit without actually testing the circuit. While the reverse recovery time rating of a diode gives a relative indication of its speed, the rating is based on controlled laboratory conditions. In an actual circuit, the conditions which affect reverse recovery time, such as forward operating current,  $dv/dt$  of the voltage waveform, reverse voltage, and temperature, can vary considerably.

The best way to evaluate reverse recovery losses is to monitor diode current and reverse voltage waveforms while the diode is operating in the circuit. Figure 1 shows waveforms for a simulated circuit. The voltage waveform shows a peak reverse voltage of 2400V and a nominal reverse voltage of 2000V. The current waveform shows a peak forward current of 600mA and a peak reverse recovery current of 600mA. The operating frequency is 40kHz.

**FIGURE 1**

*Simulated Current Waveforms*

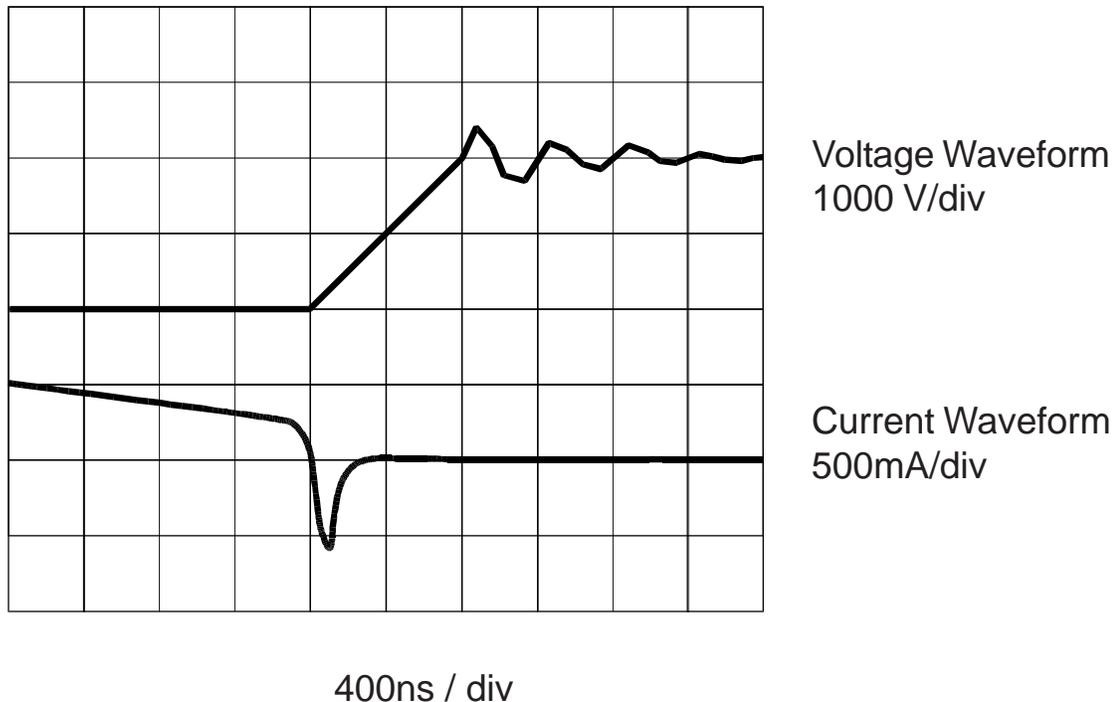


# Appendix B: Diode Thermal Analysis

## Reverse Recovery Power Loss Management (continued)

**FIGURE 2**

Area of the waveform circled in Figure 1 - expanded in time to show reverse recovery current in detail



Theoretically, reverse recovery power losses can be calculated by integrating reverse recovery current times reverse voltage over the time region in which reverse recovery time is a factor and then multiplying the result by the operating frequency. It is not practical to integrate the waveforms, though. An estimate of reverse recovery losses can be found by multiplying reverse recovery time by reverse voltage, multiplying that result by the measured reverse recovery time, and then multiplying by operating frequency. For Figure 2:

$$P_{Trr} = 0.5 \times 0.6A \times 250V \times 200ns \times 40kHz = 0.6 \text{ watts}$$

The factor of 0.5 was used because the reverse recovery current waveform is triangular. A peak recovery current of 0.6A was used, along with an average reverse voltage during recovery of 250 V. A recovery time of 200ns was used in the calculation.

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## ***Reverse Recovery Power Loss Measurement (continued)***

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Factors that influence reverse recovery losses include the diode recovery time, operating frequency,  $dv/dt$  of the voltage waveform, and operating temperature. The faster the recovery time of the diode, the lower the reverse recovery losses will be. Higher operating frequencies and a faster  $dv/dt$  will cause higher reverse recovery losses.

The reverse recovery time of a diode is dependent on its junction temperature. The reverse recovery time of a 70ns diode will increase by approximately two and a half times from 25°C to 100°C, so that its reverse recovery losses will also increase by at least two and a half times at 100°C. It is important, when evaluating reverse recovery losses, to take measurements at the maximum operating temperature of the circuit. If reverse recovery losses are too high, the diodes can go into a thermal runaway condition and can fail catastrophically.

## ***Diode Mounted on a PC Board***

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The two major thermal paths for a mounted diode are through the diode leads to the PC board and through the diode body and leads to the surrounding air or other medium.

The thermal resistances of VMI diodes are given for several lead lengths in the diode data sheets. The diode's temperature rise over the temperature of its mounting location can be determined by multiplying the diode's thermal resistance through its leads by the power dissipated in the diode. The temperature or thermal impedance of the diode will have a major effect on the junction temperature of the diode. This is because any mounting location temperature rise will be added to temperature rise of the diode itself.

The medium surrounding the diode can reduce the diode's junction temperature by adding a parallel thermal path. If the surrounding medium is air, its cooling effect will depend largely on its temperature and on its movement. Forced air can significantly reduce a diode's junction temperature. However, still air, such as would be present in an enclosed box, may have very little cooling effect on the diode junction.

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## ***Diode Mounted on a PC Board (continued)***

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If the surrounding medium is a potting material, its cooling effect on the diode junction will depend on the temperature and thermal conductivity of the material, the power dissipation of any neighbor components, and on the thermal path through the material to any outside surface or heat sink.

## ***Diode Operating in Oil***

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The heat generated by a diode operating in oil will be largely dissipated to the oil through the diode leads. A small percentage of the heat will also be dissipated to the oil through the diode body. Thus, typically oil operation is an excellent way to remove heat from the diode. As such, it is generally possible to drive the diode at increased forward current levels (up to twice the VMI published ratings), when operating in an oil environment. For oil operation, use the zero lead length power derating curve.

## ***Diode Encapsulated in a Potting Material***

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The heat generated, in a diode encapsulated in potting material, must be dissipated through the material to an outside surface or heat sink. The thermal conductivity of the potting material used can be critical. Silicon potting materials typically have a lower thermal conductivity than rigid epoxies. However, there are other characteristics of a silicon potting material that may make it more desirable.

Other potting materials, such as glass or alumina, can be added to the potting material to increase its thermal conductivity. Thermal conductivities for various materials are given in Table 1.

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## Reverse Recovery Power Loss Measurement

**TABLE 1**

*Materials Commonly Used in Potted Rectifier Assemblies*

Material	Thermal Conductivity W/in°C	Linear Thermal Expansion ppm/°C
Silver 99.9%	10.500	23.5
Copper OFC	10.000	17.0
Tungsten	4.250	4.5
Aluminum 6061T6	3.960	23.5
Silicon (pure)	3.700	3.0
Molybdenum	3.400	5.1
Beryllia 95%	3.000	7.5
Tin	1.600	23.5
Solder 63Sn-37Pb	1.270	25.0
Alumina 96%	.890	6.4
Lead	.880	29.0
Solder 96.5Sn-3.5Ag	.840	30.0
Epoxy Stycast 2850KT	.106	28.8
Epoxy Stycast 2850MT	.075	29.2
PC Board G-10 (unclad)	.052	21.1
Epoxy Stycast 2850FT	.036	29.0
RTV 1200 HTC	.036	80.0
Glass	.031	3.3
Epoxy Scotchcast 281	.013	150.0
RTV 3120	.008	350.0
RTV 615	.005	270.0

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## Diode Encapsulated in a Potting Material

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The mechanical configuration of the diode in the package will also have an effect on thermal impedance. Thermal impedance may be calculated with the following formula:

$$\theta_{jc} = \frac{L}{\sigma \times A}$$

Where " $\theta_{jc}$ " is the thermal impedance from the diode to the heat sink or outside surface, "A" is the area of the thermal path, " $\sigma$ " is the thermal conductivity as given in Table 1, and "L" is the length of the thermal path from the diode to the heat sink.

In many practical cases, the area or length of a thermal path may be difficult to determine exactly. Also, in some cases there are several thermal paths that must be considered in parallel. The above formula should be used to arrive at a close approximation of the thermal impedance of the package. Calculation of thermal impedance should be followed by an actual test of the diode junction temperature in the package.

As the above formula indicates, thermal impedance is inversely proportional to the thermal area. Thus, thermal impedance and junction temperature can be reduced by increasing the thermal area. One way to increase the thermal area is to add metal heat dissipators to the diode leads. Also, the shorter the distance between the diode and the heat sink (or outside surface), the lower the thermal impedance.

In high voltage applications, the minimum distance required between the diode and outside surfaces will depend on the package voltage stress and on the dielectric strength of the potting material. See figure 4 for a typical potted rectifier configuration.

### Thermal Impedance Formula (for conduction):

$$Q = \frac{\sigma \times A \times T}{L} \quad \text{or} \quad \theta = \frac{L}{\sigma \times A}$$

Q=Heat conducted (watts)  
A=Cross-section area of heat path (in<sup>2</sup>)  
 $\sigma$ =Thermal conductivity (watts/in<sup>2</sup>°C)  
L=Length of heat path (in)  
T=Temperature difference (T1-T2)  
 $\theta$ =Thermal resistance (°C/watt)

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## Surface Mount Diode

In a surface mount application, the diode is mounted to a ceramic substrate or PC board. The heat generated in the diode junction flows through the end tabs directly to the substrate or PC board. The diode's thermal impedance (given in the diode data sheet) is added to the substrate or PC board thermal resistance to obtain the total thermal impedance of the package. See figure 5, for a typical surface mount configuration.

### Typical Diode Configurations

#### Axial Lead Diode, PCB Mounted

Diode = 1N5550  
L = .375  
 $\theta_{J-PCB} = 20^{\circ}\text{C/Watt}$

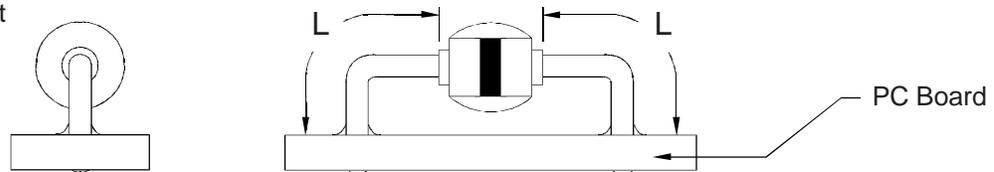


FIGURE 3

#### Axial Lead Diode with Copper Heat Sink

Isolation Voltage = 15kV  
 $\theta_{J-MS} = 12^{\circ}\text{C/Watt}$

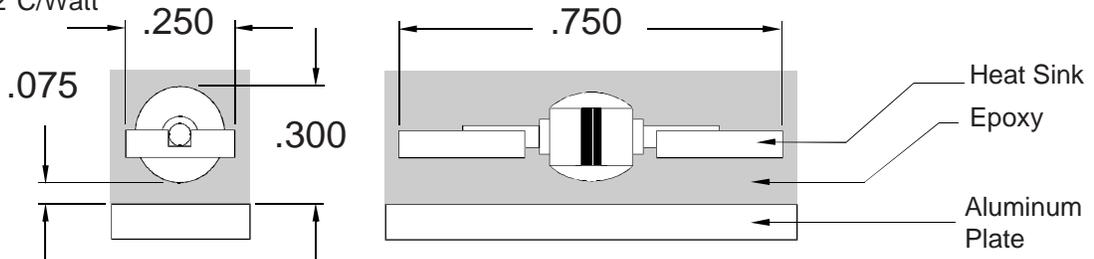


FIGURE 4

#### Surface Mount

Isolation Voltage = 15kV  
 $\theta_{J-MS} = 7^{\circ}\text{C/Watt}$

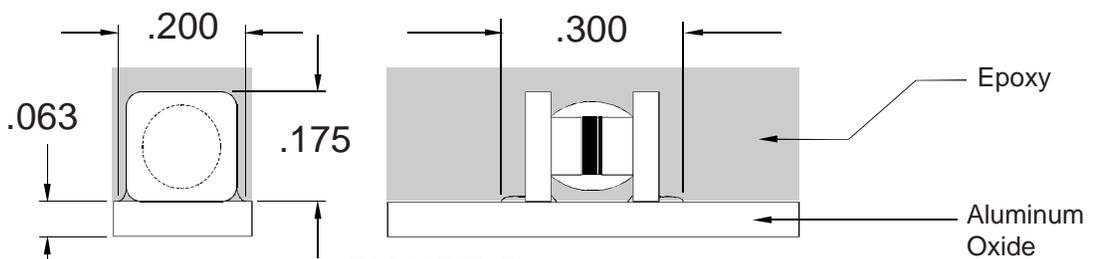


FIGURE 5