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Transient Peak Power Effect on Diodes

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Generally, it is common knowledge that when excessive power is dissipated within a diode junction, its junction temperature (T_J) rises. As T_J rises beyond the critical limit, the diode would suffer irreversible damage. Although all diodes are specified with maximum operating temperature (T_J), maximum thermal resistance (Θ), and maximum power dissipation (P_D), some diodes still fail during operation despite the appearance that they operate within the maximum ratings. During the transient period, abnormally high current and voltage spikes may be present, thus resulting in high peak power (Ppk) that the diodes must be capable of withstanding. From the average standpoint, the operating average T_J may be within the maximum rating. Presented here is a discussion of thermal stability from the transient peak power standpoint.

Transient Examples

Practically all electrical systems experience transient periods immediately after input power is turned on or off. During this period, high current and voltage spikes are present, thus resulting in peak power and thermal stress on the electrical components. Semiconductors such as transistors and diodes must be able to withstand such stress, otherwise their characteristics would deteriorate and the device would eventually fail.

One popular application for diodes is in DC power supplies wherein the diodes are used to rectify the line input voltage waveform. As soon as the line power is turned on, the filter capacitors at the rectifier output instantaneously act as a short circuit. Hence, the initial surge current would be extremely high, resulting in severe thermal stress on the diodes. Even after the DC power reaches steady state, surge current still may occur when the load is suddenly changed to a low impedance condition. One good example is that within any electronic system, the electronic models such as PC boards are composed of many IC chips and active components. It is standard practice that filter capacitors are used at the DC bias inputs to the IC chips and other active components. Even though the value of the capacitors, typically at 0.01 µF, may be small, however when hundreds or perhaps thousands of these small capacitors are used, it becomes significant. As DC power is applied to these modules, surge current would result because all the filter capacitors act instantaneously as short circuits.

The turn-off transient usually involves inductive loads as in solenoid drivers, horizontal deflection and ignition systems. During turn-off, high voltage spikes develop because of inductive kick-back. To absorb the turn-off transient, Zener diodes usually are used to clamp the spikes of regular diodes used as dampers. There are many other applications wherein surge currents are present with notable examples in light control and medical equipment. In light control systems, the lamp impedance is always low before warming up so initially, the current is always high. Whereas in medical equipment, such as a cardiac defibrillator, its output is a wave form lasting a few milliseconds with current over 100 amps and voltage typically at several thousand volts.

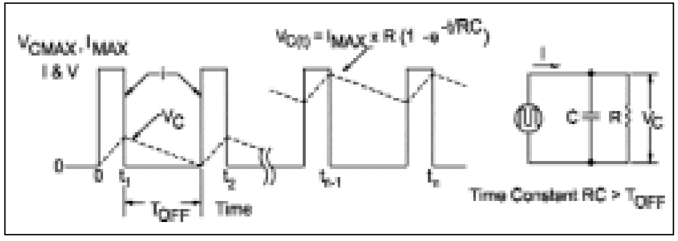


Figure 1. Characteristic of RC CKT vs. Time.

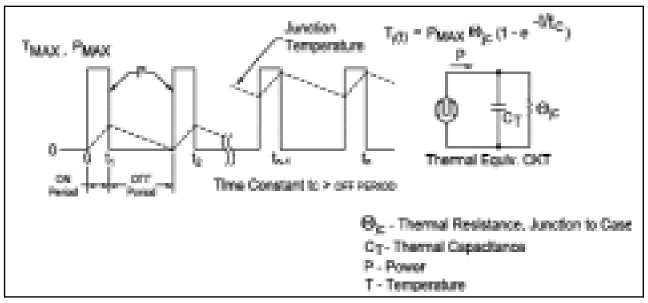


Figure 2. Characteristics of Thermal CKT vs. Time.

Thermal Response of Diode Junction

When a diode is in operation, heat is generated within its junction. The rate of heat generation is a function of Power (P). Heat is transmitted from the junction to the case, case to heat sink, and then heat sink to ambient. Or if no heat sink is used, heat is dissipated from case to ambient. The junction temperature (T_J) will rise until equilibrium is reached when the rate of heat generation is equal to the rate of heat dissipation. How fast and how high T_J rises depends on the conducting medium.

Generally, the characteristics of the conducting medium are defined in terms of thermal resistance (Θ). Using an electrical analogy where the temperature gradient is equivalent to the voltage gradient, power to current, and Θ to resistance, the junction temperature rise ΔT_J relative to the case would be the product of the power (P) and thermal resistance junction to case (Θjc) ($\Delta T_J = P \times \Theta jc$). If relative to ambient, $\Delta T_J = P \times \Theta ja$.

There are times when a diode would fail during operation even though its T_J is seemingly below the maximum rating based on the DC or average power dissipation. It is very possible that some time during operation when a transient surge occurs, the excess heat associated with the surge may not dissipate fast enough from the junction to the case, thus causing T_J to rise beyond the critical limit. Another possible scenario would be if the diode current is in the form of repetitive pulses. There is a

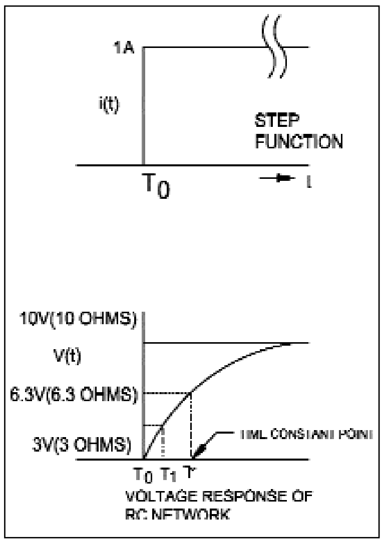
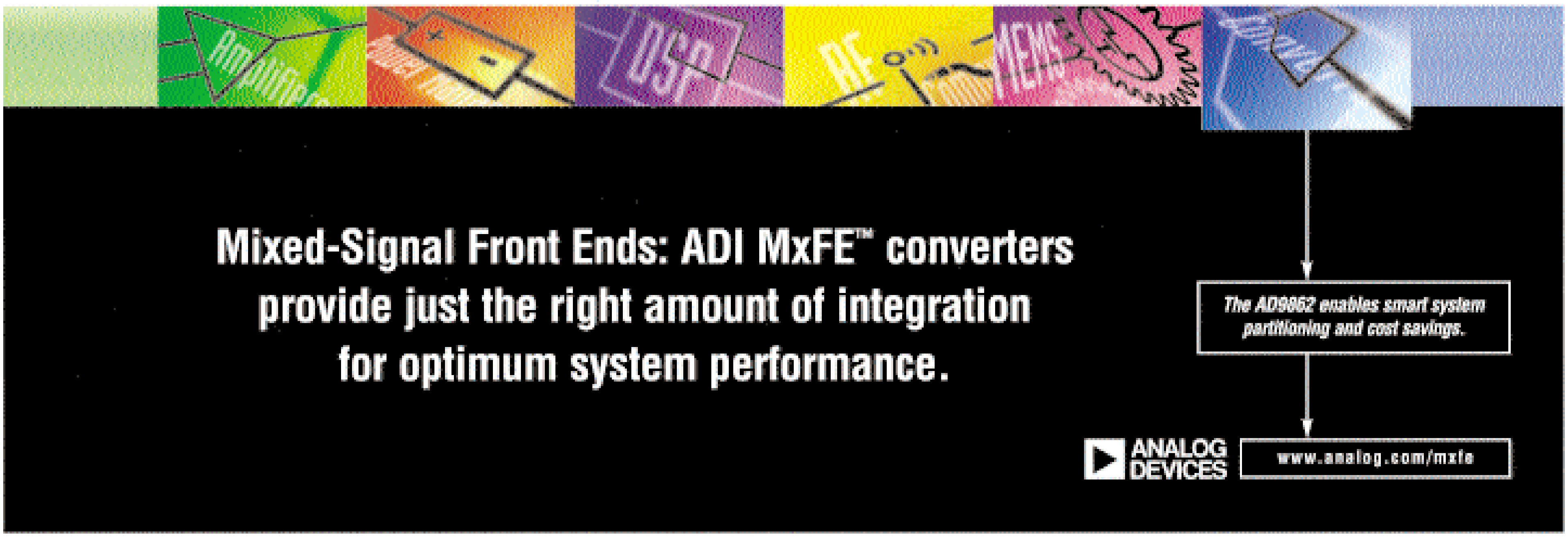


Figure 3. Characteristics of Thermal CKT vs. Time.



significant difference when ΔT_J is analyzed from the average current standpoint as opposed to the current in pulse form.

Transient Peak Power Analysis

As an illustration for transient peak power (Ppk) analysis, Figure 1 illustrates an RC network fed by a current pulse source. Assuming the current max. (Imax) is 10 amps, duty cycle 20 percent, resistance 10 Ω and the capacitor value is such that the RC time constant is greater than the off-pulse period. from the average point of view, the average current is 2 amps. However, the voltage across the resistor is a function of time, and eventually, when the steady state is reached, it may be near 100 V, but not 20 V.

An analogy may be drawn in analyzing the temperature and power relationship on semiconductor diodes. Figure 2 shows a thermal equivalent circuit where power is equivalent to current, temperature to voltage. Assuming the power pulse max. (Pmax) is 100 W, duty cycle 20 percent and a junction to case thermal resistance (Θjc) 2°C/W, from the average point of view, the junction temperature rise ΔT_J is only 40°C (20W × 2°C/W). However, T_J would rise more than 40°C if the thermal time constant is larger than the pulse-off period.

Transient Peak Power/Current Determination

The same basic $T_J = P \times \Theta$ governing the temperature gradient, power and thermal resistance may be applied in determining the maximum allowable peak power Ppk for a given maximum T_J rating. The only difference here is that P is Ppk and Θ is Θjc (t), the effective transient thermal resistance which is a function of time.

Θjc (t) is analogous to the transient electrical resistance, if, as shown in Figure 1, the current pulse is a step function with an amplitude of 1 amp, and the resistor value 10 Ω. The RC network's response to the step function is shown on Figure 3. As shown on Figure 3, the network's voltage at the steady state is 10 V, and at the RC time constant point the voltage is 6.3 V. At another time instant, less than the time constant, the voltage would be less, based on the formula

$$V(t) = \text{Imax}\, R\, (1- e^{-t/RC}).$$

If the transient voltage response V(t) is divided by Imax, it becomes the transient resistance $R(t) = R(1-e^{-t/RC})$ and R(t) becomes 10 Ω when the steady condition is reached. Before the steady state, R(t) is less than 10 Ω because of the transient effect caused by the capacitor C. Hence, at the time constant point, R(t) is 6.3 Ω, and at some earlier point T_1, it may be 3 Ω. Once the transient resistance R(t) of an RC network is known, the transient voltage may be calculated or predicted for any current pulse with a known pulse width PW. As an example, referring to Figure 3, at T_1, R(t) = 3 Ω and for a current pulse with PW = T_1, the voltage V(t) is Imax × 3 Ω. If the current pulse amplitude is 10 amps, then V(t) is 30 V at T_1. Using the above analogy, the transient thermal response of a diode junction may be analyzed or predicted by applying the basic formula:

$$T_J = P \times \Theta jc\ (t) + T_C \text{ or } \Delta T_J = P \times \Theta jc\ (t).$$

From the known Θjc (t), one can determine the maximum tolerable peak power Ppk and peak current Ipk for a given transient pulse width and reference case temperature, or one can determine the peak operating T_J for given peak power or current surge.

Single Pulse Ppk/Ipk Determination: Regular Diode

Rewriting the above formula, $P=(T_J-T_C) / \Theta jc\ (t)$, to find the maximum tolerable peak power Ppk, it is just a matter of using this formula once the maximum tolerable T_J, the reference case temperature T_C and the effective thermal resistance are known. For illustration, the CMR1U-10M diode is used. Shown in Figure 4 is the device's effective thermal resistance as a function of time. Using 200°C as the maximum T_J and T_C of 50°C, the peak powers Ppk's for various pulse width PW are calculated on the following Table 1:

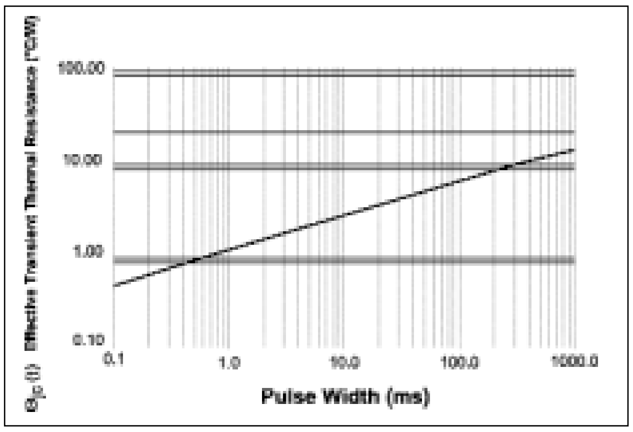


Figure 4. Thermal Response of CMR1U-10M.

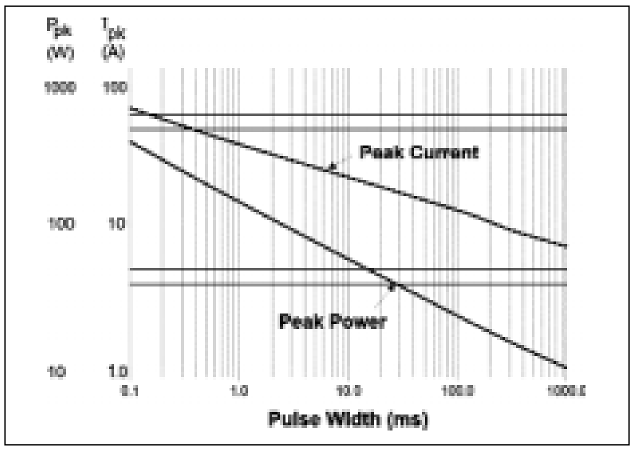


Figure 5. Peak Power vs. Pulse Width of CMR1U-10M @ T_C = 50°C

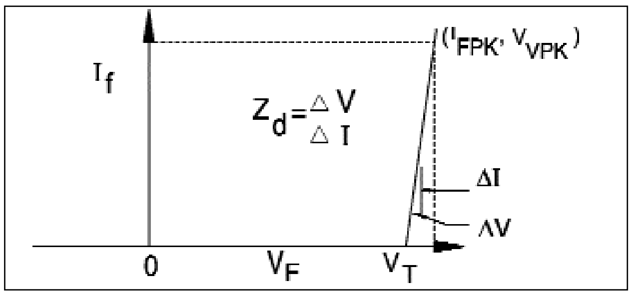


Figure 6.

PW (mS)	Θjc (t) (C/W)	Ppk (W)
0.1	0.45	333
0.3	0.67	224
1.0	1.10	136
3.0	1.70	88
8.0	2.2	68
20	3.2	47
70	5.5	27
100	6.0	25
300	9.0	17
1000	13	11.5

Table 1.
$T_J$max = 200°C, T_C = 50°C

Figure 5 is a plot of the peak power vs. pulse width. From this graph, one can determine the maximum tolerable Ppk at T_C = 50°C for various pulse widths.

To determine the peak forward current I_{fpk}, the formula $Ppk = I_{fpk} \times V_{fpk}$ may be used.

As shown on Figure 6, $V_{fpk} = Vt + I_{fpk}\, Zd$, where Vt is the diode threshold voltage and Zd is the dynamic impedance. Therefore,

$$Ppk = I_{fpk}\,(V_T + Ipk\ Zd), \text{ or } Ppk = I_{fpk}\, V_T + I^2_{fpk}\, Zd.$$

The forward peak current of the corresponding Ppk may be determined graphically or analytically via the root of the quadratic equation. The derived peak current vs. transient pulse width PW is plotted and superimposed on Figure 5.

Zener/TVS Diodes

The procedure in determining the peak tolerable power and current for Zener/TVS Diodes is the same as regular diodes except that the forward threshold

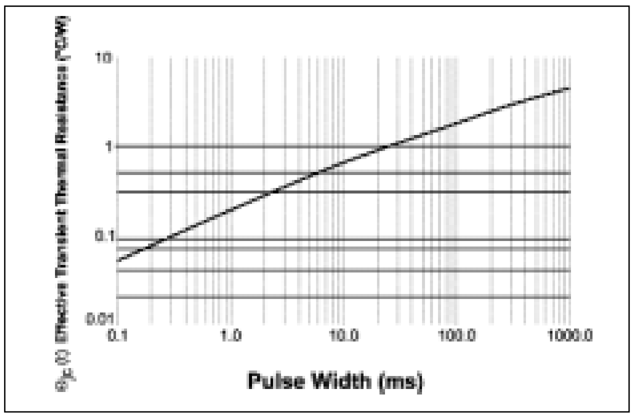


Figure 7. Thermal Response of CMZ5340B

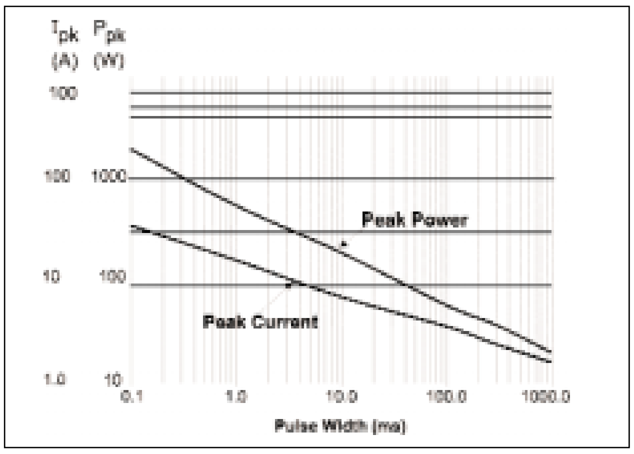


Figure 8. Peak Power/ Peak Current vs. Pulse Width of CMZ5349B at T_C = 50°C.

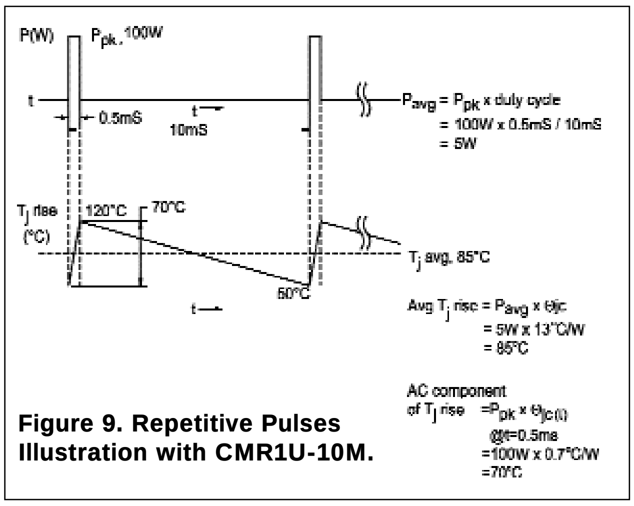


Figure 9. Repetitive Pulses Illustration with CMR1U-10M.

PW (mS)	Θjc (t) (C/W)	Ppk (W)	Ipk (A)
0.1	0.051	1960	35
0.3	0.11	909	23
1.0	1.19	526	16
3.0	0.26	385	11
8.0	0.59	169	7.7
20	0.81	123	5.4
70	1.50	67	3.9
100	1.80	56	3.6
300	2.80	36	2.4
1000	4.50	22	1.6

Table 2
$T_J$max = 150°C, T_C = 50°C.

voltage V_T is replaced by V_Z, the Zener or Transient Voltage Suppressor (TVS) clamping voltage. Hence, Ppk = Ipk V_Z + I^2pk Zd. For illustration, the CMZ5349B Zener is used for Ppk and Ipk determination. Figure 7 shows the device's effective transient thermal resistance Θjc(t) VS transient pulse width PW. Using T_J max. at 150°C, reference case temperature T_C at 50°C, V_Z at 12.6 V, Zd at 1.25 Ω and Θjc(t) from Figure 7; the maximum Ppk, (T_J max - T_C)/Θjc (t) and the corresponding Ipk for various pulse width is calculated and presented in Table 2.

Figure 8 is a plot of Ppk and Ipk VS PW based on the above data. From this plot, the peak tolerable power or current at T_C of 50°C may be determined for various pulse widths.

Repetitive Pulse Ppk/Ipk Determination

When the peak power pulse is repetitive, the off period between pulses is an important factor to consider. If the off period P_{off} is long enough for the junction temperature T_J to recover to the equilibrium case temperature T_C before the start of the next pulse, it should be treated as a non-repetitive case. However, if P_{off} is not long enough for T_J to recover to the original equilibrium with the case reference temperature T_C, then the repetitive case for Ppk/Ipk analysis would be valid. Normally, the repetitive case applies if P_{off} is less than four time constants of the device.

One simple and practical way to analyze the repetitive pulse case is by considering that the repetitive peak power pulses consist of a DC or average component and a super-imposed AC component. Since the peak junction temperature is proportionally related to the peak power, the resultant T_J rise consists of a DC and also an AC component. Using the CMR1U-10M diode as an example, and assuming as shown in Figure 9 a pulse train with peak power at 100 W, pulse width PW at 0.5 ms, and period at 10 ms, the duty cycle is 5 percent, hence the Pavg is 5 W. Referring to Figure 4, the steady state thermal resistance is 13°C/W; hence the average T_J rise is 85°C. Also from Figure 4, the effective thermal resistance at 0.5 ms is 0.7°C/W and the AC component due to 100 W peak is 70°C. Therefore, as shown on Figure 9, one would expect T_J to move between 120°C and 50°C with an average at 85°C. If the case reference T_C is 25°C, the peak T_J would be 145°C.

From the above example and the simple formulas of Figure 9 relating Ppk, T_J rise, duty cycle, and effective transient thermal resistance, one can determine the maximum tolerable Ppk for any given T_J max. Once Ppk is determined, the corresponding Ipk may be readily determined using the same procedures shown on previous examples.

Summary

The conventional maximum junction temperature T_J and maximum power ratings are for DC or steady state operation. For transient peak power operation, the thermal response of the diode junction should be analyzed from the transient peak power standpoint using the effective transient thermal resistance. When the peak power pulses are repetitive, thermal response may be analyzed by considering that the power consists of two components, DC and AC.

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