

Application Note AN-949

Current Ratings of Power Semiconductors and Thermal Design

Table of Contents

	Page
1. What is a current rating?.....	2
2. Current ratings of power semiconductors	2
3. Continuous current ratings.....	3
4. Current ratings in switchmode operation	5
5. Junction temperature in pulsed conditions	6
Appendix: Determining the RMS value of common current waveforms	8

This application note described the methods commonly used to calculate peak junction temperature in a power circuit. It also explains the assumptions behind the current ratings of power semiconductors.

1. What is a current rating?

The current rating of an electrical device, be that a circuit breaker or a motor or a transformer, is the current at which the temperature within the device itself reaches a value that may impair its reliability or functionality. The manufacturer knows the temperature limits of the materials used in the device, but he does not know the temperature of the ambient where the device will be used. So he makes an assumption on ambient temperature. This has two important consequences:

- 1) Every current rating is associated with a temperature specified at one location (ambient, heatsink, case). A current rating is meaningless without its associated temperature.
- 2) The temperature at which the rating applies may or may not be related to actual operating conditions. If it is, the current rating can be used as an indication of the current capability of that device in real applications. If the device is rated at a temperature that is not encountered in a typical operating environment, e.g. 25°C, it does not provide useful information about the actual device capability in an application. It can only be used to compare the ratings of similar devices rated at the same temperature.

The ratings of electrical devices like motors and circuit breakers are dictated by various agreements and regulations. The ratings of many other devices, like transformers, resistors and semiconductors are specified in their data sheets. As a result, the user must verify that the device is capable of operating:

- a) at the maximum current encountered in the application
- b) at the maximum ambient temperature
- c) without exceeding the maximum temperature specified in the data sheet.

To verify these three elements, the user has to do a “thermal design”. This can be a simple undertaking or the result of a complex finite element analysis. [Application note AN-1057](#) goes through the most important aspects of thermal design.

At this point the astute reader realizes that, the moment he has done a thermal analysis, he has found the current rating for the specific device in his own application and does not need the rating provided by the manufacturer. The various ratings provided by the manufacturer are just pointers to convey the capability of the device and narrow down the selection process.

2. Current ratings for power semiconductors

Thermal design is particularly important for power semiconductors for two reasons:

- 1) They operate with very large current densities and with a steep temperature gradient between junction and ambient.

- 2) The thermal mass of the semiconductor is extremely small and it can go into a thermal runaway in a fraction of a millisecond.

For these reasons power semiconductors need to be heatsunk and it is the task of the designer to select the heatsink or other cooling method, i.e. to do the “thermal design”.

3. Continuous current ratings

A typical data sheet of a power semiconductor contains one or more “continuous current ratings”, frequently complemented by a graph, as the one shown in Figure 1. These are based on the following assumptions:

- 1) The power semiconductor is conducting a fixed amount of current (no switching losses)
- 2) The heat generated in the junction flows into an infinite sink
- 3) The temperatures of the heat source and of the case are constant. The temperature of the heat source (junction) is at its maximum value.

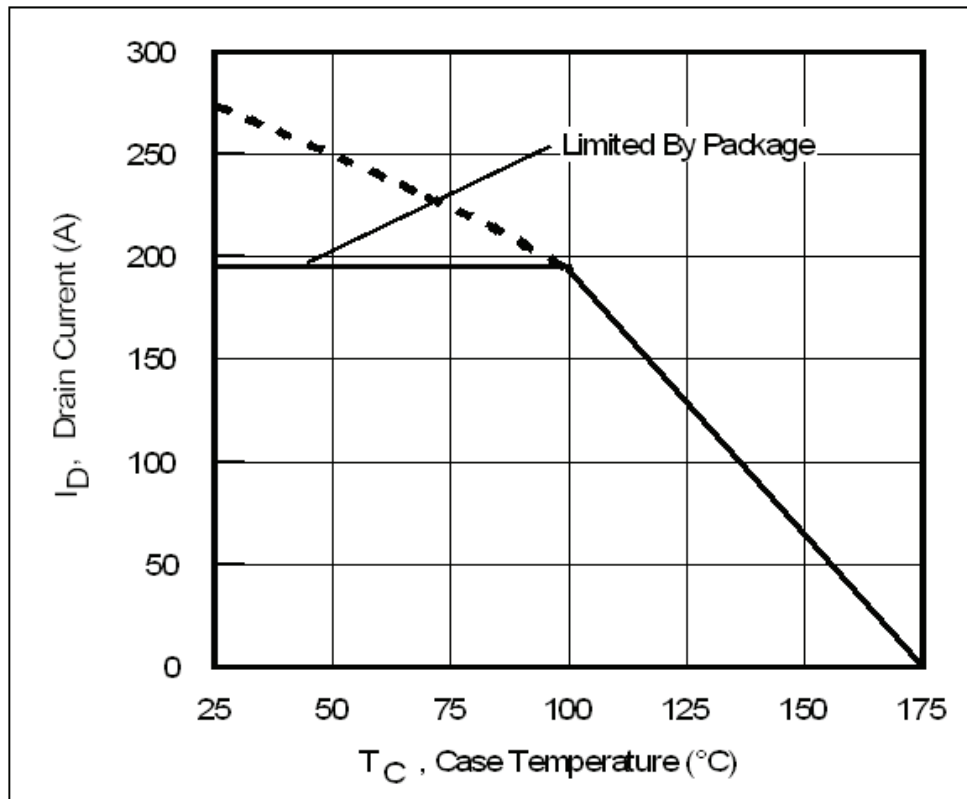


Figure 1. Continuous current rating as a function of the case temperature within the limitations imposed by the package of the device (IRLS3036PBF)

Under the above assumptions, the thermal equations can be reduced to the well known relationship:

$$\Delta T_{JC} = P_d \times R_{thJ-C}$$

Considering the device manufacturer does not know the thermal environment where its devices are going to be used, using the case temperature as a reference point is a convenient way of establishing a rating.

In a practical application, however, the entire thermal system needs to be taken into account and the equation above becomes the following:

$$T_J = T_A + (R_{thJ-C} + R_{thC-S} + R_{thS-A}) P_{AV}$$

where:

- T_J = junction temperature
- T_A = ambient temperature
- R_{thJ-C} = junction-to-case thermal resistance
- R_{thC-S} = case-to-sink thermal resistance
- R_{thS-A} = sink-to-ambient thermal resistance
- P_{AV} = average power dissipation

The continuous current rating for semiconductors is typically calculated from the equations above. The MOSFET is unique in one respect: it has a square relationship between current and power dissipation. Hence, the current rating can be calculated with a simple equation:

$$I_D = \sqrt{\frac{T_{JMAX} - T_C}{R_{DS(on)} R_{th(JC)}}}$$

where $R_{DS(on)}$ is the value of the on-resistance at rated T_{Jmax} . R_{thJC} is the maximum value of internal junction-to-case thermal resistance, and T_C is the case temperature. Other power devices have a non-linear relationship and their current rating must be determined with an iterative process.

In the vast majority of applications the case temperature of a power semiconductor is higher than 80°C. Thus, the usable continuous direct current of a power device is whatever is applicable to a case temperature between 80° and 110°C. This allows a sufficient differential between case and ambient temperature for the heat

dissipator to handle the heat transfer. The 25°C rating is a legacy of the first JEDEC standard for bipolar transistors and lingers on in modern-day data sheets.

Advances in the low-voltage MOSFET technology have reduced conduction losses to the point that the package has become the limiting factor in their continuous current rating. This is shown in Figure 1 and explained in [DT 93-4](#).

4. Current capability in switchmode operation

The continuous current rating discussed in the previous section is, however, of little direct use to the designer, other than as a benchmark, for the following reasons:

- 1) Power transistors are usually operated in switchmode, with duty cycles considerably less than 100%. What is of real interest to the designer is the current-carrying capability in the actual “switched” operating conditions.
- 2) When operated in switchmode, power transistors have switching losses. These have to be calculated and added to the conduction losses.
- 3) The selection of the power device may be dictated by surge requirements that override both, continuous current rating and current-carrying capability in switchmode.

As long as conditions 2 and 3 stated in Section 3 stay valid, we can use the basic thermal equation to calculate junction temperature. This assumes that we know power dissipation and the thermal resistance of the system.

The power dissipation is normally divided in two components: conduction and switching. Conduction losses in a power MOSFET can be calculated as $I_{\text{rms}}^2 \times R_{\text{DS(on)}}$. The RMS content of waveforms of different shape can be found in the Appendix. Switching losses can be calculated from the switching waveforms, from the gate charge or from analytical methods. The calculation of conduction and switching losses for IGBTs is more complex, as explained in [AN-990](#).

The power entered in the basic equation of Section 3 is the “average” power and the results are valid as long as the frequency of operation is high with respect to the thermal inertia of the system. As frequency increases, thermal mass of the junction irons out instantaneous temperature fluctuations and the junction responds more to average than to peak power dissipation. At frequencies above a few kHz and duty cycles above 20% or so, cycle-by-cycle temperature fluctuations become small, and peak junction temperature rise becomes equal to the average power dissipation multiplied by the DC junction-to-case thermal resistance, within one or two percent.

When the frequency is very low (tens of Hz) temperature ripple may have to be calculated. The transient thermal impedance curves discussed below show how to calculate the temperature ripple for operation at low frequency.

5. Junction temperature under pulsed conditions

Under pulsed conditions the three assumptions listed in Section 3 become invalid:

- 1) The device does not conduct current in a steady-state mode
- 2) The heat generated in the junction goes partly in the thermal mass of the system and partly in the ambient
- 3) The temperatures at the various points of the thermal system increase during the surge.

The proper way to calculate junction temperature is by taking into account the three-dimensional nature of heat flow, as shown in Figure 2. This is normally done with finite element analysis. Since the on-resistance is a function of temperature, power dissipation also increases with time and the proper electrical model for the power semiconductor has to be entered into the analysis.

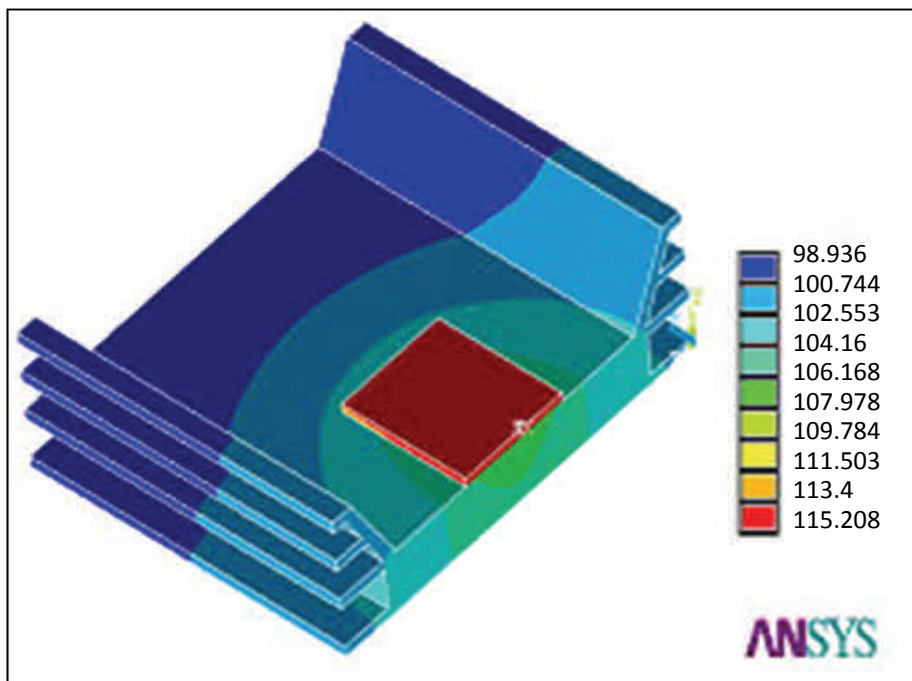


Figure 2. Since heat flows three-dimensionally the term “junction temperature” is an approximation. Different points in the junction and in the rest of the thermal system have different temperatures. An animated version of this figure can be viewed by clicking [here](#) (please note the file is 2MB).

In many applications an approximate value for junction temperature is sufficient. In this case there are two methods that can be used to achieve an approximate result, as explained below.

The Transient Thermal Impedance

An example of the Transient Thermal Impedance (or, more correctly, Thermal Response Curve) is shown in Figure 3 and can be found in virtually all data sheets.

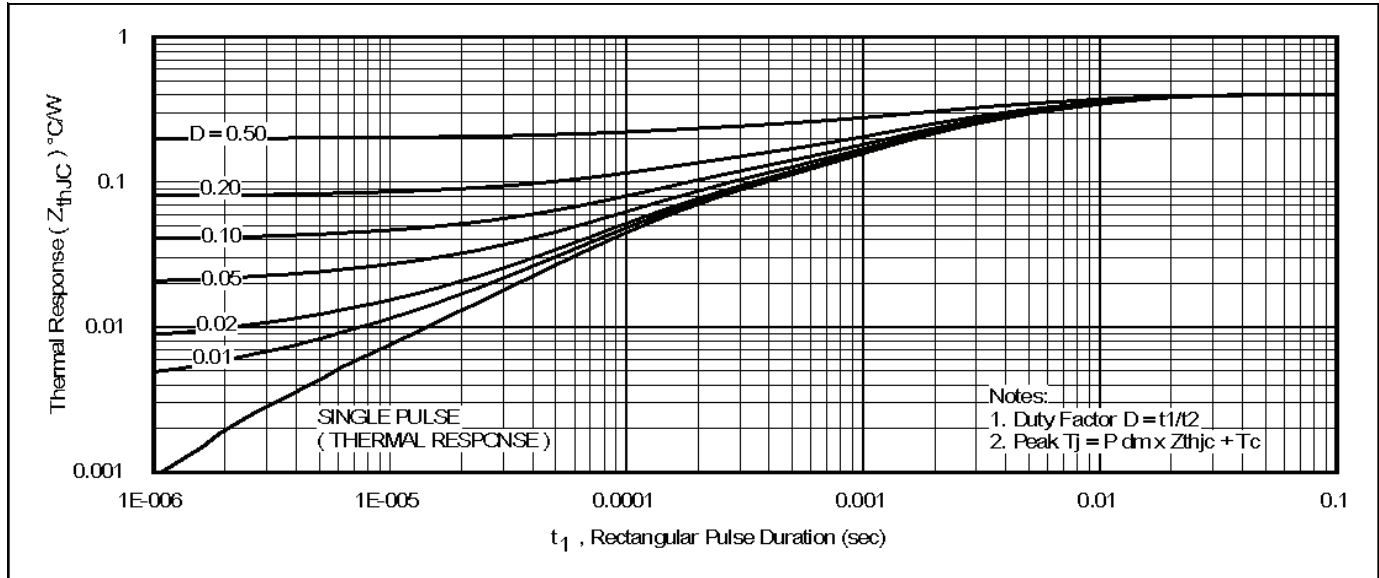


Figure 3. Transient thermal impedance curve. Notice the thermal parameters for a SPICE simulation (IRLS3036PBF)

For a surge of given duration (x axis), this curve gives a thermal response factor (y axis). The thermal response factor (or thermal impedance), when multiplied by the power dissipation *during the conduction period* *t* (i.e., the power *within* the conduction pulse itself, *not* the power averaged over the whole cycle), gives the value of the repetitive peak junction-to-case temperature rise, as indicated in the figure itself. The power dissipation is calculated from the voltage and current across the device during the surge.

Notice that for long pulses (approximately 10ms in Figure 3) the thermal response becomes equal to the thermal resistance.

In some data sheets the thermal response factor is normalized to 1. This means that it needs to be further multiplied by the data sheet thermal resistance.

The transient thermal response curve *assumes constant case temperature*. This is generally valid for pulses shorter than 1 to 5ms, depending on the thermal mass of the package. For longer surges the case temperature starts to rise and the results are of questionable accuracy. For operation in free air or PQFN packages, case temperature starts to rise within a millisecond or so and this curve does not provide any useful information. In these cases the entire thermal system must be modeled with finite element analysis

For most applications (short pulses and significant thermal mass), T_C can be calculated as indicated in Section 3 since its temperature is determined mainly by the average power dissipation. The absolute value of the peak junction temperature is obtained superimposing the temperature ripple to the average case temperature under steady-state operating conditions.

The transient thermal impedance curve can also be used to calculate the peak temperature for power pulses with a very low repetition rate, when the ripple in junction temperature is significant. The appropriate thermal response is at the crossing of the pulse width on the x axis with the curve of the appropriate duty cycle. As stated above, the thermal response thus obtained must be multiplied by the power dissipation during the pulse and superimposed to case temperature.

Appendix

Determining the RMS Value of I_D Waveforms

The conduction losses of a MOSFET are proportional to the square of the RMS drain current. The current waveforms are rarely simple sinusoids or rectangles, and this can pose some problems in calculating the value for I_{RMS} . The following equations and procedure can be used to determine I_{RMS} for any waveform that can be broken up into segments for which the RMS value can be calculated individually.

The RMS value of any waveform is defined as

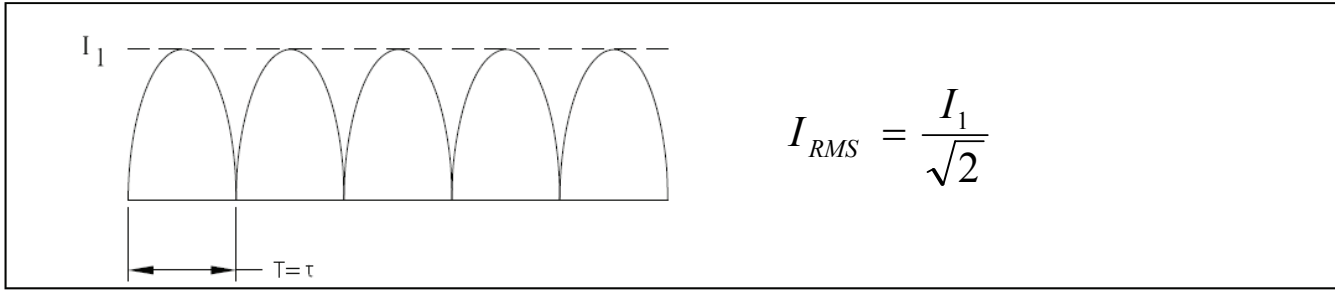
$$I_{RMS} = \sqrt{\frac{\int_0^t I^2(t) dt}{T}}$$

The figures below shows several simple waveforms and the formulas to calculate I_{RMS} using equation above.

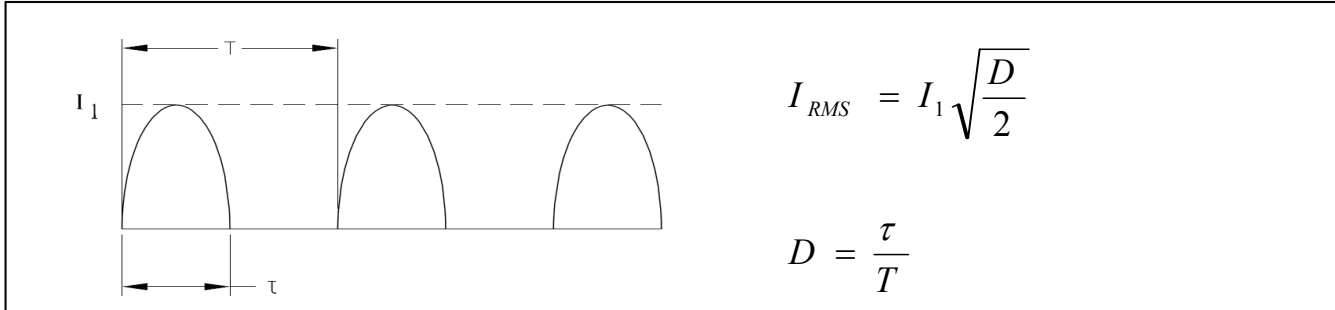
If the actual waveform can be approximated satisfactorily by combining the waveforms in the figure, then the RMS value of the waveform can be calculated from:

$$I_{RMS} = \sqrt{I_{RMS(1)}^2 + I_{RMS(2)}^2 + \dots + I_{RMS(n)}^2}$$

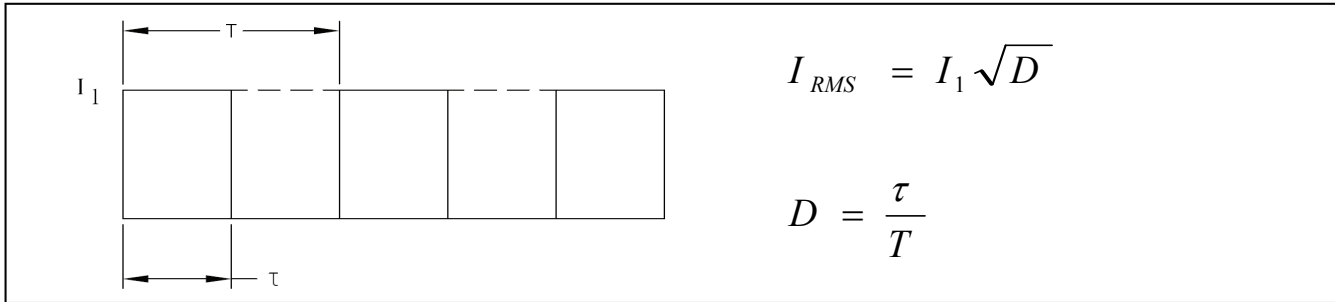
This is true to the extent that no two waveforms are different from zero at the same time.



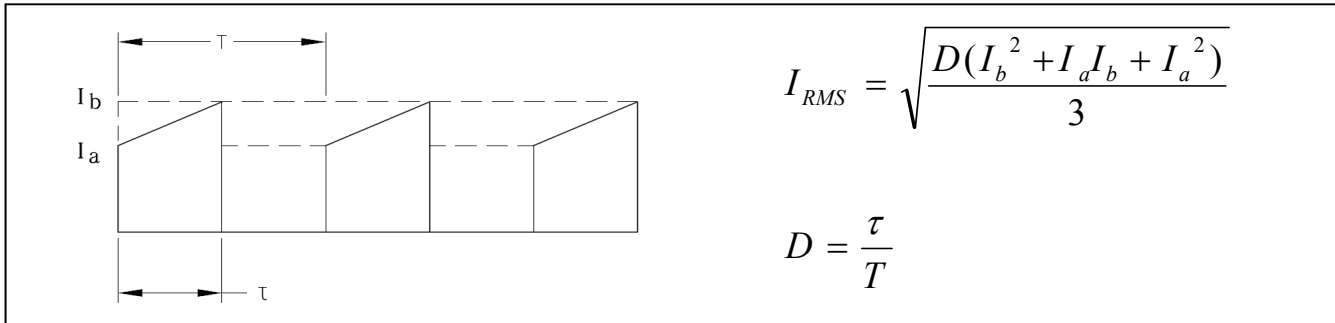
Fullwave Sinusoidal



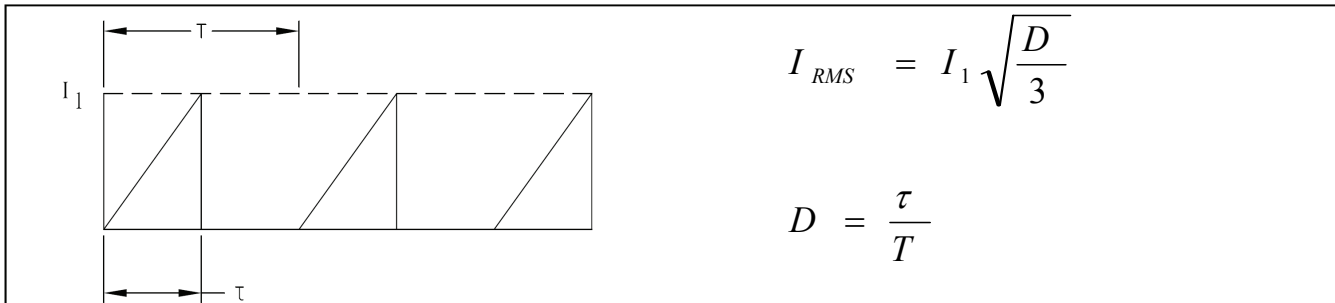
Pulsed Sinusoidal



Rectangular



Trapezoidal



Triangular