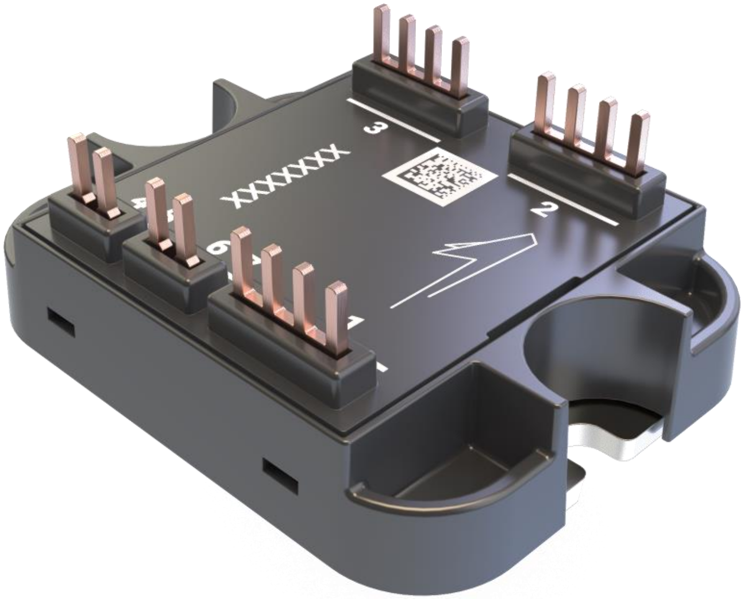
Application Note **PRD-07635**

Impact of PCB Design on Wolfspeed DM Module Ampacity



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Printed Circuit Board (PCB) design is an essential part of the thermal management of power electronic systems. The Wolfspeed DM power module is a solder-pin power module where the PCB sinks heat away from the power module terminals into the ambient air through heat conduction and convection. The number of PCB layers, the copper weight, the dielectric thickness, and the size of the board all affect the thermal resistance of the PCB. Thus, the power module terminal ampacity (current carrying capability) will be limited by the PCB design. This application note demonstrates the effect of PCB design on the Wolfspeed DM module terminal ampacity and provides guidance for PCB design to account for the module's terminal ampacity limit in addition to other PCB design parameters.

Contents

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1. Introduction

In power modules, the PCB acts as a heat spreader for the power module terminals. Figure 1 shows the heat spreading mechanisms of a power module terminal (pin) mounted on to PCB. Most of the heat generated by the power module terminal as current travels through it is dissipated laterally via the PCB copper layers through heat conduction [1]. The PCB dielectric material (commonly FR4) has very poor thermal conductivity (0.25 W/m-K) compared to copper (398 W/m-K), hence it contributes very little to lateral heat spreading. The heat spreading for the dielectric layer is mainly vertical through heat conduction [2]. Heat is also dissipated from the PCB surface into the ambient air through convection.

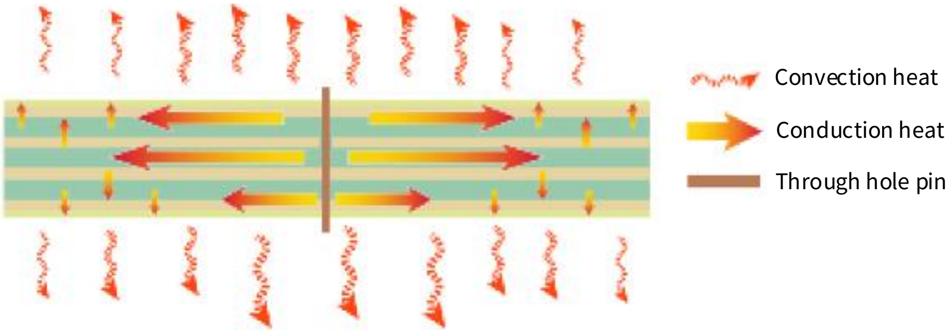

Figure 1: PCB heat spreading mechanisms

Increasing the copper weight and coverage area on the PCB structure improves the PCB thermal performance by increasing the effective copper area for lateral heat spreading. As the copper area increases, the effective thermal resistance of the PCB reduces but the heat spreading reaches saturation beyond a certain point [1], [3]. Therefore, further increases in PCB copper area will not provide substantial PCB thermal resistance reduction. Reducing the thickness of the dielectric material also reduces the thermal resistance of the PCB; however, care should be taken not to compromise the mechanical integrity of the PCB when doing so.

2. PCB Thermal Resistance Model

The distributed thermal resistance model of a typical PCB is shown in Figure 2 [1]. The thermal resistance of the copper layer is modeled as a horizontal resistance branch (R_{CU}) since the heat spreading in the copper layer is predominately lateral. On the other hand, the heat spreading in the FR4 layer is mainly vertical due to the poor thermal conductivity of FR4 material, hence the FR4 thermal resistance to vertical heat spreading is modeled as a vertical resistance branch (R_{FR4}). The thermal resistance to the heat spreading from the PCB surface to the ambient air is represented as thermal resistance of the ambient air (R_A).

The thermal resistance of the copper layer to lateral heat spreading can be modeled using equation (1).

$$R_{\mathrm{CU}} = \frac{l_{\mathrm{CU}}}{\lambda_{\mathrm{CU}} A_{\mathrm{CU}}} \qquad (1)$$

where l_{CU} is the length of the copper layer; A_{CU} is the cross-sectional area of the copper layer (product of the copper layer thickness and copper layer width); and λ_{CU} is the thermal conductivity of copper.

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The thermal resistance of the FR4 layer to vertical heat spreading can be modeled using equation (2).

$$R_{\mathrm{FR4}} = \frac{t_{\mathrm{FR4}}}{\lambda_{\mathrm{FR4}} A_{\mathrm{FR4}}} \qquad (2)$$

where t_{FR4} is the thickness of the FR4 layer; A_{FR4} is the cross-sectional area of the FR4 layer (product of the FR4 layer length and width); and λ_{FR4} is thermal conductivity of the FR4 material.

The thermal resistance of the ambient air to convective heat spreading from the PCB surface to the ambient air can be modeled using equation (3).

$$R_{\mathrm{A}} = \frac{1}{h A_{\mathrm{PCB}}} \qquad (3)$$

Where h is the convective heat transfer coefficient of air (0.001 W/ °C- cm^2) and A_{PCB} is the area of the PCB board.

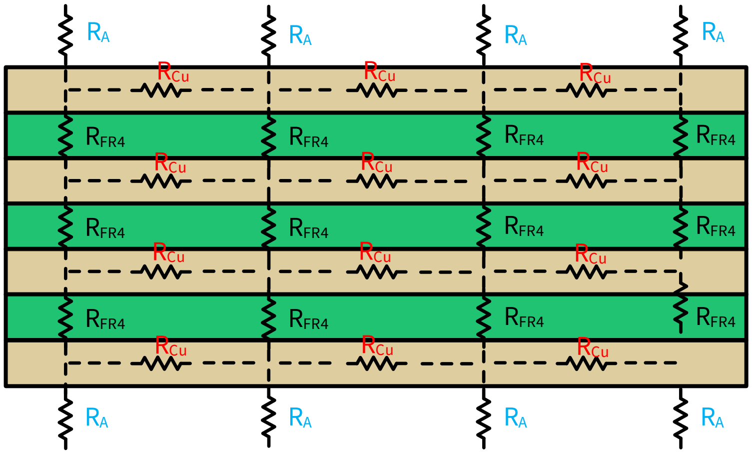

Figure 2: Expanded PCB thermal resistance model

Calculating the thermal resistance of a PCB from its expanded thermal resistance model is arduous. The process can be simplified by considering a 1 square cm portion of the PCB and calculating its thermal resistance. The thermal resistance of this PCB piece can then be used to compare the thermal performance of different PCB designs in terms of copper thickness, FR4 thickness, and the number of layers.

To demonstrate this, consider two PCB design options: a two-layer, four-ounce copper PCB and a four-layer, two-ounce copper PCB with the same overall board thickness. Because the PCBs have the same board thickness and the same total copper layer thickness (eight ounces), they will have the same total FR4 layer thickness. However, due to the difference in the PCB stack-up structure, they will have different thermal resistances.

Figure 3 shows the thermal resistance model of the two-layer, four-ounce copper PCB with 2.4 mm board thickness over a 1 square cm area. Using equations (1) – (3), the thermal resistance of the copper layer (R_{CU}), the thermal resistance of the FR4 layer (R_{FR4}), and the thermal resistance of the ambient air to the surface of the PCB (R_{A}) can be calculated; the results of this analysis are shown in Table 1. Please note that a one-ounce copper weight is equivalent to a copper thickness of 0.0035 cm.

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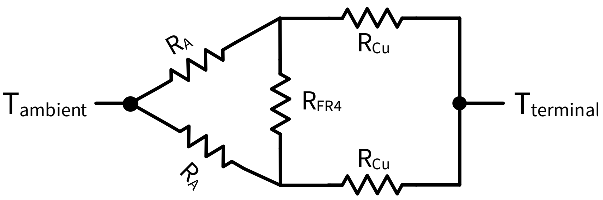

Figure 3: Thermal resistance model of a two-layer 1 cm square PCB

Table 1: Thermal Resistances for a 2-layer, 4-oz Copper PCB with 1 cm Square Area and 2.4 mm Thickness

Thermal Resistance	R_{CU} (°C/W)	R_{FR4} (°C/W)	R_A (°C/W)
Value	17.86	92.17	1000

Using the thermal resistance model in Figure 3 and the thermal resistance values in Table 1, the thermal resistance of a two-layer, four-ounce PCB with 1 cm square area and 2.4 mm board thickness will be 526 °C/W.

Figure 4 shows the thermal resistance model of a four-layer, two-ounce copper PCB with 1 cm square area and 2.4 mm board thickness. The thermal resistance of the copper layer (R_{CU}), the thermal resistance of the FR4 layer (R_{FR4}) and the thermal resistance of the ambient air to the surface of the PCB (R_A) for this piece of PCB again can be calculated using equations (1) – (3); the results of this analysis are provided in Table 2.

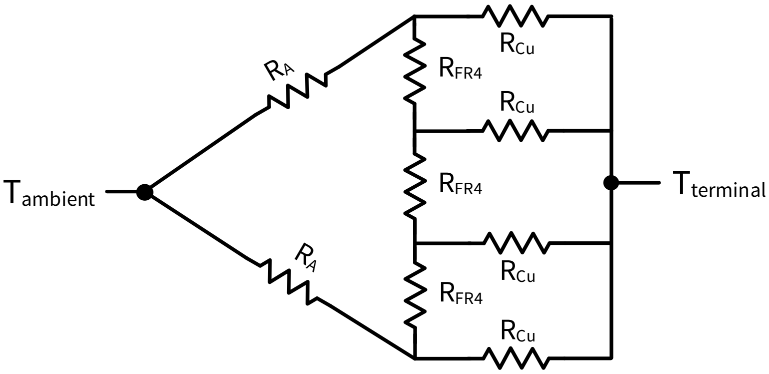

Figure 4: Thermal resistance model of a four-layer 1 cm square PCB

Table 2: Thermal Resistances for a 4-layer, 2-oz Copper PCB with 1 cm Square Area and 2.4 mm Thickness

Thermal Resistance	R_{CU} (°C/W)	R_{FR4} (°C/W)	R_A (°C/W)
Value	35.71	30.72	1000

Using the thermal resistance model in Figure 4 and the thermal resistance values in Table 2, the thermal resistance of a four-layer, two-ounce PCB with 1 cm square area and 2.4 mm board thickness will be 561 °C/W.

As can be seen from the thermal resistance of the two 1 cm square PCB pieces, the thermal resistance of a four-layer, two-ounce copper PCB is slightly higher than the thermal resistance of a two-layer, four-ounce copper PCB despite having the same board thickness, the same total FR4 layer thickness, and the same total copper layer thickness.

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3. Package Ampacity Test setup

The effect of PCB design on the DM module terminal ampacity is verified by experimental test. The size and layout of the PCB used for the test is shown in Figure 5. The finished thickness of the board is 0.093 inches. The DC+, DC- and MID nets are assigned to all layers. Please note this layout is a simplified layout, as the purpose of the PCB board is only for thermal testing of the DM module terminals. This should not be interpreted as a general layout recommendation of DM module PCB design. For general layout recommendations of DM module PCB design, please contact your regional sales representative or check the official product page on www.wolfspeed.com.

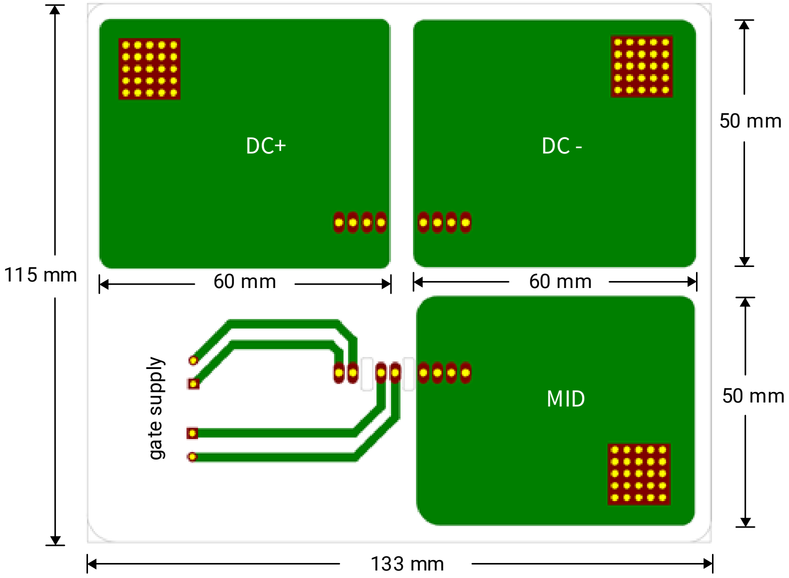

Figure 5: PCB layout used for the DM module terminal ampacity test

A modified version of the DM module is used to monitor the thermal behavior during operation. This module is unlidded, unpotted, and is coated with a high-emissivity black paint. This allows for the temperature of each die to be monitored with a thermal camera during testing, ensuring that the maximum operating temperature of the die are not exceeded during the test. Wolfspeed offers black-painted thermal modules for customers intending to do similar thermal testing. Please contact your regional sales representative to order these types of modules.

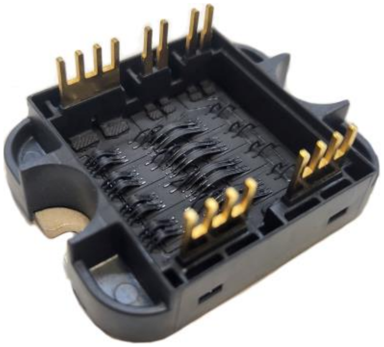

Figure 6: Black-painted DM thermal module

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A FLIR® thermal camera (FLIR T1010) with 3X (51 µm) close-up lens is used to monitor the temperature of the die and the module terminals during the test. This thermal camera lens has a high temperature measurement resolution and enables accurate measurement of temperature. Please make sure you properly adjust the camera focus to the point where temperature measurement is intended to be made.

Figure 7: FLIR® thermal camera (FLIR T1010) with 3X (51um) close-up lens

FLIR Thermal Studio® software can be used to remotely access the thermal camera screen during the test and take snapshots of the thermal images. This software can also be used to later process thermal images and prepare test result presentations or reports.

Figure 8 shows the test setup for die temperature monitoring. The thermal camera is placed vertically above the power module. The camera focus is adjusted carefully until good image resolution is achieved. The bottom switch position is powered in this test, so the current source is connected between the mid-point and the negative DC terminal of the power module. A positive 15 V is applied to the bottom switch gate position.

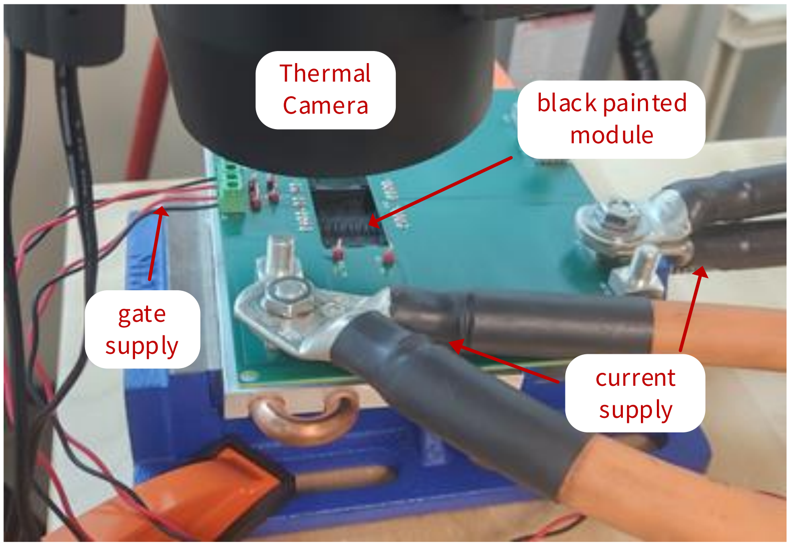

Figure 8. Setup for die temperature measurement

Figure 9 shows the side view of the test setup. The negative DC power terminal is painted black to avoid reflection of infrared signals during thermal measurement. High-heat black spray is used as black paint for this

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terminal. It is recommended to apply the black paint to the module terminal after the module is soldered to the PCB and allow the black paint to cure for at least one day before testing the module.

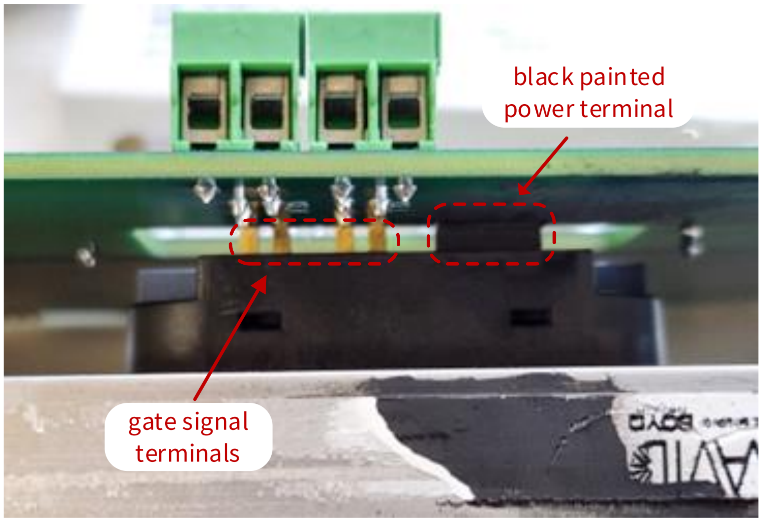

Figure 9: Side view of the thermal power module

Figure 10 shows the module terminal temperature measurement setup. The thermal camera is placed to the side of the power module where the terminal temperature needs to be measured and its focus is carefully adjusted until good image resolution is achieved. The current supply is increased slowly in discrete steps while allowing enough time for the temperature to reach to steady state in between the current steps. Thermal images of the module die and the module terminal are taken for each current step. The current is increased until any die reaches its maximum allowable junction temperature.

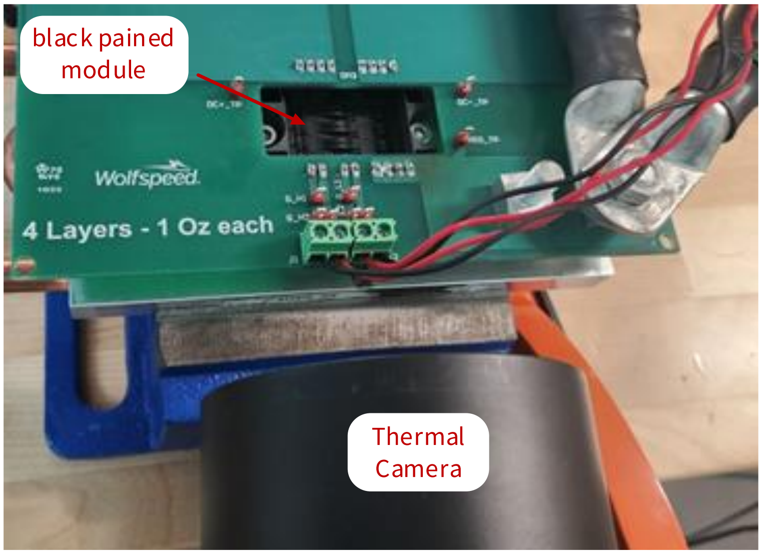

Figure 10: Setup for module terminal temperature measurement

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4. Package Ampacity Test Results

Figure 11 shows the terminal ampacity test results of the DM module for six different PCBs with the same finished board thickness but different numbers of layers and different copper layer thickness. Two primary conclusions can be drawn from the results.

For PCBs with the same number of layers, increasing the copper layer thickness (and decreasing the FR4 layer thickness) causes a decrease in the terminal temperature of the module. This is because the thermal resistance of the PCB decreases when the copper layer thickness increases (and the FR4 layer thickness is reduced).

For PCBs with the same total copper layer thickness and total FR4 layer thickness, increasing the number of layers in the PCB stack-up increases the thermal resistance of the PCB. Therefore, a PCB with more layers results in a higher module terminal temperature than a PCB with fewer layers when the board thickness and the total copper layer (FR4 layer) thickness are the same.

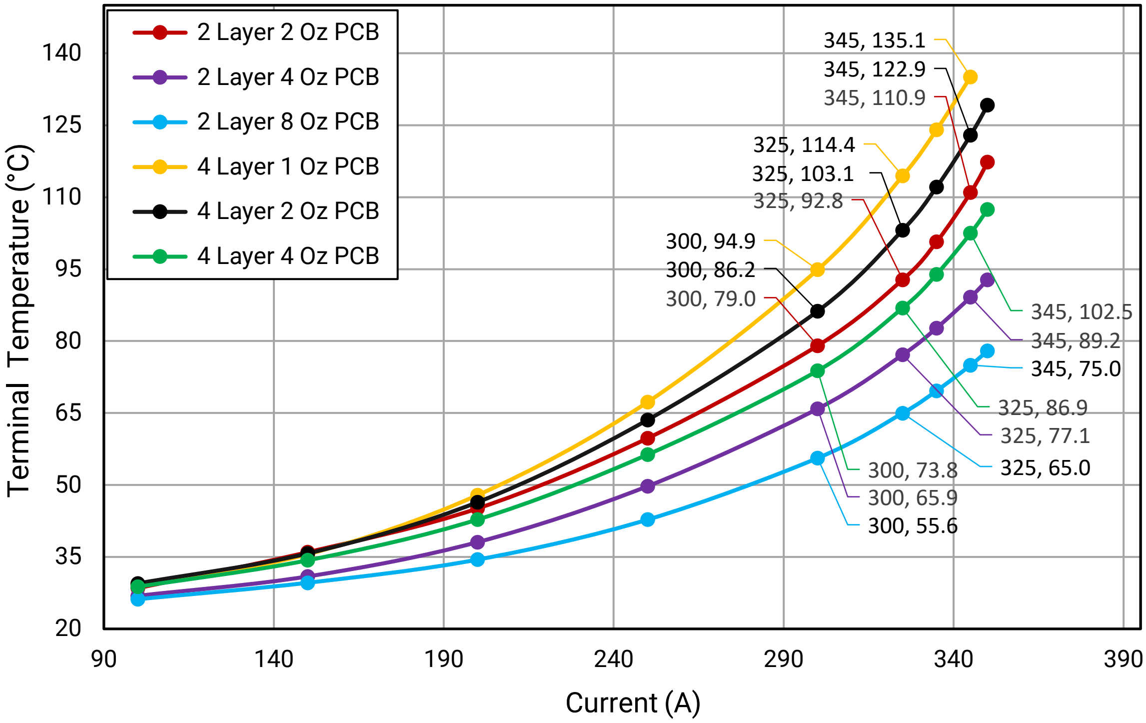

Figure 11: Terminal temperature vs. current for different PCB designs

The thermal images of the module terminal (negative DC terminal) for the different PCB designs are shown in Figure 12 – Figure 14.

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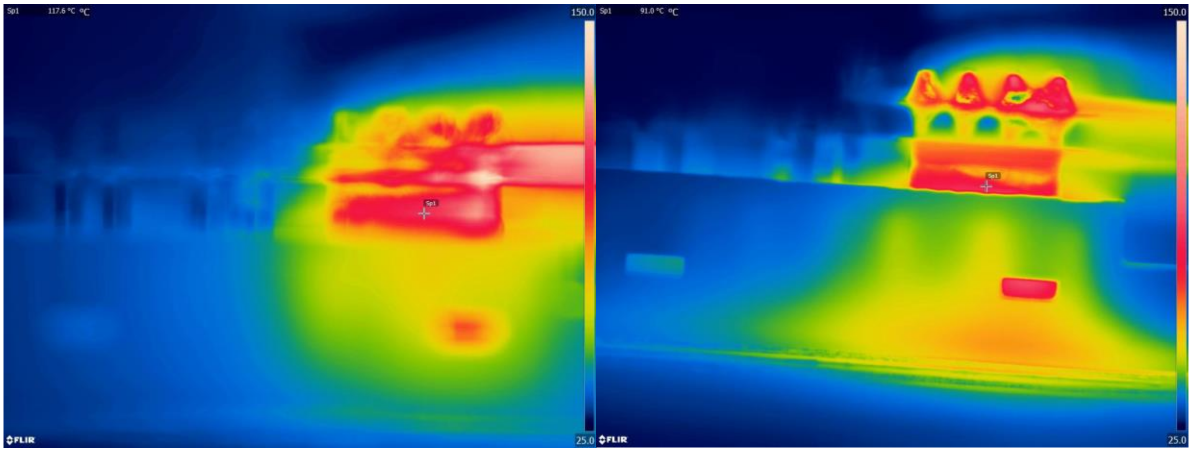

Figure 12: Thermal Images for 2-Layer, 2-oz Copper PCB at 350 A (left) and 2-Layer, 4-oz PCB at 350 A (right)

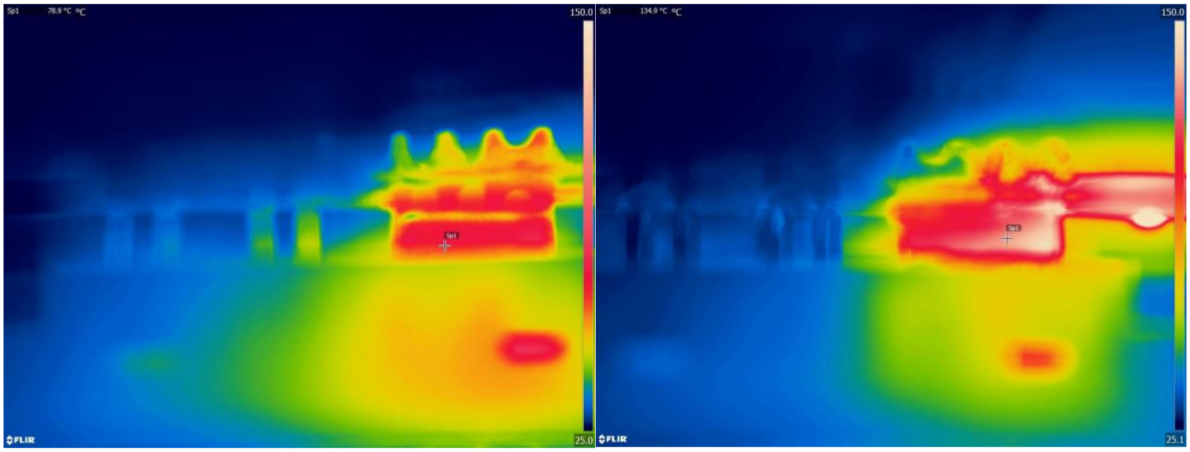

Figure 13: Thermal Images for 2-Layer, 8-oz PCB at 350 A (left) and 4-Layer, 1-oz PCB at 350 A (right)

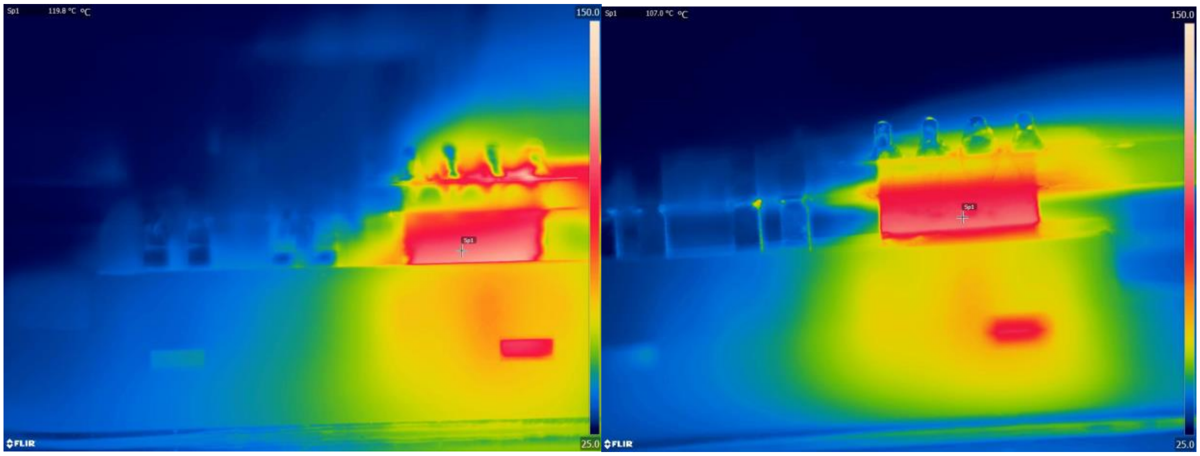

Figure 14: Thermal Images for 4-Layer, 2-oz PCB at 350 A (left) and 4-Layer, 4-oz PCB at 350 A (right)

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5. Summary

The PCB is an essential part of the thermal management of power electronic systems. For solder-pin power modules mounted to a PCB, the PCB is the main heat drain for the power module terminals. Therefore, the thermal performance of the PCB is critical for the thermal performance of the module terminals.

If cost and assembly are not a constraint, increasing the PCB copper layer thickness helps to reduce the PCB thermal resistance. Reducing the PCB dielectric (FR4) layer thickness also helps to reduce the thermal resistance of the PCB, but care should be taken not to compromise the mechanical integrity of the board. Minimizing the number of layers is also another way of reducing the thermal resistance of the PCB, but this might compromise the signal integrity of the PCB design especially when the design consists of both power signals and high-frequency signals. Therefore, it is important to consider the tradeoffs between cost, assembly, and signal integrity of the PCB apart from its thermal performance.

Revision History

Date	Revision	Changes
December 2023	1	Initial Release

References

[1] *AN-2020 Thermal Design by Insight*, Not Hindsight, Application Report, Texas Instruments, SNVA419C, April 2013.

[2] *PCB Thermal Design Guide for GaN Enhancement Mode Power Transistors*, Application Note, GaN Systems, GN005 Rev 150318.

[3] *Thermal Management of Bottom-Side Cooled Surface Mount Devices and Design Considerations*, Application Note, Wolfspeed, PRD-06701.

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