

Thermal Simulation of Switching Pulses in an Insulated Gate Bipolar Transistor (IGBT) Power Module

by Gregory K Ovrebo

ARL-TR-7210

February 2015

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Adelphi, MD 20783-1138

ARL-TR-7210**February 2015**

Thermal Simulation of Switching Pulses in an Insulated Gate Bipolar Transistor (IGBT) Power Module

Gregory K Ovrebo

Sensors and Electron Devices Directorate, ARL

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) February 2015		2. REPORT TYPE Final		3. DATES COVERED (From - To) 07/2013–09/2013	
4. TITLE AND SUBTITLE Thermal Simulation of Switching Pulses in an Insulated Gate Bipolar Transistor (IGBT) Power Module			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Gregory K Ovrebo			5d. PROJECT NUMBER R.0005875.1		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-SED-P 2800 Powder Mill Road Adelphi, MD 20783-1138			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-7210		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A simulation was performed to predict the thermal behavior of a commercial power module with silicon insulated gate bipolar transistors (IGBTs) during switching of multiple power pulses.					
15. SUBJECT TERMS thermal, simulation, pulse, insulated gate bipolar transistor					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 24	19a. NAME OF RESPONSIBLE PERSON Gregory K Ovrebo
A. Report Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) (301) 394-0814

Contents

List of Figures	iv
List of Tables	iv
1. Introduction	1
2. Model and Boundary Conditions	1
3. Simulation Results	3
3.1 Alumina Circuit-Board Simulations.....	3
3.2 Thermal-Impedance Calculations.....	6
3.3 AlN Circuit-Board Simulations	8
4. Conclusions	14
List of Symbols, Abbreviations, and Acronyms	16
Distribution List	17

List of Figures

Fig. 1	Rendering of the SolidWorks 3D model of the IGBT power module.....	1
Fig. 2	Power dissipated in each of the components of the switch module	2
Fig. 3	Top view of the simulation mesh of the IGBT switch	3
Fig. 4	Average temperature of IGBTs and diodes during a single pulse	4
Fig. 5	Temperatures on the module at $t = 1.1$ s	4
Fig. 6	Average temperature of IGBTs during a series of 5 pulses	5
Fig. 7	Average temperature of diodes during a series of 5 pulses.....	5
Fig. 8	Temperatures on the module at $t = 5.9$ s	6
Fig. 9	Maximum temperature on bottom of mounting plate.....	6
Fig. 10	Calculated vs. manufacturer-spec thermal resistance for IGBTs	8
Fig. 11	Calculated vs. manufacturer-spec thermal resistance for diodes.....	8
Fig. 12	Temperatures on the module surface at $t = 400$ ms.	9
Fig. 13	Temperatures on the module surface at $t = 1.1$ s	9
Fig. 14	Temperatures on the module surface at $t = 6.1$ s	10
Fig. 15	Average temperature of IGBTs over 1 pulse plus 6 s.....	10
Fig. 16	Average temperature of diodes over 1 pulse plus 6 s	11
Fig. 17	Maximum temperature of bottom of Al plate over 1 pulse plus 6 s.....	11
Fig. 18	Temperatures on the module's surface at the end of the fifth pulse.....	12
Fig. 19	Average temperature of IGBTs over 5 pulses.....	12
Fig. 20	Average temperature of diodes over 5 pulses	13
Fig. 21	Maximum temperature of bottom of aluminum plate over 5 pulses	13
Fig. 22	Temperatures on the bottom of mounting plate, end of fifth pulse	14

List of Tables

Table	Specified thermal impedances in the Microsemi power module	7
-------	--	---

1. Introduction

The Power Conditioning Branch of the US Army Research Laboratory (ARL) is investigating the use of a commercial power module employing insulated gate bipolar transistors (IGBTs) in switching high-power pulses on the order of 1 s in duration. Silicon IGBTs combine high efficiency with fast switching and can handle pulses with currents of several hundred amperes and power dissipation of hundreds of watts (Ws). Such power switching may be used in Army electronics applications such as power supplies and electric-motor control. Investigators at ARL wanted to know what thermal effects might occur as a result of multiple pulses being switched by a commercial power module with 8 IGBTs.

2. Model and Boundary Conditions

The power module being used by the ARL is the model APTGF300A120G manufactured by Microsemi Power Products Group. Figure 1 shows the 3-dimensional (3D) model of the IGBT power module prepared with SolidWorks computer-aided design software. The module has 8 silicon IGBTs mounted on copper (Cu) lands bonded onto a dielectric circuit board. The material used in the circuit board was assumed to be alumina (Al_2O_3). The Cu base of the power module is mounted with a conducting compound to an aluminum plate, which serves as a heat sink. The 8 IGBTs are depicted in the picture as larger dark rectangles; the smaller gray rectangles are silicon diodes. Four resistors are located on the underside of the mounting plate.

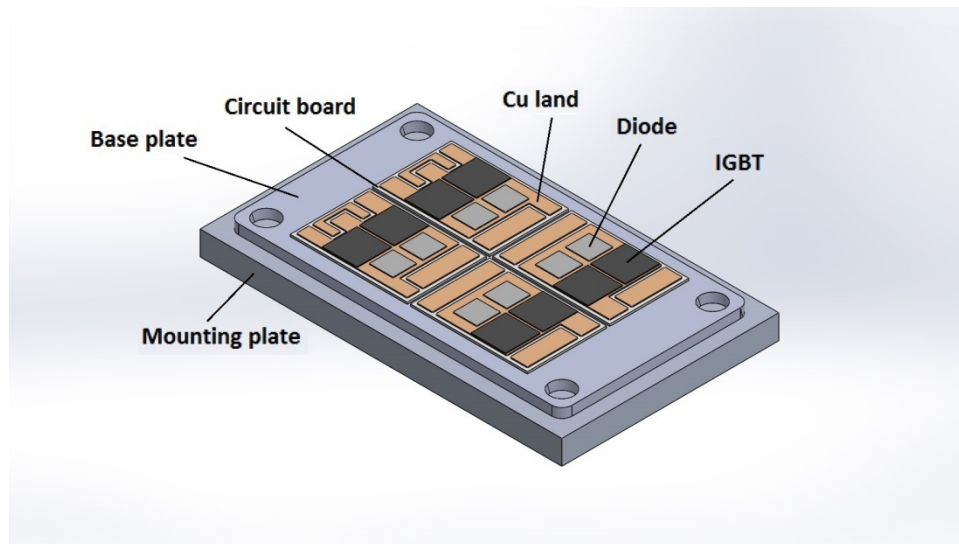


Fig. 1 Rendering of the SolidWorks 3D model of the IGBT power module

The initial temperature of the module was defined to be 50 °C, while the temperature of the air was defined to be 20 °C. We also defined a convective flow of air perpendicular to the bottom surface of the mounting plate, with a velocity of 10 ft/s. The thermal simulations were executed with SolidWorks Flow Simulation, a computational fluid-dynamics code.

The graph in Fig. 2 shows the timing and amplitudes of power pulses dissipated in the 3 types of components in the power module during one cycle of operation. During this 1.1-s pulse, the IGBTs see a constant power of 27.75 W per device. The diodes see an initial power level of 44.25 W per device, which drops to 10.5 W per device at $t = 0.4$ s. Resistors on the bottom of the mounting plate see a power level of 67.75 W each during the pulse.

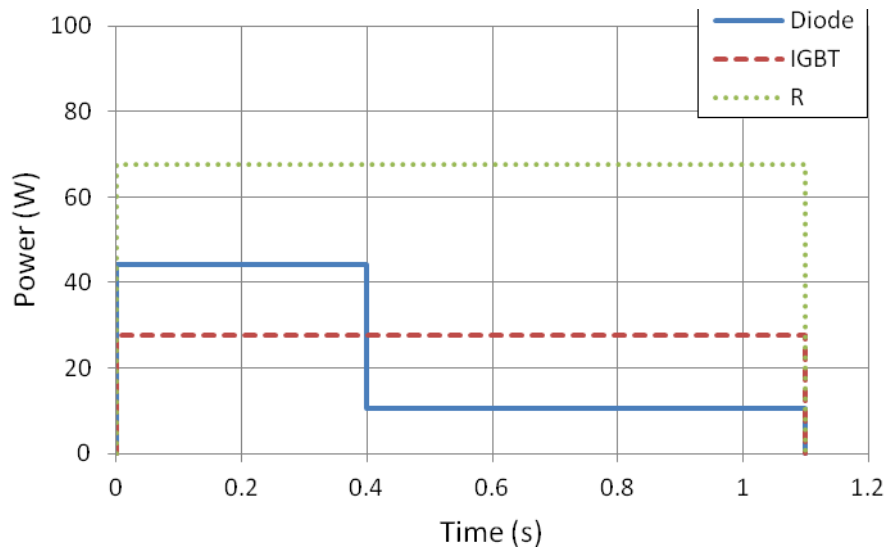


Fig. 2 Power dissipated in each of the components of the switch module

The 3D switch model was divided into a 3D mesh before thermal simulation. Temperature and other thermal properties were calculated at each node of the mesh at discrete time steps during the power pulse and during a cooling period after the end of the pulse. Figure 3 shows part of the mesh in and around the solid-model solids. Note that a finer mesh is used on the central part of the model in order to improve the resolution of the thermal calculations in and around the silicon devices.

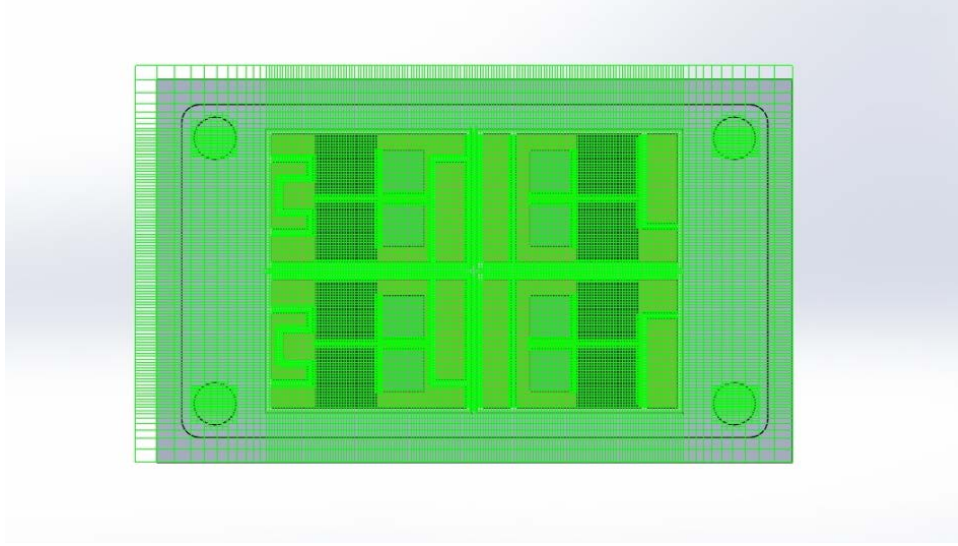


Fig. 3 Top view of the simulation mesh of the IGBT switch

3. Simulation Results

Our simulation of thermal effects due to power pulses in the Microsemi power module had 2 parts. We first simulated a single pulse (Fig. 2) and verified the simulation by comparing it to laboratory measurements of temperatures on the module after switching a single pulse. We then simulated 5 pulses in quick succession, which is a worst-case situation for our applications. This calculation was performed before the 5 pulses were attempted in the laboratory to avoid damage to the power module due to overheating of the silicon IGBTs.

3.1 Alumina Circuit-Board Simulations

Using the boundary conditions described above, we ran a thermal simulation of power-module operation during one 1.1-s. pulse, followed by 2 s during which the module power was off and the system cooled. Figure 4 shows the average temperatures of the 8 IGBTs and 8 diodes calculated in that simulation.

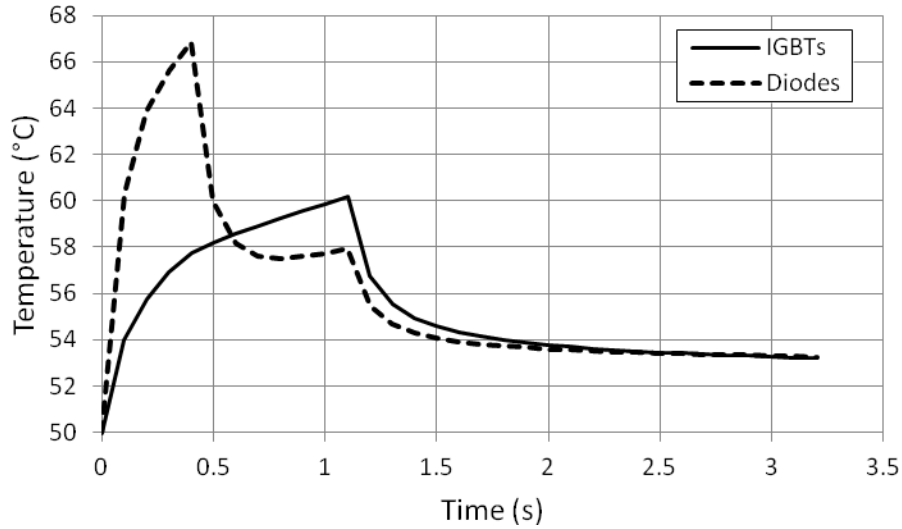


Fig. 4 Average temperature of IGBTs and diodes during a single pulse

Figure 5 is a thermal-contour plot of temperatures on the module's circuit board at the end of one power pulse. The maximum temperature on the surface is 64 °C. Temperatures are higher on one end of the module than the other because the resistors are located at one end of the mounting plate.

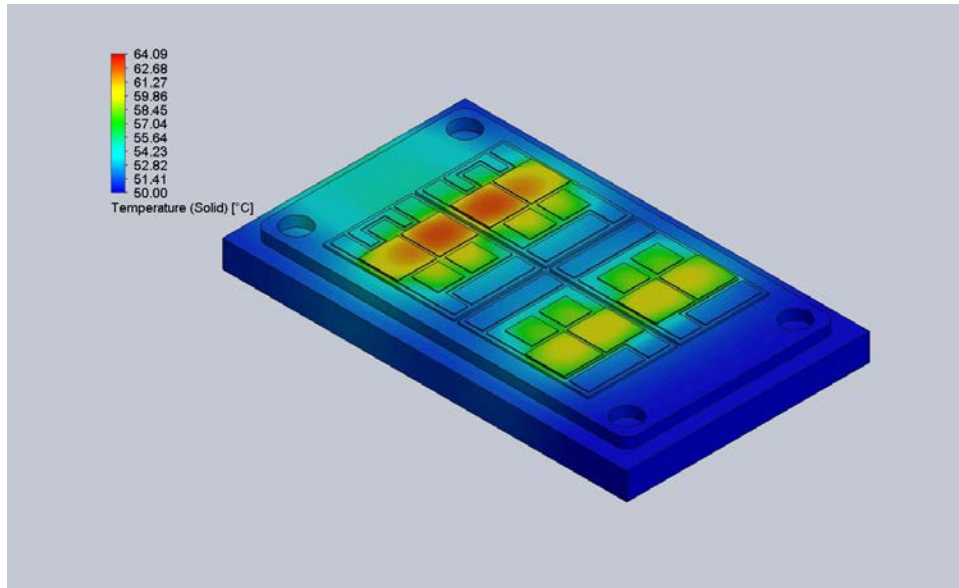


Fig. 5 Temperatures on the module at $t = 1.1$ s

We next simulated five 1.1-s pulses applied back to back, with the module power switched off for 0.1 s between pulses. With minimal time for cooling between pulses, device temperatures rose from peak to peak, as shown in Fig. 6 and 7.

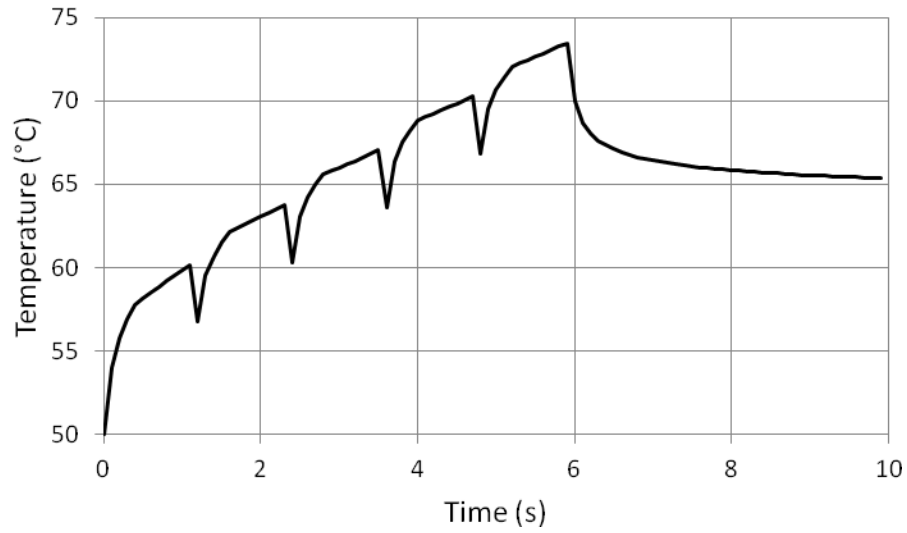


Fig. 6 Average temperature of IGBTs during a series of 5 pulses

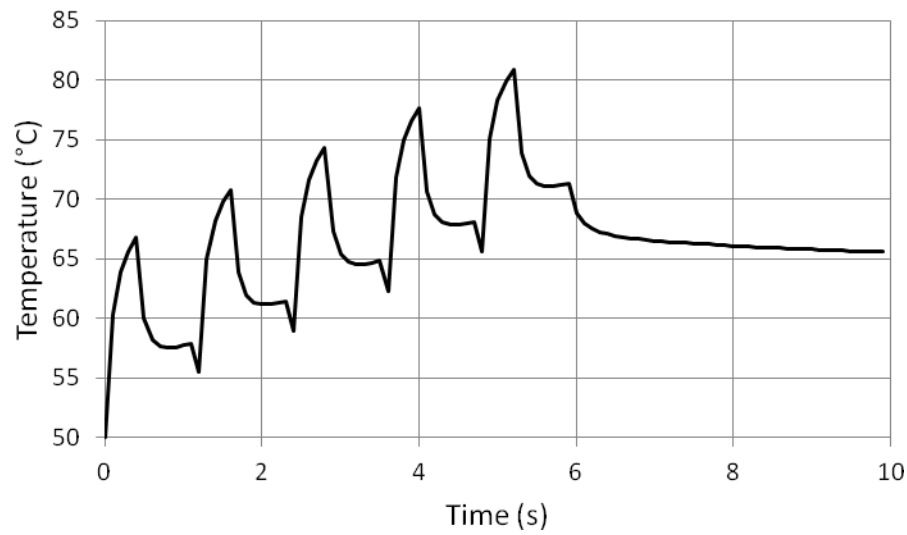


Fig. 7 Average temperature of diodes during a series of 5 pulses

Figure 8 shows temperature contours on the surface of the circuit board at the end of the fifth pulse. Maximum surface temperature at this point is 85 °C.

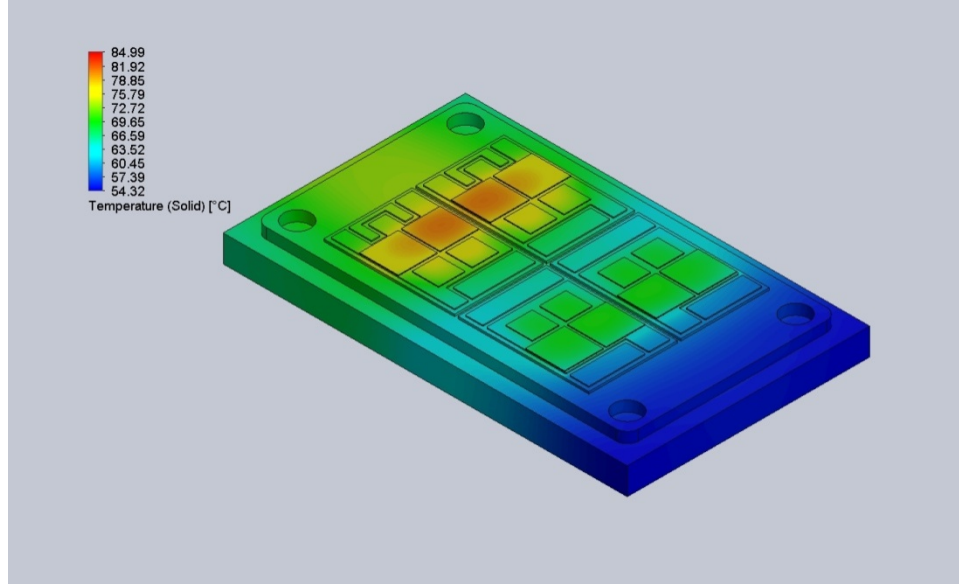


Fig. 8 Temperatures on the module at $t = 5.9$ s

We also extracted the calculated temperatures on the bottom of the aluminum mounting plate, the prime location for mounting thermocouples in the laboratory. A plot of the maximum calculated temperature over 5 pulses is shown in Fig. 9.

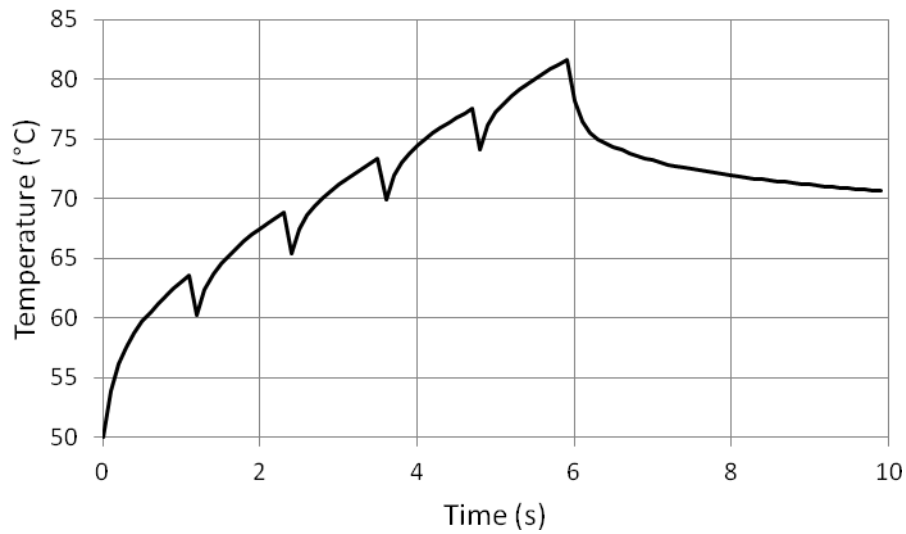


Fig. 9 Maximum temperature on bottom of mounting plate

3.2 Thermal-Impedance Calculations

Preliminary laboratory results suggested that our model predictions for IGBT and diode temperatures were too high. In the lab, thermal sensors were mounted to the bottom of the module's mounting plate, directly opposite from the IGBT location. The thermal sensors had time constants of 2–4 s and so were not fast enough to capture temperatures during a single

pulse; however, they could measure temperatures on the mounting plate as it started to cool after the 1.1-s pulse. The thermal sensors measured a temperature rise of 2–4 °C after the pulse, lower than our predicted temperature rise of 4–5 °C.

The most likely sources of error in the model are the thermal impedances in the IGBT module's materials. We had assumed that the circuit-board material in the Microsemi IGBT module was alumina, but the exact composition was unknown. We attempted to determine the identity of the circuit-board material by calculating the junction-to-case thermal impedance in our model using both alumina and aluminum nitride (AlN) and then comparing the calculated thermal impedances with those quoted in the manufacturer's specifications for the power module. (The data sheet for Microsemi's power module, part number APTGF300A120G, can be found online at www.microsemi.com/existing-parts/parts/60000#docs-specs.) The specifications for junction-to-case thermal impedance, measured at the IGBTs and at the diodes, are summarized in Table 1. We will consider the device's thermal impedances measured during a single pulse.

Table Specified thermal impedances in the Microsemi power module

Pulse Duration (s)	IGBT R_{th} (°C/W)	Diode R_{th} (°C/W)
0.01	0.025	0.042
0.1	0.052	0.09
1	0.07	0.12

We calculated the thermal impedance of the IGBTs by isolating 4 of the devices and calculating temperatures resulting from one rectangular pulse of 100-W amplitude, or 25 W per device. We used pulse lengths of 1 s, 100 milliseconds (ms), and 10 ms in individual simulation runs. We then calculated the difference between the average temperatures on the IGBTs and the average temperatures on the base plate and divided by the 25-W pulse power. From those calculations we get the curves in Fig. 10. Note that the manufacturer's specification for thermal impedance is much closer to the thermal impedance calculated for AlN than for that calculated for alumina. Similar calculations were performed for the thermal resistance of the diodes, using rectangular pulses of 25 W per device. The results are shown in Fig. 11.

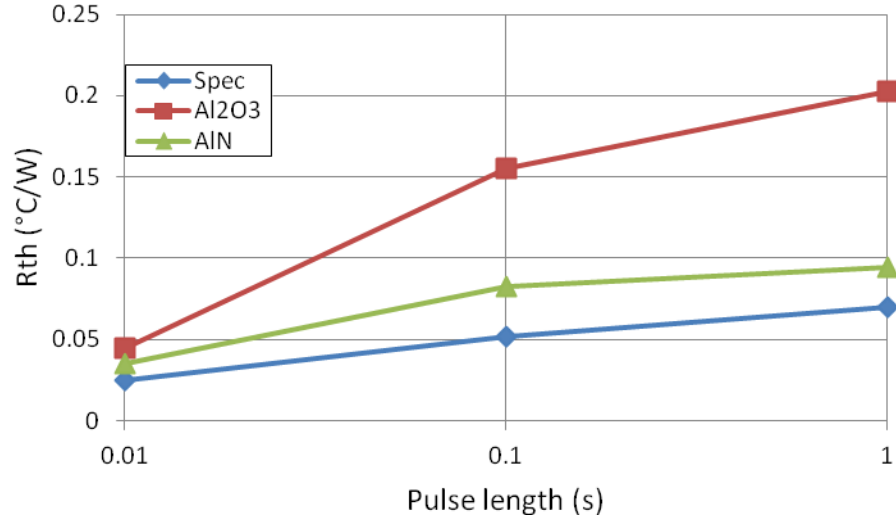


Fig. 10 Calculated vs. manufacturer-spec thermal resistance for IGBTs

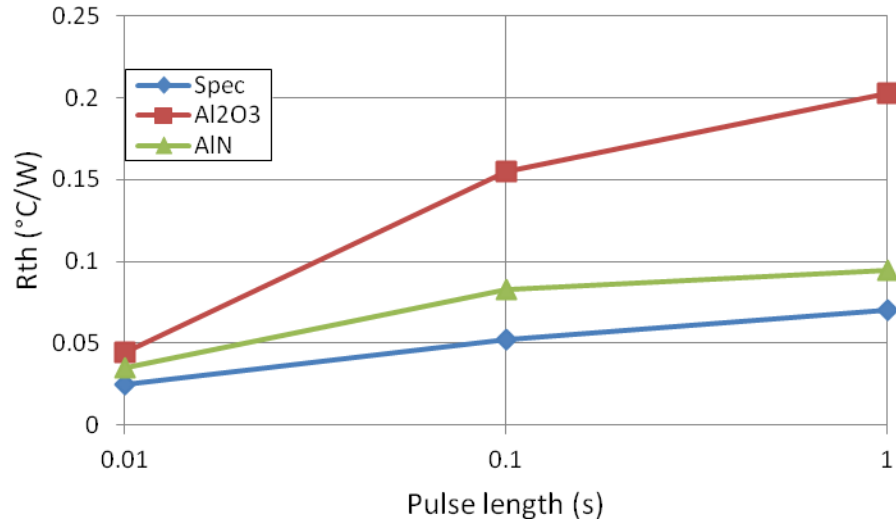


Fig. 11 Calculated vs. manufacturer-spec thermal resistance for diodes

The thermal impedance of the IGBTs and diodes that we calculated with an AlN circuit board is much closer to the manufacturer's specification than the thermal impedance calculated with the alumina circuit board. As a result, we repeated the thermal simulations with AlN circuit boards in the material stack, replacing the alumina boards.

3.3 AlN Circuit-Board Simulations

We repeated the earlier thermal simulations of module heating from a single pulse, as shown in Fig. 4. We included 5 s of device cooling after the end of the pulse. Figure 12 is a plot of surface temperatures at $t = 0.4$ s, when the diode power drops from 44.25 W to 10.5 W. The maximum surface temperature has increased from 50 °C to 62 °C at this point. Figure 13 shows the

temperature distribution at $t = 1.1$ s, at the end of the power pulse, when the maximum surface temperature has risen to $67\text{ }^{\circ}\text{C}$.

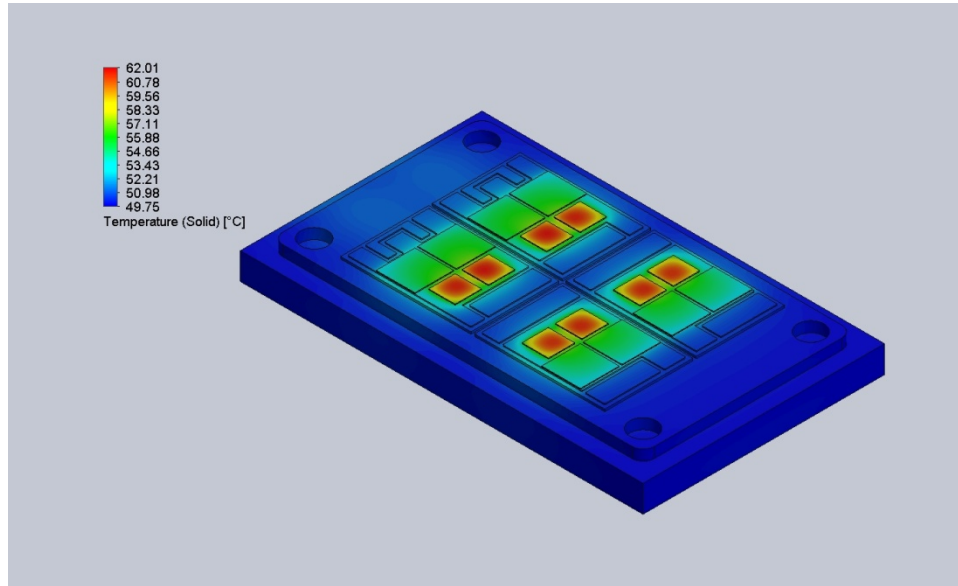


Fig. 12 Temperatures on the module surface at $t = 400$ ms.

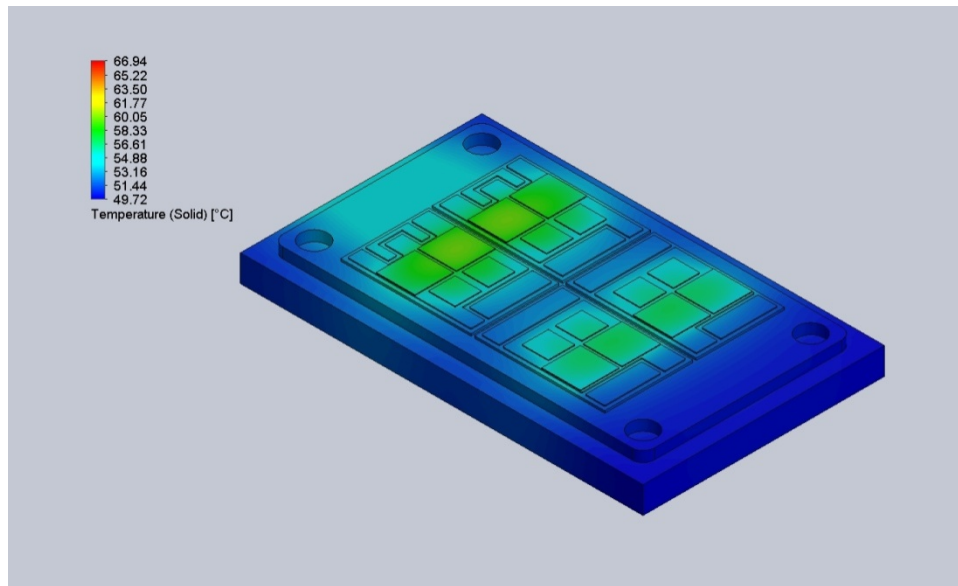


Fig. 13 Temperatures on the module surface at $t = 1.1$ s

Figure 14 shows the model at $t = 6.1$ s; the power module has cooled for 5 s and the maximum surface temperature has dropped below $54\text{ }^{\circ}\text{C}$.

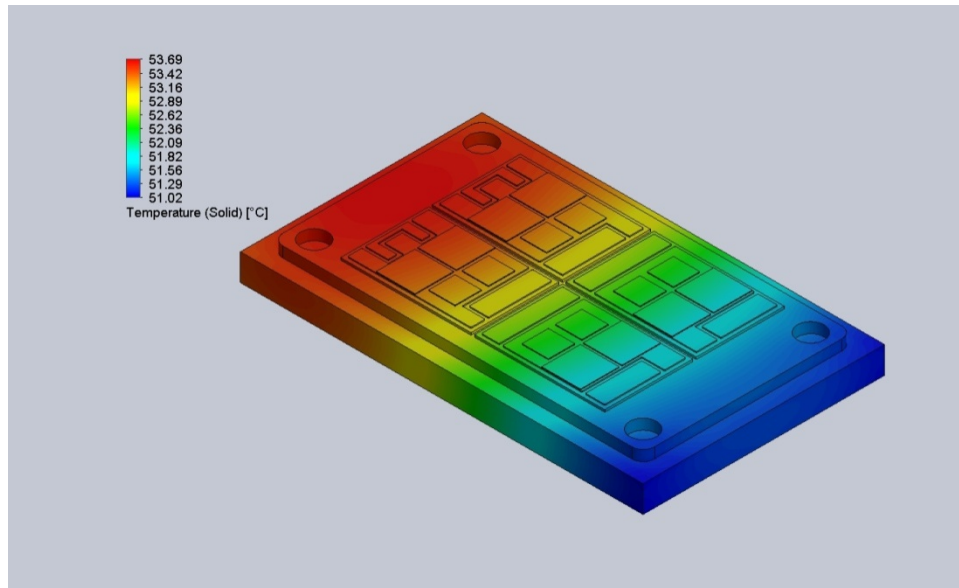


Fig. 14 Temperatures on the module surface at $t = 6.1$ s

Figure 15 shows the average temperature of the IGBTs during a single pulse, using the AlN dielectric boards. Compare this chart with Fig. 4 and note that the peak temperature predicted for the IGBTs is about 3 °C lower with AlN boards than with alumina boards.

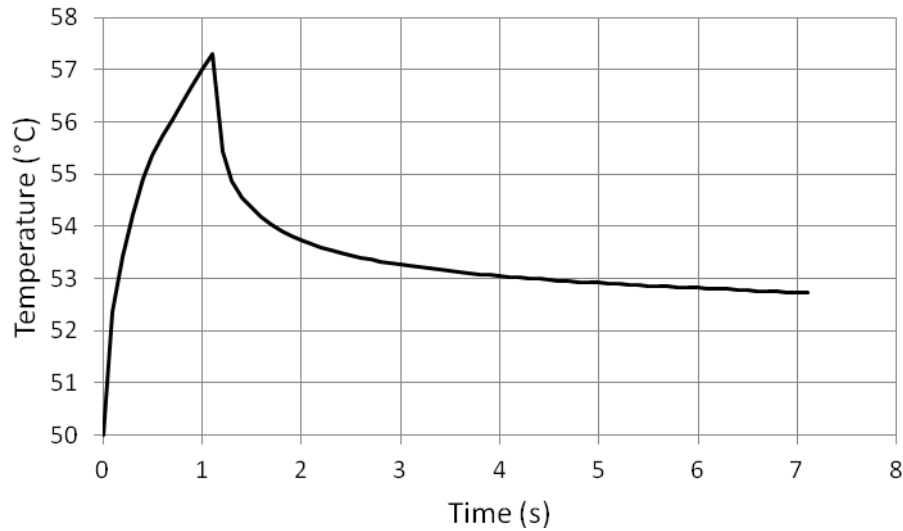


Fig. 15 Average temperature of IGBTs over 1 pulse plus 6 s

When we compare the calculated diode temperatures in Fig. 4 and in Fig.16, we see a difference of 7 °C in peak temperatures between AlN and alumina boards.

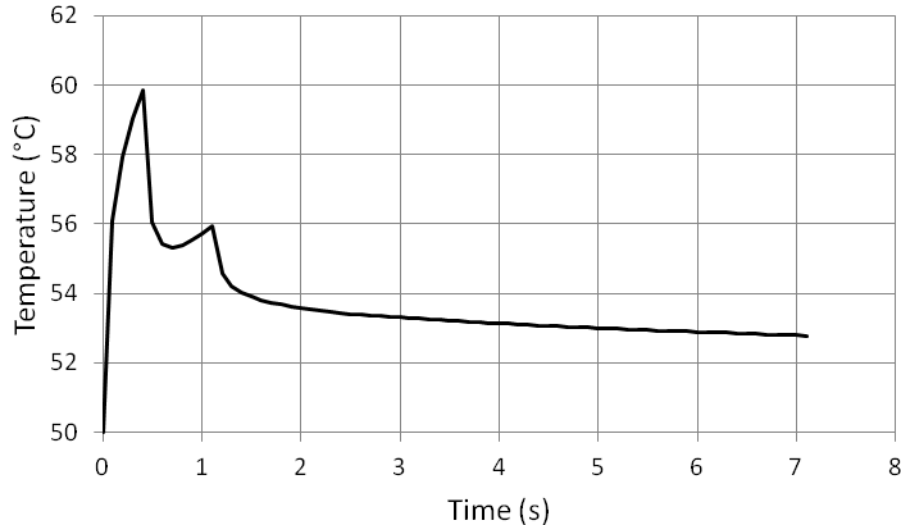


Fig. 16 Average temperature of diodes over 1 pulse plus 6 s

Figure 17 shows the maximum calculated temperature on the bottom of the mounting plate. After 2 s of cooling, we still see a maximum temperature 4–5 °C above the initial temperature. The temperature on the bottom of the mounting plate is roughly equal to the temperature of the devices 2 s after the end of the single pulse.

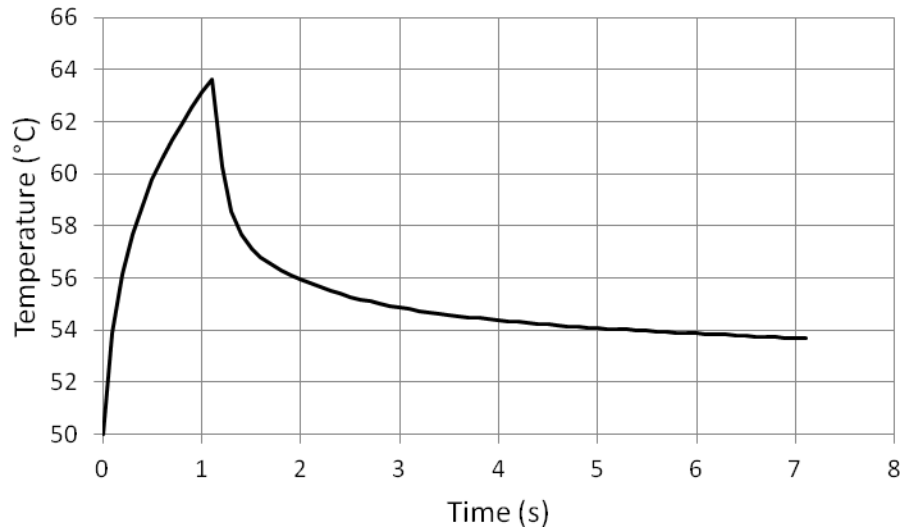


Fig. 17 Maximum temperature of bottom of Al plate over 1 pulse plus 6 s

We next performed a new simulation of 5 consecutive pulses with power off for 0.1 s between pulses. Figure 18 shows a thermal-contour plot of temperatures on the surface of the power module at $t = 5.9$ s, the end of the fifth pulse. The maximum temperature is about 85 °C, an increase of 35 °C from the base temperature.

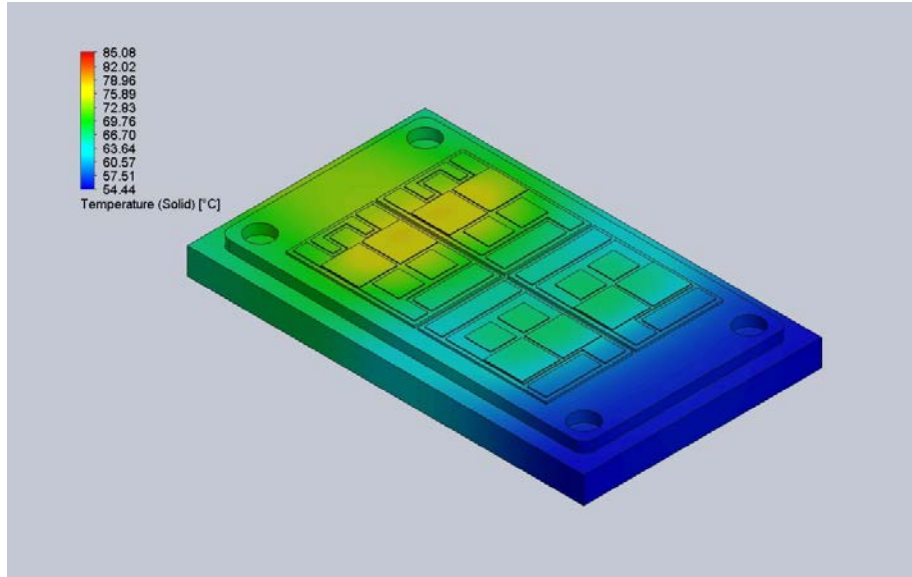


Fig. 18 Temperatures on the module's surface at the end of the fifth pulse

Figure 19 is a plot of the average temperature of the IGBTs in the power module over the course of 5 pulses followed by 4 s of cooling. The peak temperature is about 70 °C, within the safe operating range for silicon devices. Figure 20 is a plot of the average temperature of the diodes over that same period. Diode temperatures peak below 75 °C. The end of each pulse is marked by a sharp decline in temperature as heat is dissipated within the module and mounting plate between pulses; this helps to moderate the total temperature increase at the end of the pulse train.

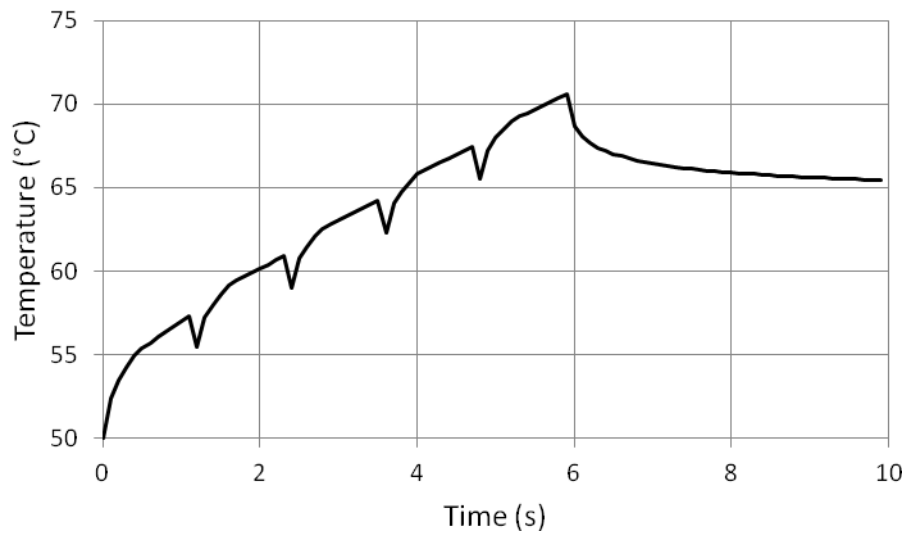


Fig. 19 Average temperature of IGBTs over 5 pulses

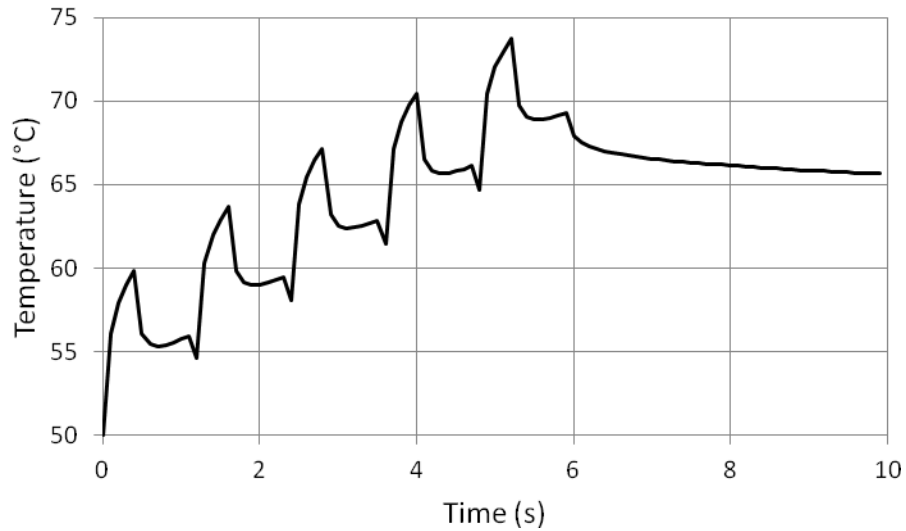


Fig. 20 Average temperature of diodes over 5 pulses

Figure 21 plots the maximum temperature calculated on the bottom of the aluminum mounting plate, the location of the thermocouples on the laboratory experiment. Temperatures at this location track with the temperatures on the IGBTs during the pulses and are 20–25 °C above the base temperature in the 2–4 s after the end of the pulse. The exterior temperature measured after 5 pulses is more than 15 °C higher than the temperature measured after a single pulse. Compare those numbers with the average temperature on the IGBTs after 5 pulses, which is about 15 °C higher at its peak than the temperature measured after a single pulse.

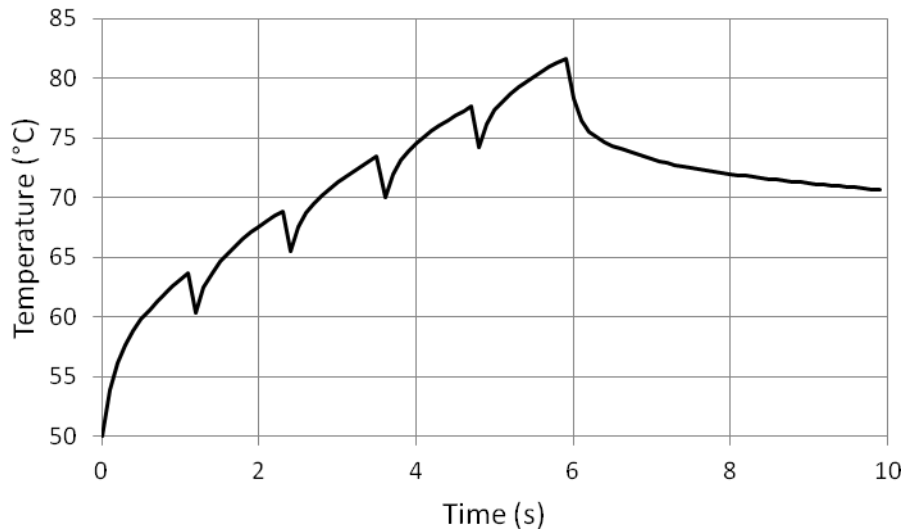


Fig. 21 Maximum temperature of bottom of aluminum plate over 5 pulses

Figure 22 shows the temperature distribution on the bottom of our model, as calculated at the end of the last power pulse.

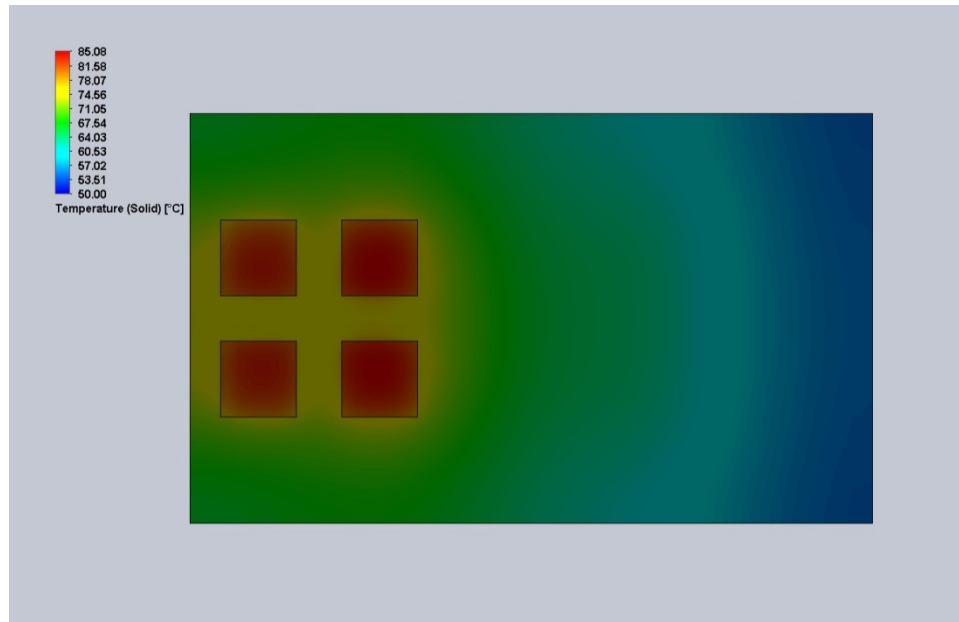


Fig. 22 Temperatures on the bottom of mounting plate, end of fifth pulse

The measured temperatures on the bottom of the mounting plate correlate roughly with temperatures inside the sealed module package. For example, the temperature on a location between the resistors in Fig. 22 is approximately 75 °C at $t = 5.9$ s, and the plot in Fig. 21 puts the average temperature of the IGBTs at approximately 70 °C at $t = 5.9$ s.

4. Conclusions

We have performed thermal simulations of the effects of time-varying pulses 1.1 s long on a commercial power module being used as a power switch for an Army pulsed-power application. The Microsemi modules use silicon IGBTs and diodes. We also performed calculations of thermal resistance with our model to determine the composition of the power module's circuit board and refine the description of the model's thermal characteristics.

Our simulations of a single pulse showed maximum temperature increases in the silicon devices of less than 10 °C. Simulation of a series of 5 pulses 0.1 s apart yielded temperature increases in the range of 20–25 °C. Our simulations predict that the temperature increases in the IGBTs and diodes resulting from 5 closely spaced pulses should be small enough that the devices would still be within their safe operating range and operating at close to normal specifications. Operating the switch at these power levels should cause no harm to the silicon devices on the board.

Our simulations show that we can correlate temperature readings on the bottom of the mounting plate to temperatures inside the power module, within limits. Measureable increases in exterior temperatures will occur when interior temperatures vary significantly; we could distinguish

between a single power pulse and 5 pulses. Exterior temperature sensors may not be able to distinguish between relatively minor differences in peak temperatures. For instance, we found that if we changed the dielectric material in the material stack, we caused modest changes in device and mounting-plate peak temperatures of 3–7 °C; however, this had little effect on the predicted temperatures after 2 s of cooling, when the temperature sensors would register their readings.

List of Symbols, Abbreviations, and Acronyms

AlN	aluminum nitride
ARL	US Army Research Laboratory
Cu	copper
IGBT	insulated gate bipolar transistor
ms	millisecond
3D	3-dimensional
W	watt

1 DEFENSE TECH INFO CTR
(PDF) ATTN DTIC OCA

2 US ARMY RSRCH LAB
(PDF) ATTN IMAL HRA MAIL & RECORDS MGMT
ATTN RDRL CIO LL TECHL LIB

1 GOVT PRNTG OFC
(PDF) ATTN A MALHOTRA

5 US ARMY RSRCH LAB
(PDF) ATTN RDRL SED C W TIPTON
ATTN RDRL SED P D PORSCHE
ATTN RDRL SED P D URCIUOLI
ATTN RDRL SED P G OVREBO
ATTN RDRL SED P M BERMAN

INTENTIONALLY LEFT BLANK.