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Thermal Simulation of a Silicon Carbide (SiC) Insulated-Gate Bipolar Transistor (IGBT) in Continuous Switching Mode

by Gregory Ovrebo

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT Thermal simulations were used to calculate temperatures in a silicon carbide (SiC) Insulated-Gate Bipolar Transistor (IGBT), simulating device operation in a DC-DC power converter switching at a frequency of up to 15 kHz. Calculations also estimated the effect of solder layers on temperature in the device.					
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1. Introduction

The US Army Research Laboratory (ARL) designed and fabricated a DC-DC converter circuit as a test bed for investigating silicon carbide (SiC) Insulated-Gate Bipolar Transistors (IGBTs) in continuous switching mode.¹ ARL is interested in the IGBTs for use in high-voltage applications for Army power systems. Thermal simulations of the continuous switching operation of the IGBTs were performed to predict steady-state temperatures in the devices, which might dictate limitations on the use of these devices.

2. Modeling and Simulation

Figure 1 is a rendering of the 3-D model prepared in SolidWorks and used in simulating the thermal behavior of the SiC IGBT during switching. The module consists of a single SiC die, 9 mm $\times$ 9 mm, with gold and aluminum contacts. The die is mounted on an aluminum baseplate.

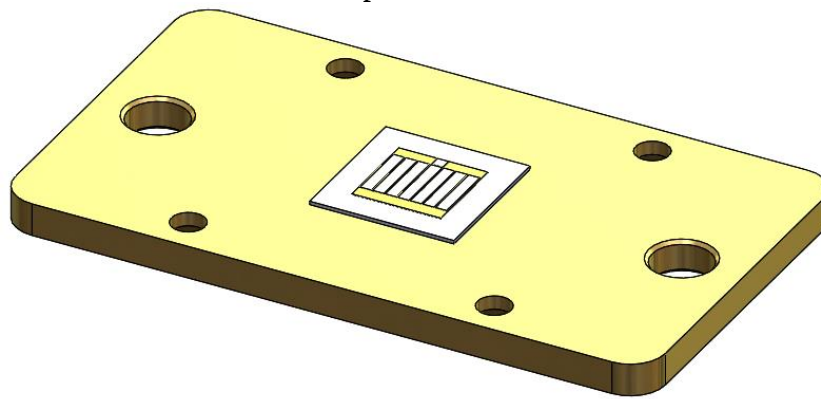


Fig. 1 SolidWorks model of the IGBT with baseplate

2.1 Simulation Conditions

Figure 2 is a plot of the gate voltage of the IGBT during switching, demonstrating the general shape and length of a single pulse during the DC-DC converter operation. Our simulation would consist of a series of such pulses, repeated until we reach a temperature equilibrium.

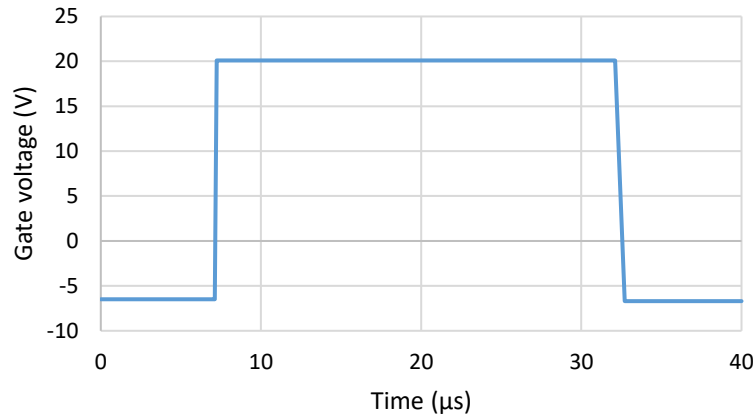


Fig. 2 Gate voltage during one cycle of the IGBT

Each pulse through the IGBT can be broken down into 4 parts: 1) switching on, 2) the on state, 3) switching off, and 4) the off state. Figures 3 and 4 show the time history of power dissipated in the IGBT during turn-on and turn-off. The power pulse at turn-on had a peak of 66 kW and the power pulse at turn-off had a peak of 40 kW. The IGBT was on for 25 μs, dissipating 170 W. Leakage during the off-state was defined as 0.05 W.

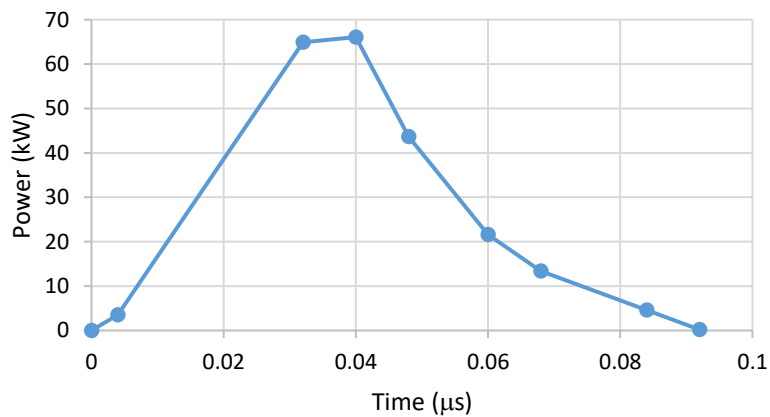


Fig. 3 Power dissipation during IGBT turn-on

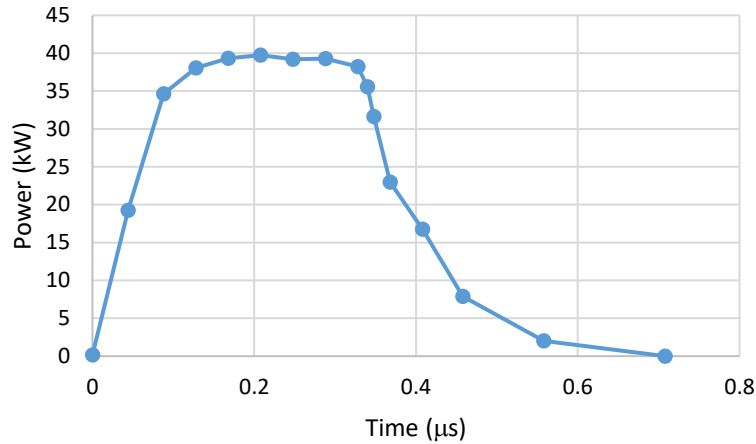


Fig. 4 Power dissipation during IGBT turn-off

Switching frequency is defined by setting the length of the off state. A 5-kHz frequency has an off-state time of 174 μs , a 10-kHz frequency has an off-state time of 74 μs , and a 15-kHz frequency has an off-state time of 40.7 μs . Because each pulse required about 2 h of physical time to run a simulation, we limited ourselves to running a simulation for the 15-kHz case only, which has the shortest time between pulses and should yield the highest device temperatures at equilibrium. The duty cycle for this case is 37.5%.

2.2 IGBT Pulse Simulation Results

A thermal simulation was performed for each individual switching cycle, which was 25- μs wide. We used SolidWorks Flow Simulation to perform the simulation. Temperatures in the model were calculated step-wise in time through the duration of the cycle. We assumed a base temperature of 20 $^{\circ}\text{C}$ for the IGBT fixture and ambient air.

Figure 5 shows the maximum temperature in the IGBT die during each pulse over 1,932 pulses at the 15-kHz repetition rate. This corresponds to a physical time of 128.8 ms. The maximum temperature during the last pulse is 47.8 $^{\circ}\text{C}$.

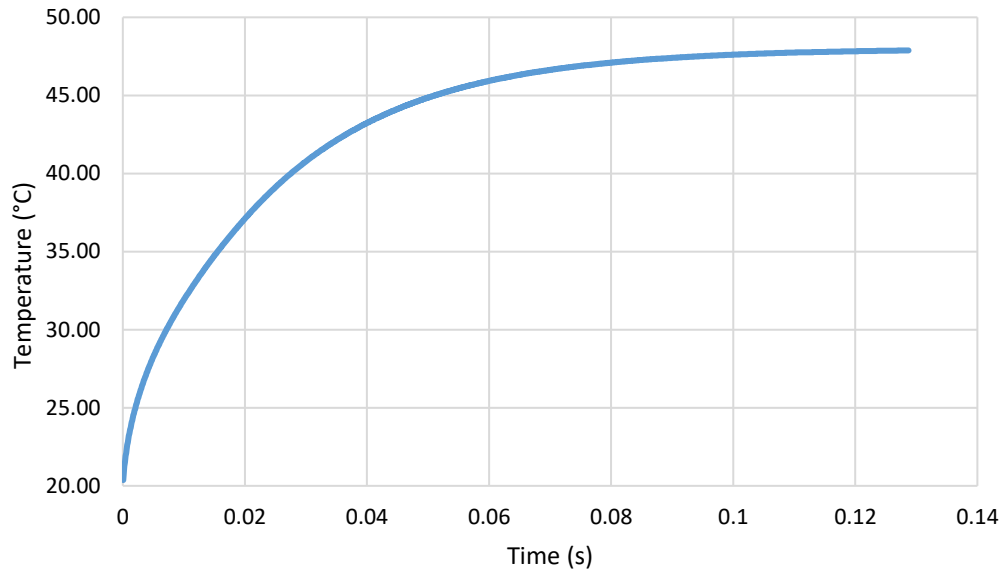


Fig. 5 Maximum temperature in the IGBT die vs. time

Figure 6 is a contour plot of temperatures on the IGBT fixture at the end of pulse number 1,932 ($t = 0.1288$ s). The maximum plotted temperature in the SiC die is 47.72 °C.

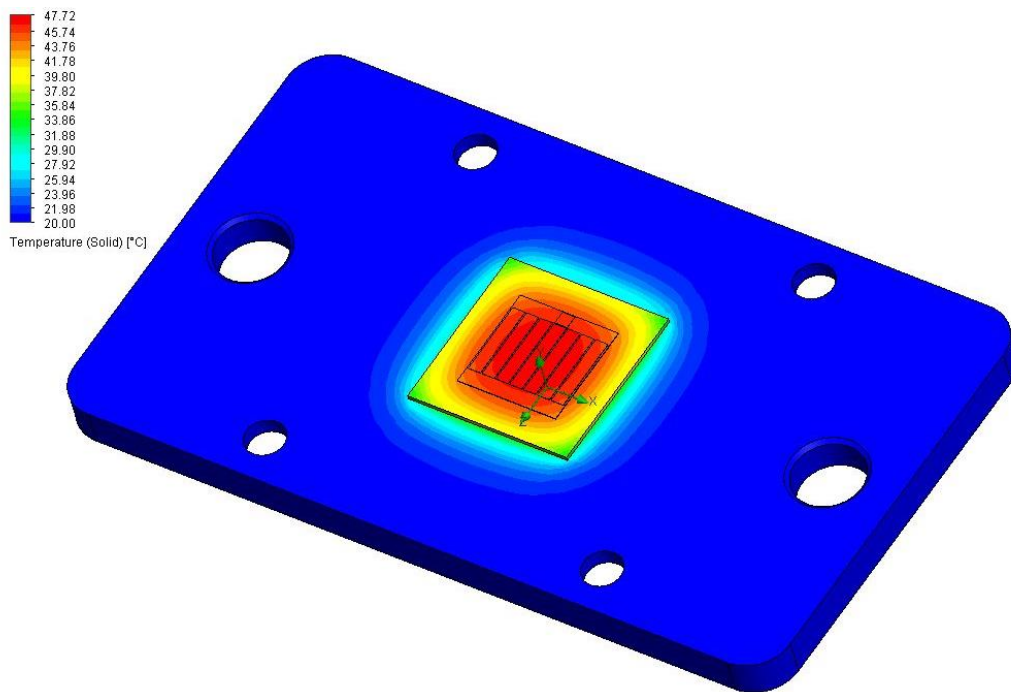


Fig. 6 Temperatures on the IGBT fixture at thermal equilibrium

These calculations assumed direct contact between the SiC die and the baseplate, with no solder layer and zero thermal resistance between the die and baseplate. The introduction of a tin-silver-copper, or SAC, solder layer between the die and baseplate would increase thermal resistance in the model and increase the temperature in the die. To account for solder layers of unknown thickness, we calculated the approximate equilibrium temperatures in the IGBT die by substituting a steady state thermal load for the time-varying input power used previously.

We used the total energy dissipated in the die over one cycle to derive a steady-state power input. Using the figures for power dissipated in the die, which are embedded in the graphs in Figs. 3 and 4, we calculated an energy deposition of 21.1 mJ per pulse. This yields an average power in the die of 105.6 W at 5 kHz, 211.2 W at 10 kHz, and 316.8 W at 15 kHz.

Steady-state calculations were made for 3 switching frequencies and 4 different SAC solder thicknesses: 0, 1, 2.5, and 4 mil. The graph in Fig. 7 plots the computed maximum temperature in the die for each of the 12 cases. In the case of our 15-kHz switching frequency, a thick solder layer between the device and the mounting plate could increase the maximum die temperature by nearly 10 °C.

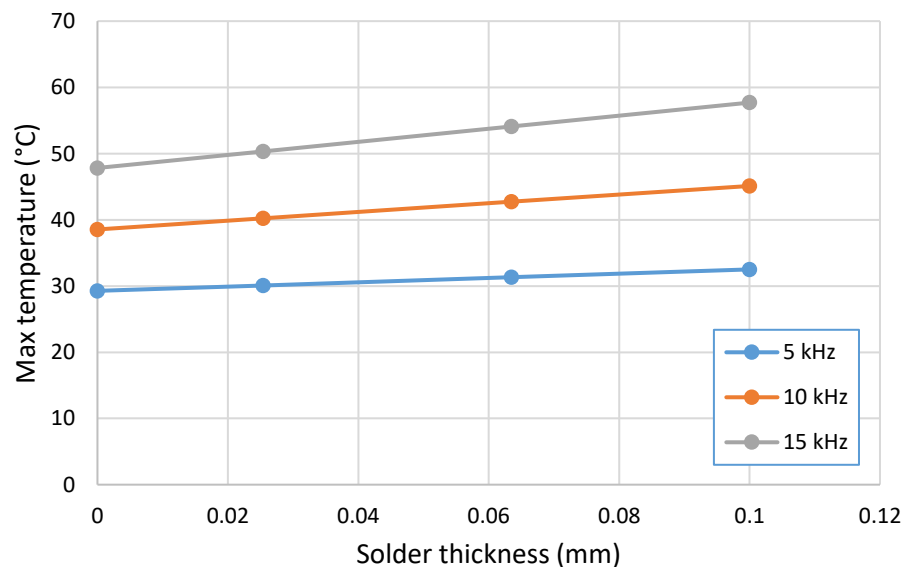


Fig. 7 Approximate maximum die temperatures with varied solder thickness

3. Conclusions

We performed a thermal simulation of an SiC IGBT that could be used in continuous switching mode in a DC-DC power converter. We assumed a 15 kHz switching rate as a worst case for thermal loading. A time-dependent calculation of over 1900 cycles saw the maximum die temperature rise to an asymptotic value of 47.8 °C, a change of 27.8 °C from the baseline.

Further calculations approximated the effects of solder layers on the temperature of the SiC die. In the case of our 15-kHz switching rate, a 1-mm layer of solder might raise the maximum die temperature by another 10 °C.

4. References

1. Hinojosa M, Ogunniyi A. High voltage, step-down converter design using 20-kV silicon carbide IGBTs. In: Garner A, editor. 2016 IPMHVC. Proceedings of the IEEE International Power Modulator and High Voltage Conference; 2016 July 5–9; San Francisco, CA.

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List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
ARL	US Army Research Laboratory
DC	direct current
IGBT	Insulated-Gate Bipolar Transistor
SAC	tin-silver-copper (SnAgCu)
SiC	silicon carbide

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