Multi-physics Modeling of a Power Electronics Package with Integrated Cooling

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***Abstract*— Recent efforts have shown that the integrated cooling approach is a promising solution to dramatically increase the power density of modern power electronics systems. With the ever-increasing demand in various industries, the overall size and cost of power electronics packages need to be minimized with multi-functional components. Thus, this study focuses on a novel integrated packaging concept for SiC MOSFET-based power modules, with expanded functionality of package components. Considering multiple trade-offs in design, the benefits of the proposed integrated approach are explored over a standard package solution in a multi-physics modeling environment. Results show that maximum stress in devices and maximum strain in joints can be significantly reduced by 58.4% and 50.0%, respectively, compared to the standard package solution. Parasitic inductance of 1.6 nH can be achieved with optimal design of electrical busbars if special care is given to the maximum electric field and minimum allowable feature sizes in design. Moreover, Joule heating effect should be addressed in miniaturized structures if the electrical input current exceeds a critical level at the electrical busbars. Overall, integrated packaging with multi-functional terminals offers superior performance over standard packaging solutions. With the understanding of the package behavior, main challenges are discussed to guide multi-physics-based design efforts in future studies.**

Keywords—power electronics, SiC, integrated cooling, multi-physics modeling, thermomechanical, electrothermal.

I. Introduction

As SiC-based power modules replace their Si-based counterparts, new packaging architectures are increasingly developed to fully benefit the superior characteristics of SiC devices. High breakdown voltage, high switching frequency, and high operating temperature are some of those advantages that promote their wide range of use in various industries, including electric vehicles, renewable energies, and industrial motors [1]. Although significant progress has been made in developing advanced package structures in the last decade, ever-increasing power density requirements continuously demand high power solutions in more compact and miniaturized forms. To address this challenge, various integrated cooling approaches have been offered as a viable solution for future power modules.

Zhou et al. [2] have studied chip-scale single-phase cooling of vertical current power electronics combining microchannel with jet impingement array architectures, which enabled a heat dissipation of 1.02 kW/cm^2 over a 0.25 cm^2 area. Compared with conventional external cooling techniques, a 5-to-10 times reduction was expected in package size using the chip-scale coolers. Boteler et al. [3] introduced stacked power devices by integrating heat sinks at the top and bottom of each device. Single function components were replaced by multi-functional ones, achieving a total package thermal resistivity of 0.25 K-cm^2/W and showing a significant advantage in terms of size, weight, and cost reduction. Liang [4] designed and fabricated advanced SiC power converters with integrated cooling using double-sided cold plate structures with pin fins. Additively manufactured special manifolds were utilized to serve matched cooling channels to the modules. Parasitic electrical impedance and thermal resistance were significantly reduced by 75% and 40%, respectively, compared to the traditional packaging approach. Jung et al. [5] designed and fabricated a silicon-based monolithic micro-cooler with embedded microchannels, capable of dissipating 250 W/cm^2 at a maximum temperature of 90˚C and a pressure drop below 3 kPa. Experimentally validated models have demonstrated the possibility of removing up to 850 W/cm^2 when the same cooling conditions are provided, which is shown as a potential solution for high heat flux power electronics.

Considering the potential of an integrated cooling solution to enhance the performance of future power modules, this study focuses on a SiC MOSFET-based power module with double-sided and integrated cooling structures. The standard power package and the proposed package with integrated cooling configurations are shown in Fig. 1 in various cross-sectional views. As depicted in the figure, Direct Bonded Copper (DBC) layers, thermal interface materials (TIMs), and single-functioning cold plate structures increase the overall thermal resistance and volume of a standard package significantly. In addition, CTE mismatch is significantly increased due to a large number of components in the package. To address the high-power density requirements, we propose a novel package with integrated cooling. In this configuration, electrical terminals, or multi-functional cold plates with current-carrying pin fins (diameter of 600 μm), are utilized as multi-functional components responsible both for power delivery and effective cooling. DBC layers, TIMs, and external cold plates are eliminated, and the power terminals are directly cooled.

Due to the significant advantages expected with the new configuration in this study, we aim to explore the benefits of the proposed integrated cooling approach over a standard package solution in a multi-physics modeling environment. With the understanding of the package behavior, key challenges are discussed to guide multi-physics-based design efforts in future studies.

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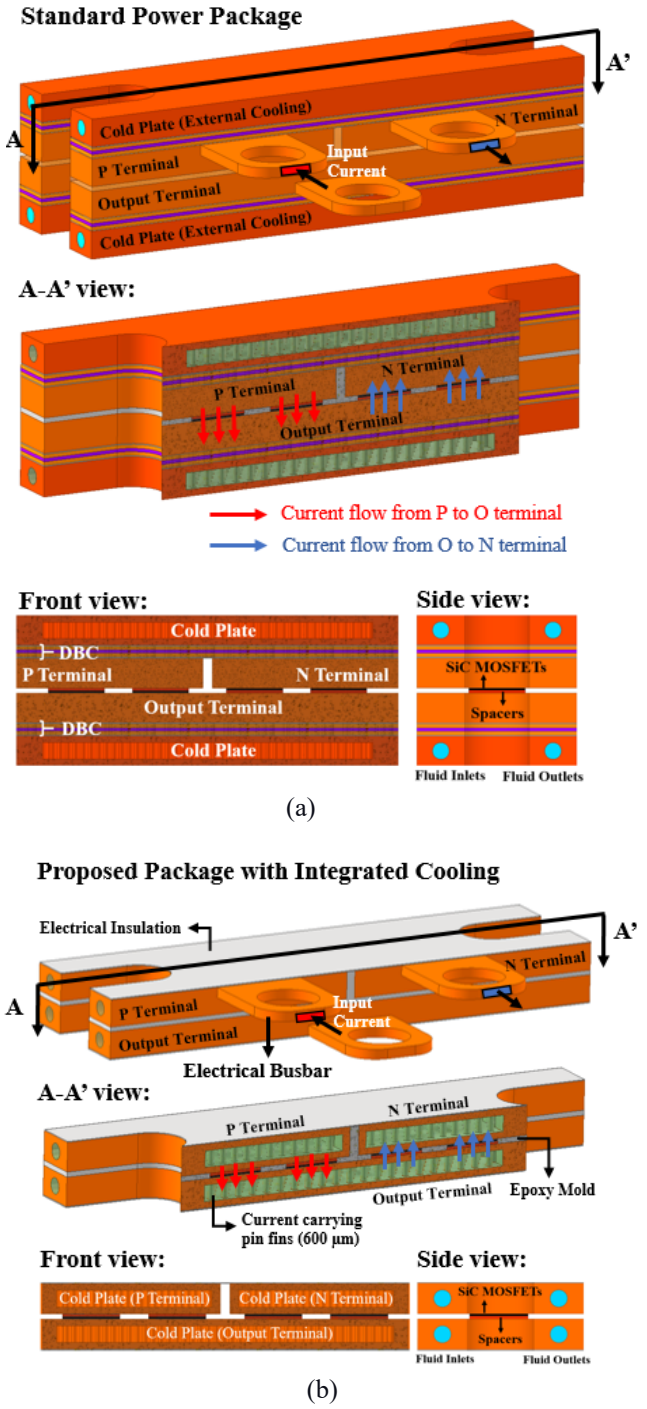

Fig. 1: (a) Standard power package, (b) Proposed package with integrated cooling, in full, A-A', front and side views.

II. METHODOLOGY

Due to the compact nature of the proposed integrated package, multiple design trade-offs must be considered to achieve overall performance superior to the standard packaging approach. In this study, the thermal, mechanical, and electrical performance of a novel integrated package has been studied with a particular focus on maximum temperature, coolant pressure drop, parasitic inductance, thermomechanical stress, and strains in vulnerable parts of the package. For this purpose, electrical, thermal, and mechanical models were created, and the potential performance improvement over standard package solutions was explored.

The required number of devices, maximum peak current, and power losses in devices were determined to achieve a 50 kW Voltage Source Inverter with Space Vector Pulse Width Modulation (SVPWM). Baseline dimensions of a half-bridge power module were determined with a multi-objective Bayesian optimization approach applied for a standard package configuration [6]. Design improvements were made over the baseline dimensions to achieve a novel power electronics package with integrated cooling, which results in maximum pressure drop below 300 mbar, junction temperature below 175°C, and maximum strain in devices and joints below 0.2%. Temperature-dependent thermal, mechanical, and electrical properties were utilized for Copper, Aluminum Nitride (AlN), Silicon Carbide (SiC), Thermal Grease, Epoxy Mold [7], [8], [9], for sintered silver [10], and for OptiCoolA [11]. Based on the design requirements above, P and N terminals or cold plates were designed with dimensions of 25.6 mm × 14.5 mm × 2.7 mm, and the Output terminal with dimensions of 52 mm x 14.5 mm x 2.7 mm (fluid channel height of 1.5 mm in each terminal). SiC MOSFET devices were attached to the terminals and Cu spacers with 20 μm thick sintered silver joints. 220 μm thick Cu spacers were utilized to enhance the thermomechanical reliability of SiC MOSFET devices (5.1 mm x 5.1 mm x 180 μm). OptiCoolA was used as a dielectric coolant to avoid short-circuit during fluid circulation. It has desirable electrical isolation properties, and its moderate thermal conductivity, and low viscosity are well suited for a wide range of power electronics applications requiring high-temperature operation. It is provided and collected from the sides of terminals with 10 mm long fluid ports. This facilitates the power module assembly as the electrical connections are provided from the front and back sides of the module.

Total power losses of SiC MOSFET devices, including conduction and switching losses, have been calculated using the device specifications [12] and guidelines [13] found in [7]. In summary, the output current passing through the inverter is determined as 208 A, based on a battery voltage of 400 V and an output power of 50 kW. Since the maximum current rating is 160 A for the SiC MOSFET device, two devices are needed per switch position with an equal current sharing. Based on the device dimensions and power loss calculations, volumetric heat generation corresponding to a heat flux of 357 W/cm^2 has been set for each device (in total, four devices).

Multiphysics analysis has been done to understand coupled fluid-structure interactions, mechanical performance under steady-state and thermal cycling conditions, Joule heating impact on cooling structures, and overall parasitics performance of the module. ANSYS Fluent, Static Structural, Thermal-Electric, and Q3D Extractor modules were utilized for the described analyses.

Thermal simulations were conducted by solving heat conduction, Navier-Stokes, and energy equations under laminar flow conditions, considering the range of Reynolds numbers between 126 and 686 in the analysis. Then, thermal and pressure loads were extracted and coupled with the static structural models to determine the stress and strain distributions under steady-state operating conditions. To

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further assess the reliability of the package, models were simulated under isothermal cycling of components in a wide range of temperatures between -30°C and 175°C. Three cycles of 600 s were implemented with ramp and dwell periods of 150 s as shown in Fig. 2. Stress and strain distributions were extracted due to the CTE mismatch of package materials at a stress-free temperature of 80˚C.

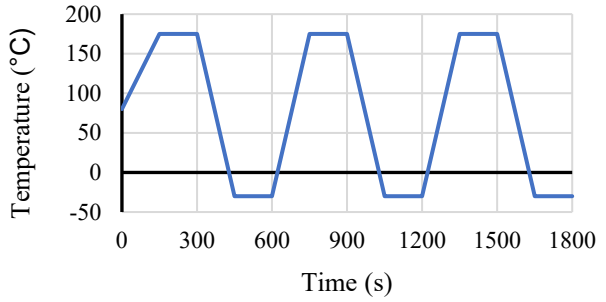

Fig. 2: Thermal cycling profile in a temperature range of -30˚C to 175˚C

Furthermore, electrical simulations extracting parasitic inductance (ANSYS Q3D Extractor) and Joule heating effect (ANSYS Electrical) were conducted to evaluate the electrical behavior of the package. A power delivery path was defined in the P, N, and Output terminals, as shown in Fig. 1.

III. RESULTS

Computational models were built for thermomechanical and electrothermal analysis of the power modules. A mesh independence study was conducted for each model to decrease the computational time and improve the accuracy of numerical solutions. Hexagonal mesh elements were utilized in SiC devices, sintered silver joints, and Cu spacers. Tetrahedral mesh elements were used in the cold plate structures and fluid domain with a sufficiently fine mesh size. In electrothermal models, grid independence is obtained above 376,600 mesh elements with negligible changes in maximum temperature and current density results (below 1% and 2%, respectively). In thermomechanical models, a larger number of mesh elements around 2.1 million was required to keep the variations in maximum temperature and pressure below 3%.

A. Thermomechanical Analysis of Integrated Package

Considering the maximum pressure drop (300 mbar) and minimum feature size (600 µm) limits of design, the thermomechanical performance of the integrated cooling solution has been improved, and the overall performance has been compared with a standard package under identical cooling conditions. Fig.1 shows the thermal and flow analysis of the standard and the integrated package at the same pumping power. Overall thermal resistance, total pressure drop, and total pumping power were evaluated based on the following definitions:

$$R = \frac{\Delta T}{Q} = \frac{T_J - T_{in}}{Q} \tag{1}$$

where R, T_j, T_{in}, and Q represent overall thermal resistance, junction temperature, inlet temperature of coolant, and total heat dissipation rate.

$$\Delta P_{total} = \Delta P_{Pterminal} + \Delta P_{Nterminal} + \Delta P_{Oterminal} \tag{2}$$

where ΔP_{total}, $\Delta P_{Pterminal}$, $\Delta P_{Nterminal}$, and $\Delta P_{Oterminal}$ stand for total pressure drop, pressure drop in P, N and Output terminals, respectively.

$$W_{pump,total} = \Delta P_{Pterminal} * V_{Pterminal} + \Delta P_{Nterminal} * V_{Ntemrinal} + \Delta P_{Oterminal} * V_{Oterminal} \tag{3}$$

where $W_{pump,total}$, $V_{Pterminal}$, $V_{Nterminal}$, $V_{Oterminal}$ indicate total pumping power, volumetric flow rate in P, N, and Output terminals, respectively.

A coupled thermomechanical model was run for volumetric flow rates of 53, 68.9, 84.8, 106, 132.5, 159, 212.1, 254.5, 286.3, and 381.1 mL/min through each cold plate at a heat flux of 357 W/cm^2. The fluid was provided at an inlet temperature of 80˚C to evaluate the design performance under harsh conditions. Since the same cold plates under identical pumping power were used in the standard and integrated packages, the total pressure drop behavior of the cold plates in both package configurations was represented as a single plot in Fig. 3. Based on the analysis, the optimal flow has been determined in the range of 159 mL/min - 255 mL/min to extract the maximum thermal benefit from integrated cooling, without exceeding the maximum pressure drop limit of 300 mbar. At a volumetric flow rate of 212.1 mL/min and the corresponding pumping power of 85 mW, the overall thermal resistance of packages is found to be 0.22 ˚C/W, and 0.16 ˚C/W for standard and integrated solutions, respectively. At this condition, the maximum increase in temperature of devices is 81.6˚C and 60.5˚C, for the standard and integrated packages respectively. This shows a significant reduction in junction temperature when the integrated solution with multi-functional cold plate structures is utilized.

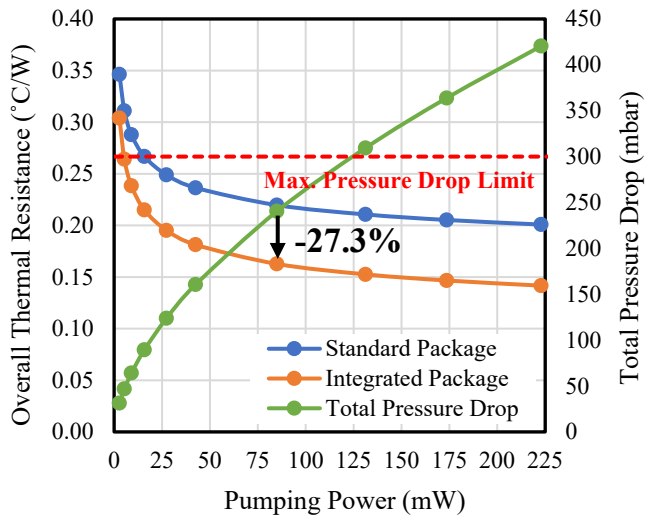

Fig. 3: Variation of overall thermal resistance and total pressure drop of the standard and integrated package with pumping power

Fig. 4 shows the temperature distribution in the integrated package (a), with a zoom-in flow distribution in the P terminal (b), and a-zoom in temperature distribution in devices (c). Fluid spreads at the entrance region of the cold plate and is then distributed to the inner parts of the cold plate. Due to the diagonal flow direction in the cold plates, devices close to the center plane of the package are observed to be at lower temperatures than the ones at the sides. Temperature variations in devices could be further reduced using novel fin

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structures that may help deliver the fluid to the inner sides of the cold plate more effectively. Additive manufacturing can be a promising option to enhance the thermal performance of the cold plates in designing such novel structures.

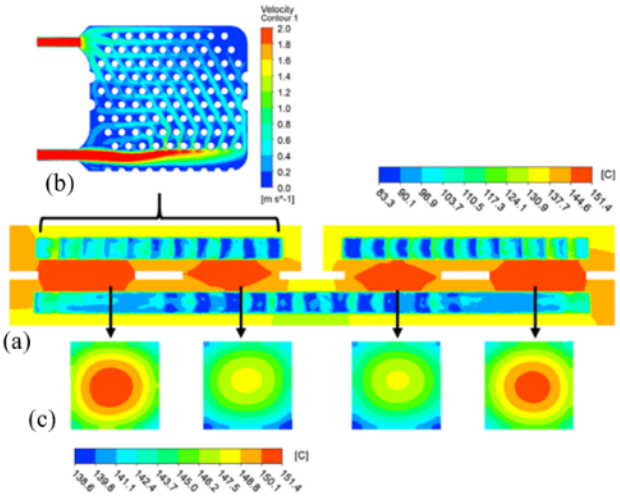

Fig. 4: (a) Temperature distribution in the package with integrated cooling solution, (b) a zoom-in flow distribution in the P terminal, (c) a zoom-in temperature distribution in power devices (volumetric flow rate of 148 mL/min through each terminal)

In addition to thermal and flow analysis, coupled thermomechanical analysis was conducted to evaluate the stress in power devices in the standard and integrated packages due to the flow pressure and temperature gradients in the package. The maximum stress in devices and maximum strain in joints has been determined as the critical parameters to assess the reliability of the package under steady-state operation and thermal cycling conditions respectively.

Von-Mises (Equivalent) stresses under steady-state operation were plotted for a range of pumping powers in Fig. 5. Compared to the standard package, a significant reduction by 52.2% to 60.2% has been observed for the integrated package, depending on the flow conditions. Considering the pressure drop limit and the maximum improvement in thermomechanical performance, a pumping power in the range of 43 – 130 mW has been determined as a viable choice. For the pumping power of 85 mW, maximum stresses in the devices are 420.6 MPa and 174.8 MPa, and the average stresses are 350 MPa and 112.4 MPa, respectively, for the standard and integrated packages. In addition, the maximum strain in joints with integrated cooling solutions is 0.17%, compared to 0.34% in the standard package under the same pumping power condition (85 mW). Similar analysis has been made under isothermal cycling of package components in standard and integrated packages. It has been determined that the maximum stress in devices is 668.9 MPa and 362 MPa, and the average stress is 568.9 MPa and 241.8 MPa in the standard and integrated packages, respectively. A noticeable reduction was observed in the maximum strain of joints, from 0.57% to 0.36% when integrated cooling approach replaced the standard solution. Although thermal cycling resulted in relatively higher stress and strain compared to steady-state condition, both analyses show that the reliability of devices and joints is significantly increased when the integrated cooling solution is used.

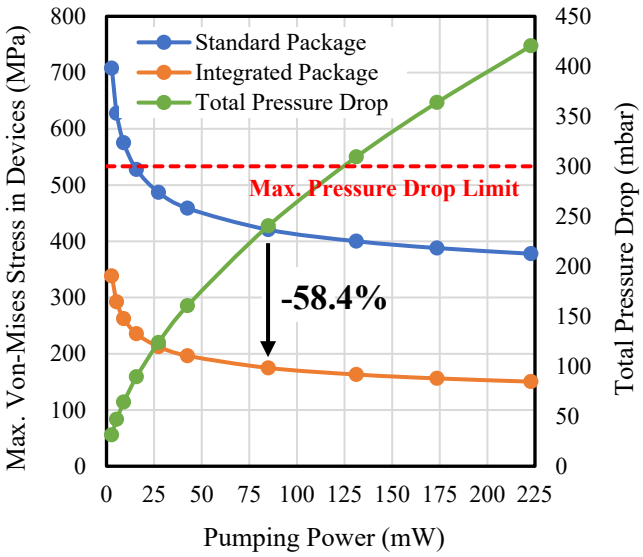

Fig. 5: Variation of maximum Von-Mises stress in devices and total pressure drop of the standard and integrated package with pumping power

One of the key challenges that need to be addressed in the proposed integrated cooling solution is to provide sufficient heat spreading at the die level. Since a number of layers is eliminated to achieve a more compact module, effective heat spreading with a few numbers of layers becomes a challenging task as the overall size of components is reduced significantly. Thus, multi-physics design efforts should target a compromise between heat spreading, heat removal, and power density levels of these multi-functional miniaturized systems. In fact, rapid evolution of additive manufacturing technologies in the recent years may offer novel and effective solutions to achieve multi-objective goals in these structures.

B. Electrical Analysis of Integrated Package

The parasitic inductance of a power module is a critical parameter that should be evaluated to ensure desirable electrical performance with minimum power losses. The switching transients in terms of the current slope di/dt are affected by the parasitic inductance. If the parasitic inductance is not sufficiently reduced, it may lead to high voltage overshoots and dangerous stress levels in devices during their transient operation. In addition, the maximum achievable switching frequency could be significantly reduced due to undesirable parasitics [1].

Since the cooling structures are integrated as electrical terminals in the package, and there is no external cooling medium that creates the common mode noise issue, parasitics analysis has only focused on extracting parasitic inductance of the package. The parasitic stray inductance generated in the interconnections of the package was evaluated to achieve improved electrical performance in the integrated package. The main switch loop stray inductance was identified as the equivalent series inductance created between the P and N terminals. Parametric analysis was made to understand the impact of the dimensions of the cold plates, the number of pin fins, and the dimensions of the electrical busbars. The most dramatic change in parasitic inductance is observed when the electrical busbar design is altered. Shorter, wider, and thicker busbars result in lower parasitic inductance values. In the initial design configuration with integrated cooling, parasitic

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inductance was calculated to be 10 nH when the busbars were 10.5 mm x 9 mm x 1 mm in size and separated with 11 mm distance between the P and N terminals. However, it can be greatly reduced to 1.6 nH if the distance between the busbars is decreased to 2.5 mm, and their dimensions are modified to 4 mm x 13.3 mm x 2.7 mm. The significant reduction in parasitic inductance values with the change in distance and dimensions of the busbars can be attributed to the magnetic field cancellation between P and N terminals [14]. To come up with an optimal package design, trade-offs should be considered in terms of the maximum allowable electric field in the package, the dielectric strength of air and insulation materials, and the minimum feature sizes allowed for manufacturing and assembly processes.

Another set of electrical simulations was made to understand if Joule heating of multi-functional cold plate structures creates a significant problem due to high current delivery through these structures. Temperature-dependent electrical properties were defined for all conducting components of the package. The electrical current entered from the busbar of the P terminal and exited from the busbar of the N terminal (as it is defined as 0 V). Furthermore, all devices were defined as perfect conductors to allow the current flow from P to N terminal.

To analyze the impact of Joule heating under a realistic cooling condition, internal finned and plain surfaces of the cold plates (P, N, and Output terminals), where the heat removal occurs, were defined with an effective heat transfer coefficient of 3,500 W/m^2.K. The temperature distribution is analyzed for different electrical input currents at a fixed power loss of devices (92.9 W for each), as shown in Fig. 6. Critical regions of the package are identified at various electrical conditions to assess the impact of Joule heating.

It is expected that Joule heating could significantly raise the temperature at locations with small feature sizes due to increased current density levels. Since it increases with the square of the current, and temperature-dependent resistance of a conducting material (I^2.R), the thermal performance of the structures against Joule heating should be examined carefully as they are miniaturized. Joule heating analysis of the integrated package demonstrates that the maximum temperature of devices does not change by more than 2.5˚C in the range of 50 A to 400 A. On the other hand, the temperature of busbars increases significantly beyond a critical current level. Fig. 6 shows the change in maximum temperature of the P terminal with a 1 mm-thick busbar. If the package is operated beyond the critical current, the location of maximum temperature in the terminal changes from the nearby device region to the electrical busbar region. A similar trend is observed when the thermal behavior of the N terminal is examined. At the critical current level, the maximum temperature in the package is observed in electrical busbars rather than in devices.

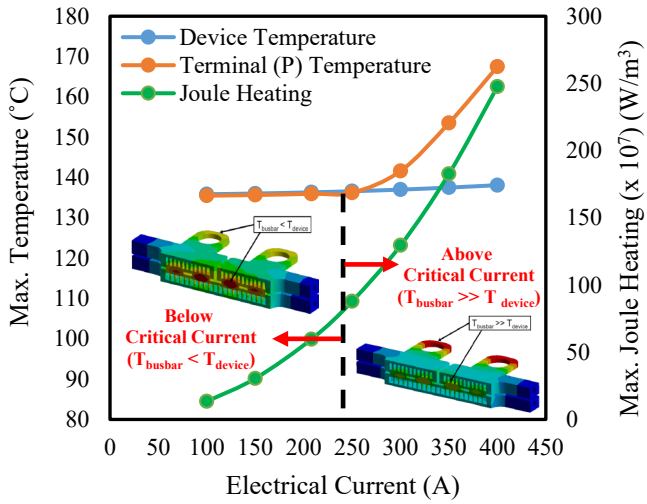

Fig. 6: Joule heating impact below and beyond critical input current

Joule heating gets more impactful as thinner busbars are used due to lowered critical current levels. Since the electrical properties are a strong function of temperature, the electrical performance of a power module may be negatively affected due to excessive Joule heating in the critical regions of a module. Higher critical current levels and lower parasitic inductance values can be achieved if thicker busbars are utilized. However, the power density of a module is decreased if thicker busbars and terminals are used. Therefore, design trade-offs between the size of structures and critical current levels should be considered as more compact packages are designed.

IV. CONCLUSIONS

Integrated cooling with multi-functional components is found to be a promising approach to improve the performance of SiC-based high-power electronics. However, multi-objective design trade-offs should be performed to maximize the benefits of this solution. Achieving sufficient heat spreading and heat removal in high power electronics applications is recognized as one of the main issues as the integrated structures are miniaturized to reach higher power density levels. Constraints regarding maximum pressure drop, maximum junction temperature, and minimum stress and strain levels may pose significant challenges that require multi-physics-based understanding of the novel package structures. In addition, as the number of functionalized components increase in the packages, higher magnitudes of electrical currents may create unexpected thermal issues or may decrease the reliability of the components as their feature sizes are lowered. Novel geometries enabled by additive manufacturing solutions could alleviate multi-physics design challenges, however, minimum feature sizes and available material options are currently one of the main limitations in this technology. Overall, integrated cooling with enhanced functionality introduced in this study shows favorable performance based on the multi-physics-based analyses. With the understanding of the package behavior in this study, future studies will focus on exploring the practical approaches to implement the proposed solution.

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