Thermal and Mechanical Design of a High-Voltage Power Electronics Package

Preprint

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***Abstract*—This paper presents the thermal and mechanical design aspects of a power electronics package with 5-kV GaN devices. Through finite element analyses, we investigated the impact of different cooling configurations and device locations on the thermal performance and reliability of the package. We found that placing the devices closer to the direct bond copper substrate as opposed to a centered approach in the proposed double-sided cooling configuration resulted in improved heat dissipation. This approach also reduced the total number of attachment layers, thereby likely improving the reliability of the package. Furthermore, simulations revealed that the device location had a negligible impact on the thermomechanical behavior of the attachment layers, as they are more prone to the local coefficient of thermal expansion mismatch.**

Keywords—electronic packaging, wide-bandgap device, gallium nitride, thermal management, reliability

I. Introduction

Power electronics systems play a critical role in driving innovation and growth in renewable energy and energy-efficiency technologies such as wind turbines, smart grids, concentrating solar power systems, solar photovoltaics, and electric-drive vehicles [1]. At the heart of a power electronics system are the semiconductor switching devices and the package surrounding these devices. Device properties and package robustness determine the range of applicability of a power electronics system. In today's electric drivetrains, silicon (Si) is widely used as the semiconductor device. However, demands for higher efficiency and power density, improved performance, and lower cost have motivated a paradigm shift in power electronics to wide-bandgap devices such as silicon carbide (SiC) and gallium nitride (GaN) [2]. Although these wide-bandgap devices have started to enter the commercial space in recent years, their packaging designs [3] have not reached maturity, especially for high-temperature and high-voltage applications. To this end, a double-side cooled, 5-kV GaN power module was designed under an Advanced Research Projects Agency–Energy-funded project. In this paper, we report on the thermal and thermomechanical simulations conducted to study and improve the performance and reliability of the proposed power module design.

II. Package Design

Fig. 1 shows the schematic of the GaN power module designed in this project. The design consists of four GaN devices at the center of the package bonded to molybdenum posts at the top and bottom. The outer ends of the posts are attached to a direct bond copper (DBC) substrate with alumina (Al_2O_3) as the ceramic material. Although the package design presented here shows baseplates attached to the outer faces of the DBC substrates, the material stack-up can also be terminated at the DBC layer. In some cases, having a baseplate can be beneficial as it allows for more heat spreading within the package and thus increases the effectiveness of the thermal management solution. We considered sintered silver as both the device-attach material and at the attachment layers between the posts and the DBC.

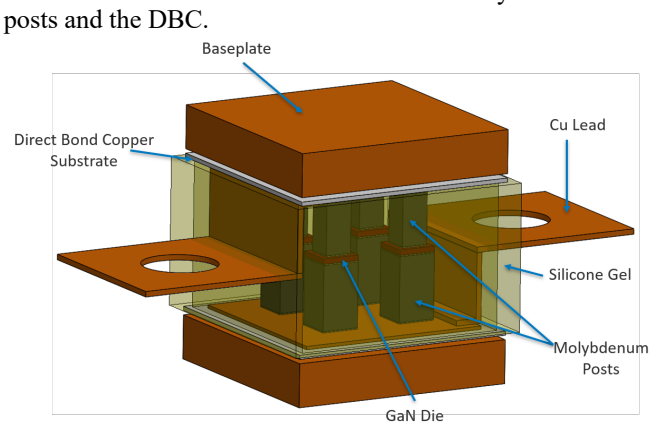

Fig. 1: GaN power module design.

III. Thermal Analysis

The objective of the thermal simulations was to evaluate the effectiveness of the proposed cooling methods, identify and

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resolve thermally problematic areas in the package, and determine the best method of cooling the device within the design constraints. Two cooling approaches, as shown in Fig. 2, were evaluated using finite element analysis. The heat exchanger approach (Fig. 2 - top) is similar to traditional cold-plate cooling where heat exchangers are placed on either side of the package. The heat exchanger is represented as a convective heat transfer coefficient (*h* in the figure). The 5-kV design requires physical separation of the terminals and the package to be filled with a dielectric fluid for electrical insulation, which makes heat removal from the package using traditional means (Fig. 2 - top) more difficult due to long conduction pathways. The second approach (Fig. 2 - bottom) attempts to turn this disadvantage into a cooling advantage by utilizing the dielectric fluid as the coolant and using the long electrical standoffs or posts as fins, effectively turning the package into its heat exchanger. Utilizing electrically insulating fluids for thermal management is common practice in utility transformers [4] and is also being studied for power electronics applications [5].

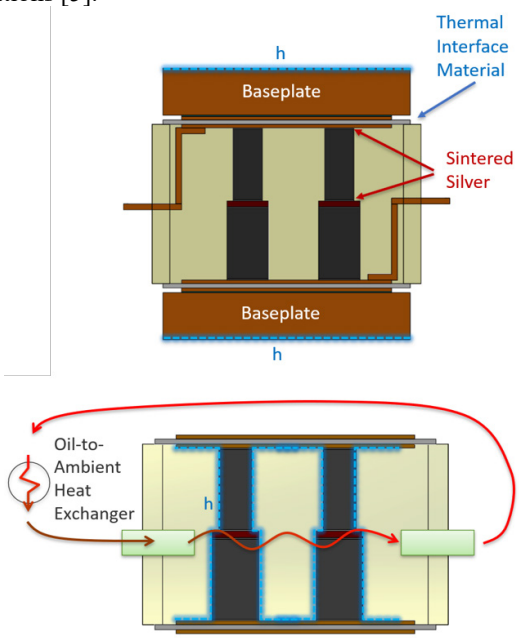

Fig. 2: Thermal management solutions: heat exchanger approach (top) and oil flow-through approach (bottom).

To evaluate and compare the two cooling methods, the convective heat transfer coefficient was swept across a range of values from 10 W/m²·K, representative of natural convection in air, to 100,000 W/m²·K, representative of a very aggressive single-phase liquid-based heat exchanger or phase-change heat transfer. For each convective heat transfer coefficient, a heat flux boundary condition was determined such that the maximum junction temperature of the devices equaled 200°C. The heat flux boundary condition applied to the devices represents the total average losses in them. The oil flow-through design performed better (required less-aggressive cooling) than the heat exchanger design. However, to work effectively it would require additional surface enhancement (such as fins) to be added to the posts, which in turn would require additional design and evaluation on the electrical design to ensure the surface enhancements would not result in unwanted electrical discharge. Additional design work would also be required to optimize the fluid flow through the package. The uncertainty with the oil flow-through technique and limited project resources made pursuing the oil flow-through concept prohibitive, and so the heat exchanger approach was utilized moving forward. However, the oil flow-through technique shows promise for applications where it is not possible to get water-based (electrically conducting) coolants near the devices.

To identify thermally problematic areas within the package, the temperature was plotted along a path through the center of the device (1 to 2 in Fig. 3). Locations of high-temperature gradients (horizontal lines in the plot) indicate highly thermally resistive components, whereas regions of low-temperature gradients (vertical lines) indicate highly thermally conductive components. The thermal interface material (TIM) and the DBC substrate represent the highest thermal resistance per length in the package. However, long sections with moderate temperature gradients also posed significant thermal resistances, as shown in Fig. 3 with a 100°C temperature drop.

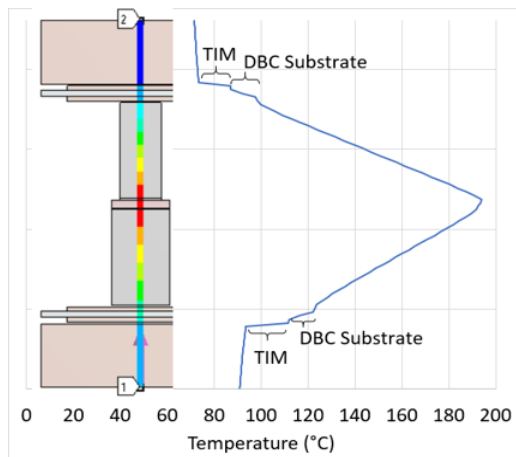

Fig. 3: Temperature profile through the package.

It is not critical to the electrical performance of the package to have the devices in the center of the molybdenum posts as shown in Fig. 1. Hence, it was possible to evaluate designs where the devices were moved closer to the DBC, thereby significantly eliminating the thermal resistance of the molybdenum posts. Three alternative designs were evaluated: all the devices on one DBC, and two variations of placing half the devices on one DBC and the other half on the other DBC to fully utilize the double-sided cooling. Fig. 4 shows a comparison of the different cooling configurations. The plot shows the 300-W/cm² target heat flux, along with the baseline (devices in the middle) for comparison. Placing all devices on one side reduces the heat exchanger performance requirement for the target heat flux to 3,100 W/m²·K if the package uses one heat exchanger on the DBC with the devices, or 2,200 W/m²·K if the package uses heat exchangers on both sides. Dividing the devices evenly between the two DBCs (inline or diagonal configuration shown in Fig. 4) reduces the heat exchanger performance requirement for the target heat flux to 1,400 W/m²·K.

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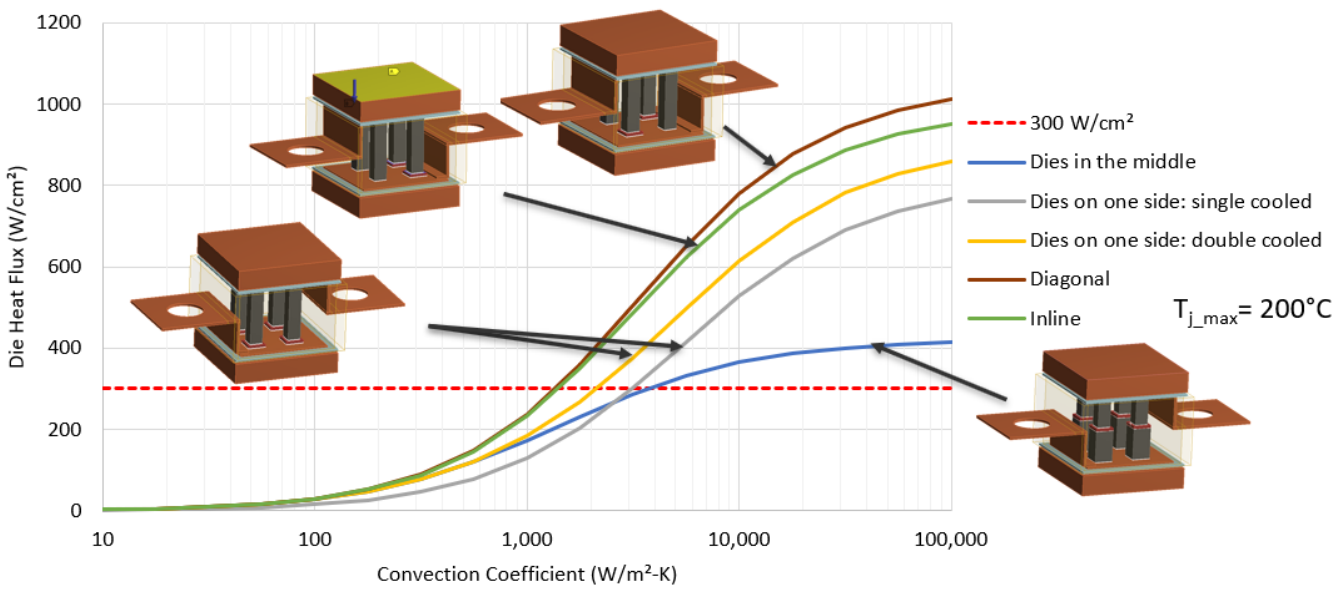
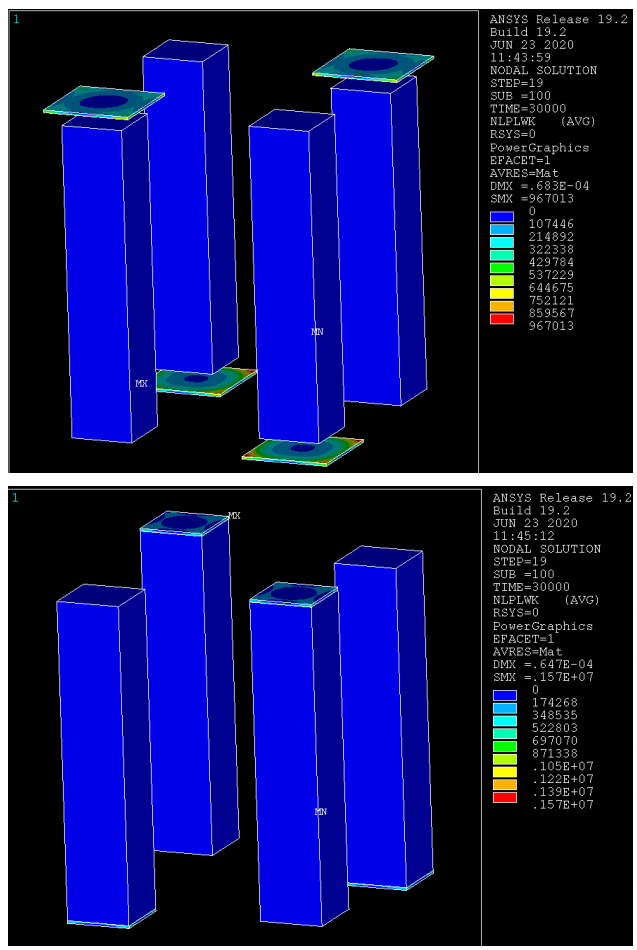


Fig. 4: Comparison of package configurations.

With the knowledge of cooling requirements determined, it was possible to select an appropriate heat exchanger. Computational fluid dynamics was used to quantify the performance of an off-the-shelf heat exchanger, and it was determined that the heat exchanger could be used on the double-side cooling layouts but not the single-side layout or the layout with devices in the center.

IV. Thermomechanical Analysis

The objective of the thermomechanical simulations was to investigate the reliability of select package designs, as shown in Fig. 4—specifically the diagonal, inline, and baseline (devices at the center of the package as shown in Fig. 1) configurations. Strain energy density values in the various attachment layers within these package designs under a thermal cycling loading condition were computed and compared. In these simulations, linear elastic material properties were used as inputs to define the different material components, and the Anand viscoplastic constitutive model [6] was included, in addition to the elastic properties, for the attachment layers. Sintered silver was assumed as the material for these attachment layers. In the Anand model, the strain increment due to creep (time-dependent) and plasticity (time-independent) is combined into a single equation and is suitable for capturing the degradation behavior of a material under thermal cycling. A thermal cycle from −40°C to 200°C with a 5°C/min ramp rate and 10-min dwell at both extreme temperatures was applied as the load, and as noted above, values of strain energy density per cycle were computed at the different attachment layers. Strain energy density is a theoretical parameter that is obtained as the product of stresses and strain increments within the model. The higher the strain energy density value, the lower the lifetime of the attachment layer.



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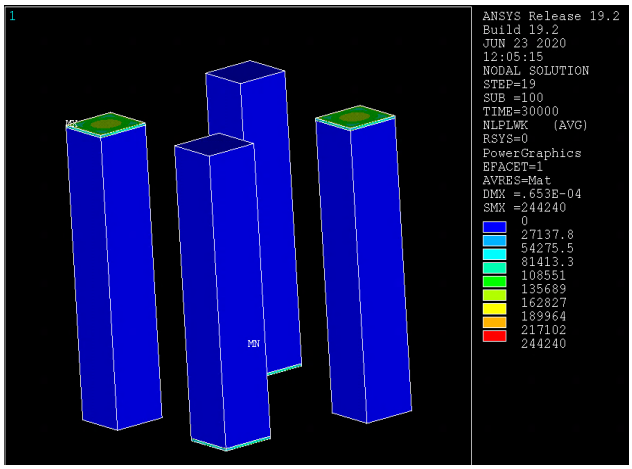

Fig. 5: Strain energy density contour plots of device attach (top), post attach (middle), and device-post attach (bottom). Molybdenum posts are included for visual reference.

Copper leads and the encapsulant were excluded from thermomechanical simulations, as they would have minimal impact on the main regions of interest—the attachment layers. In these package designs, the attachment layers can be broadly classified into three categories: device attach (between devices and DBC), post attach (between molybdenum posts and DBC), and device-post attach (between devices and molybdenum posts). After the solution phase, strain energy density values were volume-averaged [7] over these regions and then calculated per thermal cycle. Fig. 5 shows the strain energy density contour plot of the different attachment layers in the diagonal package design.

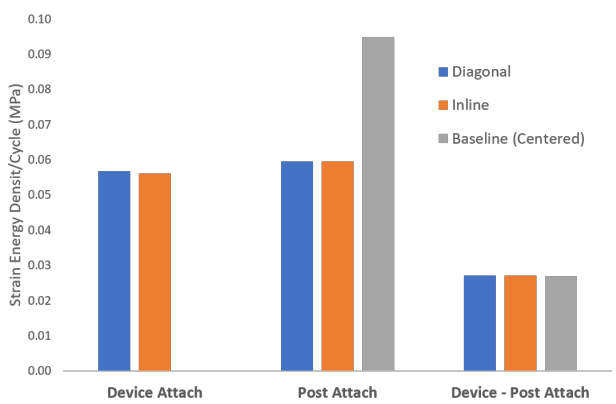

Fig. 6: Strain energy density results of different package configurations.

The strain energy density values of various layers in the baseline, diagonal, and inline package designs are shown in Fig. 6. In general, little difference was noted between these configurations for all three attachment layers except for the post attach in the baseline design. This difference is due to the thicker posts used in the bottom half of the baseline design. Also, these results predict that the post attach is more prone to degradation under thermal cycling, followed by the device attach and device-post attach. The relatively lower values of strain energy density at the device-post attach layers is due to the negligible coefficient of thermal expansion mismatch between the GaN devices and the molybdenum posts. The magnitude range of the strain energy density values possibly indicates a reasonably sufficient lifetime of these packages, although this cannot be quantified without any accelerated thermal cycling experiments.

V. Conclusions

- Although oil flow-through cooling enables higher heat dissipation in the devices, it is significantly more difficult to implement than a standard heat exchanger cooling method. The heat exchanger cooling method met the heat dissipation targets for this project.
- Modifying the package by placing devices closer to the DBC and distributing them between the top and bottom DBCs reduces cooling requirements to enable the use of simple, off-the-shelf heat exchangers, reducing cost and design complexity. Also, no significant change in the thermomechanical performance of the attachment layers was observed among the different package design configurations.
- The next steps include studying the impact of the length of molybdenum posts on the thermal performance and reliability of the package, as well as increasing the number of devices to improve the voltage rating.

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