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Thermal Characteristics and Simulation of an Integrated GaN eHEMT Power Module

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Keywords

≪Packaging≫, ≪Gallium nitride (GaN)≫, ≪Thermal design≫, ≪Simulation≫.

Abstract

Compact power modules are emerging which combine both direct bonded copper (DBC) and printed circuit boards (PCB) in integrated structures to achieve fast switching of wide bandgap semiconductors. The literature presenting the new integrated structures only include the DBC in their thermal analysis, and thus the influence of the PCB is often disregarded. In this paper the thermal characteristics of a new integrated GaN eHEMT power module are obtained experimentally. A simulation workflow to extract the thermal characteristics of the integrated module structure using finite element method software is presented and verified. The results predict an error of up to 13 % in thermal impedance if the PCB board is not included in the simulation model.

Introduction

New power module and packaging solutions are being developed to better utilize the benefits of new commercially available wide bandgap (WBG) semiconductor devices, based on silicon carbide and gallium nitride. Compared to silicon one of the main benefits offered by the new WBG devices are faster switching speeds, resulting in lower switching losses and higher power densities. The full potential of WBG is difficult to achieve using conventional packaging structures. Typically, semiconductor devices are soldered to a direct bonded copper (DBC) and packaged as a standalone component. External leads of the component are then soldered to a printed circuit board (PCB) for interconnection with crucial elements such as DC-link capacitors and gate driver circuits. This typically results in power loop and gate driver loop inductances in the range of 10-30 nH. Recent developments in power module packaging is to integrate the semiconductor device with both the DBC and PCB, such as the structure shown in Fig. 1 [1]. Using such hybrid DBC/PCB approaches enable parasitic inductances as low as 1.1-2.7 nH [1–4], while the thermal performance is maintained at a level similar to conventional power modules.

However, the literature presenting thermal analysis of the integrated DBC/PCB hybrid power modules is done without the modelling of the PCB and its copper layers/traces [1, 3, 5]. This could suggest that

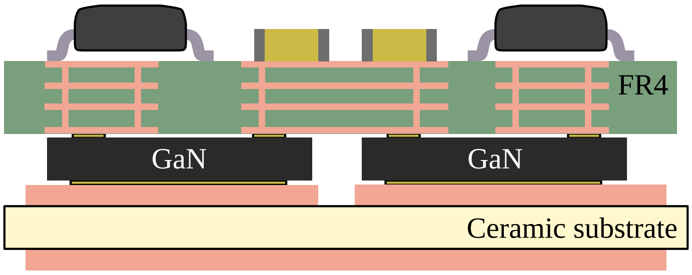

Fig. 1: Structure of integrated GaN eHEMT power module.

simulation of the total power module structure including the PCB is cumbersome or that the thermal impact of the PCB is insignificant and therefore can be rightfully left out. Secondly, no literature has experimentally verified the thermal performance of the new integrated DBC/PCB power module structures.

In this paper, the thermal characteristics are experimentally demonstrated of an integrated DBC/PCB power module based on GS66508T GaN eHEMT devices, as shown in Fig. 2. Additionally, this paper presents a software framework to build up a model of the DBC/PCB power module which includes the influence of the PCB on the thermal performance.

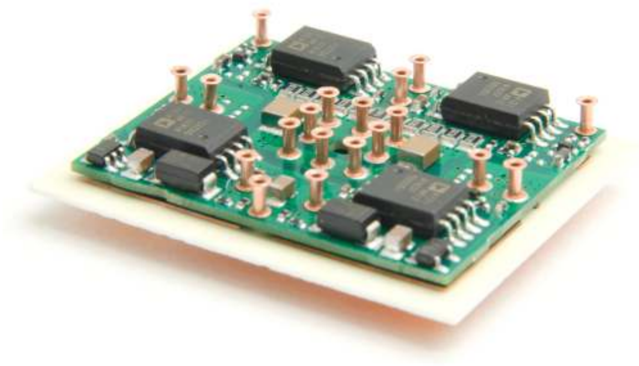

Fig. 2: Picture of integrated GaN eHEMT power module.

Methodology

The methodology to obtain the thermal characteristics of the power module is the same for both the simulation and the experiment. The approach, as described in [6], is to apply a step input of power to one of the devices in the power module and measure the device temperatures as a function of time. This gives information about the thermal impedance of the device and its thermal coupling to other devices. The procedure is then repeated once per device. The thermal impedance from a device to ambient based on its power dissipation is calculated

$$Z_i(t) = \frac{T_i(t) - T_a}{P_i(t)} \tag{1}$$

where Z_i is the thermal impedance of device i, T_i is the temperature of device i, T_a is the ambient temperature and P_i is the power dissipation of device i. To model the thermal coupling between devices in the power module, the thermal characteristic parameter, Ψ, is defined as

$$\Psi_{ij}(t) = \frac{T_i(t) - T_a}{P_j(t)} \tag{2}$$

where T_i is the temperature of device i and P_j the power dissipation of device j. Thus, the thermal characteristic parameter Ψ_{ij} describes the temperature increase of a device i due to the power dissipation of one of its neighbor devices j. While the definition of Ψ and Z looks similar and they share the same unit, it is important to note the distinction. The use of Ψ is of more value in a practical case, as power flow distribution in different paths throughout the power module is difficult to measure, but the temperature and power dissipation in devices are known. When combining the thermal impedance of a device in (1) and the temperature gained from neighboring devices in (2) the temperature of all devices in the power module can be calculated [6–8], and is given by

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} Z_1 & \Psi_{12} & \Psi_{13} & \Psi_{14} \\ \Psi_{21} & Z_2 & \Psi_{23} & \Psi_{24} \\ \Psi_{31} & \Psi_{32} & Z_3 & \Psi_{34} \\ \Psi_{41} & \Psi_{42} & \Psi_{43} & Z_4 \end{bmatrix} \cdot \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} + T_a \tag{3}$$

The designed PCB board of the power module in Fig. 2, has floating non-filled vias directly on top of each GS66508T GaN eHEMT device, which allows for fiber optic temperature sensors of diameter 0.28 mm to measure the device temperatures [9]. The devices and their measurement points are labelled as shown in Fig. 3.

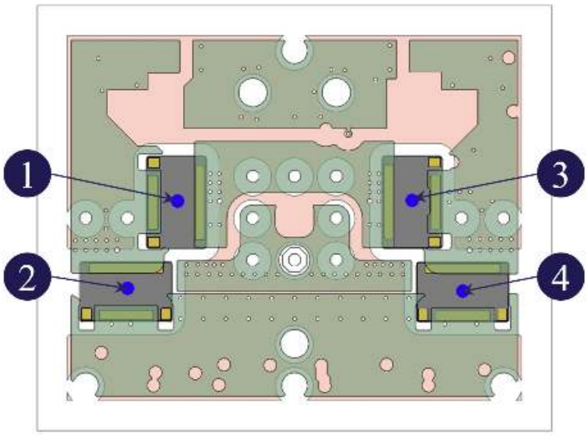

Fig. 3: Labelling of devices and measurement points.

Experimental results

An experimental test setup is constructed, as shown in Fig. 4. A DC power supply is connected to the drain-source of the device under test and a positive gate signal is given. Temperatures are logged using OTG-M280 fiber optic temperature sensors from Opsens. The gate driver circuit components are not soldered to the PCB for two reasons. The power module of Fig. 2 uses a bootstrap circuit which limits the duty cycle and thus must be bypassed to apply the DC power step. Secondly, the thermal models of all components on the PCB board are not available, and thus it is unknown how the added thermal mass of the SMD components alters the thermal response.

A current of 6 A is conducted through the GaN eHEMT device. For an on-state resistance of 50 mΩ this equals 1.8 W in power dissipation. Temperatures of all four devices in the power module are measured, and (1) and (2) are applied to the data. The thermal characteristics obtained are shown in Fig. 5. The steady state thermal impedance from device to ambient is 2.07 K/W for the device under self-heating. The results show that device 1 is thermally coupled to device 2, 3 and 4 by 0.84 K/W, 0.37 K/W and 0.09 K/W, respectively.

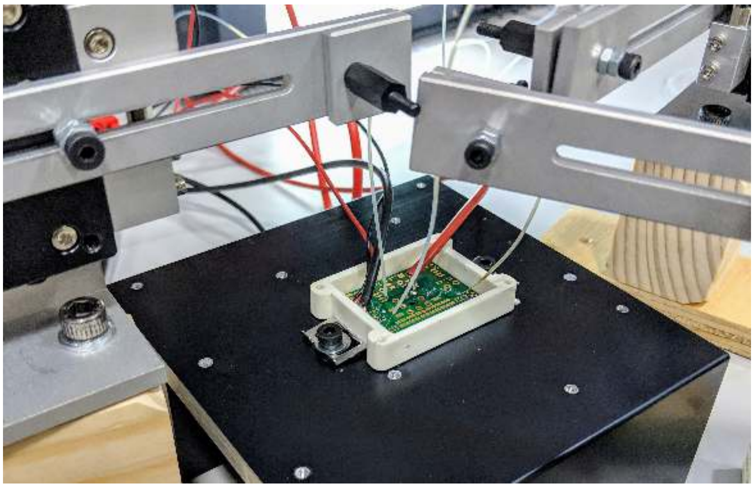

Fig. 4: Picture of the experimental setup.

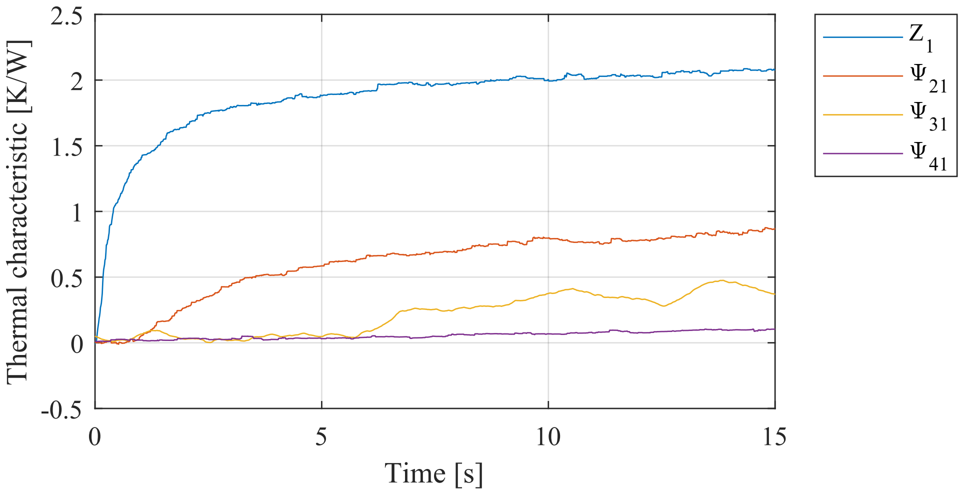

Fig. 5: Experimental thermal response of the integrated GaN eHEMT power module.

Thermal modelling using finite element method software

The following section describes the finite element method simulation of the designed integrated GaN eHEMT power module. To get a three dimensional model of the PCB the board files are imported into ANSYS Siwave, which allows conversion of the two dimensional layer information into a three dimensional model. Solidworks is then used to assemble the three dimensional models of the GaN Systems GS66508T devices, the DBC and the PCB including its copper planes and vias. The full power module model is imported to the finite element method software COMSOL, as shown in Fig. 6. A relatively fine mesh is used because of the thin vias and features of the PCB board. A thin resistive layer boundary is added to the contacts of the GaN Systems GS66508T to model its junction to case thermal resistance of 5 K/W to its top electrical contacts and 0.5 K/W to the bottom heat pad [10]. The material properties used in the transient simulation model are listed in Table I. Accurate thermal modelling of the FR4 layers in the PCB board is complex as it is made up of different core and prepreg layers. Their woven structure of glass fiber laminates results in different thermal conductivities in lateral and vertical directions [11, 12], but for this paper its value is approximated as a single value of 0.3 $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$.

A power dissipation of 1.8 W is applied to device 1 and temperatures of all four devices are logged. The boundary condition on the DBC backside facing the heatsink is modelled as

$$q = h \cdot \Delta T \quad (4)$$

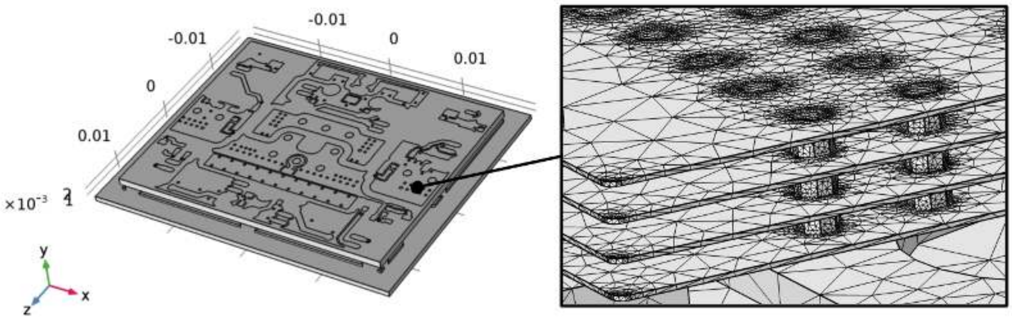

Fig. 6: 3D model of the power module in COMSOL and close-up of the mesh around via array.

Table I: Material properties used in the simulation model [11–13].

Material	**Thermal conductivity** $\left[\frac{W}{m\cdot K}\right]$	**Heat capacity** $\left[\frac{J}{kg\cdot K}\right]$	**Density** $\left[\frac{kg}{m^3}\right]$
Cu	400	385	8960
Al_2O_3	24	765	3970
FR4	0.3	1369	1900

where q is the heat flux, h is the heat transfer coefficient and ΔT is the temperature difference between the solid surface and surrounding environment. One of the main unknowns of the simulation is the h-coefficient. For a power module connected to a heat sink it may vary from approximately 500 to 3000 $\frac{W}{m^2K}$ [3, 14, 15] depending on parameters such as the thermal interface material used, heatsink coolant, the applied pressure and surface roughness etc. For this paper the h-coefficient is chosen as 1800 $\frac{W}{m^2K}$, based on achieving the same temperature for device 1 in steady state for both simulation and experiment. By applying (1) and (2) the transient thermal characteristics of the integrated power module are extracted as shown in Fig. 7.

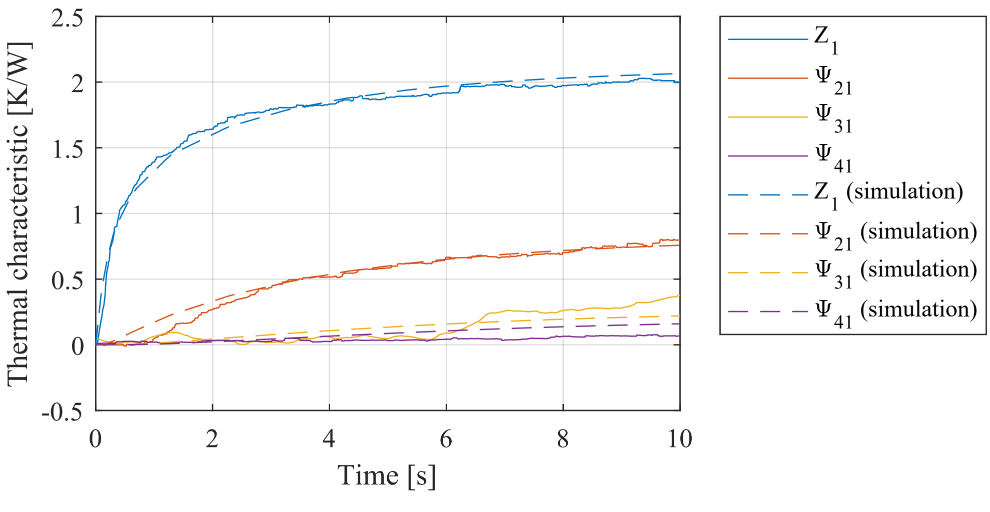

Fig. 7: Combined experimental results and simulated responses (in dashed lines) during 6 A conduction losses in device 1.

The simulation model predicts a Z_1, Ψ_{21}, Ψ_{31} and Ψ_{41} of 2.07 K/W, 0.76 K/W, 0.22 K/W and 0.16 K/W, respectively. For the power dissipation of 1.8 W, the absolute errors between experiment and simulation of devices 2, 3 and 4 temperatures are 0.14 °C, 0.27 °C and 0.12 °C. The OTG-M280 fiber optic temperature sensors have an accuracy of ± 0.3 °C [9]. Thus the simulation result is within bounds of the expected error from the experiment.

As the finite element method simulation is verified with the experimental results, it allows for the investigation of how much influence the PCB has on the thermal performance. The dashed lines of Fig. 8 show the thermal characteristics of the power module when the PCB is not included in the simulation.

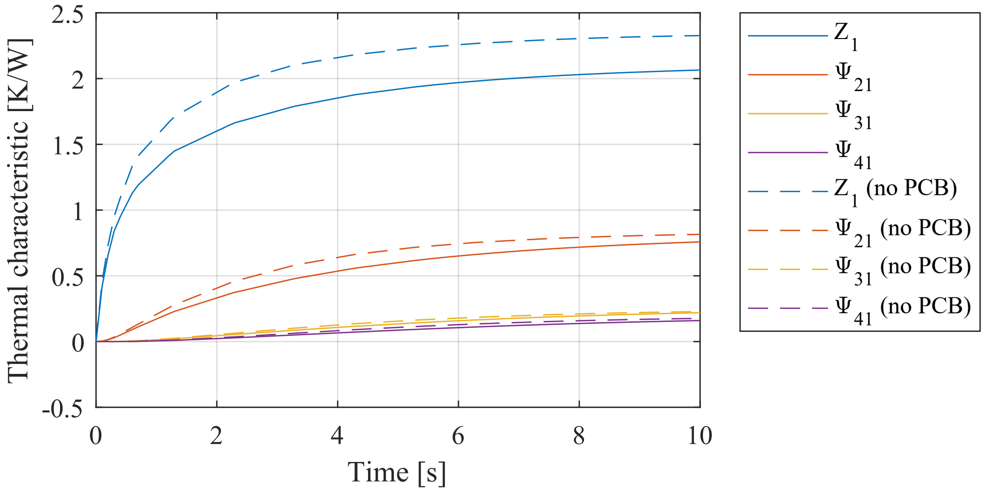

Fig. 8: Simulated thermal response of the integrated GaN eHEMT power module.

The thermal impedance of the heated device is increased to a steady state value of 2.33 K/W, and a slight increase of Ψ is experienced by the other devices in the module. Compared relatively to the temperature of device 1 the remaining devices are less thermally coupled, but their absolute temperature is increased. Thus without the PCB the entire power module is heated more for the same power dissipation. The copper layers of the PCB distributes the generated heat to other devices and thus utilizes more area of the top side copper. In conclusion, the PCB enables double sided cooling of the GaN eHEMT devices and without the influence of the PCB the thermal impedance of the self-heated device under test increases by 13 %. Failure to model the copper layers of the PCB may result in a wrong prediction of device temperatures.

Conclusion

New integrated and low inductive power module structures are being developed to better utilize the benefits of new WBG semiconductors. However, current literature presenting the thermal capabilities of the integrated power module structures all lack the modelling of the PCB and the thermal characteristics are not experimentally verified. A new integrated hybrid DBC/PCB full-bridge power module using GaN eHEMT devices is tested experimentally. The steady state thermal impedance from a device to ambient is 2.07 K/W for the device under self-heating. A three dimensional model of the PCB is obtained by exporting the board from ANSYS Siwave. Solidworks is used to assemble the models of GaN devices, PCB and DBC, and the finite element method software COMSOL is used for thermal simulation. The finite element method simulation is verified by matching it with the experimental results. The simulation predicts an increase of the thermal impedance by 13 %, if the PCB board is not included in the thermal simulation of the GaN eHEMT device. While the FR4 PCB board material has low thermal conductivity, the copper layers of the PCB facilitates additional heat distribution. Disregarding the influence of the PCB board may result in a significant error in predicting the temperature of devices in integrated DBC/PCB hybrid power modules.

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