Thermal dissipation enhancement using a metal-diamond composite heat spreaders in high-power RF MMICs

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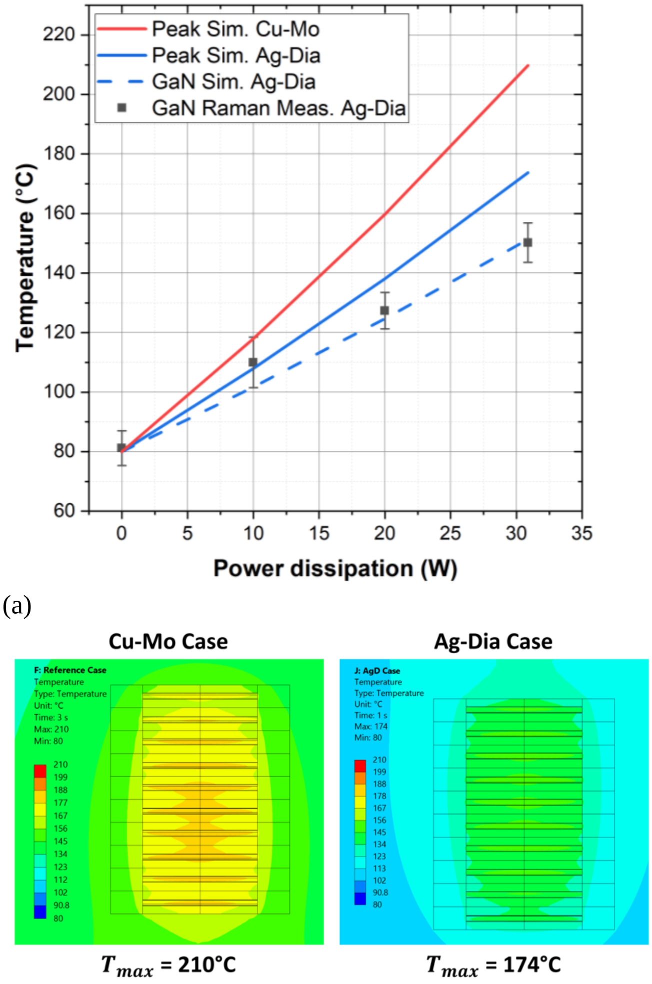
Owing to the huge power density increase in semiconductor technology, especially for high-power applications, there is an increase demand for an effective thermal management at the packaging level to improve the heat spreading between the semiconductor die and the heatsink. The carrier (i.e. heat spreader), onto which the semiconductor die is directly attached, is an integral part of the package and ideally has as high thermal conductivity as possible, while also having acceptable coefficient of thermal expansion mismatch. Metal-diamond composites are a suitable candidate since the coefficient of thermal expansion can be tailored accordingly while maintaining a much higher the thermal conductivity than conventional materials. In this work, we compare the thermal performance of a high-power RF amplifier with a standard and metal diamond composite heat spreader, using finite element model thermal simulation, frequency domain thermoreflectance and Raman thermography measurements.

Ensuring reliability is crucial for electronic devices, especially with increasing power densities. A study of the major causes of electronics failure showed that at least 50% of these failures are related to thermal issues [1]. Thus, effective thermal management is important to improve the devices mean time to failure and therefore the overall reliability. There is focus on improving the thermal interfaces between the main elements of a packed device, mainly between the die and the heat spreader (known as carrier/flange), and on the thermal properties of the carrier's material itself. Having a highly thermally conductive carrier is crucial, but it must also have a suitable coefficient of thermal expansion (CTE) that matches to other components in the package (in the range of 3×10^{-6} and 7×10^{-6} K^{-1}) [2]. Over time, different carrier materials have been studied and used. Firstly, the pure metals, like the copper and aluminum have reasonably high thermal conductivities (e.g., κ_{copper} = 400 W/m·K) but unacceptably high CTEs (e.g., $\alpha_{\text{copper}} \sim 17 \times 10^{-6}$ K^{-1}). Metal alloys were developed to have CTEs over a range of desired values, like the copper-molybdenum (Cu-Mo $\alpha \sim 7 \times 10^{-6}$ K^{-1}). However, these alloys have lower thermal conductivities of around ~170-220 W/m·K for Cu-Mo and Cu-W, respectively. Notably, a third category of heat spreaders, composites, have been developed to deal with the challenge of having at the same time a high thermal conductivity and acceptable CTE values. Composites like CMC [3], and metal-diamond [4] have higher thermal conductivities while still enabling the CTE to be tailored as needed. Diamond has high thermal conductivity (~2000 W/m·K), but a very low CTE value ($\sim 1 \times 10^{-6}$ K^{-1}). To address this, diamond particles are embedded into a metal matrix, like copper and silver, to increase the CTE to an acceptable level ($\sim 7 \times 10^{-6}$ K^{-1}) and achieve high thermal conductivity (up to ~800 W/m·K reported). The CTE and thermal conductivity of metal diamond composites are highly dependent on the diamond particle sizes, volume fraction, to name only a few variables [5]. Accurate thermal conductivity measurement is needed, for which we use the low-frequency range frequency-domain-thermoreflectance method (FDTR) reported in [6].

In this paper, we demonstrate the thermal resistance improvement using a silver-diamond (Ag-Dia) composite heat spreader versus a conventional Cu-Mo carrier in a high-power device. Two RF GaN MMIC high-power amplifiers are characterized using thermal simulation and Raman thermography measurement, mounted on Cu-Mo and Ag-Dia composite carriers. The GaN MMICs contain three-stage amplifier based on the GH15 technology [7].

The Ag-Dia composite consists of 68% diamond particles by volume fraction with a diameter of 320 µm [5]. The Ag-Dia composite has been planarized by adding a 300 µm silver cladding layer on both side of the composite to aid packing assembly. The overall thickness of the clad Ag-Dia composite is around 3.1 mm [5]. The clad Ag-Dia composite thermal conductivity was measured using the low-frequency range FDTR [5],[6]. The advantage of the low-frequency range FDTR technique is that it can measure separately the Ag-Dia composite layer thermal conductivity, the thickness of the cladding and the thermal boundary resistance between the cladding and the composite layer [5]. The measured thermal conductivity values of the Ag-Dia composite and the clad Ag-Dia composite sample are 620 W/m·K and 550 W/m·K, respectively, illustrating the effect of the cladding. Additionally, the composite heat spreader's CTE value, at room temperature, is 6.9 $\times 10^{-6}$ K^{-1}.



(a)

(b)

Figure 1. (a) Simulated peak channel temperatures (Peak Sim.) for MMIC with Cu-Mo heat spreader at different DC operating powers, along with measured temperatures obtained by Raman thermography (GaN Raman Meas.) and the same Raman location simulated temperature (GaN Sim.) for MMIC with Ag-Dia composite heat spreader. (b) Temperature distribution in GaN HEMT (10 fingers) for a DC operating power of 30.8 W obtained from 3-D FE thermal simulation for MMIC with Cu-Mo heat spreader (Cu-Mo Case) and with Ag-Dia composite heat spreader (Ag-Dia Case).

Firstly, steady-state thermal finite element (FE) models were implemented using ANSYS. Both models use sintered silver die attach (120 W/m·K) and an 8 mm aluminum plate. The thermal simulations have been performed at different DC power dissipations up to 30.8 W, while the backside of the aluminum plate has been fixed at a temperature of 80°C. Fig. 1 (a) presents the simulated channel peak temperatures (Peak sim.) for the MMIC (at the center of the 3rd stage) with Cu-Mo and with Ag-Dia composite heat spreaders. The Ag-Dia composite heat spreader model has a 35ºC lower temperature than that of Cu-Mo model at P_{diss} = 30.8 W (174ºC versus 210ºC). Fig. 1 (b) illustrates the temperature distribution for both MMICs in the center transistor of the 3rd stage, for DC operating power of 30.8 W.

Raman thermography [8] was used to measure close to the peak channel temperature location for the MMIC which has Ag-Dia heat spreader. Given that the peak channel location is covered by the metal field plate rendering it inaccessible, the measurements have been performed at a distance of 0.5 μm from the field plate edge, with a lateral resolution of 0.5 μm [8]. The schematic illustration in Fig. 2 depicts the cross-section of the gate finger along with the Raman measurement's location. The backside of the aluminum plate was kept at 80°C during the measurements, matching the simulation. Measurement results are shown in Fig. 1 (a) (GaN Raman Meas.), aligning well with the simulated temperature at the measurement location (GaN Sim.), giving confidence in the accuracy of the thermal model. Naturally, this is aided by having prior knowledge of the composite thermal conductivity provided by FDTR. It is worth noting that FDTR can also be used to determine the in-situ die attach and the thermal interface material thermal conductivities [6],[9].

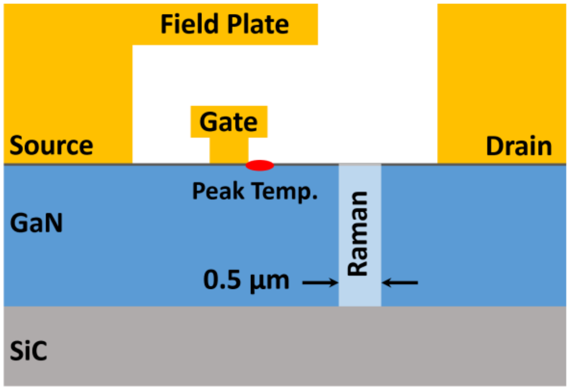


Figure 2. Schematic cross-section of the GaN HEMT gate finger, illustrating the area within the GaN layer measured by Raman thermography relative to the channel where the peak temperature occurs.

CONCLUSIONS

Detailed 3-D finite element thermal simulations, verified using Raman thermography measurements, have been performed in order to quantify how much thermal resistance can be reduced by changing a Cu-Mo carrier to a metal diamond composite heat spreader used in a GaN MMIC. Experimentally verified simulations demonstrate a 35°C peak channel temperature reduction at a power dissipation of 30.8 W, compared to the Cu-Mo heat spreader, and therefore a 27% reduction in the thermal resistance.

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