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New GaN Power-Electronics Packaging Solutions: A Thermal Analysis Using Raman Thermography

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***Abstract*—Raman thermography measurements were performed on AlGaN/GaN multifinger high electron mobility transistors (HEMTs) to determine their channel temperature at various power levels. The devices were mounted on both silver diamond composite and CuW baseplates, in order to benchmark the thermal performance of novel diamond composite baseplates compared with traditional materials. We illustrate that AlGaN/GaN HEMT devices mounted on silver diamond composite baseplates show peak temperatures that are 50% lower than the peak temperatures exhibited by devices mounted on traditional CuW baseplates. This is a dramatic improvement in terms of heat extraction as a basis to enable longer device lifetimes and better performance. In addition, time-resolved Raman thermography measurements were carried out to obtain the thermal dynamics of devices on the silver-diamond baseplate and on heat diffusion during pulsed device operation. This time-dependent information is of great importance for reliability and failure analyses, as pulsed operation of a HEMT is a typical device operation condition. Finite-element thermal simulations were performed for comparison with experimental results, and good agreement with the experimental data was obtained.**

***Keywords*—Diamond composites, GaN, Raman thermography, thermal analysis, thermal management, thermal modeling**

Introduction

Thermal management of gallium-nitride based power electronics has become a crucial design step. Indeed, GaN devices, in particular high electron mobility transistors (HEMTs) and monolithic microwave integrated circuit (MMICs), are typically operated at high power densities [1], which are typically an order of magnitude higher than for devices based on GaAs and Si technologies. This means that long-term reliability and performance of these devices will be strongly affected by self heating [2, 3] and by thermal management.

On the other hand, the mismatch in the coefficient of thermal expansion (CTE) between the baseplate and the semiconductor needs to be kept to a minimum, otherwise distortions, cracks, and even catastrophic damage to the device are possible.

In view of this, the use of innovative high performance materials for packages that are capable of removing a high density of generated heat are very desirable. Silver diamond composites are a very promising candidate for this application with their excellent thermal conductivity (700 W/mK at room temperature) and a good coefficient of thermal expansion (CTE) match with that of semiconductor materials [4]. We present here a detailed thermal analysis (steady-state and transient) of GaN power bars on such novel baseplates showing the benefit of using silver diamond composite as a baseplate in packages to reduce GaN power bar device channel temperatures.

A. Samples and Characterization

Raman thermography measurements were performed on AlGaN/GaN 18-finger HEMTs (power bars) grown on SiC substrates to determine their channel temperature at different power levels. The power bars were mounted on both silver diamond composite and CuW baseplates by using standard AuSn solder under the same conditions and with the same thickness of 23 ± 1 μm, in order to benchmark this new material, that is, the silver diamond composite, to a more traditional material such as CuW (see Fig. 1). The back side of the baseplate was kept at a temperature of 25°C during all performed measurements using a Peltier cooled stage.

The Raman measurement technique can determine device temperature with submicron spa'tial resolution and nanosecond time resolution [5]. It is a technique that allows for the measurement of frequency of atomic/molecular oscillations, that is, phonons in quantum mechanical terms. In semiconductor materials with well defined crystal structure, there are only a limited number of possible phonons of the crystal lattice, due to its symmetry. These allowed crystal atom movements are evident in a measured Raman spectrum as well-defined peaks. A change in temperature leads to a change in the volume of a solid body, that is, the distance between atoms in a crystal is increased or decreased as a result of such a change. Moving an atom closer or further away from its neighbor forces them to oscillate at a different frequency, that is, phonon energy, and this allows for temperature probing of a material by means of measuring the frequency of phonons. The temperature dependence of phonon frequencies can be described by a relatively simple empirical

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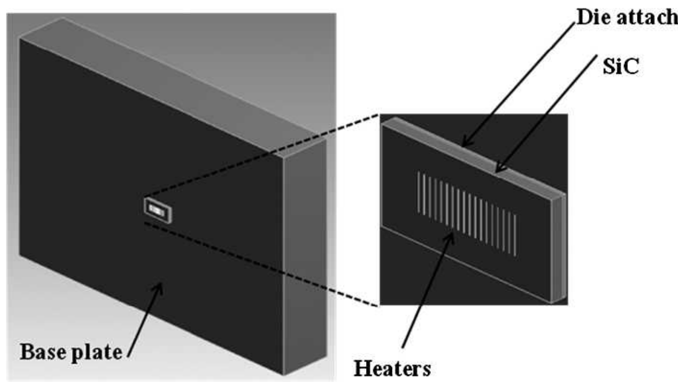

Fig. 1. Schematic diagram of the mounted GaN power bars on the baseplate.

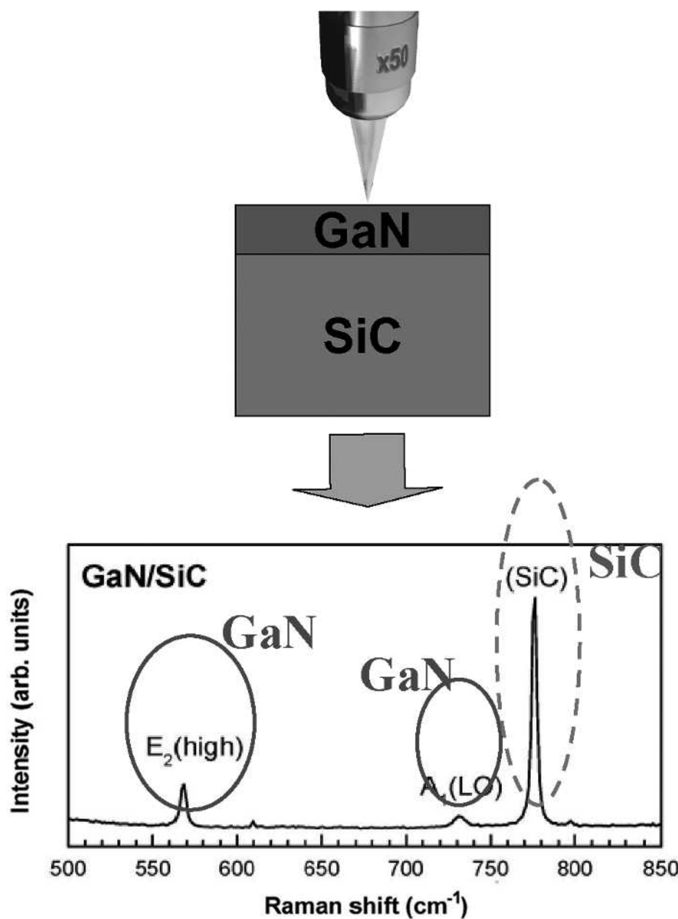

Fig. 2. Schematic example of Raman spectroscopy technique applied upon a GaN active layer on a SiC substrate. The phonon peaks relative to both GaN and SiC layers are clearly distinguishable.

formula. Fig. 2 shows an example of Raman measurement of a GaN layer on an SiC substrate.

B. Thermal Results in DC Operation

The peak GaN power bar channel temperature obtained from Raman measurements at different power values, with the devices operated in DC, is shown in Fig. 3. Devices

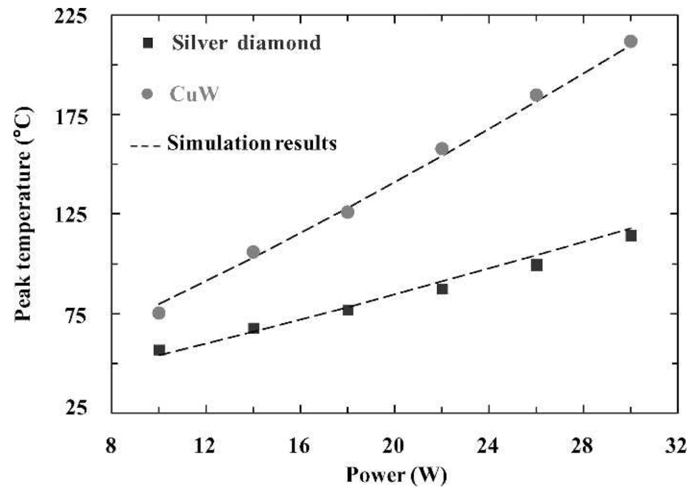

Fig. 3. Peak channel temperature at the center finger of AlGaN/GaN HEMTs devices (18-finger power bars) mounted on silver diamond composite and CuW baseplates as a function of the dissipated power, obtained by Raman thermography. 3D finite element thermal modeling results are shown for comparison.

mounted on silver diamond composite baseplates show temperature increases of approximately half that of those exhibited by devices mounted on CuW baseplates. Considering the level of 30 W of power, the peak temperature with copper tungsten is about 215°C, while with silver diamond the peak temperature is about 115°C. This is a significant improvement from the point of view of heat extraction, with obvious benefits for device performance and reliability.

C. Thermal Simulations

A 3D finite element model (FEM) of the devices including packaging was built utilizing the ANSYS software package [6] to compare with the experimental data. This model is shown in Fig. 1. The model is also used to extract from the Raman thermography measurement GaN the peak channel temperature of the power bar. In order to provide heat flux in the device, a 0.4 μm heat source was used at the top of the GaN layer next to the gate contact on its drain side for each of the 18 fingers, similar to our previous work [7]. This is the location of heat generation in a HEMT. The thermal conductivities and their temperature dependence for GaN and SiC are similar to the ones used in [8], while for silver diamond and CuW, we used values measured by laser flash method, namely 250 W/mK for CuW and 770 W/mK for silver diamond composite at room temperature. It is important to point out that the measured data produced by Raman thermography represents the temperature in an area of about 0.5 μm in the GaN power bar, averaged over the depth of the 2 μm thick GaN layer. The measurement location was chosen to be next to the device gate contact on its drain side, that is, the peak temperature location; however, lateral scanning and 3D scanning for temperature measurement are obviously possible. This temperature averaging effect produces a temperature slightly lower than the actual peak channel temperature. Simulation is used to extract channel temperature from the measured data. For this procedure, FEM data are averaged through the GaN layer and correlated to the Raman data, with a possible additional input

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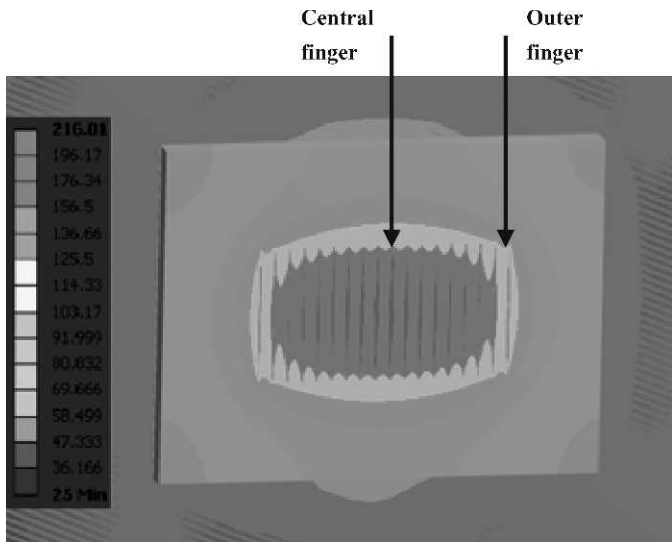

Fig. 4. Simulated temperature distribution within the fingers of the power bar mounted on a CuW baseplate.

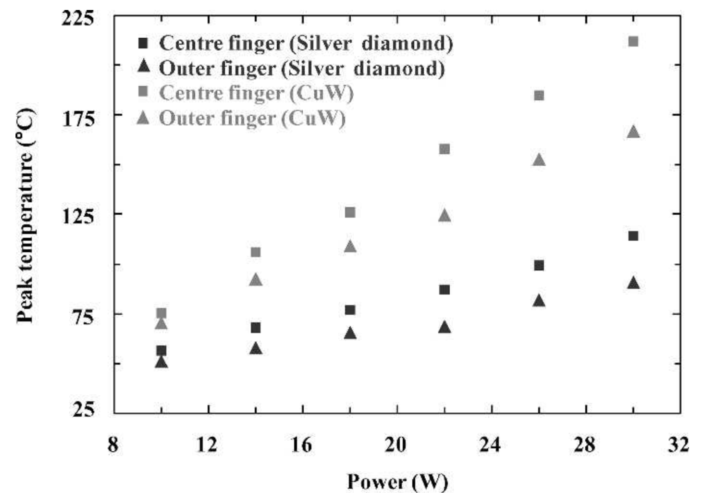

Fig. 5. Channel temperature at the center finger and outer finger of AlGaN/GaN HEMTs devices (18-finger power bar) mounted on bare silver diamond composite and CuW baseplates as a function of the dissipated power, obtained by Raman thermography. The device had a gate pitch of 50 μm.

parameter such as substrate temperature, here SiC, and a temperature outside the active device area, also measured using Raman thermography. Subsequently, channel temperature is determined from the calibrated FEM. The accuracy of this methodology has been tested extensively [9, 10]. As shown in Fig. 3, the outcome of the thermal simulation is consistent and in good agreement with the data obtained experimentally. This was achieved by considering a die-attach thermal conductivity of 40 W/mK.

D. Thermal Crosstalk

For the devices studied here with multifinger geometry, the channel temperature at each device gate finger is influenced by heat dissipation from neighboring fingers due to lateral heat transport. Fig. 4 shows the simulated temperature distribution within the fingers of the power bar mounted on the copper tungsten baseplate. The temperature at the center of the device is higher than in the other regions.

As can be seen from Fig. 5, which shows the measured temperature at the center finger of the device as well as at the most outer finger for both GaN power bars mounted on CuW and silver diamond baseplates, the temperature measured in the center finger is about 15% higher than the one measured in the outer finger. This illustrates that such thermal crosstalk can lead to large temperature variations in a multifinger device from gate finger to gate finger with an associated effect on device performance. This effect is important to take into consideration when trying to experimentally extract the maximum temperature in a device. Fortunately, Raman thermography enables spatially resolved temperature measurements with high spatial resolution; however, such temperature variation in a device needs to be taken into account when electrical methods are used to determine device temperature [11]. We also note that IR thermography, which is often used to determine device temperature, was not used in this work, as it has limits in temperature accuracy due to the very small active device regions, as we demonstrated in previous work [9].

E. Thermal Transient

Since many systems employing GaN based HEMTs operate in modes other than DC or continuous RF, that is, in pulsed mode, it is of great importance to understand the thermal transient response of GaN power bars, especially when used here with the new silver diamond composite baseplates. In view of this, time-resolved Raman measurements were carried out on devices mounted on the silver diamond composite baseplate. Time-resolved device temperature measurements using the Raman method work very similar to DC Raman temperature measurements described in the previous section. Temperature is determined from measuring phonon frequency shifts. In contrast to DC measurements, however, a CW laser is not used for the Raman measurement but rather a pulsed laser source is used. The laser pulse length determines the time resolution achievable in the temperature measurement, and this pulse impinges on the device after a well-defined time delay after its electrical excitation. Currently we easily achieve about 10 ns time resolution, but in principle, shorter time resolutions are possible. The time delay between the electrical and the optical pulse is varied to measure temperature as a function of time. This new technology opens new opportunities to study thermal dynamics of devices, heat diffusion, adiabatic device heating, that is, thermal device characteristics of great relevance for device reliability and failure studies, and also for device physics. It enables researchers to push the thermal analysis of a device well beyond what has been possible until very recently [12, 13].

Fig. 6 shows the measured temperature time response. When the devices are initially switched on, time evolution of device temperature is dominated by an adiabatic heating process within the initial few 10s of ns, followed by a slower heat diffusion which reaches steady state after about 1 ms. This result is consistent with our earlier work on single-finger GaN HEMTs [12]. Good agreement to simulation was achieved.

Fig. 7 shows a simulated time evolution of the normalized temperature for devices mounted on silver diamond and CuW

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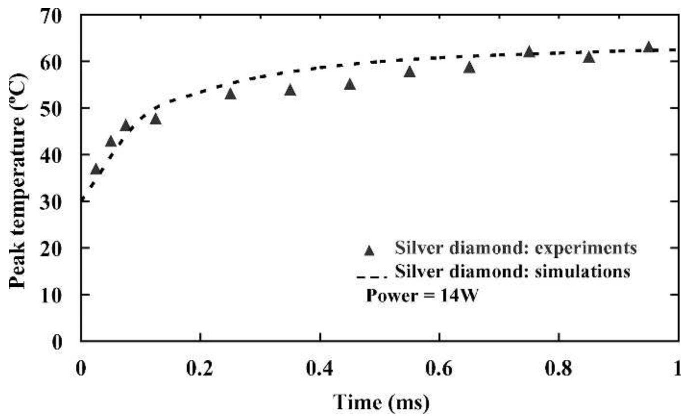

Fig. 6. Peak channel temperature at the center finger of AlGaN/GaN HEMTs devices (18-finger power bar) operated at 14 W with 1 ms long pulses and a duty cycle of 50%, mounted on a silver diamond composite baseplate as a function of time, obtained by time-resolved Raman thermography. 3D finite element thermal modeling results are also shown.

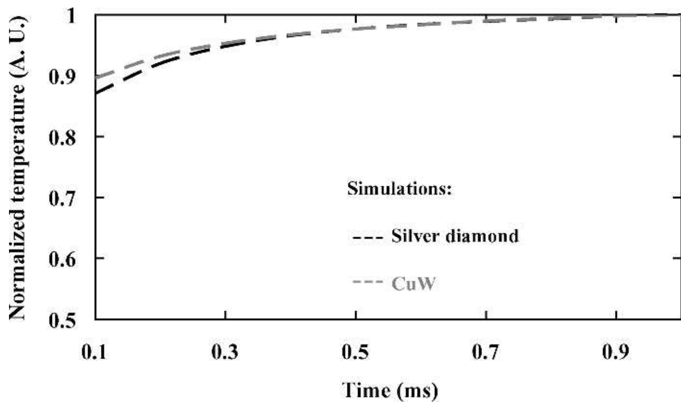

Fig. 7. Simulated time evolution of the normalized temperature for devices mounted on silver diamond and CuW baseplates.

baseplates. We found that there is a small difference in time response between the two materials due to the difference in the specific heat.

Conclusions

Raman thermography measurements and finite element thermal modeling were performed to assess the thermal management performance of GaN power bars on silver diamond composites and for benchmarking on CuW baseplates. The results show a significant improvement in terms of heat extraction when using silver diamond composites in the packages, by up to a factor of two. This unprecedented new packaging solution will allow the achievement of longer lifetime and more reliable GaN power electronics. In addition, time resolved Raman measurements were performed to characterize the time evolution of device temperature, initially dominated by adiabatic heating within the initial few 10s of ns, followed by a slower heat diffusion which reaches steady state at about 1 ms.

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