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

M. Faqir[1]*, A. Manoi[1], T. Mrotzek[2], S. Knippscheer[2], M. Massiot[3], M. Buchta[4], H. Blanck[4], S. Rochette[5], O. Vendier[5], M. Kuball[1]

[1]Center for Device Thermography and Reliability (CDTR), H.H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, United Kingdom
[2]Plansee SE, 6600 Reutte, Austria
[3]Egide, Site Industriel du Sactar, 84500 Bollene, France
[4]United Monolithic Semiconductors, Wilhelm-Runge-Strasse 11, 89081 Ulm, Germany
[5]Thales Alenia Space, 26 av JF Champollion 31037 Toulouse, France
*Mustapha.Faqir@bristol.ac.uk, phone: +44 117 3318109

Keywords: Thermal management, diamond composites, thermal modeling, GaN, thermal analysis, Raman thermography

Abstract

Raman thermography measurements were performed on AlGaN/GaN multi-finger 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 base plates, in order to benchmark the thermal performance of novel diamond composite base plates compared to traditional materials. We illustrate that AlGaN/GaN HEMT devices mounted on silver diamond composite base plates show peak temperatures which are 50% lower than the peak temperatures exhibited by devices mounted on traditional CuW base plates. This is a dramatic improvement in terms of heat extraction, as basis to enabling longer device life-times and better performances. In addition, time-resolved Raman thermography measurements were carrier out to obtain thermal dynamics of devices on the silver-diamond base plate 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 typically device operation condition. Finite-element thermal simulations were performed for comparison with the experimental results, and good agreement with the experimental data was obtained.

Introduction

Thermal management of GaN-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 essentially strongly affected by self heating [2], [3] and how it can be managed. 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]. CTE mismatch between base plate and the semiconductor needs to be kept minimal as otherwise distortions, cracks and even catastrophic damages to the device are possible. We present here a detailed thermal analysis (steady-state and transient) of GaN power bars on such novel base plates showing the benefit of using silver diamond composite as a base plate in packages to reduce GaN power bar device channel temperatures.

Samples and Characterization

Raman thermography measurements were performed on AlGaN/GaN 18-fingers HEMTs (power bars) grown on SiC substrates to determine their channel temperature at different power levels. More details on Raman measurements technique can be found in [5]. It can determine device temperature with submicron spatial and nanosecond time resolution. The power bars were mounted on both silver diamond composite and CuW base plates 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, i.e. silver diamond composite, to a more traditional material such as CuW (see Figure 1). Base plate backside was kept at a temperature of 25 ºC during all performed measurements, using a Peltier cooled stage.

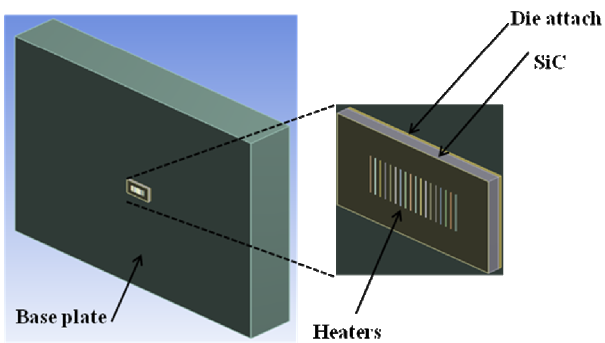

Figure 1: Schematic diagram of the mounted GaN power bars on base plate.

Experimental Results: 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 Figure 2. Devices mounted on silver diamond composite base plates show peak temperatures approximately half that of the peak temperatures exhibited by devices mounted on CuW base plates. This is a significant improvement from the point of view of heat extraction, with obvious benefits for device performance and reliability.

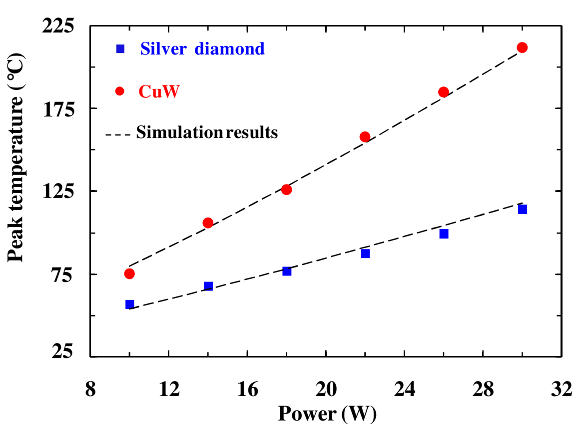

Figure 2: Peak channel temperature at the centre finger of AlGaN/GaN HEMTs devices (18 fingers power bars) mounted on silver diamond composite and CuW base plates as a function of the dissipated power, obtained by Raman thermography. 3-D finite element thermal modeling results are shown for comparison.

Thermal Simulations

A 3-D finite element model (FEM) of the devices including packaging was built utilizing the ANSYS software package [6] to compare to the experimental data. This model is shown in Figure 1. The model is also used to extract from the Raman thermography measurement GaN power bar peak channel temperature. 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 used thermal conductivities and their temperature dependence for GaN and SiC are similar to the ones used in [8], while for silver diamond and CuW values measured by laser flash method, namely 250 W/mK for CuW and 690 W/mK for silver diamond composite at room temperature, are used. 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 here 2 µm thick GaN layer. The measurement location was chosen here to be next to the device gate contact on its drain side, i.e., the peak temperature location, however lateral scanning as well as 3D scanning in the 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 is averaged through the GaN layer and correlated to the Raman data, with possible additional input parameter such as substrate temperature, here SiC, and 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 Figure 2, 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.

Thermal Crosstalk

For the here studied devices with multi-finger geometry, channel temperature at each device gate finger is influenced by heat dissipation from neighboring fingers due to lateral heat transport. As can be seen from Figure 3 showing measured temperature at the centre finger of the device as well as at the most outer finger for both GaN power bars mounted on CuW and silver diamond base plates, temperature measured in the centre 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 multi-finger device from gate finger to gate finger with an associated effect on device performance. This effect is important to into consideration when trying to extract the maximum temperature in a device experimentally. 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 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].

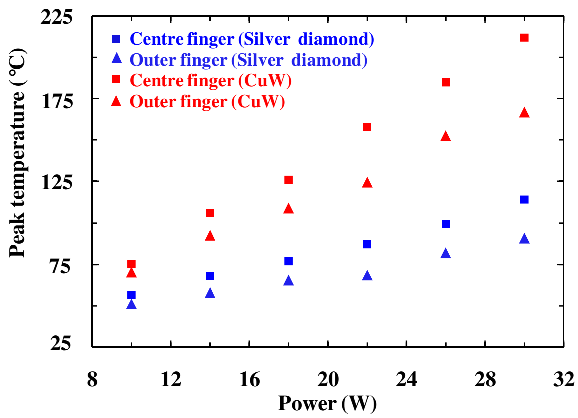

Figure 3: Channel temperature at the centre finger and outer finger of AlGaN/GaN HEMTs devices (18 fingers power bar) mounted on bare silver diamond composite and CuW base plates as a function of the dissipated power, obtained by Raman thermography. The device had a gate pitch of 50 µm.

Thermal Transient

Since many systems employing GaN based HEMTs operate in modes other than DC or continuous RF, i.e. 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 base plates. In view of this, time-resolved Raman measurements were carried out on devices mounted on the silver diamond composite base plate. More details on time-resolved Raman thermography can be found in [12], [13]. Figure 4 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 tens of nanoseconds, followed by a slower heat diffusion which reaches the steady state after about 1ms. This result is consistent with our earlier work on single-finger GaN HEMTs [12]. Good agreement to simulation was achieved. Also shown in the inset is a simulated time evolution of the normalized temperature for devices mounted on silver diamond and CuW base plates. We found that there is a small difference in time response between the two materials due to the difference in the specific heat.

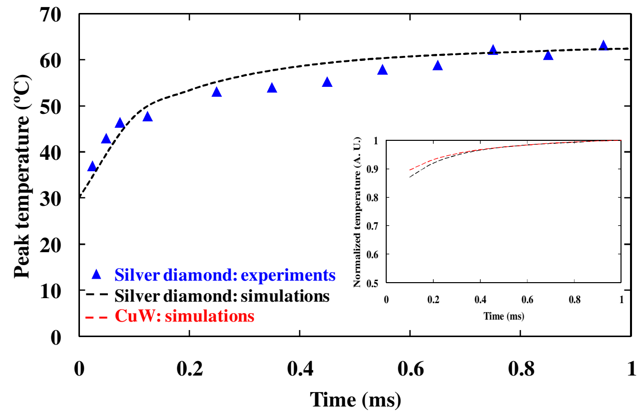

Figure 4: Peak channel temperature at the centre finger of AlGaN/GaN HEMTs devices (18 fingers power bar) operated at 14W with 1ms long pulses and a duty cycle of 50%, mounted on silver diamond composite base plate as a function of time, obtained by time-resolved Raman thermography. 3-D finite element thermal modelling results are also shown. In the inset simulated time evolution of the normalized temperature for devices mounted on silver diamond and CuW base plates.

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 its benchmarking also on CuW base plates. 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 time evolution of device temperature, initially dominated by adiabatic heating within the initial few tens of nanoseconds, followed by a slower heat diffusion which reaches the steady state at about 1ms.

Acknowledgements

This work was carried out in the framework of the European Framework 7 project AGAPAC (Advanced GaN Packaging). The authors would like to thank Dr. T. Batten and Dr. J. Pomeroy for their support during measurements and for fruitful discussions.

References

[1] Y. Pei, R. Chu, N. A. Fichtenbaum, Z. Chen, D. Brown, L. Shen, S. Keller, S. P. DenBaars, and U. K. Mishra, "Recessed slant gate AlGaN/GaN high electron mobility transistors with 20.9 W/mm at 10 GHz," Japan. J. Appl. Phys., vol. 46, no. 45, pp. L1 087–L1 089, Dec. 2007.

[2] R. Gaska, A. Osinsky, J. W. Yang, and M. S. Shur, "Self-heating in high power AlGaN-GaN HFETs," *IEEE Elect. Dev. Lett.*, vol. 19, no. 3, pp. 89–91, Mar. 1998.

[3] S. Nuttinck, B. K. Wagner, B. Banerjee, S. Venkataraman, E. Gebara, J. Laskar, and H. M. Harris, "Thermal analysis of AlGaN-GaN power HFETs," *IEEE Trans. Microw. Theory Tech*., vol. 51, no. 12, pp. 2445–2452, Dec. 2003.

[4] R. Bollina and S. Knippscheer "Advanced Metal Diamond Composites - Love and Heat Relationship," *Electronics Cooling,* Nov. 2008.

[5] A. Sarua, H. Ji, M. Kuball, M.J. Uren, T. Martin, K.P. Hilton, and R.S. Balmer, "Integrated micro-Raman/Infrared Thermography Probe for Monitoring of Self-Heating in AlGaN/GaN Transistor Structures," *IEEE Transactions on Electron Devices*, vol. 53, no. 10, pp. 2438-2447, Oct. 2006.

[6] *ANSYS Workbench 2.0 Framework*, ANSYS, Inc.

[7] S. Rajasingam, J. W. Pomeroy, M. Kuball, M. J. Uren, T. Martin, D. C. Herbert, K. P. Hilton, and R. S. Balmer, "Micro-Raman temperature measurements for electric field assessment in active AlGaN–GaN HFETs," IEEE Electron Device Lett., vol. 25, no. 7, pp. 456–458, Jul. 2004.

[8] M. Kuball, J. M. Hayes, M. J. Uren, T. Martin, J. C. H. Birbeck, R. S. Balmer, and B. T. Hughes, "Measurement of temperature in active high-power AlGaN–GaN HFETs using Raman spectroscopy," IEEE Electron Device Lett., vol. 23, no. 1, pp. 7–9, Jan. 2002.

[9] A. Sarua, H. Ji, M. Kuball, M. J. Uren, T. Martin, K. P. Hilton, and R. S. Balmer, "Integrated Micro-Raman/Infrared Thermography Probe for Monitoring of Self-Heating in. AlGaN/GaN Transistor Structures", IEEE Trans. Electron Dev., Vol. 53, no. 10, pp. 2438-2447, Oct 2006.

[10] N. Killat, M. Kuball, T.-M. Chou, U. Chowdhury, J. Jimenez, 2 Temperature Assessment of AlGaN/GaN HEMTs: A Comparative Study by Raman, Electrical and IR Thermography", IEEE International Reliability Physics Symposium, IRPS Anaheim, CA, May 2010.

[11] R. J. T. Simms, J. W. Pomeroy, M. J. Uren, T. Martin, M. Kuball, "Channel Temperature Determination in High-Power AlGaN/GaN HFETs Using Electrical Methods and Raman Spectroscopy", IEEE Trans. Electron Dev. , Vol. 55, no. 2, pp. 478-482, Feb 2008.

[12] M. Kuball, G.J. Riedel, J.W. Pomeroy, A. Sarua, M.J. Uren, T. Martin, K.P. Hilton, J.O. Maclean, and D.J. Wallis, "Time-Resolved Temperature Measurement of AlGaN/GaN Electronic Devices using Micro-Raman Spectroscopy," *IEEE Elect. Dev. Lett.*, vol. 28, no. 2, pp. 86-89, Feb. 2007.

[13] G. J. Riedel, J. W. Pomeroy, K. P. Hilton, J. O. Maclean, D. J. Wallis, M. J. Uren, T. Martin, and M. Kuball, "Nanosecond Timescale Thermal Dynamics of AlGaN/GaN Electronic Devices", IEEE Electron Dev. Lett., Vol. 29, no. 4, pp. 416-418, May 2008.