Nanosecond Time-Resolved Raman Thermography: Probing Device and Channel Temperature in Pulsed-Operated GaN and GaAs HEMTs

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Keywords: Thermography; Time-resolved; HEMT; Self-heating; AlGaN/GaN; GaAs.

Abstract

We report our recent progress in developing technology to probe the temperature of electronic devices, illustrated for GaN and GaAs-based HEMTs with high time and sub-micron spatial resolution, demonstrating a temporal resolution as short as 10 ns. Understanding transient heating in pulsed-operated HEMTs is important in order to optimize device performance and reliability. It is also important to assess the validity of electrical testing methods. Quasi-adiabatic heating in GaN based devices is identified within the first ~70 ns of device operation, and we find that the temperature reaches as high as 25% of the DC temperature when operated with 200 ns electrical pulses. The technique is also applied to GaAs HEMTs for the first time, demonstrating the versatility of time-resolved Raman thermography.

INTRODUCTION

Transistors used in radar or communications applications are typically operated in pulsed mode. Assessing the associated transient self-heating is crucial because an excessive temperature rise is detrimental to both device performance and reliability. It is also important to understand whether significant device temperature rises occur in electrical test methods which attempt to minimize device self-heating by employing several short electrical pulses, typically about 100-200 ns-long. Conventionally, infrared (IR) thermography has been used to image the temperature of electronic devices. However, it lacks the both the spatial (5-10 μm)[1] and temporal resolution (2 μs)[2] required to measure DC temperature and transient temperature in HEMT devices.

Micro-Raman thermography, a method based on the temperature dependence of phonon frequencies, has been developed in Bristol to overcome the spatial resolution limit of IR thermography,[3] enabling sub-micron temperature measurements of GaN,[1,3] and more recently GaAs-based devices.[4] In the past, micro-Raman thermography has been restricted to steady-state DC measurements. To enable this technique to be extended to transient measurements we have recently developed time-resolved Raman thermography, employing laser pulses to probe device temperature with a temporal resolution of 50-200 ns, giving an insight into the general temperature evolution in pulse-mode operated GaN based electronic devices.[5,6] Here, we report on the further improvement in temporal resolution to 10 ns for even more detailed measurements of heat diffusion within GaN electronic devices on very fast time-scales. We also report for the first time the application of time-resolved Raman thermography to measure the transient channel temperature of GaAs pHEMTs, widening the application area of the technology beyond GaN device systems.

EXPERIMENTAL DETAILS

Raman scattering measurements were performed on the devices using a Renishaw inVia spectrometer and a 532 nm DPSS laser. Laser light was focused onto the device, and Raman scattered light was collected through a 50× 0.55 NA objective lens, achieving a lateral resolution of 0.5-0.7 μm. Laser pulses were generated by acousto-optically modulating the output of the laser, enabling continuously adjustable pulse widths (temporal resolution) >10 ns for the Raman measurements. Devices were contacted using 50 Ω G-S-G picoprobes and square voltage pulses were supplied to the device under test by a pulse generator. Devices were thermally attached to a copper heat-sink mounted on a computer controlled XYZ mapping stage, which has 0.1 μm step precision for XY movement control. The back plate temperature used for the measurements was 25 °C, unless otherwise stated.

The thermal dynamics of ungated (no gate metal) AlGaN/GaN devices grown on a 4H-SiC substrate was studied. Device temperature was determined from the Raman shift of the E_2 and A_1(LO) phonon modes of GaN, similar to our previous work.[5,6] The devices were 150 μm wide and had contact separation of 5-15 μm. The 532 nm laser wavelength used to probe the device is below the GaN band gap. Laser absorption and laser heating was therefore negligible. Due to the transparency of the semiconductor, the measured temperature corresponds to a depth average though the 1.2 μm-

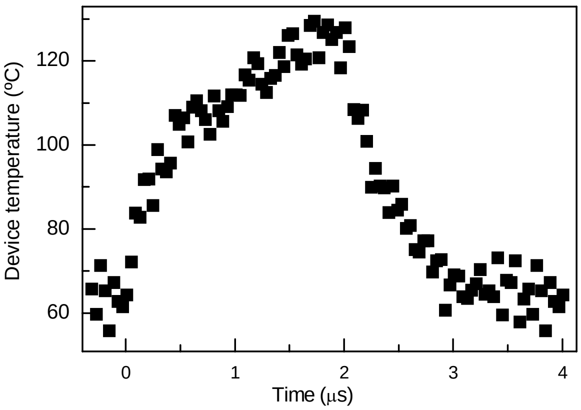

Figure 1: Temperature at the center of an 150×15 μm ungated AlGaN/GaN device operated at 5.3 W with 2 μs drain pulses and a 50% duty cycle. Data was recorded with a temporal resolution of 40 ns.

thick GaN layer. Channel temperature can be extracted from the experimental data with the aid of thermal simulations.

Further measurements were performed on single finger GaAs pHEMTs. The devices had a source-drain opening of ~3 μm and a recessed T-gate with a footprint and width 0.25-0.5μm and 75-100 μm, respectively. The GaAs pHEMTs were operated with a pulsed drain voltage and had a constant DC gate bias applied through a 50 Ω terminated bias tee. In contrast to GaN, the laser wavelength is above the band gap of GaAs. A benefit of the resulting laser light absorption in the device is that the Raman measurement probes only <80 nm (1/2 laser absorption depth) near the device top surface, enabling the channel temperature to be measured directly. However, in order to minimize the impact of laser heating and electron-hole pair generation in the device, it is necessary to reduce the peak laser power to below 300μW. Negligible laser heating and no significant influence on the device IV characteristics were observed under this condition. The device channel temperature was determined from the GaAs LO-phonon frequency, similar to our previous DC measurements on such devices.[4]

RESULTS AND DISCUSSION:

A) ALGAN/GAN ELECTRONIC DEVICES

Figure 1 shows a typical temperature trace recorded with 40 ns temporal resolution at the center of an ungated AlGaN/GaN device operated with a 2 μs square drain electrical pulse. We observe that within the first 0.5 μs there is a rapid temperature rise, followed a more gradual temperature increase thereafter, typically with a time constants on the order of 10 μs for a device on SiC. With the improved temporal resolution of 10 ns, it is now possible to focus on the initial temperature rise, illustrated in Fig. 2 for a similar device. Even within the 200 ns-long pulse there is a significant tem-

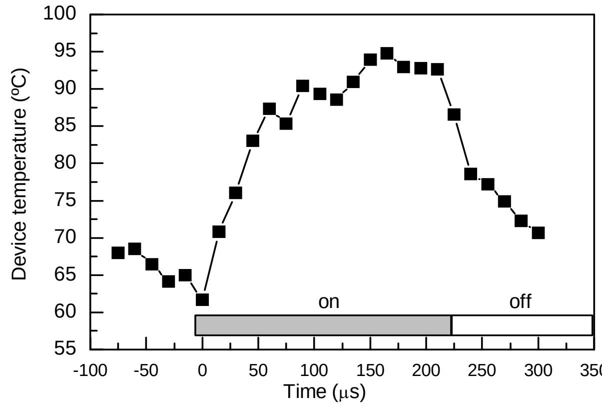

Figure 2: Temperature at the center of an 150×5 μm ungated AlGaN/GaN device recorded with 10 ns temporal resolution. Input power is 3.5W, with electrical pulse length of 200 ns and a 50 % duty cycle.

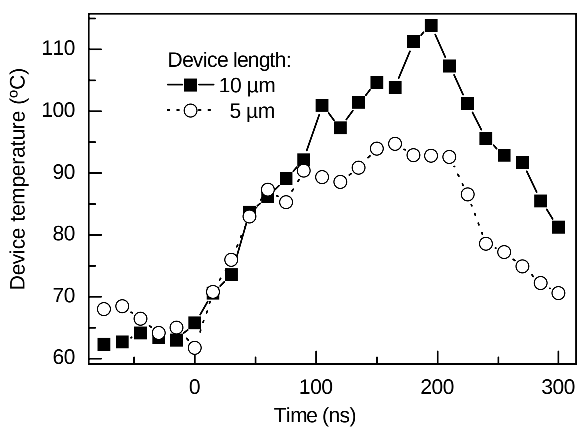

Figure 3: Temperature of two ungated AlGaN/GaN devices with of dimensions 150×5μm and 150×10μm, operated with 200 ns pulse length, recorded with 10 ns temporal resolution. Input powers were 3.5W and 7W, respectively, providing the same power density.

perature rise of ~30 °C. This is about 25% of the DC temperature rise measured for this device. Heating on this time scale is particularly relevant because similar electrical pulse lengths are often used in electrical measurements with the aim of avoiding device self-heating effects. As demonstrated here, this is not a valid assumption.

To gain a better understanding of heat diffusion on very short timescales, transient temperature traces were recorded for different device layouts, compared in Fig. 3. The devices measured have contact openings of 5 μm and 10 μm. In ungated devices power is dissipated uniformly between the contacts. Therefore, to achieve the same power density in both devices, the input power was set to 3.5 W and 7 W for the shorter and longer device, respectively. Within the first ~70 ns after turning on the devices, both temperature traces recorded are identical within the experimental resolution.

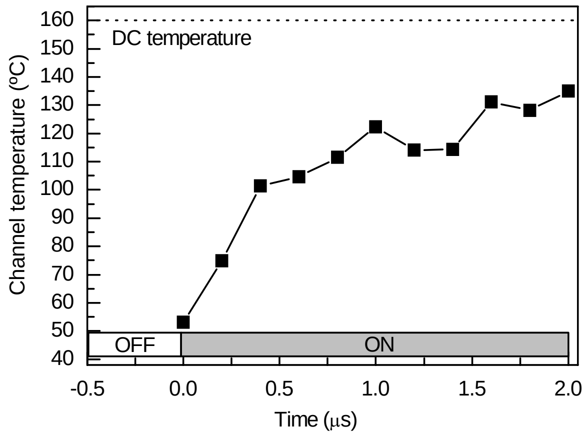

Figure 4: Channel temperature at the centre of a 75 µm-wide GaAs pHEMT, operated at 1.8 W/mm with 2 µs square-drain pulse and a 50% duty cycle.

Within this initial period of device operation heat neither propagates significantly laterally nor into the substrate and the heating of the device can therefore be termed *quasi-adiabatic*. In this regime, only the thermal properties of the GaN in close vicinity to the heat generating region determine the device thermal dynamics. After about 70 ns the temperature traces split as the temperature of the longer device continues to increase at nearly the same rate and the temperature of the shorter device begins to level off. In this longer time scale regime, lateral heat diffusion becomes more important and is more efficient for a narrower heat source (2-D-like diffusion) than for a wider one (1-D-like diffusion). These results illustrate that in the quasi-adiabatic heating regime device layout has little influence on the temperature rise initially after turning the device on. However, it does influence thermal dynamics once heat diffusion sets in. After switching off both the devices at 200 ns, the device temperature decreases as expected, as seen in Figure 3.

B) GaAs Electronic Devices

Figure 4 shows a typical temperature trace recorded in the channel of a GaAs pHEMT operated with a 2 µs drain voltage pulse and a 50% duty cycle. There is a fast initial temperature increase of ~40 ºC, which is 30% of the DC temperature rise, within the first 400 ns of switching the device on. This is followed by a more gradual asymptotic increase towards the DC temperature (~160°C), already reaching within 30 ºC of this temperature by the end of the pulse.

In order to further investigate the time constants associated with GaAs pHEMT self-heating, the temperature rise during the on-pulse was measured for a range of electrical pulse lengths, ranging from 200 ns to 20 ms, shown in Fig. 5. Based on a one-dimensional heat diffusion model, a sum of several different time constants is expected to determine the thermal dynamics of a device.[5] The very fast initial temperature rise within 400 ns, which is also apparent in Fig. 4, may be related to quasi-adiabatic heating, similar to the case discussed in the context of the AlGaN/GaN electronic devices. The following 10 µs can be described by a single time constant (constant gradient in Fig. 5). A more gradual increase in temperature, apparent after 10 µs and extending to the millisecond timescale, is likely due to heat diffusion into the device substrate and die. By assuming a single time constant for the data recorded below 10 µs and extrapolating the temperature in Fig. 5 (dotted line), we find that zero temperature rise would occur within a pulse of duration less than ~10-50 ns.

HEMTs are typically operated at elevated ambient temperatures, due to environmental conditions, for example when operated in aircraft. To investigate the effect of back-

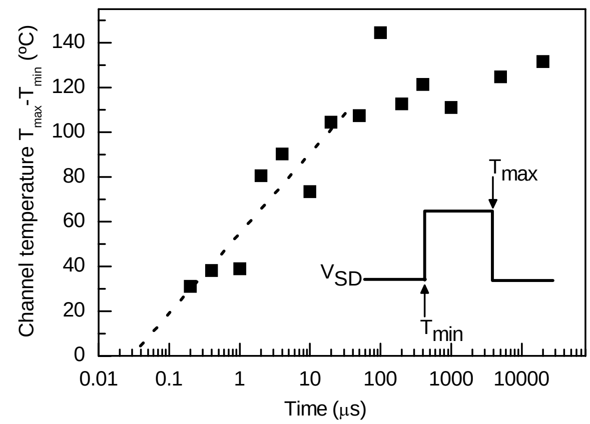

Figure 5: Peak channel temperature rise at the centre of a 75 µm-wide GaAs pHEMT during an on-pulse, when operated at 1.8 W/mm with a variable width and 50% duty cycle. The dotted line shows a linear extrapolation to the experimental data. Inset shows the temperature rise measured (T_{max}-T_{min}) in relation to the applied voltage pulse.

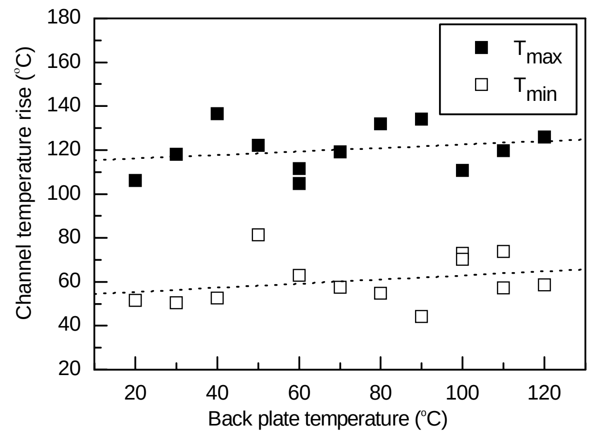

Figure 6: The maximum (T_{max}) and minimum (T_{min}) channel temperature rise above the back plate temperature, recorded at the center of an 100 µm wide single finger GaAs pHEMT operated with 2 µs wide drain voltage pulses, 50 % electrical duty cycle and a power density of 1.8 W/mm. Linear trend lines are shown as a guide to the eye.

ground temperature on the device thermal time constants a device was operated in pulsed mode with increasing back plate temperature. The maximum (heating cycle) and minimum (cooling cycle) temperatures relative to the back plate, recorded for 2 μs, 50 % duty cycle drain voltage pulses, are depicted in Fig. 6. The maximum absolute channel temperatures measured for a 20 °C and 120 °C back plate temperature were 125 °C and 245 °C, respectively. Over the temperature range measured here, the device temperature increases by a factor of 1.1-1.2 relative to the back plate temperature, attributed to the decreasing material thermal conductivity. However, the temperature increase during the electrical pulse remains constant within the experimental resolution, indicating that the thermal time constants remain unchanged.

Conclusions

The thermal dynamics of AlGaN/GaN and GaAs electronic devices has been studied by employing time resolved Raman thermography with an improvement in temporal resolution over our earlier work. In the quasi-adiabatic heating regime, within the first 70 ns of device operation, the thermal parameters of the GaN surrounding the heat generating region primarily determine the device transient temperature. After this time, within the heat diffusion regime, device layout and substrate thermal conductivity become increasingly important factors. Time resolved Raman thermography measurements of GaAs pHEMTs have been demonstrated for the first time, giving insight into the thermal time constants of these devices when operated under pulse-mode conditions.

Acknowledgements

The work at Bristol was supported by the EPSRC. The work at QinetiQ was supported by the Korrigan project**.**

References

[1] 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 Devices, vol. 53, pp. 2438-2447 (2006).

[2] A. Hefner, D. Berning, D. Blackburn, C. Chapuy, S. Bouche, "A High-Speed Thermal Imaging System for Semiconductor Device Analysis", in Proc. of 17th Annual IEEE Semiconductor Thermal Measurement and Management Symposium, pp. 43-49 (2001).

[3] 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 high-power AlGaN/GaN HFETs using Raman scattering", IEEE Electron Dev. Lett., vol. 23, pp. 7-9 (2002).

[4] A. Sarua, A. Bullen, M. Haynes, and M. Kuball, "High-resolution Raman temperature measurements in GaAs p-HEMT multi-finger devices", IEEE Trans. Electron Dev., vol. 54, pp. 1838-1842 (2007).

[5] 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 Electron Dev. Lett., vol. 28, pp. 86-89 (2007).

[6] M. Kuball, G.J. Riedel, J.W. Pomeroy, R. Simms, A. Sarua, M.J. Uren, T. Martin, K.P. Hilton, J.O. Maclean, and D.J. Wallis, "Reliability of High-Speed Devices: Probing of Self-Heating with Nanosecond Time-Resolution", Proceedings of MANTECH 2007, pp. 55-58, (2007).

Acronyms

HEMT: High Electron Mobility Transistor
LO: Longitudinal Optical
NA: Numerical Aperture
DPSS: Diode Pumped Solid State