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# Development of Time-resolved UV Micro-Raman Spectroscopy to measure temperature in AlGaN/GaN HEMTs

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ABSTRACT

We report on the development of Time-resolved Ultraviolet Micro-Raman Scattering to measure transient self-heating effects in semiconductor devices. Temperature measurements are performed on AlGaN/GaN High-electron-mobility transistors (HEMTs) grown on SiC substrate. Ultraviolet excitation probes the temperature close to the AlGaN/GaN interface, in the two-dimensional electron gas (2DEG) region. This new measurement setup allows us to obtain a temporal, spectral and measured spatial resolution of 200 ns, 0.8 $cm^{-1}$ and 1.7 μm respectively. The temperature accuracy is better than 5–10 K. Temperature evolution as function of time has been studied. Self-heating effects are immediately observed. A fast thermal response is demonstrated during the first microsecond after switching the device ON then, a slower thermal response is established during the second microsecond.



## 1. Introduction

AlGaN/GaN HEMTs devices are very promising devices for high power microwave applications. Indeed, output power densities are ten times higher than the best previous results on silicon devices [1]. High-power and high temperature applications are due to superior material properties of these wide band gap AlGaN/GaN heterostructures. GaN based devices will play a major role in spatial, radar and telecommunication systems as soon as the reliability problem will be solved. One of the key points regarding the reliability is the self-heating phenomenon. Indeed, as the power density is ten times higher the self-heating effects are much higher than the usual III/V devices (GaAs, InP) for a same total gate width. In these conditions the knowledge of Time-dependent device temperature in active area is essential to improve device reliability and relevant for AlGaN/GaN transistors design optimization. Device temperature measurements have been already investigated using optical methods [2–6].

Photoluminescence has been used as a common characterization tool and has appeared in many publications on GaN and related materials. In spite of an exceptional signal-to-noise ratio with this technique, features are typically spectrally broader than in Raman spectra. But spectral resolution obtained with Raman Spectroscopy is better than spectral resolution obtained with this technique. Temperature measurements by infrared technique are limited by spatial resolution on the order of 10 μm whereas AlGaN/GaN HEMT active region size is on the order of micrometer. Temperature measurements by visible Micro-Raman scattering [2] enable submicrometer spatial resolution but correspond to average temperature of the whole heterostructure thickness because GaN is transparent to visible light. Confocal Micro-Raman Spectroscopy provides three-dimensional thermal analysis of AlGaN/GaN HEMTs [7]. z-Analysis is possible if thickness of analyzed sample is larger than the depth of focus of the used confocal microscope. For the HEMT AlGaN/GaN, AlGaN and GaN layers thicknesses are slightly thicker than the depth of focus. Therefore, z-analysis in these two layers is impossible, measured temperature is average temperature of each layer. The only way to probe temperature close to the AlGaN/GaN interface, in the active two-dimensional electron gas (2DEG) area, is the use of UV light as excitation source. Up to now, only steady state bias point measurements have been studied with UV Micro-Raman Spectroscopy [8].

The objective of this work is to develop Time-resolved UV Micro-Raman Spectroscopy to measure transient temperature in active region of pulsed-operating AlGaN/GaN HEMT. In this paper,

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we study transient self-heating effects in an AlGaN/GaN HEMT grown on SiC substrate. This one has a better heat dissipation than those grown on Si or Sapphire substrates [2,9]. This is attributable to the higher thermal conductivity of SiC than those of Si or Sapphire. Up to now, there have been few techniques on Time-resolved temperature measurements: Transient Interferometric Mapping technique [10] and visible Time-resolved Micro-Raman Spectroscopy [11,12]. The first technique needs combination with electrical measurements to determine temperature maps, and the second determine directly the temperature but the average temperature of the whole heterostructure. Development of UV Time-resolved Micro-Raman Spectroscopy is a new way to measure directly transient self-heating effects in active region of AlGaN/GaN HEMT under pulsed operation with high spatial resolution and high temporal resolution. This method of temperature measurements has already done on others devices. Pomeroy et al. [13] used an above band gap laser to directly probe Time-resolved channel temperature on GaAs pHEMTs. Contrary to this case where the use of a visible laser is enough, to measure AlGaN/GaN interface area temperature, the use of UV laser is necessary.

## 2. Experimental setup

AlGaN/GaN heterostructure consists of 30 nm of undoped AlGaN (∼30% Al) on 1.2 μm-thick undoped GaN grown on a 330 μm-thick SiC substrate. The technological steps are described in detail elsewhere [1]. The studied device has a single 100 μm-wide finger with 0.5 μm-long gate, source–drain contact spacing of 3 μm and gate–drain contact spacing of 2 μm. Concerning electrical measurement conditions, the drain is pulsed from 0 to 10 V by a function generator and the gate source voltage is maintained to 0 V. In these conditions the drain current density is around 530 mA/mm. Pulses length is on order of microsecond. This allows us to simulate the device switching ON or OFF. Micro-Raman Spectroscopy measurements were performed on the device using a Horiba Jobin Yvon LabRam HR UV Micro-Raman system combined with a Coherent MBD-266 nm solid laser as excitation source. UV light is focused by a 40× objective into the device along the (0 0 0 1) crystal axis of the GaN between drain and gate and more precisely nearest the gate edge. Temperature measurements during bias operation at this location of the device correspond to hot spot temperature [8]. Taking into account of the 1.7 μm measured UV laser spot diameter at the output of the microscope, temperature measurements are in fact 1.7 μm lateral averaging of temperature nearest the gate edge between drain and gate of the device. The scattered light is collected by the same objective in backscattering configuration, dispersed by a 800 mm focal length monochromator and detected by a backthinned illuminated CCD. UV light absorption by the device corresponds to an optical penetration depth of around 60 nm for 266 nm excitation [14]. Thus, scattered light gives us information about AlGaN/GaN interface, near the 2DEG area. To minimize the influence of self-heating effect due to the UV light absorption, we put optical density filters across the beam which decreases UV light power focused on the device to microwatts. Furthermore, in our experiment, the duty cycle of the pulsed laser is around 0.05%. Therefore, laser heating does not occur, which can be verified by the absence of Raman frequency thermal shift of GaN modes of the unbiased device. On the other hand, OBIC phenomenon exists when the component is DC biased but is negligible when the component is AC biased. Acquisition time is increased to obtain an intense and nondisturbed signal. This disadvantage is compensated by a major advantage which is a direct analyse of the thermal state at the AlGaN/GaN interface where the temperature is maximum. Direct measurement of temperature is important since parameters required for thermal device simulations are not always accurately known. Device temperature is deduced from the Raman phonon frequency shift [8,15,16]. In the chosen analyse configuration, Raman scattering by the $A_1$(LO) and the $E_2$(high) phonons can be observed with spectral resolution of 0.8 cm$^{-1}$. We focus on the $E_2$(high) mode to study temperature dependence of the AlGaN/GaN HEMT because this mode is more sensitive to self-heating effect than the $A_1$(LO) mode [16]. This method of determining temperature via the phonon frequency shift requires in first step a calibration procedure. This one gives a relation between experimental $E_2$(high) phonon frequency shift and the measured temperature of the unbiased device. To control the device temperature a Linkam temperature stage with a quartz window was used to heat the sample from 298 K to 523 K. For each measurement point, the temperature was stabilized for 5 min before acquiring a spectrum. The Raman phonon frequency was determined using the Gaussian–Lorentzian line shape fitting [17]: measure precision achieved is 0.1 cm$^{-1}$, which corresponds to temperature accuracy better than 5–10 K. The experimental data were fitted using the following relationship proposed by Cui et al. [18] for modelling the temperature dependence of the Raman modes of diamond and used by Liu et al. [16] for GaN:

$$\omega(T) = \omega_0 - \frac{A}{\exp[B(\hbar\omega_0/k_B T)] - 1} \quad (1)$$

where $\omega_0$ is the Raman phonon frequency at 0 K, $A$ and $B$ are fitting parameters, $\hbar$ the reduced Planck constant and $k_B$ the Boltzmann constant. Fig. 1 shows experimental data of the calibration curve obtained by fitting with the above equation. The other Raman method of determining temperature via the Stokes to Anti-Stokes intensity ratio is not adequate here because a UV excitation source is used. In fact, near the absorption edge, the UV light is absorbed by the material (following absorption coefficient) what distorts the relative intensities of the Raman modes. Therefore, the Stokes to Anti-Stokes intensity ratio is distorted and not suited for this application.

The laser pulses were generated from the Coherent MBD-266 nm solid laser combined with an acousto-optic modulator (AOM) synchronized with the drain bias pulses. Generated optical pulses achieve a temporal resolution of 200 ns. Temporal resolution should be better with a pulsed laser but laser power could damage the sample. The use of an acousto-optic modulator allows a variation of the pulse length. For our study, pulse length is fixed to 200 ns. This value correspond to the best temporal resolution obtained with our UV system (laser, AOM and Micro-Raman spectrometer). Time-delay is defined as time between laser and electri-

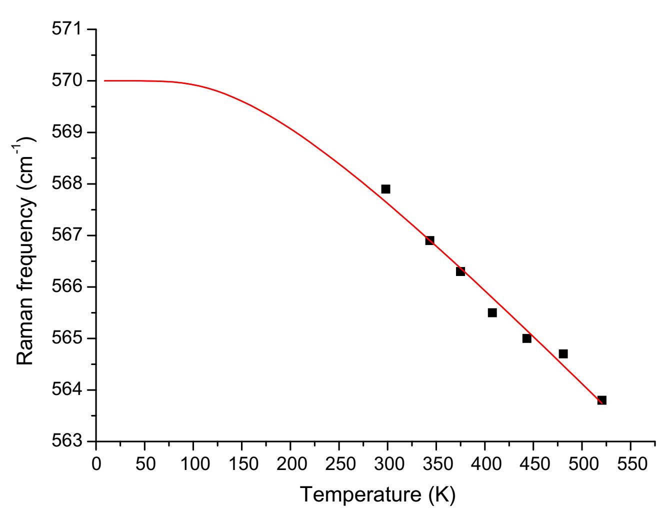


**Fig. 1.** Temperature evolution of the $E_2$(high) phonon frequency (calibration curve) of the studied AlGaN/GaN HEMT.