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Anass Jakani, Raphaël Sommet, Florent Gaillard, Jean-Christophe

Nallatamby

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Comparison of GaN HEMTs Thermal Results through different measurements methodologies: Validation with 3D simulation

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Anass JAKANI CCSNL Team XLIM laboratory Brive-la-Gaillarde, France anass.jakani@xlim.fr

Jean-Christophe NALLATAMBY CCSNL Team XLIM laboratory Brive-la-Gaillarde, France jean-christophe.nallatamby@xlim.fr Raphael SOMMET CCSNL Team *XLIM laboratory* Brive-la-Gaillarde, France raphael.sommet@xlim.fr Florent GAILLARD CCSNL Team XLIM laboratory Brive-la-Gaillarde, France florent.gaillard@unilim.fr

Abstract—In this work, thermoreflectance measurement technique is applied to GaN HEMTs transistors, GH15 8x50µm and 6x50µm from the UMS foundry. These measurements are compared to 3D simulation, but also to measurements based on an electrical approach we developed previously in [1]. The good agreement between results and the thermalization time constant proposed in [2] for GaN HEMTs validate finally all our approach dedicated to thermal resistance or thermal time constant

Keywords—Thermoreflectance, thermal impedance, GaN HEMT, thermal simulation

I. INTRODUCTION

The improvement of the GaN HEMT technology offers answers to the need for efficient solid-state operation at RF frequencies. However, self-heating can degrade the performance and reliability of the device by affecting the electron mobility in the channel. Hence, the knowledge of the temperature of the device under operating conditions and the location of the hot spot became mandatory in the RF electronic industry.

In our work, we propose a comparison between both an electrical and an optical method dedicated to temperature measurement. Concerning the electrical method our approach has been developed in [1] but other methods like [8] [9] can be also used. Concerning the optical method, we have chosen the thermoreflectance method and the Microsanj test setup for its ability to measure the temperature with a high spatial resolution (<1um) and high time resolution(<50ns). Micro-Raman is reputed to offer also very good results [10]

II. METHODS AND SETUP

A. Thermoreflectance setup and measurement method

The reflectivity of the materiel changes when the temperature changes [3]. Thus, the relationship between the relative surface reflectance variation ($\Delta R/R_0$) and the surface temperature for a given surface can be expressed:

$$\frac{\Delta R}{R} = C_{th}.\,\Delta T \tag{1}$$

 C_{th} represents the TR coefficient which is a material parameter and wavelength of probing light dependent.

Typically, the spatial resolution of 365 nm is the best for GaN with SiNx passivation. The TR coefficient is obtained through a calibration process by putting the Device Under Test (DUT) on a thermal stage with two temperatures, hot (50°C) and cold (20°C). When the temperature changes, the reflectance also changes. This TR coefficient is controlled by a piezo stage for each point of CCD camera. Two types of measurement are possible with this test setup: steady state or transient temperature measurement. For the transient measurement the timing delay for measuring inside the excitation pulse is precisely controllable.



Figure 1: Thermoreflectance experimental setup

B. Pulsed I-V measurement method

Two steps are needs for this measurement: The first step consist in the calibration process. The quiescent point selected is $V_{GSq} = V_{DSq} = 0V$. We measure the pulsed I-V characteristics of the device for different thermal chuck temperatures from 25°C to 75°C. We extract the on-state resistance from the slope of the linear region of the I(V) characteristics and we plot it as a function of the chuck temperature. In the second step, we fix the baseplate temperature to 25°C, V_{GSq} at 0V and we vary V_{DSq} from 0 to 10V, the device dissipates a different amount of DC power

by self-heating effects. Thus, the R_{ON} was measured as a function of dissipated power (P_{diss}). The thermal resistance can be determined by the ratio of the two slopes:

$$R_{th} = \left(\frac{\partial R_{ON}}{\partial P_{diss}}\right) / \left(\frac{\partial R_{ON}}{\partial T}\right)$$
(2)

III. GAN HEMT RESULTS AND DISCUSSION

A. Device description

Measurements have been performed on a GH15 $8x50\mu m$ and $6x50\mu m$ based on AlGaN/GaN heterostructure grown on a 70 μm thickness silicon carbide substrate (SiC). The gate length L_G is 0.15 μm .



Figure 2: Cross section of the device structure

B. Thermoreflectance measurement on GaN transistors

In order to measure the temperature under the SiNx passivation where the 2-Dimentional Electron Gas is located and where also the peak value of temperature is localized, we use the 365 nm wavelength. Note that the illumination source chosen here is an incoherent dispersed low power UV LED in order to minimize the photo-induced current during the thermoreflectance measurement [4]. We use a 50X objective with NA = 0.42 resulting in a diffraction limited lateral spatial resolution of ~ 0.3µm. The thermoreflectance measured through the calibration process on the region of interest is $(C_{th} = -3x10^{-3} \pm 2x10^{-5} \circ C^{-1})$. On the same region the thermoreflectance coefficient obtained respectively for 530nm (green) and 470nm (blue) is $(C_{th} = -2x10^{-4} \circ C^{-1} \text{ and } C_{th} = -7x10^{-5} \circ C^{-1})$.



Figure 3: Calibration process for GH15 transistor using 365nm LED

So, the thermal coefficient for the UV signal is large enough to obtain accurate measurements results. We have performed two types of measurements for two device developments: a transient measurement for the GH15 $8x50\mu m$ and a steady state one for a the GH15 $6X50 \mu m$. For the transient measurement, the square wave pulse is used and the following pulse conditions are applied: pulse width = 100 μ s and pulse period = 1ms. The bias condition chosen is Vds = 7V and Ids = 100 mA



Figure 4: Timing diagram for transient thermal analysis

The measurement of the temperature variation leads to $\Delta T = 22^{\circ}$ C. Then according to the dissipated power, we can extract the thermal resistance:

$$R_{th} = \frac{\Delta T}{P_{diss}} = 31.4 \,^{\circ}C/W \qquad (3)$$

Moreover, the time constant measured for the transient behavior is $\tau \simeq 40 \ \mu s$ as shown in figure (5).

Bagnall [2] in his work, demonstrates that the longest 2D-thermal time constant can be expressed as:



Figure 5: Transient temperature vs time for the 8x50µm device

Where $\alpha = \frac{\kappa}{\rho \cdot C_p}$ is thermal diffusivity, L_{sub} is the thickness of the substrate. In our case the thickness L_{sub} of the SiC substrate is 70µm and $\alpha = 1.82 \times 10^{-4} \text{ m}^2/\text{s}$.

The thermal time constant calculated by this simple formula [2], gives $\tau = 10.9 \,\mu s$. We observe a difference of approximately 30 μ s. This difference may be due to

measurement conditions. (the width of the optical signal chosen for the TR measurement is 20μ s).

For the steady state measurement, the measured temperature variation is $\Delta T = 27^{\circ}C$ for a drain-source signal Vds = 9V and Ids = 70mA ($P_{diss} = 0.63W$).

The measured thermal resistance in the region of interest is:

 $R_{th} = 42.86^{\circ} \frac{C}{W}$



Figure 6: GH15 8x50µm heated

C. Pulsed I-V measurement to extract thermal resistance

The method proposed in [1] is used to extract the thermal resistance (R_{TH}) on a GH15 6x50µm. Using the on-state resistor method described in II-B, the thermal resistance obtained for the GH15 6x50µm is 41.25°C/W. Similar measurements have been performed for GH15 8x50µm. The corresponding measurement results were previously published in [5] (R_{th} =32.5°C/W). The ratio between each thermal resistance is correlated to their finger number



Figure 7: Ron at different temperatures for GH15 6x50µm



Figure 8: Ron at different dissipated power for GH15 6x50µm

Material	Thermal conductivity (W/m. K)	Density (g/m ³)	Specific heat (J/K.g)	Nodes
SiC	390	0.665	3.21	
GaN	130	0.431	6.15	
SiN	35	0.68	3.2	211318
AlGaN	40	0.604	5.184	
Au	315	0.13	19.32	

D. 3D simulation using Salome-Meca software

Table 1: Physical parameters used in the 3D simulation [6], [7]

For the steady state simulation, the device structure of a GH15 6x50µm is symmetric with respect to X-axis and Y-axis and therefore quarter of the structure is used for the simulation. We consider adiabatic boundary condition on the area of the structure. We apply a dissipated power equal to 1W on the quarter of the structure. The applied DC power is 29.63 W/um² per heat source. Figure 9 shows that the maximum temperature obtained in the channel is $T_{max} = 196.2$ °C (for a baseplate temperature of 25°C so $\Delta T = 171.2$ °C). Thus, the simulated thermal resistance for the GH15 6x50µm is $R_{th} = 42.8$ °C/W.



Figure 9: Steady state simulation for a 6x50µm device

We perform also a transient simulation with the same boundary conditions as for the steady state simulation performed earlier for the GH15 8x50µm. Figure (10) shows that the maximal temperature obtained in the channel which is $T_{max} = 147.76$ °C (for a baseplate of 25°C so $\Delta T =$ 122.76°C). The thermal resistance obtained through simulation is $R_{th} = 30.7$ °C/W In order to determine the thermal time constant, we used the Foster thermal network to fit the data obtained by the simulation, the longest thermal time constant found is $\tau = 9.1\mu s$. The two-time constants simulated and calculated exhibit approximately the same value.



Figure 10: Transient Simulation on a GH15 8x50µm and fitting curve using ADS software

IV. SUMMARY AND DISCUSSION

Good agreement is found between the thermoreflectance method that measures the surface temperature, and the electrical methods that measures the average temperature in the channel. Normally those temperatures should be different but in fact they are very close. Several elements can be considered to justify this result:

On one hand, the measured channel temperature is an average temperature that is lower than the maximum temperature

On the other hand, the surface temperature is measured at the end of the fingers due to air bridges so the measured temperature is also lower than the maximum surface

Last element, the use of the 365nm wavelength allow to measure temperature through the SiN layer, so close to the cap layer. So, the measured "surface" temperature is not really a surface temperature.

For the thermal time constant, the simple formula given in [2] and the results of the 3D simulation gives approximately the same value, but for the optical measurements we found a difference of 30μ s. This difference can be explained by the width of LED pulse which is probably to large to be accurate enough. The discrepancy between the experimental time constant and the theoretical one obtained with a 1-D approximation requires further investigation

GH15 8x50μm – <mark>6x50μm</mark>	TR	3D simulation	Bagnall equation	Pulsed I-V
Thermal resistance R _{th} (°C/W)	31.4 – 42.86	30.7 - 42.8		32.5 – 41.25
Thermal time constant (µs)	40	9.1	10.9	

Table 2: Comparison of the results of GaN HEMT transistor 8x50µm in black and 6x50µm in red

V. CONCLUSION

In this work, we have cross-validated the static thermoreflectance approach with an electrical approach and compared the thermal time constant obtained using both thermoreflectance approach and simulation values. Results obtained for 6x50 and 8x50 reveal a good scaling rule concerning the thermal resistance ratio.

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