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GaN HEMTs thermal time constants: Theory and Measurements

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Abstract

The focus of this paper is to provide a better understanding on the role of the different layers as well as the gate length in determining thermal time constants in GaN High Electron Mobility Transistors (HEMTs). The paper is divided in two parts. In the first one, a theoretical approach is proposed where a comparison between numerical Finite Element Analysis (FEA) coupled to Model Order Reduction technique based on Ritz vector method and analytical approach is performed. It has been shown that real physical thermal time constants obtained from the analytical solution of the heat equation of simple realistic structures which represent GaN HEMTs can be obtained through a coupled approach between a numerical solution and a model order reduction technique. The second part explores a measurement approach to identify the transient time constant behavior of GaN HEMT devices. This measurement technique is based on a transient thermoreflectance imaging.

1. Introduction

With the increasing level of integration of electronic components, the management of the generated heat has become one of the most important aspects of the design of components and circuits and has induced major changes in the direction of technology development these last years.

Moreover, the complexity of the applied signals is increasing and in many applications, the average dissipated power in the transistor evolves at frequencies which are of the order of the inverse of the thermal time constants. In these cases, designers need a complete dynamic description of the thermal behavior.

The measurement of thermal time constants is not an easy task, in particular because their number increases and their value decreases at the nanometric scale[1][2]

Several types of measurements can be performed, especially to determine the thermal resistance of the transistor. Most of electrical methods involve finding a sensitive parameter in the device and usually to measure the temperature dependence of it.

Since this method is fully device-dependent, we prefer to focus here on measurement techniques that are independent of the device itself. Therefore, we will focus on thermoreflectance technique which can be used to measure the thermal properties from bulk materials to thin films, multilayers, suspended structures, and nanomaterials.

This technique is very interesting but require an expensive and heavy equipment. Moreover, there are many variations within the thermoReflectance techniques [3]. This technique is also comparable to Raman thermography in terms of capabilities. However, thermoreflectance techniques are based on the change of the sample reflection coefficient as a function of temperature whereas Raman thermography is based on the temperature dependence of phonon frequencies

The advantages and drawbacks of each method really depends on the application but both can be used at microscale/nanoscale and can achieve very short time resolution of less than 1ns [4] [5]

2. Discussion on the use of Model Order Reduction associated with Finite Element Analysis

Several approaches have been discussed in literature for the thermal simulation of electronic devices.

One of the most widely used methods is the Finite Element Method (FEM). The principle of this method is well established, but thanks to the results obtained, we have developed a complete calculation of the thermal time constants that

appear in the transient response of transistor devices.

The second important point is when a thermal simulation is carried out, a temperature map is obtained, hence the maximum temperature for given boundary condition and dissipated power.

In this paper we want to point out the limitation of one RC cell modelling for GaN HEMT devices with gate length smaller than $1\mu\text{m}$ and also to prove that the real thermal time constants present in the device can be achieved by using numerical simulation and Model Order Reduction.

3. Determination of thermal time constants

To represent the transient behavior of the temperature the thermal time constants have to be determined. Let's study this first case which is very common.

1-D, Single-Layer Simulation

Figure 1 shows the 1-D Silicon Carbide structure implemented in ANSYS software. A uniform distributed heat flux $Q_0 = 1 \text{ W/m}$ was used on the top of the structure and a constant temperature $T_0 = 0 \text{ }^\circ\text{C}$ was applied to the bottom of the layer.

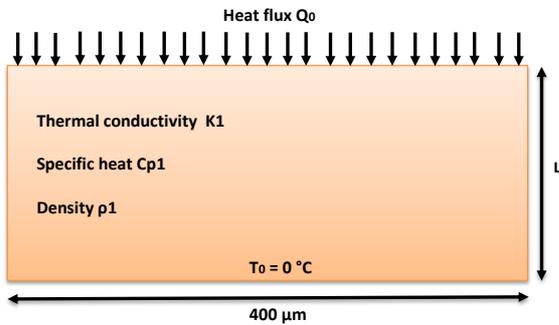


Figure 1: 1-D single-layer structure.

For this simple 1D-device there are several ways to extract thermal time constants

The first one has been performed in [1] by Bagnall and al. The authors proposed an analytical solution of this problem with leads to the following formula for the real physical thermal time constants present in the structure

$$\tau_n = \frac{4 \cdot L^2}{(2n - 1)^2 \cdot \pi^2 \cdot \alpha}$$

Where α is the thermal diffusivity of the layer defined by:

$$\alpha = \frac{K}{\rho \cdot C_p}$$

The second way is based on a purely numerical approach that we have developed [2]. Our approach is based on

- a Finite Element formulation of the (linear) problem
- an extraction of the matrices representing the problem
- a reduction of the linear system based on the Ritz vector approach

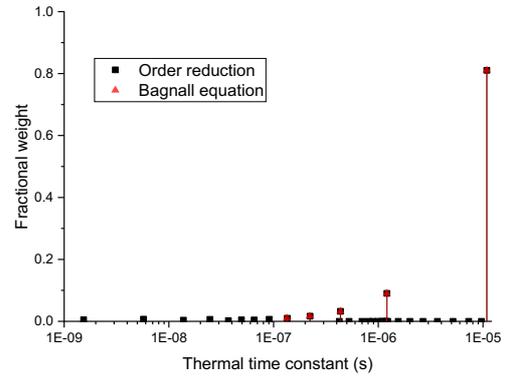


Figure 2: Thermal time constant spectrum for a 1-D single layer structure using MOR in black and Bagnall equation in red (analytical solution).

Figure 2 exhibits several important elements. The first one is that

-At least three thermal time constants are necessary to represent with a good accuracy the real transient behavior for time greater than 100ns.

-the thermalization of the device is proportional to the square of the thickness. For example, if we consider a SiC substrate of $70\mu\text{m}$, $10.9\mu\text{s}$ is obtained (Figure 2), so we need between $40\mu\text{s}$ and $50\mu\text{s}$ to obtain the thermal steady state for the device as shown in red in Figure 4

-Our numerical approach resulting from model order reduction applied to the FEM matrices give the real physical thermal time constants.

The next step consists to see what happens if the heat source is reduced.

Figure 3 shows the new structure with a heat source of 100nm. For this simple structure the analytical transient solution is complex and can be found only by using Green function in [6], instead of a conventional representation with a sum of exponential terms as expressed below:

$$T(t) = \sum_{i=1}^n R_i(1 - e^{-t/\tau_i})$$

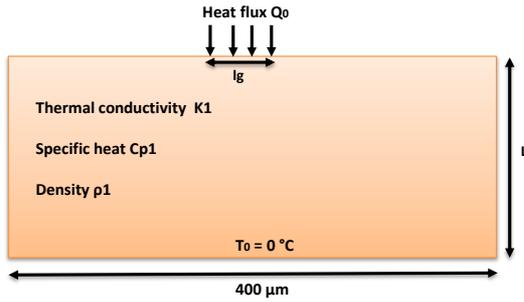


Figure 3: 2-D single-layer structure.

The transient response is proposed and compared to the previous one in Figure 4. We can observe in this figure that the maximum temperature is more than 50% of the final temperature after 10ns.

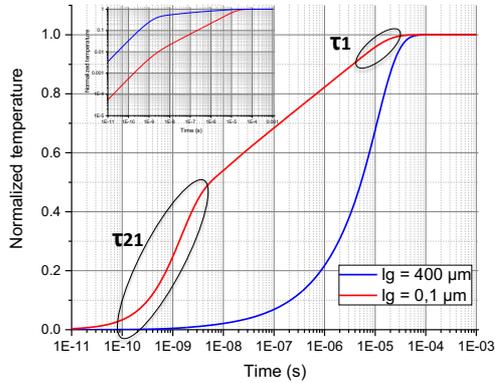


Figure 4: Normalized temperature response versus time (inset log (Temperature) vs log (time)).

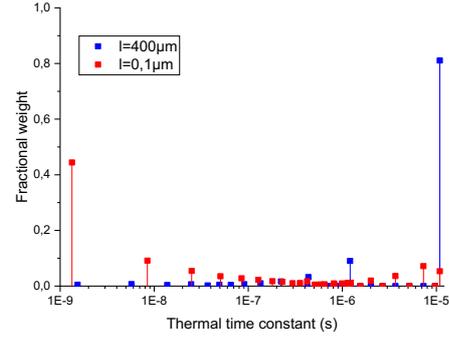


Figure 5: Thermal time constant spectrum for 2D structure using different gate length

The number of thermal time constants is increasing and their fractional weight indicates that time constants values lower than 10ns are very important as shown in Figure 5. This result exhibits also the difficulty to measure with accuracy the transient behavior of the temperature

Other studies have been performed, including a more realistic structure, including the GaN layer.

Results are not fundamentally different and we have only observed a small shift of the values of the thermal time constants

3. Transient Thermal Measurements

In this section, the measurements of thermal transient of GaN HEMTs have been performed with a thermoreflectance setup from Microsanj.

The HEMT structure is presented in Figure 6

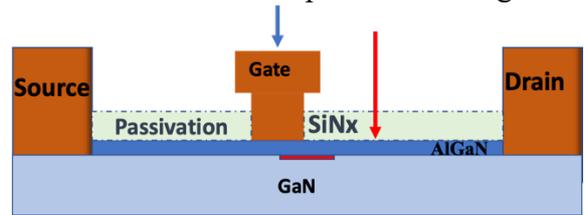


Figure 6 : GaN HEMT structure

For sake of clarity, only one finger is shown. The red area corresponds to the heat generation in the device. The thickness of the AlGaN barrier is around 20nm. The measurement is performed with LED of 365nm. This wavelength allows to measure temperature through SiN layer close to the hot area with the best sensitivity. Another measurement is performed directly on the metal

of the gate. For this measurement, a wavelength of 530nm is chosen. Figure 7 shows the thermal imaging of a two-finger GaN HEMT designed by IEMN. Figure 8 exhibits the transient evolution of the temperature of this device.

Two main observations can be made on transient measurements.

The first one is that temperature is warmer with the red measurement because the measurement has been done near the heat dissipation area, only at 20nm of the heat source.

The second point is that we can also see a small difference in the time spectra between the red and the blue curves. It corresponds to the delay of the diffusion time.

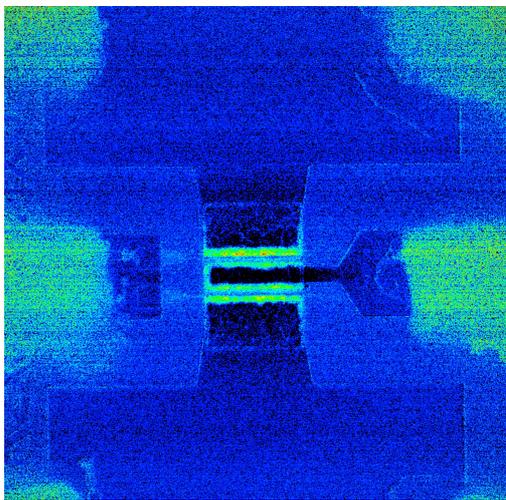


Figure 7: Thermal imaging`

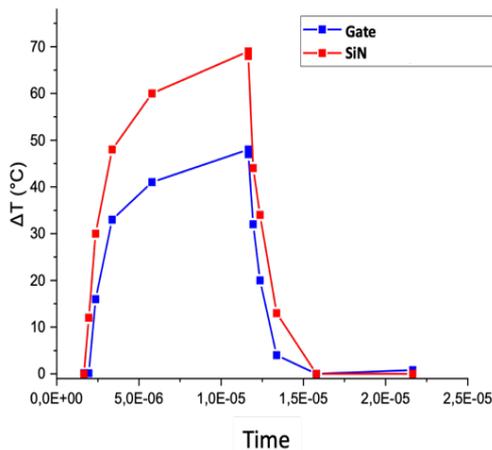


Figure 8 : Transient measurement of GaN HEMT from IEMN

Our measurement system has also been validated using an electrical method: gate resistance thermometry (GRT) [7,8].

This kind of measurement requires a specific design of the transistors with gate connections at both ends in order to use R_g resistance as a sensitive thermometer. Figure 9 shows transient results obtained by thermoreflectance thermometry. Figure 10 shows the decrease of the normalized gate current obtained using three different heating pulses on the drain of 20 μ s. The gate is biased with a small DC voltage difference in order to allow the measurement of the gate current variation without heating the structure.

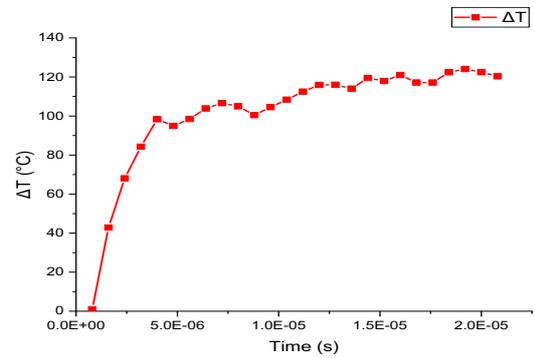


Figure 9: transient thermal thermoreflectance measurement

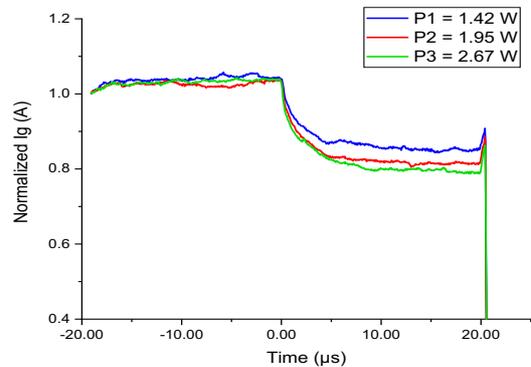


Figure 10: Electrical measurements: Normalized $I_g(V_d)$ decrease

4. Conclusions

In this paper we have reminded that more than one thermal time constants exist even in very simple device. In GaN HEMTS, we have shown that numerous thermal time constants appears when the heat source length is smaller than 1 μ m

and that the smallest ones have also an important impact. Thermoreflectance has proven to be a very interesting technique for the acquisition of temperature transients.

Acknowledgments

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