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Investigation of Thermal Resistance Extraction of GaN HEMTs through DCT Measurements Techniques and TCAD-Based Physical Simulations

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Abstract — In this paper, we extract the thermal resistance (R_{TH}) of an AlGaIn/GaN HEMT using a simple approach based on Drain Current Transient (DCT) spectroscopy technique. Previous work confirms that acceptor-like traps present in the Fe-doped GaN buffer are responsible for the drain-lag effect observed in the measurement. The main goal of this work is the use of trap emission time constant which is very sensitive to temperature. The extracted R_{TH} using the new approach was around 13 °C.mm/W. TCAD confirms that the R_{TH} determined using the new measurement approach represents the R_{TH} located around 150 nm under the gate.

Keywords — AlGaIn/GaN, iron doping, thermal resistance, traps, Drain Current Transient spectroscopy

I. INTRODUCTION

AlGaIn/GaN high-electron mobility transistors (HEMTs) are good candidates that offer high saturation velocity and high breakdown voltage properties, reaching to high performances in terms of output power, bandwidth and efficiency.

For that purpose, the GaN buffer layer is intentionally doped with compensational impurity such as iron (Fe) for reducing buffer leakage and punch-through currents, enhancing carrier confinement in the 2DEG and increasing the breakdown voltage of AlGaIn/GaN HEMT devices [1]. Acceptor-like traps induced by Fe-doping electrically compensate the residual background donor impurities in the buffer region, resulting in a highly resistive GaN buffer layer. Nevertheless, electron trapping in the buffer promotes current collapse/dispersion, increased ON-resistance (R_{ON}) and dynamic shift in threshold voltage, as well as reduced microwave output power and efficiency, hindering the dynamic operation of the HEMT [2]. Thus, buffer trapping is the major obstacle in the AlGaIn/GaN HEMT technology for its successive integration in next generation microwave and high-power systems. Hence, defect characterization and simulation studies are essential to acquire the information of deep-level traps in the device and to control Fe-doping incorporation in the buffer during the epitaxial layer growth.

DCT is a powerful time domain technique to characterize usually the deep-level traps in AlGaIn/GaN HEMTs. Slow drain current transients are often observed in these devices, if either the drain or/and gate voltage is changed suddenly [3]. This is

due to the capture-emission process of charge carriers by traps existing in the device and causing gate and drain-lag effects [4]. In this work, we investigate a new approach to extract the R_{TH} of an AlGaIn/GaN HEMT using the same measurement technique. As we all know, thermal effects remain also the biggest problem for GaN community because they limit the performances of the device.

The R_{TH} is generally evaluated using 3D thermal simulation, electrical or optical measurements. More details about the thermal model calibration and the measurement can be found in [5][6][7].

In this paper, a comparison between thermal and TCAD simulation results explaining the difference between the R_{TH} values obtained using the new approach was reported.

The organization of the paper is as follows: Section II describes briefly the HEMT structure. Section III describes the new measurement approach to extract the R_{TH} using the transient variation of the drain current by performing time domain drain lag measurement. Section IV investigates the measurement approach using TCAD 2D physical based device simulations. Finally, section V concludes the paper.

II. DEVICE DESCRIPTION

The investigated HEMT device consists of GaN/AlGaIn/GaN heterostructure grown on a silicon carbide (SiC) substrate. The epitaxial heterostructure layer contains a Fe-doped GaN buffer layer, an undoped GaN channel layer, an Al_{0.25}Ga_{0.75}N barrier layer, and a thin GaN cap layer. The transistor features a T-gate design with 0.15 μm length and a gate width size of 6×50 μm. The AlGaIn/GaN HEMT device structure also has a silicon nitride (SiN) surface passivation.

III. EXTRACTION OF R_{TH} USING THE NEW APPROACH

As mentioned previously, the DCT measurement is generally used to extract the signature of traps existing in the device. This technique is based on the measurement of the drain current characteristics after a high voltage pulse on V_{ds} or/and V_{gs} . The recovering of the drain current due to the emission of trapped charges is measured over several time decades by using a digital oscilloscope with multi-recording technique. Knowing that the constant emission time of traps is very sensitive to

temperature. The main goal of this work is to take advantage of this thermal dependence and investigate a new simple approach to extract R_{TH} . To do this, we applied a double pulse v_{dsoff} and v_{gsoff} on V_{ds} and V_{gs} respectively, for a pulse duration $T_{filling}$ of 100ms as shown in the fig.1.

Step 1 consists of measuring the drain current recovery due to the emission of trapped charges at T_{chuck} of 30°C. We configure a double pulse ($V_{dsoff}=20V$, $V_{gsoff} = -6V$), $V_{dson} = 10V$ and v_{gson} adjusted to obtain $i_{dson} \times v_{dson} = 2W/mm$. Then we obtain the emission time constant known as τ_1 for 2W/mm, using the equation shown in Fig. 2 (step 1).

$$T_{\tau_1} = P_{2W/mm} \cdot R_{th} + T_{chuck1} \quad (1)$$

Step 2 is very similar to step 1 pulse configuration, the only difference is that the drain current due to the emission of trapped charges is measured at $V_{dson}=10V$, and v_{gson} adjusted to obtain $i_{dson} \times v_{dson} = 1W/mm$. So, we can extract the constant emission time named τ_2 which correspond to 1W/mm at $T_{chuck} = 30^\circ C$ as shown in Fig. 2 (step2).

$$T_{\tau_2} = P_{1W/mm} \cdot R_{th} + T_{chuck2} \quad (2)$$

The final step consists in adjusting τ_2 obtained at 1W/mm in step 2 by increasing T_{chuck} in order to obtain τ_2 (at 1W/mm) = τ_1 (at 2W/mm) as shown in Fig.2 (step3).

Fig. 3 shows the measurement results of the drain current recovery normalized at 2W/mm for a $T_{chuck} = 30^\circ C$ (green curve), and at 1W/mm adjusted for $T_{chuck} = 44^\circ C$ to obtain the same constant emission time (blue curve).

When τ_2 (at 1W/mm) = τ_1 (at 2W/mm), the R_{TH} can be extracted using the relation (1) and (2), where ΔT is the difference between the two measured chuck temperatures, and ΔP is the difference of the two measured powers.

$$R_{th} = \frac{|\Delta T|}{|\Delta P|} = \left| \frac{T_{chuck2} - T_{chuck1}}{P_{1W/mm} - P_{2W/mm}} \right| \quad (3)$$

We obtain an $R_{TH} = 14^\circ C \cdot mm/W$. The next step consists in removing the thermal environment of the device because the measured transistor was mounted on a copper carrier to enhance the thermal contact between the transistor and the thermal chuck. To tackle this problem, we perform a fast simulation considering the copper, the substrate, and replacing the device by its footprint with 0.3 W of dissipated power. Results exhibit a value of $1^\circ C \cdot mm/W$ for the thermal resistance to be subtracted. The final approximate value of thermal resistance using the new approach is then $13^\circ C \cdot mm/W$. González et al. [8] have recently published the extraction of R_{TH} using the same new measurement approach. In this work, a complete study, based on measurements, thermal and TCAD simulations was carried out, to verify the value obtained by applying the new method.

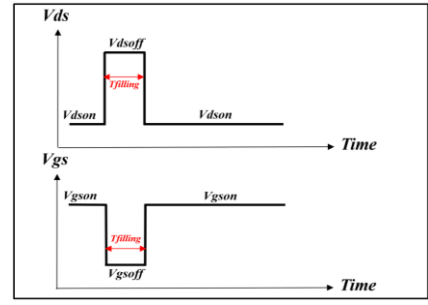


Fig. 1. DCT measurement configuration.

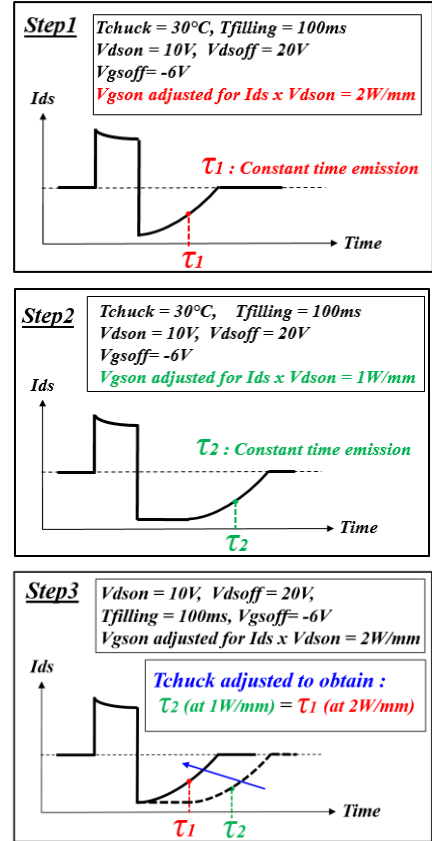


Fig. 2. Measurement steps for 2W/mm at $T_{chuck} = 30^\circ C$ and for 1W/mm with an adjusted T_{chuck}

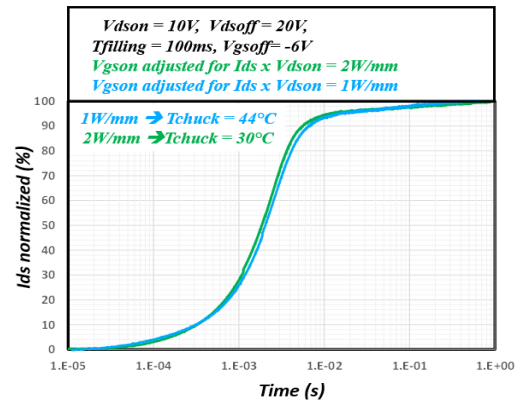


Fig. 3. Measured transient drain current recovery related to the emission of traps at $T_{chuck} = 30^\circ C$ for 2W/mm and $T_{chuck} = 44^\circ C$ for 1W/mm and for $T_{filling} = 100$ ms.

IV. TCAD –BASED PHYSICAL DEVICE SIMULATIONS

A 2D physics-based numerical simulation has been performed using TCAD Silvaco software. The AlGaIn/GaN HEMT structure considered in the simulation is shown in Fig.4.

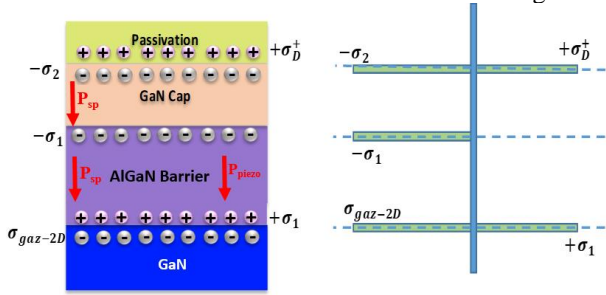


Fig. 4. Schematic cross section of the GaN/AlGaIn/GaN HEMT structure used in the simulation. Polarization charges defined at each material interface in the physical device simulation.

Poisson's equation, continuity equations for electrons and holes and the drift diffusion model are solved. Thermal module GIGA from Silvaco was activated to analyze the effects of self-heating in the device. The same simulation methodology was used in the previous work [4]. This section undertakes a set of TCAD simulations to support measurements of the impact of traps on device characteristics. A positive fixed sheet charge and an equivalent negative charge must be defined [9]. According to surface donor theory [10], the surface donors are responsible for the 2DEG channel formation in GaN HEMT devices. Hence, donor-like traps having a density of $1 \times 10^{13} \text{ cm}^{-2}$, with an energy level of 0.2 eV above the mid bandgap are introduced. Electron (σ_n) and hole (σ_p) capture cross sections are assumed to be $8.0 \times 10^{-14} \text{ cm}^2$ for σ_n and $8.0 \times 10^{-14} \text{ cm}^2$ for σ_p . For the simulation, the GaN buffer layer is doped with iron (Fe). Iron is an acceptor-like traps whose trap energy is placed at 0.7 eV below the conduction band with capture cross section value equal to $8.0 \times 10^{-14} \text{ cm}^2$. The Fe concentration varies from $\sim 0.5 \times 10^{17} \text{ cm}^{-3}$ near the AlGaIn/GaN interface to $\sim 1.0 \times 10^{18} \text{ cm}^{-3}$ in the GaN buffer. The Shockley-Read-Hall recombination model, constant mobility and field dependent mobility models were used for carrier generation and recombination. The calibration of each physical parameters was realized to achieve the best match with the measured I-V characteristics. The calibration process starts with fitting the pinch-off in simulation to experiment by adjusting the Schottky gate work-function. Then, by using the low field mobility and saturation velocity parameters of GaN material [4], the linear and saturation region drain current characteristics are calibrated.

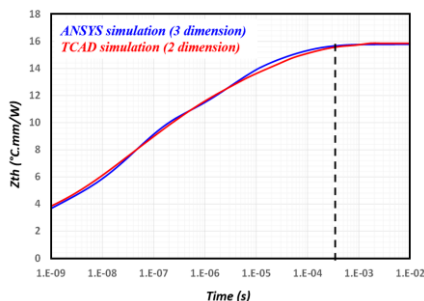


Fig. 5. Thermal impedance simulated using 3D Ansys thermal software and 2D TCAD simulation, noting that the maximum of Z_{TH} is reached around 300 μ s.

In addition, the thermal impedance (Z_{TH}) extracted from the (3D) thermal modeling using ANSYS was adjusted in Silvaco (2D) in order to obtain a similar behavior as shown in Fig. 5 noting that the maximum of Z_{TH} is reached already around 300 μ s.

Fig.6 shows a comparison between the simulated and experimental recovery drain current acquired using a Tfilling of 100ms. The solid lines and dots represent the experimental and the simulated DCT respectively. The DCT response is simulated with the same filling biasing condition of pulsed Vds and Vgs ($v_{dsoff} = 20\text{V}$, $v_{gsoff} = -6\text{V}$) and the subsequent de-trapping bias at $V_{dson} = 10\text{V}$ and for V_{gson} adjusted to obtain $I_{dson} \times V_{dson} = 2\text{W/mm}$. It is clear that the simulated DCT properties closely match the measured spectra at 30°C and confirm the calibration of the physical parameters. It can be noticed that the power starts to increase after 300 μ s (Fig.6), i.e. measurements was performed when Z_{TH} reaches its maximum value (Fig. 5).

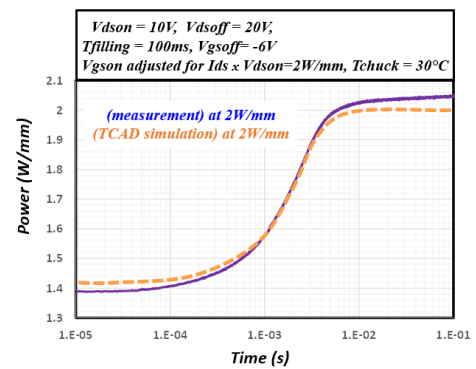


Fig. 6. Simulated drain current recovery at $T_{chuck} = 30^\circ\text{C}$ and for 2W/mm, Tfilling = 100 ms.

A second simulated drain current recovery at Tfilling of 100ms was performed with the same filling biasing condition of pulsed Vds and Vgs ($v_{dsoff} = 20\text{V}$, $v_{gsoff} = -6\text{V}$) and the subsequent de-trapping bias at $V_{dson} = 10\text{V}$ and for V_{gson} adjusted to obtain $I_{dson} \times V_{dson} = 1\text{W/mm}$. Fig. 7 shows the simulation results of the recovering drain current normalized at 2W/mm for a $T_{chuck} = 30^\circ\text{C}$ (red curve), and at 1W/mm for $T_{chuck} = 42^\circ\text{C}$ adjusted to obtain the same emission time constant (blue curve). Using relationship (3) with TCAD simulation results, we extract an R_{TH} around 12°C.mm/W which is very close to the value obtained by the measurement approach.

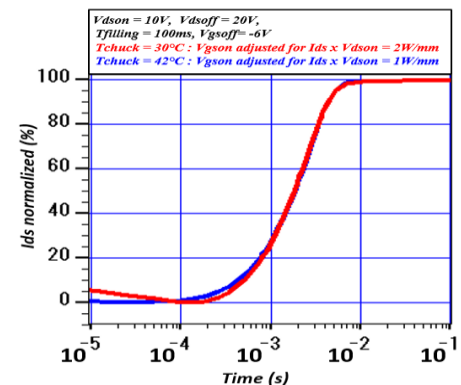


Fig. 7. Simulated transient drain current recovery at $T_{chuck} = 30^\circ\text{C}$ for 2W/mm and at $T_{chuck} = 42^\circ\text{C}$ for 1W/mm and for Tfilling = 100 ms.

Further TCAD simulations were performed to extract the maximum value of R_{TH} . Noting that the maximum of Z_{TH} is already reached around 300 μ s as shown in Fig. 5. At the hot spot, we extract an $R_{TH}=16^{\circ}\text{C}\cdot\text{mm}/\text{W}$ (fig. 8). It can be noticed that the region where we observe the maximum variation of Iron from the charged to the neutral state as shown in Fig. 9 is not located at the hot spot which is in the GaN channel near the gate (Fig. 8). TCAD highlights that for an AlGaIn/GaN HEMT with a Fe-doped GaN buffer, the new extraction method doesn't give the maximum R_{TH} at the hot spot. It gives an R_{TH} in the GaN buffer located around 150 nm under the gate. TCAD shows that this method underestimates the maximum R_{TH} value by around $4^{\circ}\text{C}\cdot\text{mm}/\text{W}$.

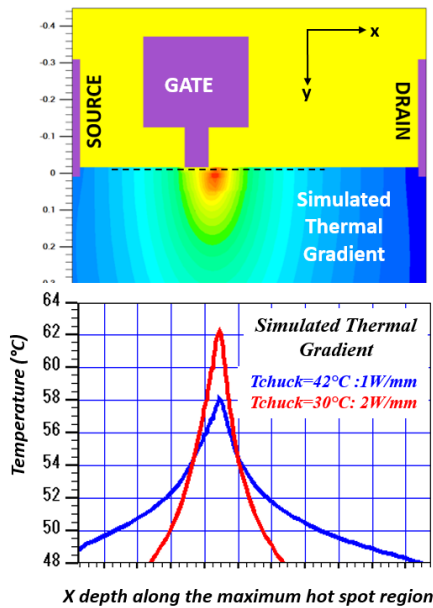


Fig. 8. Cross-sectional structure of the simulated GaN/AlGaIn/GaN HEMT simulation of thermal gradient for 1W/mm ($T_{chuck}=42^{\circ}\text{C}$) and for 1W/mm ($T_{chuck}=30^{\circ}\text{C}$).

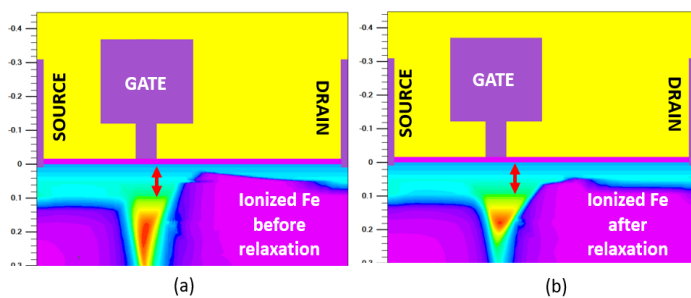


Fig. 9. Cross-sectional structure of the simulated GaN/AlGaIn/GaN HEMT (a) the trap density ionization before relaxation. (b) The trap density ionization after relaxation

V. CONCLUSION

In this work, we present a simple approach to extract the thermal resistance of GaN HEMT using DCT measurement technique, by measuring the drain current recovery due to the emission of trapped charges. Using this approach for an

AlGaIn/GaN HEMT of 0.15 μm gate length and a gate width size of $6\times 50\ \mu\text{m}$ with Fe-doped GaN buffer, we extracted an R_{TH} around $13^{\circ}\text{C}\cdot\text{mm}/\text{W}$. However, as shown by TCAD, the R_{TH} extracted by this approach was not located at the hot spot, but 150 nm below the gate. TCAD physical simulations are in progress to verify that if traps are introduced in the AlGaIn barrier, meaning very close to the GaN channel, we can obtain a better estimation of R_{TH} using the new approach.

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