Modeling Self-Heating Effects in AlGaN/GaN Electronic Devices during Static and Dynamic Operation Mode

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***Abstract*—In this paper, we present a study of the self-heating effects in GaN-based power devices during static and dynamic operation mode by means of Sentaurus TCAD. A physical model interface (PMI), accounting for the temperature dependence of the thermal boundary resistance (TBR), has been implemented in the simulator in order to realistically model self-heating effects. In particular, we take into account for the TBR associated to the nucleation layer between GaN and SiC substrate. Moreover, the thermal contribution of the mutual heating among adjacent devices has been considered. Finally, we have investigated the influence of the temperature on the surface charges trapping and de-trapping phenomena showing two different traps occupancy transients. While one of the two occurs also in the isothermal condition, the second one is temperature activated.**

Keywords — GaN HEMT, self-heating, mutual-heating, thermal boundary resistance (TBR), surface trapping/de-trapping charges, drain-lag measurement.

I. Introduction

GaN-based transistors, thanks to the intrinsic properties of the adopted materials, represent today a potential technology for switching power applications [1-3]. However, high performance is not enough, as a high level of reliability must be guaranteed under heavy-duty operation. For this reason, different works about hetero-structures reliability have been focused on the charges trapping/de-trapping mechanisms. Del Alamo et al. [4] have shown how the crystallographic defects generation in the AlGaN barrier, under high voltage conditions, is responsible for the formation of a path for gate leakage current and electron trapping, leading to the degradation of many figures of merit, whereas in [5-7] the current dispersion effects due to surface and/or AlGaN barrier traps have been investigated.

Since a power transistor is subject to high temperatures during its normal operation, in this paper a simulation study of self-heating effects has been performed in order to understand the performance limitations, under both static and dynamic operation modes. Several studies reported in the literature [8-10] have pointed out as the contribution of the thermal boundary resistance (TBR), introduced by oxide nucleation layer between GaN-buffer and Si- or SiC-substrate in order to reduce the lattice constants mismatch, is fundamental for modeling the self-heating effects in the devices. Indeed, Sarua et al. [9] have experimentally proposed a model able to describe the temperature dependence of the TBR emphasizing how its contribution becomes more and more important with the temperature increase. To this purpose, the implementation of a physical model able to account for the realistic temperature dependence of the equivalent thermal boundary resistance ascribed to oxide nucleation layer, turned out to be necessary in our study.

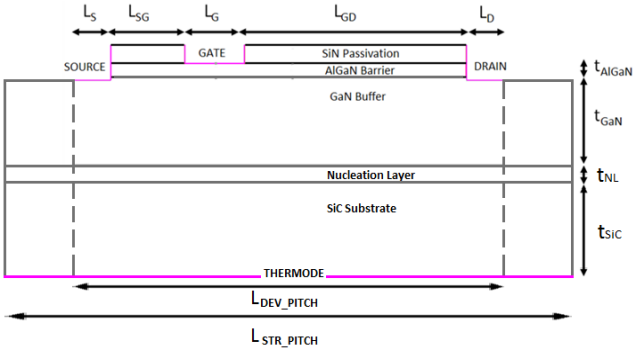

Fig. 1. Simulated AlGaN/GaN HEMT structure. To allow a self-heating study, a thermode contact, fixed at the temperature of 300 K, is introduced at the bottom of the SiC substrate. Figure not in scale.

II. Device Structure and Physical Models

Fig. 1 shows the simulated AlGaN/GaN structure. It was defined considering typical geometric characteristics and material parameters proposed in experimental works reported in the literature (e.g. [5]). The structure features a stack of SiN/AlGaN/GaN/Oxide/SiC layers with thickness of 50 nm / 29 nm / 1.5 µm / 10 nm / 100 µm, respectively. The aluminum concentration in AlGaN barrier, which plays an important role in device operation through the piezoelectric charge induced by mechanical stress, is set to 35%, representing a typical value for state-of-art devices [5]. Drain and source electrodes are modeled as ohmic contacts with length L_S = L_D = 0.5 µm, whereas the 0.7 µm long gate electrode is modeled as a Schottky contact, with 1.1 eV barrier height, representing a typical measured value for realistic devices [11, 12]. The drain- and source-to channel access regions feature lengths of L_{SG} = 0.7 µm and L_{GD} = 2 µm, respectively. Finally, a device pitch (L_{DEV_PITCH}) of 4.4 µm was assumed.

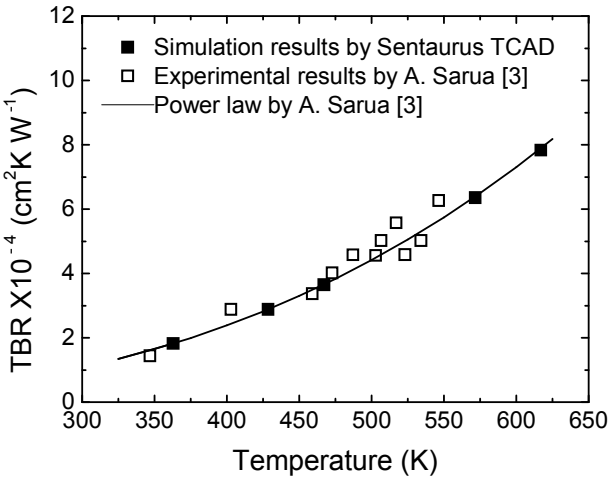

Fig. 2. Calibration of the TBR by means of experimental results [3]. A PMI model has been implemented in the TCAD device simulator in order to account for the temperature dependence of the thermal conductivity.

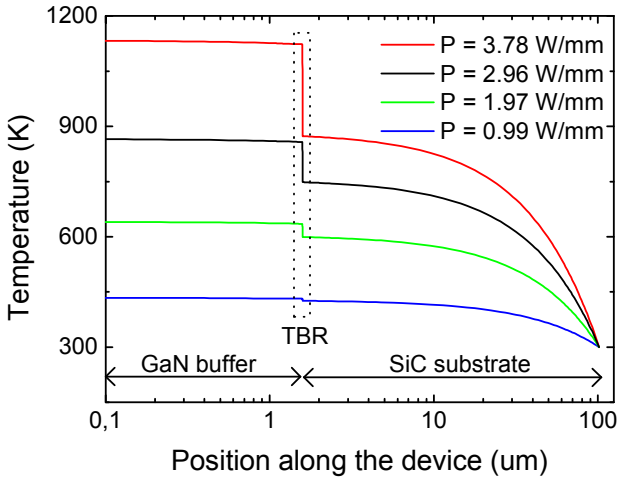

Fig. 3. Thermal distribution along the device (vertical direction) for different electric powers. By increasing the temperature, the thermal boundary resistance (TBR) contribution plays an important role in the temperature behavior of device.

Donor-traps have been added at the SiN/AlGaN interface. Their introduction is important not only for studying the dispersion effects due to de-trapping/trapping phenomena, but also because the traps occupancy is required to set an adequate channel electrical conductivity, since the combined effect of the interface trapped- and polarization-charge is indispensable for filling the channel of electrons. Moreover, since Meneghesso et al. [5] have shown that surface donor-traps are responsible for a drain current dispersion effect, a traps energy level of 0.5 eV from valence band has been adopted in order to have a finite transient time, required by traps to respond to an external voltage signal, similar to that obtained in [5] during drain-lag measurements.

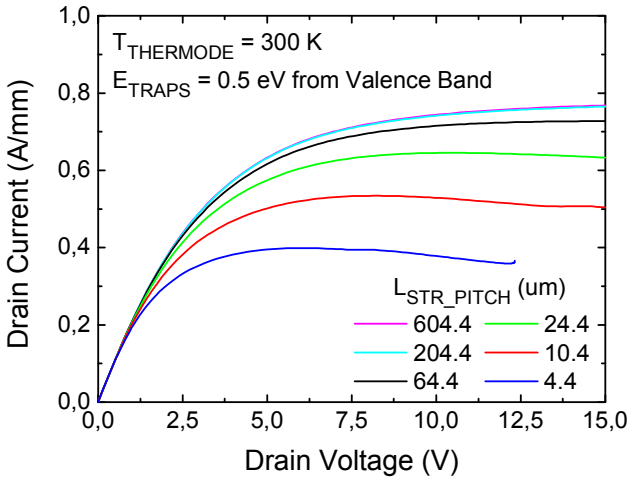

Fig. 4. Simulated static I_DV_D characteristics evaluated on devices with different pitch. By increasing the pitch, the current increases because of the lower power density, leading to a reduction of the temperature in the channel and hence to an improvement of electron mobility.

The device features an oxide nucleation layer that significantly affects self-heating effects due to low thermal conductivity. This effect has been discussed and modeled in [9] by defining an equivalent thermal boundary resistance (TBR) interposed between the GaN buffer and the SiC substrate. Sarua et al. [9] experimentally investigated the temperature dependence of the TBR in AlGaN/GaN devices proposing a model able to reproduce the experimental results. In this study, Sarua's model has been implemented and included in the simulation tool through the device simulator's model interface in order to realistically model self-heating effects. The simulator's default models for temperature-dependent thermal conductivity have been assumed for AlGaN, GaN and SiC layers. The implementation of the model for nucleation layer thermal conductivity is validated in Fig. 2 by comparison with the experimental data for TBR reported in [9] and with the empirical power law proposed in the same paper. By considering Fig. 3, it is worth noting how the TBR becomes more and more important as the temperature increases, emphasizing the importance of the developed model for a realistic simulation. In order to analyze the effect of mutual heating among adjacent devices, structures with different pitch (L_{STR_PITCH}) have been simulated.

III. Simulation Results

Fig. 4 shows the simulated static I_DV_D characteristics for structures featuring different L_{STR_PITCH} values. By increasing L_{STR_PITCH}, the mutual heating effect is reduced and a lower thermal power density is dissipated. As result a higher drain current is found. In fact, according to Fig. 5, a channel temperature of 640 K and 335 K is found in the case of structure pitch of 4.4 µm and 604.4 µm, respectively, leading to a corresponding electron mobility, averaged along the

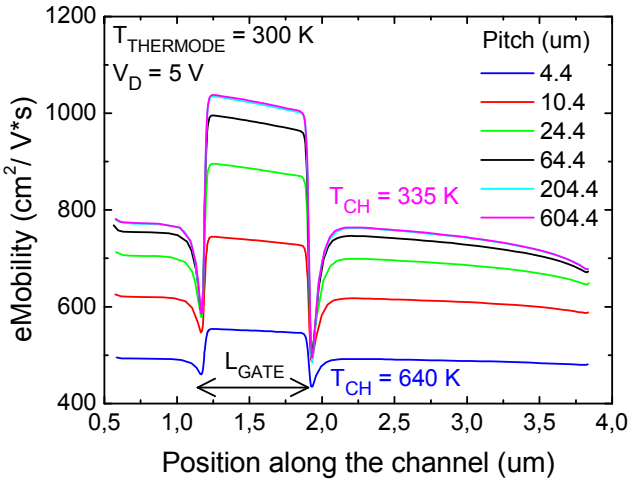

Fig. 5. Electron mobility along the channel for structures featuring different pitch. By increasing the pitch, the electron mobility increases because of the lower channel temperature, leading to an increase of the drain current (Fig. 4).

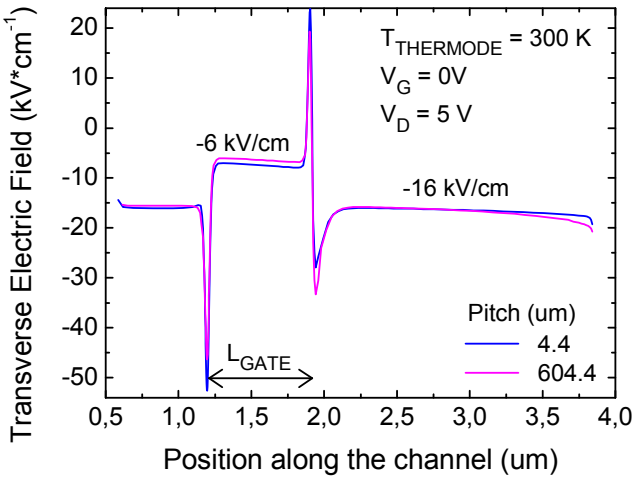

Fig. 6. Transverse electric field distribution along the channel. The different electric field values are ascribed to absence of surface donor-like traps under the gate contact where the SiN passivation is absent. To this purpose, a different channel electron mobility is observed (Fig. 5).

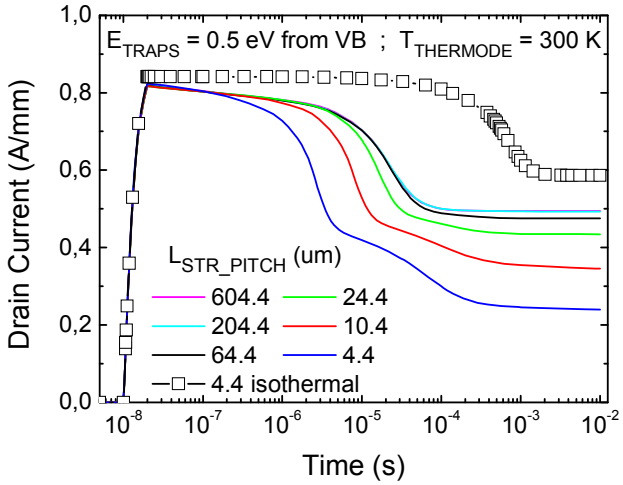

Fig. 7. Drain-lag simulations for structures with different pitch. The current overshot is linked to the transient of donor traps which is shorter but wider for higher temperatures.

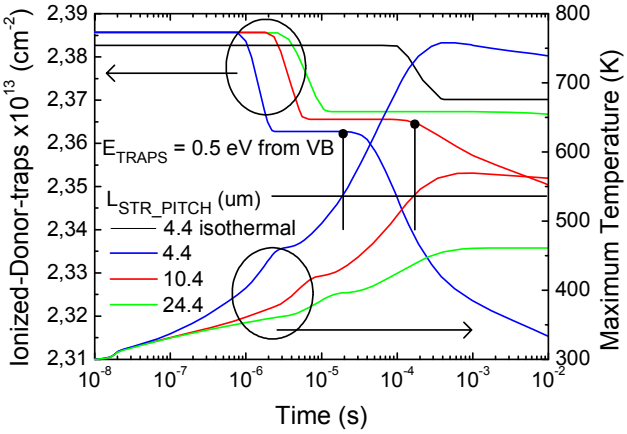

Fig. 8. Ionized-donor-traps averaged over the whole SiN/AlGaN interface (left-axis), and maximum temperature in the channel (right-axis) as function of the time during drain-lag simulations (Fig. 7). While a single traps transient appears in the case of isothermal simulations, a second one is activated if, due to self-heating, the temperature exceeds approximately 540 K.

channel, of 525 and 900 $cm^2V^{-1}s^{-1}$, respectively. The change of the electron mobility with respect to channel position is ascribed to the electric field variation. This can be attributed to the absence of surface donor-like traps under the gate contact where the SiN passivation is absent. Transverse electric field distribution is shown in Fig. 6 for structure pitch equal to 4.4 and 604 µm. It is possible to observe how it reaches about 6 kV/cm and 16 kV/cm in the region under the gate and in the drain-/source-to channel access regions, respectively. Our results are consistent with the significant decrease of electron mobility in AlGaN/GaN, for electric field larger than 5 kV/cm, reported in [13]. Therefore, the change of mobility along the channel, found in our case, can be ascribed to mobility degradation at large electric field values.

The dynamic behavior during drain-lag simulations for V_D switched between 0 and 10 V in 10 ns at $V_G = 0V$ is reported in Fig. 7 for structures with different pitch. The amplitude of drain voltage sweep has been chosen according with experimental and simulation works present in literature (e.g. [14]), whereas the ramp rate (1 V/ns) has been settled in order to have the trap transient starting after that drain voltage has reached the final level, allowing to monitor the whole traps transient. A drain current overshoot due to donor-traps transient is observable. Fig. 8 reports the time evolution of traps

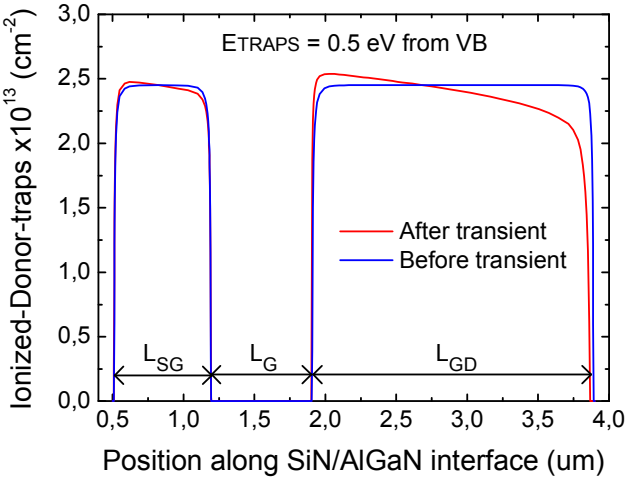

Fig. 9. Traps occupancy along the SiN/AlGaN interface. Higher trapping/de-trapping phenomena are observed in the region close to the drain contact.

occupancy for devices with different pitch values. While a single transient appears in the case of isothermal simulations, a second one is activated if, due to self-heating, the temperature exceeds approximately 540 K. Indeed, for structure pitch larger than 10.4 µm the second transient does not occur (see also Fig. 7) since the increase of temperature, induced by self-heating, is limited. Finally, Fig. 9 reports the spatial dependence of trapping/de-trapping phenomena, suggesting that drain current dispersion effects, is mainly related to traps located in the region close to the drain contact.

IV. Conclusions

A physical model accounting for the impact of the nucleation layer on self-heating in GaN-based power devices with SiC substrate has been implemented and applied to a simulation study of the static and dynamic operation, also accounting for mutual heating among adjacent devices. In the static case, it has been shown that a large pitch (> 200 µm) is necessary for avoiding the performance limitations due to mutual heating. Regarding the dynamic mode, it has been shown that two different transients occur in the traps occupancy. The first one occurs also in the case of isothermal simulations and, in general, the channel temperature influence the extension of the transient. On the other hand, the second transient is temperature activated. Finally, it has been shown that significant de-trapping/trapping phenomena occur in the region near the drain contact.

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