Current collapse associated with surface states in GaN-based HEMT's. Theoretical/experimental investigations.

A. Sleiman*, A. Di Carlo*, G. Verzellesi**, G. Meneghesso***, and E. Zanoni***

*Dept. of Electronic Engineering, University of Rome "Tor Vergata", via del Politecnico 110- I-00113 Rome. Italy

**Dipartimento di Ingegneria dell'Informazione, Università di Modena e Reggio Emilia, and INFM, via Vignolese 905, I-41100 Modena, Italy

***Dipartimento di Ingegneria dell'Informazione, Università di Padova, and INFM, via Gradenigo 6/A, I-35131, Padova, Italy

Abstract

The effect of air/AlGaN and GaN/substrate polarization charges on the performances of GaN-based HEMTs have been investigated. We find that surface charges and, with a minor extend, GaN/substrate charges are responsible for the observed premature saturation of the dc output characteristics. Moreover, our work show that the polarization charges and holes trap appear as the source of the drain current collapse observed in GaN-based HEMTs.

Introduction

GaN-based FETs have successfully demonstrated unprecedented potential in radio frequency rf power and power electronics applications, featuring both high current saturation and high breakdown voltage [1]. Even though much progress has been achieved in the high-frequency performances , there are still some issues, which should be addressed, such as dc-to-rf current collapse [2], temperature increase due to a large thermal resistance , and understandings of transport properties at high temperature. Among these issues, the current collapse is very important because the output power density at microwave frequencies is limited by this effect. Several mechanisms have been proposed as source for the current collapse such as gate bias-induced non-uniform strain, charging up of a second virtual gate [2], and hot electron injection and trapping in the buffer [3]. Different approaches have proposed to eliminate the current collapse such as passivation with Si_3N_4 film, and surface charge control with GaN cap layer. However, the explanation of the collapse phenomena is still an open issue and deserve further investigation. In this work measurements and numerical device simulation of the dc and rf current collapse phenomenon are reported. Numerical calculations show that air/AlGaN surface and/or GaN/substrate interface charges can explain by itself the dispersion observed experimentally.

Simulations and experimental results

A 2-D self-consistent Monte Carlo simulator has been used (see [4] and the references there in). The code is based on a four conduction valleys (Γ, A, M, K) and on three valence bands, where the non parabolicity factors are treated as fitting parameters and adjusted to reproduce a variety of published results. We have simulated a symmetric $Al_{0.26}GaN/GaN$ HEMT with gate length of 1.2 μm and drain source separation of 5 μm. The layer structure consists of a thick sapphire substrate, 1μm undoped GaN, 32 nm of undoped $Al_{0.26}GaN$. At the GaN/AlGaN interface we have accounted for fixed positive polarization charges (σ) of 1.0×10^{13} cm^{-2}, while negative polarization charges have been considered at the ungated AlGaN surface (σ_{top}) and at the GaN/substrate interface (σ_{bottom}).

Fig. 1 shows the calculated and experimental (Alenia Marconi System device) dc current-voltage transcharacteristics (I_{DS}-V_{GS}) for the HEMT. As it can bee seen the current obtained by MC (solid curve) for the HEMT without surface and interface charges (σ_{top}=0, σ_{bottom}=0) is higher than the measured I_{DS}-V_{GS} (line with circle). The calculated current reaches 1100mA/mm at (V_{GS}=0V) while the experimental current saturated at 400 mA/mm. Calculated pinch-off (-4.5V) is slightly higher than measurement (-4V). From this comparison it is obvious that additional mechanisms exist, capable of explaining the premature saturation of the drain current. We have first investigate the effect of the surface charges (σ_{top}) at the ungated surface of the HEMT. MC drain currents have been carried out for various density σ_{top} while holding the GaN/substrate interface charges σ_{bottom}=0. By increasing σ_{top} the drain current (dashed line) drops continuously as well as its slope. Consequently the transconductance is reduced. The decreasing of the current is associated with a slight shift of the threshold toward higher voltages.

Then, the MC simulator has been used to study the effect of substrate/GaN interface charges (σ_{bottom}) on the electrical output of the HEMT. Fig. 2 shows the calculated I_{DS}-V_{GS} for various σ_{bottom} (σ_{top}=0) compared with experimental current. The effect of the GaN/substrate charges σ_{bottom} is to shift towards higher V_{GS} the pinch-off bias. The interface charges have no effect on the slope of I_{DS}-V_{GS} and so on transconductance.

In order to reproduce the measured current we have simulated the HEMT with both the surface charges σ_{top} and interface charges σ_{bottom}. We have found that the calculated drain current fits well the experiment if we consider $\sigma_{top}=8.0\times10^{12}$ cm^{-2} and $\sigma_{bottom}=5.0\times10^{12}$ cm^{-2}. We conclude that output characteristics of GaN based HEMT are mainly influenced by the surface charges and, with a minor extend, by the GaN/substrate polarization charges.

Since the Monte Carlo analysis is a time-consuming process, a 2-D Drift-Diffusion (using the code DESSIS-ISE) has been implemented and calibrated on MC results. In order to finger out the role of the surface charges, measurements and drift-diffusion simulations of unpassivated AlGaN/GaN HEMTs have been compared. These devices are grown by MOCVD on SiC substrates and characterized by a gate width/length of 150μm/0.7μm and by gate-source and gate-drain spacings of 0.7 μm and 2 μm, respectively. A positive fixed charge sheet having a density $N^{+}_{pol}= 1.2\times10^{13}$ cm^{-2} was placed at the AlGaN/GaN hetero-interface to account for positive polarization charge and a corresponding negative charge, N^{-}_{pol}, having the same density was put at the ungated AlGaN surface. Donor-like traps with an N_{TD} density of 1.2×10^{13} cm^{-2} were uniformly distributed within 5 Å from the surface over the ungated gate-source and gate-drain regions. Electron and hole capture cross sections were assumed to be 1×10^{-15} cm^{2}. Obtained experimental and simulation results can be summarized as follows.

Experimental dc and pulsed output characteristics at V_{GS}=0 V are reported in Fig. 3 for different pulse width values. As can be noted V_{GS} pulses shorter than 1 ms induce a large current collapse. Fig. 4 shows normalized I_D vs time waveforms measured in response to a turn-on V_{GS} step (from –5 V to 0 V) at different temperatures. We found that these gate-lag waveforms can be described by a stretched exponential function. The time constant of this exponential function, τ_{ON}, depends on temperature following an Arrhenius law. By plotting τ_{ON} against 1/kT (see the inset of Fig. 4) an activation energy of 0.3±0.02 eV is extracted.

Gate-lag and current-collapse effects comparable with those observed experimentally are reproduced by drift-diffusion simulations provided that surface traps are included and placed energetically at $E_T= E_V+0.3$ eV, i.e., if the extracted activation energy is interpreted as the energetic distance of traps from the top of the valence band (E_V), see Fig. 5. Under these conditions, bands are strongly upward bent at the ungated AlGaN surface, causing (i) depletion of the underlying barrier layer and reduction of the 2-DEG density at the AlGaN-GaN interface and (ii) creation of a hole-populated layer at the AlGaN surface (with density, p_S, in the order of 10^{13}-10^{14} cm^{-3}).

Simulations attribute gate lag and pulsed-I_D collapse to the hole-trap behavior of surface deep levels. Holes are in particular captured during the turn-on transient, resulting in negative surface charge (polarization plus trap charge) decrease and delayed I_D increase. Gate lag reflects into I_D collapse (with respect to the dc values) under pulsed-V_{GS} operation, see Figs. 3 and 5.

Simulation reproduce also the correct temperature dependence of turn-on transients, compare Figs. 4 and 6. As a matter of fact, p_S and therefore the hole capture rate (which governs the device turn-on) are proportional to $\exp[-(E_T-E_V)/kT]$ (where k denotes the Boltzmann constant). This has two consequences: i) increasing T enhances p_S, thus leading to longer turn-on transients, see Figs. 4 and 6; ii) the turn-on time constant is thermally activated, (E_T-E_V) being the associated activation energy. This provide an explanation for results in Fig. 4.

Our simulations can not account for non-ideal surface conduction mechanisms due to gate electron tunneling and/or surface electron hopping, and can not therefore be used to discriminate between the enlightened hole-trap mechanism and more conventional, electron-trap-based interpretations.

Conclusion

MC and experimental dc transfer characteristics I_{DS}-V_{GS} have been compared. We find that experimental dc drain current is 2 times lower than calculation if surface and GaN/substrate polarization charges are neglected. A good agreement is, however, obtained as soon as these two polarization charge contributions are considered. Drift-diffusion simulations incorporating polarization charges and surface donor-like traps, energetically located relatively close to the top of the valence band, are able to reproduce gate-lag. The associated current-collapse effects compares well with those observed experimentally, without requiring non-ideal surface conduction mechanisms to be invoked. Within the proposed interpretation, surface deep levels behave as hole traps and the observed delayed turn-on transients are attributed to hole capture by surface traps.

References

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Acknowledgments

This work has been supported by the IMEC and ESA, Contract 14205/00/NL/PA, and by Alenia Marconi System. Monte Carlo calculations have been carried out by using the Internet Computing on Demand (http://icode.eln.uniroma2.it).

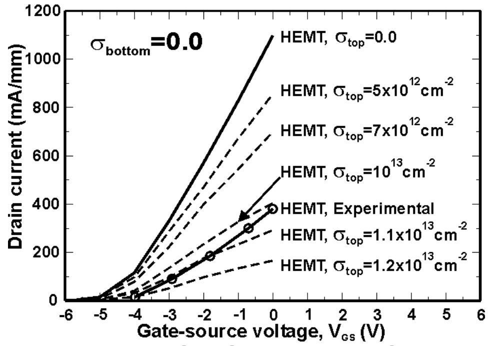

Fig. 1. Experimental and MC I_{DS}-V_{GS} characteristics obtained at V_{DS}=10 V. The line with circle refers to HEMT measurements. The solid curve is the MC current obtained for the HEMT without surface (σ_{top}) and interface (σ_{bottom}) charges. The dashed lines are the MC results for several σ_{top} and σ_{bottom}=0.

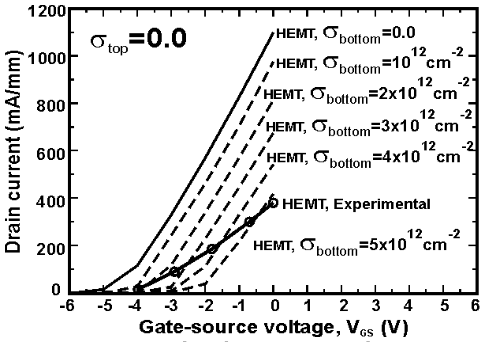

Fig. 2. Experimental and MC I_{DS}-V_{GS} characteristics obtained at V_{DS}=10 V. The line with circle refers to HEMT measurements.. The solid curve is the MC current for the HEMT without polarizations charges (σ_{top}=0, σ_{bottom}=0). The dashed lines are the MC results for several σ_{bottom} and σ_{top} =0.

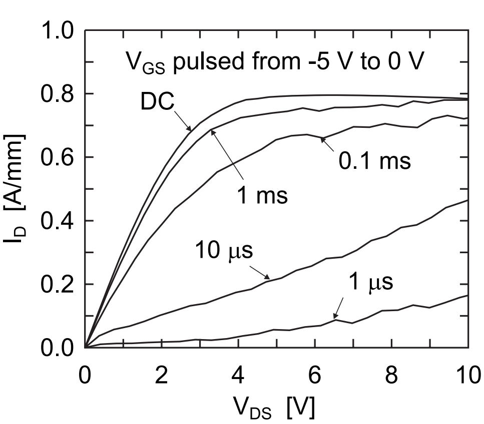

Fig. 3. I_D-V_{DS} characteristics measured from an AlGaN/GaN HEMT under dc and pulsed-V_{GS} operation.

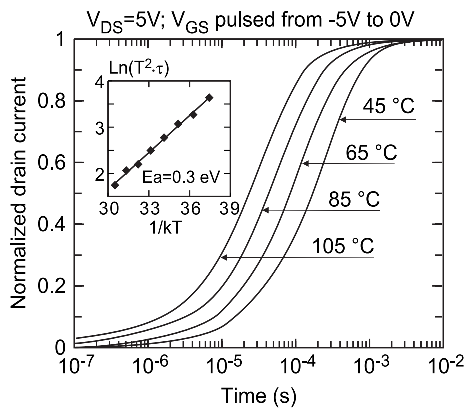

Fig. 4. $I_D(t)$ turn-on waveforms measured from an AlGaN/GaN HEMT at different temperatures. The inset shows the Arrhenius plot of the turn-on time constant, τ_{ON}, yielding the activation energy E_a=0.3 eV.

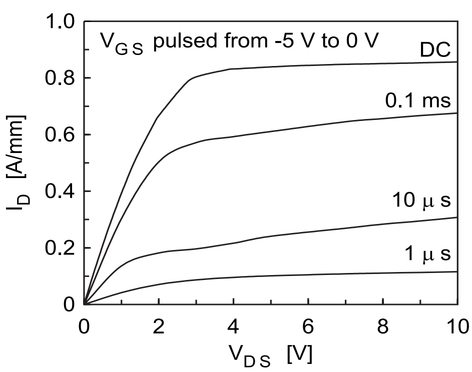

Fig. 5. Simulated I_D-V_{DS} characteristics of an AlGaN/GaN HEMT under dc and pulsed-V_{GS} operation.

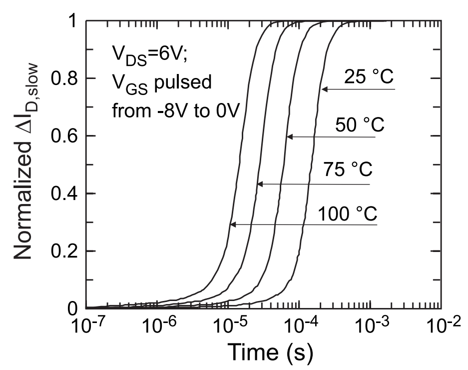

Fig. 6. Simulated $I_D(t)$ turn-on waveforms of an AlGaN/GaN HEMT at different temperatures.