Hole Virtual Gate Model Explaining Surface-Related Dynamic R_{ON} in p-GaN Power HEMTs

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***Abstract*— Dynamic on-resistance (R_{ON}) affects the stability of p-GaN power HEMTs. In Schottky-gate HEMTs, dynamic R_{ON} is associated to either electron trapping at device surface or dynamic effects occurring in the buffer. However, in p-GaN HEMTs the floating p-GaN region can have an additional role on dynamic R_{ON}, due to removal/injection of holes from/into the barrier with relatively long time constants, which can be erroneously interpreted as a reliability issue. In this letter, we present a model to explain the dynamic R_{ON} due to surface-related effects in p-GaN power HEMTs. The model, called 'hole virtual gate', attributes the experimentally observed R_{ON} instability due to negative/positive gate bias stress (NGS/PGS) to the charging/discharging of surface traps in the AlGaN barrier by the removal/injection of holes through the gate metal/p-GaN Schottky junction. We verify the validity of the model by means of calibrated numerical simulations, that correlate the activation energy $E_A \approx 0.4$ eV of both R_{ON} increase/decrease during NGS/PGS to the thermal ionization energy of traps in the barrier.**

***Index Terms*— p-GaN HEMTs, dynamic R_{ON}, hole virtual gate, gate bias stress, barrier traps, reliability.**

I. Introduction

DYNAMIC on-resistance (R_{ON}) is the most detrimental trapping-related effect for GaN-based devices that need to be employed in power switching converters as it determines an undesirable increase in conduction losses [1].

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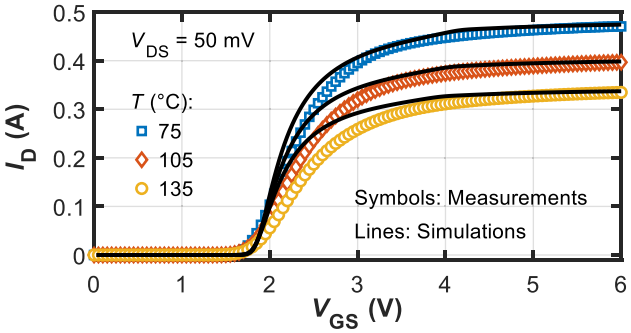

Fig. 1. Typical I_D–V_{GS} curves obtained at V_{DS} = 50 mV and T = 75, 105, 135 °C, see legend. Simulated I_D–V_{GS} curves obtained under the same experimental conditions are also reported, showing the good agreement obtained with experimental data.

In Schottky-gate GaN HEMTs, dynamic R_{ON} effects have been attributed to either electron trapping at the device surface (i.e., layers above the channel) – explained by the concept of virtual gate [5] – or electron [2], [3] and/or hole trapping [4] in the buffer (i.e., layer below the channel). Moreover, in p-GaN HEMTs, which is the common commercial technology option for normally-OFF operation (i.e., positive threshold voltage, V_T) [6], the floating p-type region in the gate stack becomes a source of device instability in terms of both V_T [7], [8], [9], [10] and R_{ON} [11], [12], [13].

In this letter, we propose a model called 'hole virtual gate' to explain the experimentally observed dynamic R_{ON} after the application of negative/positive gate bias stress (NGS/PGS). A preliminary interpretation of gate-bias induced R_{ON} instability was provided in [11], which however lacked a quantitative model to support it. Here, the hole virtual gate model is quantitatively validated by means of numerical device simulations that reproduce the data when considering hole traps in the AlGaN barrier at 0.4 eV above the valence band edge.

II. Device Characterization

Devices under test (DUT's) are 650-V p-GaN power HEMTs with Schottky gate contact. Typical drain current (I_D) vs gate-to-source bias (V_{GS}) characteristics at V_{DS} = 50 mV at T = 75, 105, and 135 °C are reported in Fig. 1. The setup presented in [11] was employed to characterize the dynamics of R_{ON} instability at different temperatures.

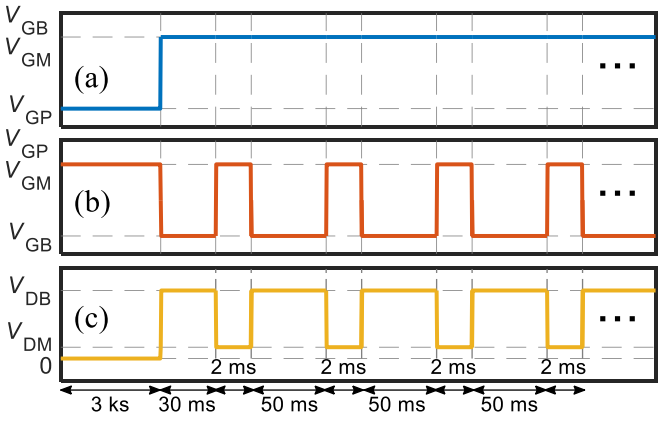

Fig. 2. Sketch of the waveforms applied at the gate and drain terminals for the characterization of I_D/R_{ON} transients in the case of (a) NGS, (b) PGS, (c) GDS. Initialization at (V_{GP}, 0) is carried out in 3 ks. Then, (V_{GB}, V_{DB}) (see Fig. 3 for the values in each case) is applied for another 3 ks during which R_{ON} is periodically probed at (V_{GM}, V_{DM}) = (6, 0.05) V for 2 ms every 50 ms (the first sensing is done after 30 ms).

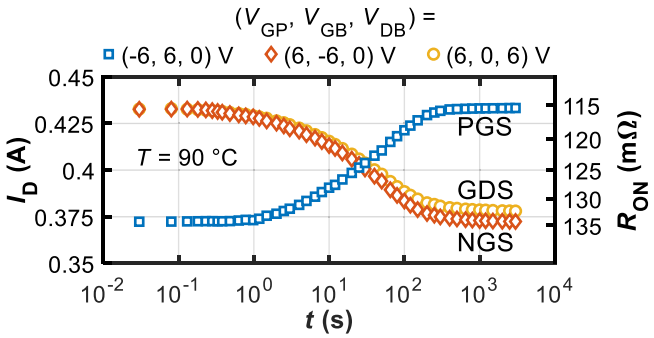

Fig. 3. I_D/R_{ON} vs time transient characterization for three different (V_{GP}, V_{GB}, V_{DB}) combinations (see legend) at T = 90 °C.

First, a 3-ks initialization step, performed at fixed gate bias (V_{GP}), ensures that traps are in a steady state prior to the subsequent I_D/R_{ON} transient characterization. Then, V_{GS} is set to a baseline bias (V_{GB}) for 3 ks and I_D/R_{ON} is sampled every 50 ms at V_{GM} = 6 V for 2 ms [11]. Fig. 2 illustrates the waveforms used during the transients characterization. Fig. 3 shows the experimental results obtained from this characterization for (V_{GP}, V_{GB}) = (+6, –6) and (–6, +6) V, which will be referred to as NGS and PGS, respectively. As can be noted, R_{ON} increases (decreases) during the NGS (PGS) transient substitute by with of ≈17%, from 115 to 135 mΩ, with relatively long time constant ≈ 40 s (T = 90 °C). The V_{GS} < 0 V bias condition is not incurred in power switching converters, because p-GaN HEMTs have V_T > 0 V and are in the OFF-state for V_{GS} = 0 V. Nevertheless, this condition is useful for two main reasons: (*i*) it allows to narrowing down the instability mechanisms to the exchange of carriers between the device and the gate terminal only; and *(ii)* it serves as a proxy for the OFF-state (in which $V_{GD,OFF} \ll 0$ V) [1], [14]. The latter point is further confirmed by Fig. 3, showing the transient labeled as GDS (Gate Drain Stress) with V_{GB} = 0 V and V_{DB} = +6 V (taken after 50-minute initialization at V_{GP} = +6 V with V_{DS} = 0 V), which has a dynamic similar to the transient acquired during the NGS. Notice that, during both stress and measurement bias conditions are such that self-heating can be completely neglected. For this reason, I_D/R_{ON} transients are only influenced by trap dynamics and not by the temperature dependence of static R_{ON}.

III. Hole Virtual Gate Model

The observed dynamic R_{ON} can be attributed to charge/discharge of hole traps present in the AlGaN barrier [11], [13]. Hole extraction (injection) during NGS (PGS) modulates the density of negatively charged traps in the gate-drain access region of the barrier, this in turn reflecting on the 2-DEG density underneath and thus R_{ON}. This mechanism is analogous to the 'virtual gate' effect related to the injection (extraction) of electrons from the gate contact in normally-ON Schottky-gate HEMTs [5]. However, in p-GaN HEMTs, it is the extraction (injection) of holes that affects R_{ON}. Numerical device simulations, carried out with SDevice™ [15], validate the model. The experimental I_D– V_{GS} curves reported in Fig. 1 were used to calibrate the simulation parameter set. More details regarding the adopted models can be found in our previous works [4], [16], [17]. Gate leakage is accounted for by thermionic emission occurring at the gate metal/p-GaN Schottky diode and hole tunneling [18]. Barrier traps are energetically located 0.4 eV above the AlGaN valence band edge. This value was set to reproduce the extracted activation energy (E_A) of the measured I_D transients shown in Figs. 4(b) and 5(b). Previously, we observed that the extracted E_A range is compatible with Mg out-diffused in the barrier during epitaxial growth (see [11] and references within). The modeling of traps in the simulation setup reflects this hypothesis, by assuming an exponentially decaying trap density profile within the barrier.

Figures 4(a) and 5(a) compare the experimental and simulated I_D/R_{ON} transients obtained during NGS and PGS, respectively, at different T's. During NGS, holes emitted by barrier traps drift towards the gate contact where they get extracted by the forward-biased Schottky junction. Hole emission increases the density of negatively charged traps in the barrier (N_{Bar}^-) thus reducing the concentration of electrons in the 2-DEG; R_{ON} therefore increases. During PGS, the opposite occurs: holes are injected from the leaky gate contact into the device [9], [18] and get trapped by barrier traps, neutralizing the negative charge and R_{ON} decreases. Figs. 4(b) and 5(b) show the Arrhenius plots extracted from the measurement and simulation results. The τ's are extracted from the stretched exponential fitting curves as described in [19]. The overall good agreement between measurement and simulation results validates the hole virtual gate model described previously.

Fig. 5 shows that the simulations underestimate the values of τ for the PGS case. Because τ's during PGS depend on the amount of injected carriers, as discussed in [11], we attribute the discrepancy to the hole injection model by the gate contact at V_{GS} = +6 V (i.e., non-local tunneling) which tends to overestimate the gate leakage current, hence accelerating hole trapping.

In [11] it was suggested that T-activation of hole trapping with the same activation energy (E_A ≈ 0.4 eV) as hole emission was due to the hole density p being proportional to $\exp[-(E_T-E_V)/kT]$, which occurs for low hole injection

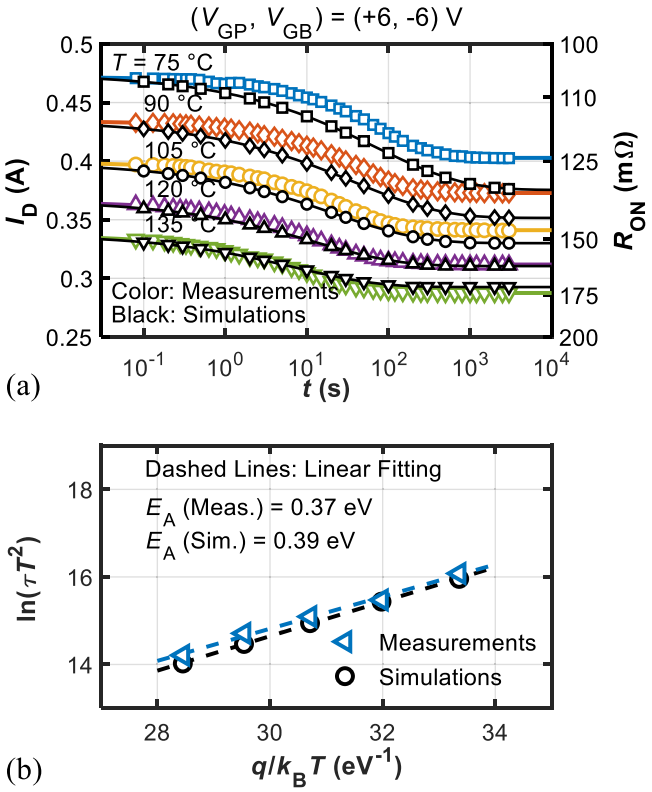

Fig. 4. (a) I_D/R_{ON} transients taken at different baseplate temperatures, T, see plot, at (V_{GP}, V_{GB}) = (+6, –6) V. (b) Arrhenius plots built from the extracted τ's. E_A's extracted from the linear fitting of the data points are also indicated.

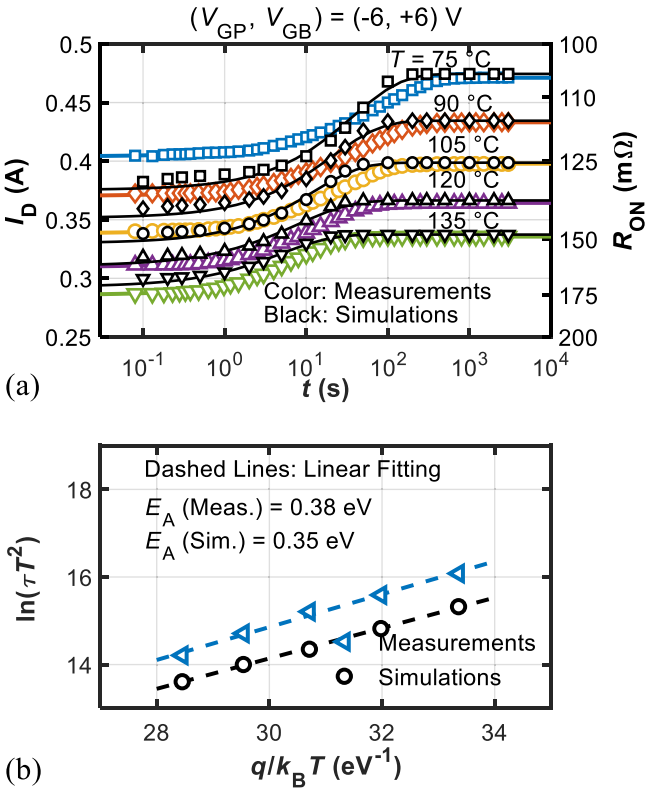

Fig. 5. (a) I_D/R_{ON} transients taken at different baseplate temperatures, T, see plot, at (V_{GP}, V_{GB}) = (–6, +6) V. (b) Arrhenius plots built from the extracted τ's. E_A's extracted from the linear fitting of the data points are also indicated.

and relatively high trap concentration in the AlGaN barrier [20]. The simulations support this interpretation, as E_A extracted in both NGS and PGS is about the same, see Figs. 4(b) and 5(b).

To further elucidate the hole virtual gate effect, we show in Fig. 6 the two-dimensional contour plot of N_{Bar}^- along the gate-drain access region at I_D/R_{ON} measurement conditions (i.e., V_{GS} = +6 V, V_{DS} = 50 mV) after 50 minutes at (a) V_{GB} = –6 V and (b) V_{GB} = +6 V, T = 90 °C. As explained previously, during NGS N_{Bar}^- increases by emitting holes that get extracted from the device by the gate contact. As a consequence, the hole virtual gate negatively charges and extends in the gate-drain access region, see Fig. 6(a). Conversely, during PGS holes are injected by the gate contact and get trapped by the barrier traps, N_{Bar}^- reduces, and the hole virtual gate depletes (of negative charge). In both cases, resulting R_{ON} depends on the two-dimensional profile of the hole virtual gate. It is worth pointing out that, conversely to the (electron) virtual gate concept proposed in [5], here it is the extraction of holes emitted by traps that determines the formation of the virtual gate itself, which extends along the whole gate-to-drain access region where traps are assumed to be present.

We ruled out buffer trapping as possible cause for the observed dynamic R_{ON} because gate stress without drain stress is not sufficient to alter significantly the state of buffer traps. Moreover, if C-related traps were to determine the dynamic R_{ON} then $E_A \approx 0.9$ eV should have been extracted from the Arrhenius plots [4], which is not the case.

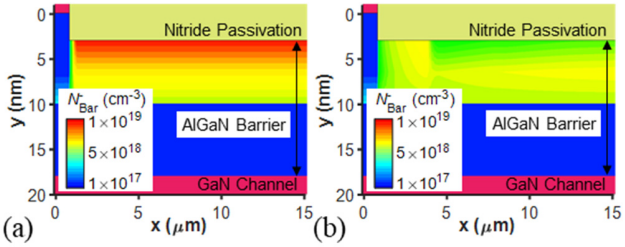

Fig. 6. Contour plot of trapped charge in the barrier (N_{Bar}^-) at I_D/R_{ON} measurement conditions (i.e., V_{GS} = +6 V, V_{DS} = 50 mV) after 50 minutes at (a) V_{GB} = –6 V and (b) V_{GB} = +6 V, T = 90 °C. Barrier traps charge (discharge) during V_{GB} = –6 V (V_{GB} = +6 V) due to the extraction (injection) of holes by the gate contact on the p-GaN layer, causing the charging (depletion) of the virtual gate in the gate-drain access region.

IV. Conclusion

We proposed a hole virtual gate model to explain the dynamic R_{ON} in p-GaN power HEMTs induced by gate bias stress. The model attributes the observed instabilities to the extraction (injection) of holes from the p-GaN gate and to the consequent emission (capture) of holes in barrier traps within the gate-drain access region. The comparison between experimental results and calibrated simulations validates the model. We attributed the activation energy $E_A \approx 0.4$ eV, extracted from the R_{ON} transients during stress, to the thermal ionization energy of traps in the barrier.

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