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Comparative Study on Dynamic Characteristics of GaN HEMT at 300K and 150K

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dynamic performance, including measurement of threshold voltage shift and possible dynamic on-resistance increase of GaN HEMT at low temperatures is still yet to be known.

Hot electron effect has been identified as one of the reasons of dynamic on-resistance increase [14]–[16]. The experimental evidence of hot electron effects was obtained previously utilizing electroluminescence (EL) techniques [17], [18]. However, the study of hot electron effects was often carried out at room temperatures or above [19], at which the hot electron induced trap effects are mixed with already-existed traps. Thus, a quantitative understanding of hot electron effect itself is still unclear. Cryogenic temperature created an ideal environment to study hot electron effects in GaN HEMT, as the trap behaviors are expected to be greatly suppressed while hot electron induced effects would thus be possibly unmasked separately. In addition, the average kinetic energy of electrons injected into the channel is enhanced at a lower temperature due to higher carrier mobility. Thus, a low driving voltage would be sufficient to trigger hot carrier injection, and self-heating effects [20] would be greatly mitigated.

In this context, a systematic comparative study of dynamic performance of GaN HEMT was performed at 300K and 150K. *I-V* characteristics of GaN HEMT upon various negative/positive gate bias & recovery conditions were summarized; switching-mode pulsed *I-V* measurements with different off-state voltage, stressing duration, and drain-gate-delay (DGD) time at 300K and 150K were analyzed. The output characteristic comparison between hard switch and soft switch at 150K help quantitatively determine consequences induced purely by hot electron effects.

II. EXPERIMENTAL

The sample used in this study was GaN-based HEMT grown on a native GaN substrate. As shown in Fig. 1 (a), the epitaxial structure includes a 2 µm undoped GaN layer, a 1 nm AlN spacer, and a 20 nm undoped $Al_{0.}$ $Ga_{0.}$ N barrier. The 270-µm-thick n-type GaN substrate has a resistivity of 0.04 Ω·cm and a dislocation density of ~10 cm^{-2}. The fabrication of the HEMT started with Cl_2-based inductively coupled plasma (ICP) etching. Then, Ti/Al/Ni/Au (20/150/50/80 nm) was deposited by e-beam evaporation and annealed at 850 °C for 30 s in N_2 ambient to form Ohmic contact on the AlGaN barrier, as the source/drain terminals. Finally, a Ni/Au (20/200 nm) Schottky metal was deposited as the gate. It is noted that the studied HEMT device was finished without any advanced passivation layers to examine possible trap behaviors at 150K.

The gate width/length of the device in this study was 20µm/0.8µm, and the distance between gate to drain and to source were both 1µm (L_g = 0. µm, L_{gd} = L_{gs} = 1µm, W_g = 20µm). In "fast" I-V measurements, various negative/positive gate bias w/wo source-drain bias & recovery time was applied onto the device before high-speed sweeping I-V measurement was performed on the device. The total sweeping measurement period was set to be merely 75 µs to highly preserve the effects induced by negative/positive bias and off-state stressing. For pulsed I-V measurements, the pulse width was set to be 20 µs to pinpoint the characteristics at various quiescent bias points and after exposure to certain amount of stressing time.

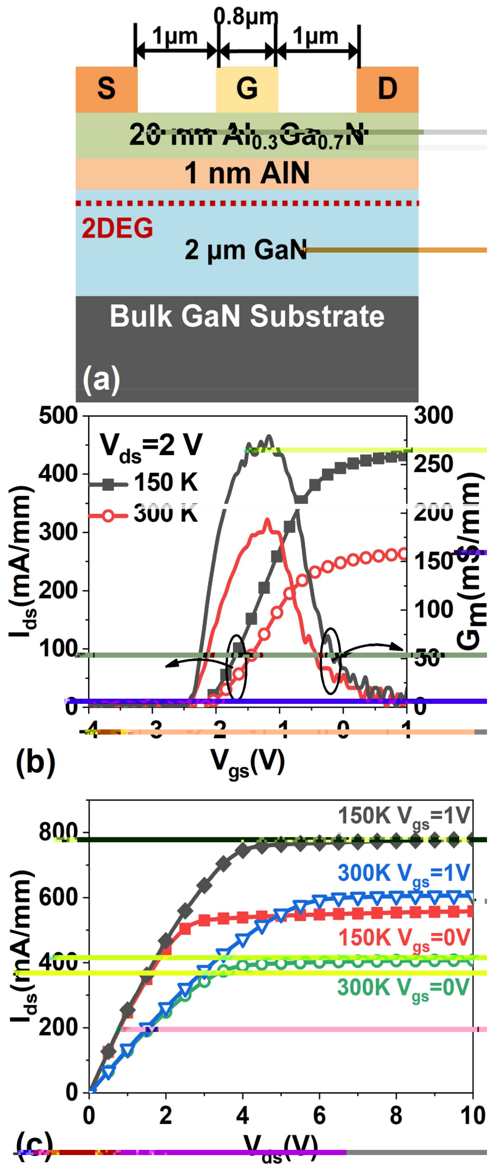

FIGURE 1. (a) Schematic cross section of GaN-based HEMT. (b) Transfer characteristics at 150K and 300K. (c) Output characteristics at 150K and 300K.

III. RESULTS AND DISCUSSIONS

A. FAST IV MEASUREMENTS

Fig. 1 (b) and (c) show transfer curves and output curves of the GaN HEMT at 150K and 300K without any pre-stressing conditions. Using the 10 mA/mm standard, the threshold voltage V_{th} was barely shifted (ΔV_{th} = 0.0 V) as the decrease of the temperature down to 150K. The device exhibited much higher peak transconductance (g_m = 2 0 mS/mm) and larger saturation current (770 mA/mm at

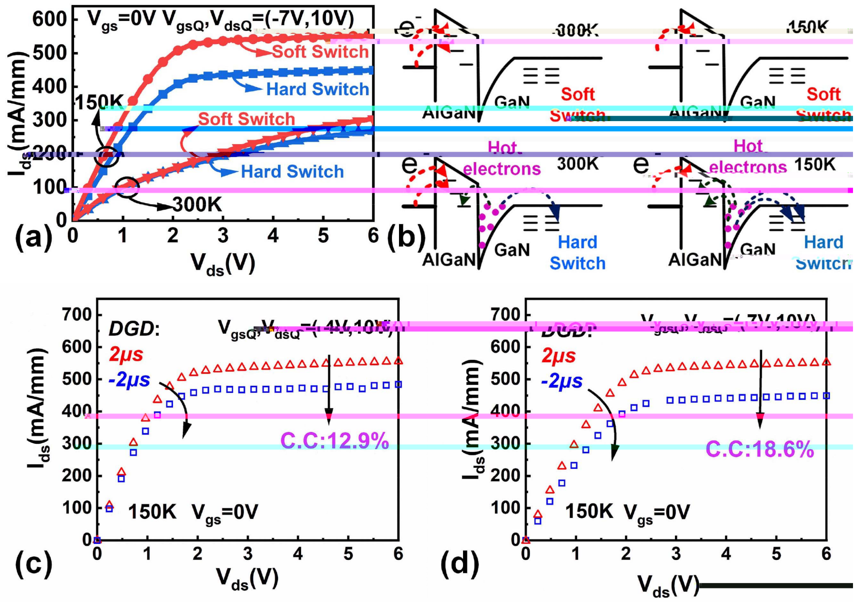

FIGURE 7. **(a) Pulsed $I_{ds} - V_{ds}$ characteristics of the GaN-based HEMTs under hard switch (DGD<0) and soft switch (DGD>0) at 300K and 150K. (b) Schematic band diagrams of the AlGaN/GaN HEMT under the soft switch conditions and under the hard switch conditions at 300K and 150K. (c, d) Pulsed $I_{ds} - V_{ds}$ under two different quiescent bias (V_{gsQ}, V_{dsQ}) at 150K.**

on the dynamic performance of GaN-based HEMTs using the same quiescent bias, leading to a current collapse free device performance. This was attributed to a very inefficient electron capture process which holds a long capture time constant [29].

In order to investigate the time-dependent trapping process, a so-called "on-the-fly" on-resistance measurement was performed. The device was subject to stressing condition (V_{gsQ}, V_{dsQ} = − V, 10V) while the variation of R_{on} was recorded by switching the device to on-state using 20-μs short pulses repeatedly without perturbing the stress process. The dynamic R_{on} was evaluated in the linear region where V_{gs} = 0V and V_{ds} = 0. V. At 300K, as seen in Fig. 6 (a), the dynamic R_{on} was significantly increased as the stressing time was prolonged up to 25s. The R_{on} was increased from initial 8.4 ohm-mm to nearly 10 ohm-mm after 25 seconds stressing. After 25s, the measured current and dynamic on-resistance reached saturated 10^{-2} mA/mm and 10 ohm-mm. This could be understood as the process of injection of electrons into traps under the gate and in the gate-drain access region. While at 150K, as the off-state stressing duration was extended up to 25 seconds, the variation of the on-resistance was greatly suppressed, in the range of (3.396 ± 0.005) ohm-mm only, suggesting a current collapse-free performance and a much prolonged time constant (at least several dozens of seconds) of the trapping process at 150K.

In addition to soft-switch operations, the device was also subject to hard switching conditions for comparisons. Fig. 7 (a) depicts output characteristics with drain-gate-delay (DGD) time of 2 μs (soft switch) and −2 μs (hard switch) at 300K and 150K. At 300K, the slightly lower drain current obtained from the hard-switch approach was regarded to be associated with hot electron effects as the difference was only observed at high V_{ds} bias range.

While for 150K, as discussed above and shown in Fig. 5 (c), overlaid I-V curves were obtained using a soft switch scheme, confirming a current-collapse-free device performance and traps being transparent to the device if there were any at 150K. However, under a hard switch scheme, current collapse was observed that the dynamic on-resistance was greatly enlarged and the saturation current was significantly compromised at low temperatures. At 150K, the average kinetic energy of electrons was enhanced due to boosted carrier mobility as well as high electrical field applied during the voltage transition. Thus, those electrons injected into the channel received sufficient energy to overcome the capture potential barrier [32] to have themselves trapped, which was not observed for soft-switch mode due to insufficient kinetic electron energy. This phenomenon is consistent with the observation that "the on-resistance increase induced by hot-electrons was decreased at higher temperatures", as reported in [33], where experiments were performed above room temperatures. Schematic band diagrams describing the above soft switch conditions and hard switch conditions were shown in Fig. 7 (b).

Fig. 7(c, d) displays pulsed $I_{ds} - V_{ds}$ curves under two different quiescent bias (V_{gsQ}, V_{dsQ}) to further investigate hot electron effects at 150K. As V_{gsQ} was enlarged from −4V to −7V while keeping V_{dsQ} = 10V, the saturation current collapse was increased from 12.9% to 18.6%. The degraded C.C. as increase of gate reverse bias also suggested the existence of capture potential barrier because injected electrons with higher kinetic energy resulted in a larger number of

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