Evidence of defect band in carbon-doped GaN controlling leakage current and trapping dynamics

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Abstract— Analysis of carbon doped GaN (GaN:C) layers in a wide temperature range reveals the same non-Arrhenius thermal behavior of capacitance transients related to trapping/detrapping dynamics on carbon defects and of the leakage current. Our results indicate that GaN:C does not behave like a classical semiconductor but is rather determined by a defect band (DB). Leakage via DB is the slowest process in charging/discharging dynamics, thus controlling it. We propose a microscopic model of carrier exchange between the carbon atom and the DB which can also explain the wide range of activation energies attributed previously to carbon. Understanding of leakage mechanisms and its interplay with charging is an important step towards optimization of GaN HEMT buffers.

I. INTRODUCTION

Carbon-doped GaN (GaN:C) buffers are used nowadays to achieve high blocking voltage of GaN high electron mobility transistors (HEMTs) for power applications. However, carbon is a trapping center contributing to current collapse as well as increasing dynamic on-resistance [1-3]. Recent models consider that negative charging of carbon defects occurs via emission of holes from the carbon level to the valence band (VB), Fig. 1a [1, 2]. The apparent activation energies measured in HEMT structures with carbon doped buffer are usually determined from an Arrhenius plot in a limited temperature interval and vary within the interval 0.5-1.0 eV, Fig. 2. For neutralization of negative carbon acceptors (i.e. recovery from collapse, or discharging) holes in VB with a small concentration in the range of 10¹⁶ cm⁻³ are considered to be captured [1]. Leakage current was found to be a limiting factor in discharging dynamics [1]. Via its temperature dependence, leakage current was also indirectly linked to capture processes, but holes in VB again have been involved [2]. In addition also the vertical leakage current has been studied in HEMT stacks and space charge limited currents [3, 4] as well as Poole-Frenkel [2, 3] and hopping conductivity [5] are considered as transport mechanisms.

We have recently analyzed steady-state (SS) capacitance-voltage (CV) characteristics in GaN:C layers embedded between a metal and n-doped GaN (Fig. 3b) which allowed us (i) identifying the voltage-dependent charge distribution in GaN:C, (ii) straightforward band diagram calculation in GaN:C which is almost impossible to achieve in conventional vertical HEMT stack structures (Fig.3a) due to the influence of other neighboring layers, and (iii) determination of carbon level position at Eᵥ⁺(0.7±0.2) eV in GaN:C just from electrostatic considerations [6] (Eᵥ being the valence band maximum).

In this work we systematically analyze the transient capacitance and DC IV behavior in these specially designed GaN:C layer structures. Time constants of charging and discharging events are found to have the same non-Arrhenius behavior as the leakage current over a wide temperature range (20 - 560 K). This indicates that transport via defect band (DB) defines the leakage current and is governing not only the discharging but also the charging processes. We propose a model which explains carrier exchange between a carbon acceptor, i.e. a trap, and the DB. Furthermore thanks to the wide temperature analysis range the model might explain the wide range of activation energies found in literature. Our understanding is relevant for further optimization of GaN:C buffers used in power GaN HEMT structures in terms of off-state leakage and Rₘ,dyn.

II. EXPERIMENTAL

Studied structures are grown on 6-inch n-doped Si(111) substrates, Fig. 3b. The electrically active structure consists of a 1.7 μm thick silicon-doped (Nᵥ = 8.5 × 10¹⁶ cm⁻³) GaN (GaN:Si) layer acting as a bottom electrode and a 200 nm thick GaN:C layer with an atomistic carbon concentration of 10¹⁰ cm⁻³. Circular Ti/Al contacts straight on GaN:C serve as top electrode. The depletion layer in the GaN:Si electrode directly relates to the potential at its interface to GaN:C. Further, forward bias currents enable the extraction of the microscopic leakage mechanism in GaN:C [6].

Transient capacitance analysis (Fig. 4a) is performed using a lock-in amplifier for impedance measurements at 1 MHz, giving a time resolution of 30 μs. The wide temperature range of 20 - 560 K is established within a cryogenic probe station.

III. RESULTS AND DISCUSSION

Fig. 5 shows the exponential increase of SS current Iₛₛ with applied forward bias Vᵥappl. Within a wide temperature range of 20 - 560 K the current increases exponentially with temperature T (Fig. 5 inset) instead of following Arrhenius law (I ∝ exp(-ΔE/kT); k...Boltzmann constant, ΔE being an activation energy) as observed previously [2, 4].

Fig. 4a shows the transient capacitance C(t) as reaction to various bias steps in both polarities. The capacitance monitors the total depletion width wₘₓ of the GaN:C/GaN:Si system which is the sum of GaN:C thickness and depletion width of GaN:Si [6]. For example the grey curve in Fig. 4a-II shows C(t) from 0 to -9.5 V, exhibiting two transitions in time: 1) the capacitance drop between 0 and 30 μs from SS C₀ to quasi-static C₀ is due to quick wₛₑ adaptation to the new bias (i.e. no change in trap occupancy); 2) the capacitance drop
C_0 \rightarrow C_{SS}(-9.5 V) between 3 and 300 ms is due to \( \omega_{dep} \) rise caused by negative charging in GaN:C. For the step -9.5 \rightarrow 0 V in Fig. 4a-I the capacitance rise from \( C_0 \to C_{sp}(0 \text{ V}) \) indicates transition to a less negative state (i.e. discharging). Recording C(t) transients for a large variety of initial and final biases (Fig. 4a) enables the extraction of \( C_0 \text{ and } C_{SS}(0 \text{ V}) \) curves before and after charging/discharging in GaN:C, respectively, Fig. 4b. C\( \text{SS-V} \) in Fig. 4b shows that the electric behavior can be separated into 2 distinct bias regimes, transitioning at 1.7 V [6], giving thus 4 classes of transients, Fig. 4a.

The structure simplicity enables straightforward calculation of time-dependent band diagrams in Fig. 6 (cf. to Fig. 4). Fig. 6b shows quasi-static (\( \Phi_0 \)) and SS (\( \Phi_{SS} \)) band diagrams for (0 \rightarrow -9.5 V). The electric field E in GaN:C after 30 \( \mu \text{s} \) (\( \Phi_0 \)) causes negative charges to be injected from the top electrode, transported through GaN:C and captured in carbon-related defects in GaN:C near its interface to GaN:Si. For \( V_{appl} < 1.7 \text{ V} \) (Fig. 6b), accumulation of negative charges (charging) raises the potential until E vanishes in SS. In case of an opposite bias step at \( v_{appl} < 1.7 \text{ V} \) (Fig. 6a) the amount of negative charges decreases until E = 0 kV/cm appears in SS (discharging) as in the previous case. The concentration \( N_0 \) of trapped neg. charge in quasi-static and steady-state is extracted in Fig. 7.

For \( V_{appl} > 1.7 \text{ V} \) (Fig. 6c,d) the interface potential (\( \Phi_i \)) in SS pins independent of \( V_{appl} \) at about 1.1 eV, explaining the capacitance plateau in Fig. 4b [6]. This effective energy barrier prevents major electron injection so that a potential drop will arise in GaN:C in SS. Decreasing forward bias as in Fig. 6c leads to reduction of negative charge analogous to Fig. 6a. For \( V_{appl} > 1.7 \text{ V} \) a finite electric field remains in SS, making trapping processes faster (factor up to 500 observed, believed due to field enhancement effect, Fig. 4a-III). Increasing forward bias even more leads to extremely fast capture of charge, see corresponding curves in Fig. 4a-IV. Even at 20 K the relaxation is faster than the setup resolution of 30 \( \mu \text{s} \). Immediately after increasing the bias, the interface charge is too small to establish the interface barrier, resulting in extremely fast electron injection from GaN:Si to GaN:C.

Exemplary temperature dependence of discharging transients is given in Fig. 8. Fig. 9 demonstrates that both charging and discharging transients exhibit remarkable exponential temperature dependence (\( e^{\alpha T} \)) which is the same as for \( I_{SS} \). Interestingly, vertical leakage in a HEMT stack shows the same exponential temperature dependence (Fig. 9).

From time-dependent band diagrams (Fig. 6) the time-dependent electric field E(t) in GaN:C can be extracted. From time-dependent \( N_d(t) \) (cf. Fig. 7) the flow of charges through GaN:C that are subsequently trapped (“trap filling current” \( I_c \)) can be evaluated: \( I_c(t) = \int q \frac{dN_d(t)}{dt} \) with \( q \) being the elementary charge. By knowing E(t) at every time point, the \( I_c(t) \) dependence can be translated into a field dependence of \( I_c \). The resulting \( I_c(E) \) curve is shown in Fig. 10 and compared to \( I_{SS}(E) \) extracted from \( I_{SS-V} \) in Fig. 5. Remarkably \( I_c(E) \) fits well to \( I_{SS}(E) \) within the entire temperature range and even for samples with GaN:C thickness of 300 nm (not shown). This means that the same process governs the C(t) transients and DC leakage current.

Our results in Figs. 9 and 10 indicate that leakage current is the determining factor which controls both charging and discharging processes with time constants \( \tau_{charge} \) (transition to more negative state; ‘0 \rightarrow -X’) and \( \tau_{discharge} \) (transition to more neutral state; ‘-X \rightarrow 0’), respectively. They are considered as serial processes where carrier transport between electrode and carbon defect with time constant \( \tau_{leak} (1/\lambda_0) \) is followed by carrier exchange between leakage path and defect, Fig. 1b. Considering holes as charge carriers one gets: \( \tau_{charge} = \tau_{leak} + \tau_{em} \) (1); \( \tau_{discharge} = \tau_{leak} + \tau_{em}^h \) (2). As \( \tau_{em}^h \) follows Arrhenius law (\( \tau_{em}^h \propto e^{-\frac{\Delta E_{A}}{k_b T}} \)) but the observed \( \tau_{charge} \) not, it must hold: \( \tau_{leak} \gg \tau_{em}^h \) (3). We emphasize that the measured time constant of charging processes at T = 150 K (Fig. 9) is 50 s which is more than 8 orders of magnitude lower than the hole emission time constant \( \tau_{em,VB}^h \) from the carbon level to VB taking into account literature values for capture cross section \( \sigma = 10^{-13} \text{ cm}^2 \) [7] and \( \Delta E_A = 0.7 \text{ eV} \) [6] (Fig. 1a), thus contradicting condition (3). The activation energy would need to be lower than 0.4 eV to fulfill (3), cf. Fig. 11. To explain this energy scale difference we propose that leakage occurs via a DB and that the carrier exchange occurs between carbon and the DB. Fig. 1b shows a model which considers a DB below the carbon acceptor level \( E_a \). Holes can be exchanged between the maximum occupied level of DB and \( E_a \) emission with \( \tau_{em,VB}^h \) capture with \( \tau_{em,AP,BDB}^h \). This would lead to apparent activation energies for hole emission \( \Delta E_{A,VB} \) being lower than \( \Delta E_{A,VB} \), in line with results of Figs. 9 and 11 and condition (3). DB could even surround \( E_a \), resulting in \( \Delta E_{A,VB} = 0 \text{ eV} \). Thus both charging and discharging processes will be governed by (electron/hole) capture processes from DB to carbon defect.

Fig. 12 demonstrates how the observed \( e^{\alpha T} \) temperature dependence of (dis-)charging can be misinterpreted as Arrhenius-like behavior. Although extracted \( \Delta E_A \) are only an artifact of the DB conductivity, their values are comparable to previously reported ones, possibly explaining its inconsistency, Fig. 2.

In conclusion, we find intrinsic non-Arrhenius behavior in isolated GaN:C structures but also in HEMTs, questioning today’s leakage and trapping models in carbon-doped III-N buffers. It indicates that the dominant role of defect bands in the individual layers should be considered for whole buffers.

REFERENCES

Fig. 4. (a) Transient capacitance $C(t)$ analysis after various bias steps at 70°C demonstrates that all transient curves can be attributed to one of the following 4 representative bias steps (thick grey lines) and their corresponding dynamic processes: I) discharging in reverse bias: $-9.5 \rightarrow 0$ V; II) charging in reverse bias: $0 \rightarrow -9.5$ V; III) discharging in forward bias: $8 \rightarrow 1.5$ V; IV) no charging/discharging in forward bias: $1.5 \rightarrow 8$ V. Quasi-static ($C_0$) and steady-state ($C_{SS}$) capacitances are extracted 30 µs and 30 s after the bias step, respectively. The time constant related to carrier transport in DB is denoted by $\tau_{leak}$. Transitions from neutral to negative (negative to neutral) defect state are denoted by '0' $\rightarrow$ '-' ( '-' $\rightarrow$ '0').

Fig. 2. Activation energies $\Delta E_A$ in literature related to carbon defects as a function of the central temperature in the measurement range. Differences between max. and min. temperatures were in the range 35-110°C.

Fig. 3. (a) Conventional GaN HEMT stack. (b) In our special designed structures the current is localized in GaN:C under the metal contact and spreads in n-type GaN:Si over the entire wafer, making the impedance of the transition layer negligible, thus letting the GaN:Si layer act as back-electrode [6].
Fig. 5. Current density $I_{SS}$ as a function of forward bias for varying temperature. For reverse bias currents do not exceed the measurement resolution of 10 pA. The inset shows the exponential increase of $I_{SS}$ with temperature (cf. $\exp(aT)$).

Fig. 6. Calculated band diagrams for 4 representative bias steps from Fig. 5. Colored band diagrams show the situation 30 µs after a bias step (quasi-static potential $\Phi_0$ before charging/discharging occurs in GaN:SiC), black ones 30 s later (steady-state $\Phi_{SS}$; charging/discharging completed). $N_0$ locates the trapped charges. In (d) no transient is measurable, the interface potential $\Phi_i$ stays constant and a steady-state leakage current $I_{SS}$ occurs.

Fig. 8. Normalized transient capacitance after a bias step (-9.5 → 0 V; i.e. discharging) for various temperatures.

Fig. 10. I-E dependence at 70°C, reconstructed from measured transient C(t) curves and calculated time-dependent band diagrams (i.e. “trap filling current” $I_t$) after bias steps to both polarities. $I_{SS}$ (dashed black line) represents the steady-state leakage current in forward bias.

Fig. 9. Charging and discharging rates $1/\tau_{\text{dis-charge}}$ (left scale) of capacitance transients after various bias steps (colored lines) and exponential function (grey dotted line). Steady-state leakage current $I_{SS}$ for forward bias (black) and vertical leakage current in a HEMT (grey) show remarkable similarity.

Fig. 12. Arrhenius plot: (Dis-)charging time constants $\tau_{\text{charge}}$ and calculated emission time constants $\tau_{\text{em,VB}}$ considering activation energies $\Delta E_A$ and capture cross sections $\sigma_h$. To ensure $\tau_{\text{em,VB}} < \tau_{\text{charge}}$ (see (3)), $\Delta E_A$ has to be smaller than 0.4 eV.