Numerical Simulation of Drain-Current Transients and Current Compression in GaN MESFETs

H. Takayanagi, K. Itagaki and K. Horio

Faculty of Systems Engineering, Shibaura Institute of Technology
307 Fukasaku, Minuma-ku, Saitama 337-8570, Japan, horio@sic.shibaura-it.ac.jp

ABSTRACT

Transient simulations of GaN MESFETs are performed in which a three-level compensation model is adopted for a semi-insulating buffer layer, where a shallow donor, a deep donor and a deep acceptor are considered. Quasi-pulsed *I-V* curves are derived from the transient characteristics, and are compared with steady-state *I-V* curves. It is shown that so-called current compression is more pronounced when the deep-acceptor density in the buffer layer is higher and when an off-state drain voltage is higher, because trapping effects become more significant. It is suggested that to minimize current compression in GaN-based FETs, an acceptor density in a semi-insulating GaN layer should be made low.

Keywords: GaN, FET, deep level, current compression

1 INTRODUCTION

GaN-based FETs are now receiving great attention because of their potential applications to high power and high temperature microwave devices [1]. However, slow current transients are often observed even if the drain voltage or the gate voltage is changed abruptly [2]. This is called drain lag or gate lag, and is problematic in circuit applications. The slow transients mean that dc current-voltage (*I-V*) curves and RF *I-V* curves become quite different, resulting in lower RF power available than that expected from dc operation [1,2]. This is called power (current) compression. These are serious problems, and there are many experimental works reported on these phenomena. However, only a few theoretical works have been reported for GaN-based FETs [3,4], although several numerical analyses were made for GaAs-based FETs [5-8]. Therefore, in this work, we have made systematic transient simulations of GaN MESFETs in which deep levels in a semi-insulating buffer layer are considered, and studied how the slow current transients and the current compression are affected by deep-level densities in the buffer layer and by an applied drain bias [9,10].

2 PHYSICAL MODEL

Fig.1 shows a device structure analyzed here. The gate length L_G is set to 0.3 μm. As a model for the semi-insulating buffer layer, we use a three level compensation model which includes a shallow donor, a deep donor and a deep acceptor. Some experiments show that two levels (E_C – 1.75 eV, E_C – 2.85 eV) are associated with current compression in GaN-based FETs with a semi-insulating buffer layer [2], so that we use energy levels of E_C – 2.85 eV (or E_V + 0.6 eV) for the deep acceptor and of E_C – 1.75 eV for the deep donor. Other experiments show shallower energy levels for the deep donor [11,12], and hence we vary the deep donor's energy level (E_{DD}) as a parameter. Here, the deep-donor density (N_{DD}) and the deep-acceptor density (N_{DA}) are typically set to 5x10^{16} cm^{-3} and 2x10^{16} cm^{-3}, respectively. The shallow-donor density in the buffer layer N_{Di} is set to 10^{15} cm^{-3}.

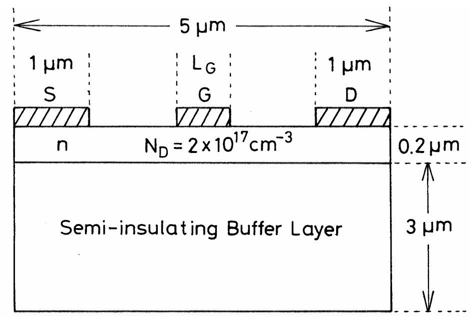

Figure 1: Modeled GaN MESFET analyzed here.

Basic equations to be solved are expressed as follows.
1) Poisson's equation

$$\nabla^2\psi = -\frac{q}{\varepsilon}(p - n + N_D + N_{Di} + N_{DD}^+ - N_{DA}^-) \tag{1}$$

2) Continuity equations for electrons and holes

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet J_n - (R_{n,DD} + R_{n,DA}) \tag{2}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \bullet J_p - (R_{p,DD} + R_{p,DA}) \tag{3}$$

where

$$R_{n,DD} = C_{n,DD}N_{DD}^+ n - e_{n,DD}(N_{DD} - N_{DD}^+) \tag{4}$$

$$R_{n,DA} = C_{n,DA}(N_{DA} - N_{DA}^-)n - e_{n,DA}N_{DA}^- \tag{5}$$

$$R_{p,DD} = C_{p,DD}(N_{DD} - N_{DD}^+)p - e_{p,DD}N_{DD}^+ \tag{6}$$

$$R_{p,DA} = C_{p,DA}N_{DA}^- p - e_{p,DA}(N_{DA} - N_{DA}^-) \tag{7}$$

3) Rate equations for the deep levels

$$\frac{\partial}{\partial t}(N_{\text{DD}} - N_{\text{DD}}^{+}) = R_{n,\text{DD}} - R_{p,\text{DD}} \tag{8}$$

$$\frac{\partial}{\partial t} N_{\text{DA}}^{-} = R_{n,\text{DA}} - R_{p,\text{DA}} \tag{9}$$

where N_{DD}^{+} and N_{DA}^{-} represent ionized densities of deep donors and deep acceptors, respectively. C_n and C_p are the electron and hole capture coefficients of the deep levels, respectively, e_n and e_p are the electron and hole emission rates of the deep levels, respectively, and the subscript (DD, DA) represents the corresponding deep level.

The above basic equations are put into discrete forms and are solved numerically. We have calculated the drain-current responses when the drain voltage V_{D} and/or the gate voltage V_{G} are changed abruptly.

3 SLOW CURRENT TRANSIENTS

Fig.2 shows calculated drain-current responses when the drain voltage V_{D} is raised abruptly from 0 V to 20 V or when V_{D} is lowered from 20 V to 6 V, where the gate voltage V_{G} is kept constant (0 V). Here, three cases with different $E_{\text{C}} - E_{\text{DD}}$ are shown. When V_{D} is raised, the drain currents overshoot steady-state values, because electrons are injected into the buffer layer, and deep traps there need certain time to capture these electrons. On the other hand, when V_{D} is lowered, the drain currents remain at low values for some periods and begin to increase slowly, showing drain lag behavior. This is due to the slow response of deep donors. It is understood that the drain currents begin to increase as the deep donors begin to emit electrons, and hence the response is faster for shallower E_{DD}. In fact, the current rise time is roughly consistent with the deep donor's electron-emission time constant given by $1/e_{n,\text{DD}}$, which becomes $3.9\text{x}10^{-5}$ s and $9.8\text{x}10^{3}$ s for $E_{\text{C}} - E_{\text{DD}} = 0.5$ eV and 1.0 eV, respectively. The above overshoot and undershoot behavior is also reported experimentally in GaN MESFETs and HEMTs [2],[3].

We have next calculated a case when V_{D} and V_{G} are both changed abruptly. Fig.3 shows calculated turn-on characteristics ($E_{\text{C}} - E_{\text{DD}}$ is 1.0 eV) when V_{G} is changed from the threshold voltage V_{th} to 0 V. The off-state drain voltage V_{Doff} is 20 V, and the parameter is the on-state drain voltage V_{Don}. The characteristics are similar to those in Fig.2, and hence the change of V_{D} is essential in this case. Fig.4 shows calculated I_{D}-V_{D} curves. In this figure, we plot by point (x) the drain current at $t = 10^{-6}$ s after the gate voltage is switched on. This is obtained from Fig.3, and this curve corresponds to a quasi-pulsed *I-V* curve with pulse width of 10^{-6} s. (We are also plotting other quasi-pulsed *I-V* curves when only V_{D} is changed (cf. Fig.2), which reflect overshoot and undershoot.) It is seen that the drain currents in the pulsed *I-V* curve are rather lower than those in the steady state. This clearly indicates that the current compression could occur due to the slow response of deep levels in the semi-insulating buffer layer. This type of current reduction is commonly observed experimentally in GaN-based FETs.

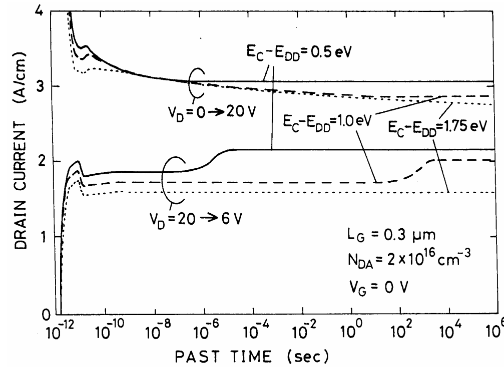

Figure 2: Comparison of drain-current responses of GaN MESFETs as a parameter of deep donor's energy level E_{DD} when V_{D} is raised abruptly from 0 V to 20 V (upper) or when V_{D} is lowered abruptly from 20 V to 6 V (lower). $N_{\text{DD}} = 5\text{x}10^{16}$ cm^{-3} and $N_{\text{DA}} = 2\text{x}10^{16}$ cm^{-3}.

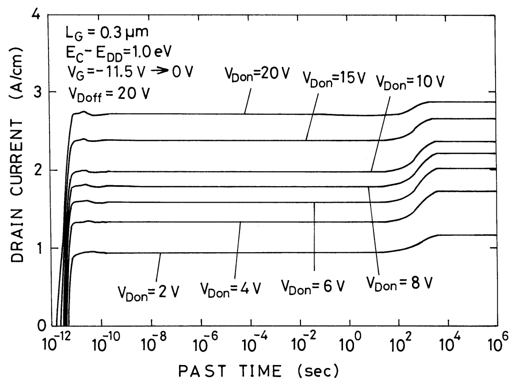

Figure 3: Calculated turn-on characteristics of GaN MESFET when V_{G} is changed from threshold voltage V_{th} to 0 V, with on-state drain voltage V_{Don} as a parameter. Off-state drain voltage $V_{\text{Doff}} = 20$ V. $E_{\text{C}} - E_{\text{DD}} = 1.0$ eV. $N_{\text{DD}} = 5\text{x}10^{16}$ cm^{-3} and $N_{\text{DA}} = 2\text{x}10^{16}$ cm^{-3}.

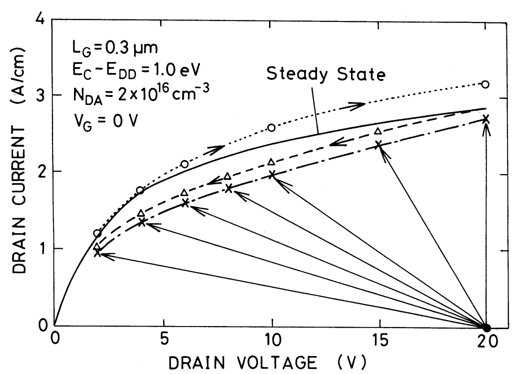

Figure 4: Steady-state *I-V* curve ($V_{\text{G}} = 0$ V; solid line) and quasi-pulsed *I-V* curves for GaN MESFET. $E_{\text{C}} - E_{\text{DD}} = 1.0$ eV. (x): $V_{\text{Doff}} = 20$ V and $V_{\text{Goff}} = V_{\text{th}}$ ($t = 10^{-6}$ s; Fig.3), (○): V_{D} is raised from 0 V ($t = 10^{-9}$ s; Fig.2), (Δ): V_{D} is lowered from 20V ($t = 10^{-6}$ s; Fig.2).

4 CURRENT COMPRESSION

4.1 Dependence on Deep-Acceptor Density

We have studied dependence of calculated *I-V* curves and drain-current responses on the deep-level densities (N_{DD}, N_{DA}) in the buffer layer. We have found that these characteristics are almost independent of N_{DD} under a condition that N_{DD} is higher than N_{DA} and $E_C - E_{DD}$ is the same, and that these are mainly determined by N_{DA}. This is because in this condition, the ionized deep-donor density N_{DD}^+, which acts as an electron trap, becomes nearly equal to N_{DA} under equilibrium [5]. Hence, we will show N_{DA} dependence of the characteristics.

Fig.5 shows calculated I_D-V_D curves of GaN MESFETs with N_{DA} = 5x10^{15} cm^{-3} or 10^{17} cm^{-3}, where N_{DD} is 2x10^{17} cm^{-3} and $E_C - E_{DD}$ is 0.5 eV. The solid lines are steady-state *I-V* curves. The dashed lines are quasi-pulsed *I-V* curves (pulse width of 10^{-8} s) derived from the calculated turn-on characteristics, as mentioned before. It is seen that the steady-state drain currents are higher for lower N_{DA}. This is because the current via the buffer layer becomes larger for lower N_{DA} due to less steep barrier at the active layer-buffer interface. It is also clearly seen that the current reduction in the pulsed *I-V* curves is more pronounced for higher N_{DA}. This is because, as mentioned before, the ionized deep-donor density N_{DD}^+, which acts as an electron trap, becomes nearly equal to N_{DA} under equilibrium, and hence the trapping effect (or the resulting current compression) should become more pronounced for higher N_{DA}.

Fig.6 shows a comparison of ionized deep-donor density N_{DD}^+ profiles between (a) N_{DA} = 5x10^{15} cm^{-3} and (b) N_{DA} = 10^{17} cm^{-3}. The left is for the off state (V_D = 20 V, $V_G = V_{th}$) and the right is for an on state (V_D = 6 V, V_G = 0 V). In the off state, N_{DD}^+ in the deep area of buffer layer is lower (negative space-charge densities are higher) than in the on state for the both cases, and hence the current reduction or current compression occurs. But the difference of N_{DD}^+ between off and on states is an order of 10^{15} cm^{-3} for the case of N_{DA} = 5x10^{15} cm^{-3} and of 10^{16} cm^{-3} for the case of N_{DA} = 10^{17} cm^{-3}, and hence the current compression becomes weaker for lower N_{DA}. Here, it should be mentioned that for lower N_{DA}, the current compression could be weakened, but the threshold voltage shifts toward negative bias because of the higher current density via the buffer layer. Therefore, there may be a trade-off relationship between reducing the current compression and obtaining sharp current cutoff.

4.2 Dependence on Off-State Drain Voltage

Next, we describe dependence of off-state drain voltage V_{Doff} on the current compression. Figs.7 and 8 show calculated steady-state I_D-V_D curves and quasi-pulsed *I-V* curves (with pulse width of 10^{-8} s) as a parameter of V_{Doff}, which are derived from calculated turn-on characteristics as described before. In Fig.7, N_{DD} = 5x10^{16} cm^{-3}, N_{DA} = 2x10^{16}

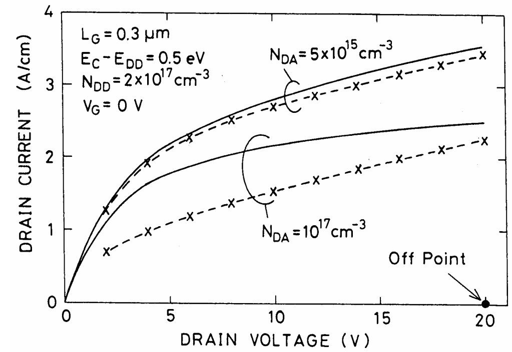

Figure 5: Steady-state *I-V* curves (V_G = 0 V; solid lines) and quasi-pulsed *I-V* curves (x ; t = 10^{-8} s) for GaN MESFETs with different N_{DA} (5x10^{15} cm^{-3} , 10^{17} cm^{-3}). Initial point is shown by (●). $E_C - E_{DD}$ = 0.5 eV and N_{DD} = 2x10^{17} cm^{-3}.

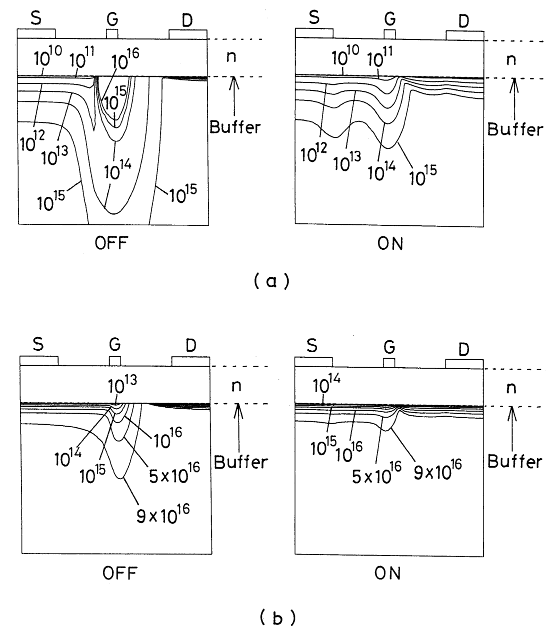

Figure 6: Comparison of ionized deep-donor density N_{DD}^+ profiles between the two cases with (a) N_{DA} = 5x10^{15} cm^{-3} and (b) N_{DA} = 10^{17} cm^{-3}. N_{DD} = 2x10^{17} cm^{-3} and $E_C - E_{DD}$ = 0.5 eV. The left is for the off state ($V_G = V_{th}$, V_D = 20 V) and the right is for an on state (V_G = 0 V, V_D = 6 V).

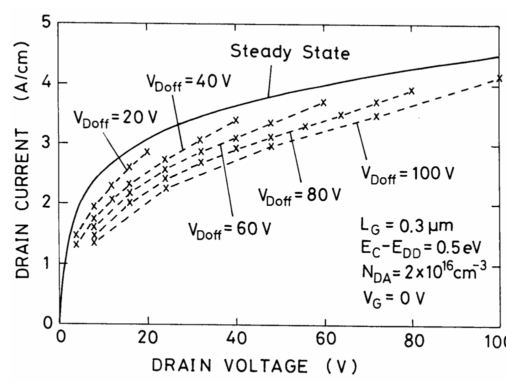

Figure 7: Steady-state *I-V* curve (V_G = 0 V; solid line) and quasi-pulsed *I-V* curves (x ; t = 10^{-8} s) for GaN MESFET, with off-state drain voltage V_{Doff} as a parameter. $E_C - E_{DD}$ = 0.5 eV. N_{DD} = 5x10^{16} cm^{-3} and N_{DA} = 2x10^{16} cm^{-3}.

cm^{-3}, $E_C - E_{DD}$ = 0.5 eV, and in Fig.8, N_{DD} = 2x10^{17} cm^{-3}, N_{DA} = 10^{17} cm^{-3}, $E_C - E_{DD}$ = 0.5 eV. It is seen that for higher V_{Doff}, the drain currents in the pulsed *I-V* curves become lower at a given V_D, indicating that the current compression is more pronounced for higher V_{Doff}.

Fig.9 shows (a) electron density profiles and (b) N_{DD}^+ profiles in the off state for the two cases, corresponding to Fig.8. The left is for V_{Doff} = 40 V, and the right is for V_{Doff} = 100 V. It is seen that for higher V_{Doff}, electron densities in the buffer layer become higher particularly under the gate and the gate-to-drain region, because electrons are injected into the buffer layer by the applied drain bias. These electrons are captured by the deep donors, and hence N_{DD}^+ becomes lower there for higher V_{Doff}, as seen in Fig.9(b). Hence, when V_G is switched on and V_D is lowered from higher V_{Doff}, the drain current remains at a lower value. Therefore, the current compression is more pronounced for higher V_{Doff}. This tendency is also reported experimentally in AlGaN/GaN HFETs [13].

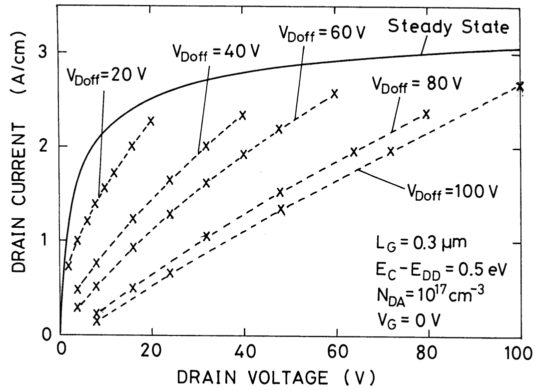

Figure 8: Steady-state *I-V* curve (V_G = 0 V; solid line) and quasi-pulsed *I-V* curves (x ; t = 10^{-8} s) for GaN MESFET, with off-state drain voltage V_{Doff} as a parameter. $E_C - E_{DD}$ = 0.5 eV. N_{DD} = 2x10^{17} cm^{-3} and N_{DA} = 10^{17} cm^{-3}.

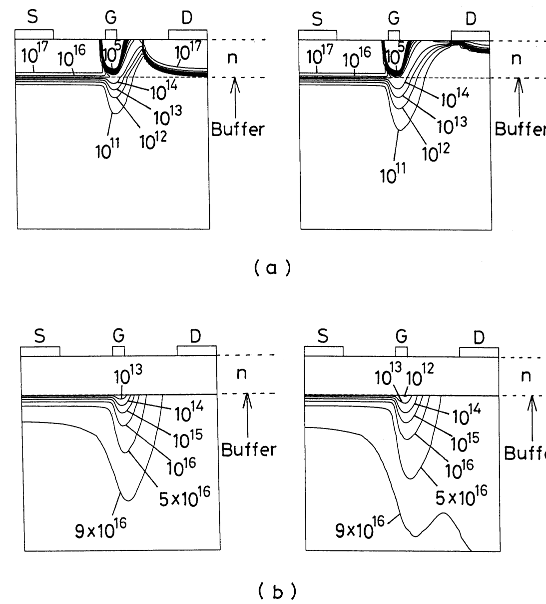

Figure 9: (a) Electron density profiles and (b) N_{DD}^+ profiles in the off state. The left is for V_{Doff} = 40 V and the right is for V_{Doff} = 100 V. N_{DD} = 2x10^{17} cm^{-3} and N_{DA} = 10^{17} cm^{-3}.

5 CONCLUSION

Transient simulations of GaN MESFETs have been performed in which a three level compensation model is adopted for the semi-insulating buffer layer, where a shallow donor, a deep donor and a deep acceptor are considered. Quasi-pulsed *I-V* curves have been derived from the transient characteristics. It has been shown that the current compression is more pronounced when the deep-acceptor density in the buffer layer is higher and when the off-state drain voltage is higher, because the change of ionized deep-donor density becomes larger and hence the trapping effects become more significant. The above buffer-trapping effects may be similar to trapping effects in an undoped GaN layer in AlGaN/GaN HEMTs. Therefore, it is suggested that to minimize current compression in GaN-based FETs, an acceptor density in a semi-insulating GaN layer should be made low.

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