Simulation of Buffer-Related Current Slump in AlGaN/GaN HEMTs

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ABSTRACT

Transient simulations of AlGaN/GaN HEMTs 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 slump 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 slump in AlGaN/GaN HEMTs, an acceptor density in a semi-insulating buffer layer should be made low.

Keywords: AlGaN/GaN HEMT, deep level, current slump, device simulation

1 INTRODUCTION

Recently, AlGaN/GaN HEMTs have received 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 the dc *I-V* curves and the RF *I-V* curves become quite different, resulting in lower RF power available than that expected from the dc operation [1],[2]. This is called power slump or current slump. These are serious problems, and there are many experimental works reported on these phenomena [1-6]. But, only a few theoretical works have been reported for GaN-based FETs [6,7], where effects of a donor-type surface state (near the valence band) on gate lag and pulsed *I-V* curves of AlGaN/GaN HEMTs are studied [6], and a bulk deep-acceptor effect (~ 1 eV above the midgap of GaN) is studied for gate lag in AlGaN/GaN HEMTs [7]. But, the type of traps and their energy levels seemed to be artificial. In this work, we have made simulations of AlGaN/GaN HEMTs with a semi-insulating buffer layer in which trap levels based on experiments are considered, as in our previous work on GaN MESFETs [8], and showed that the lag phenomena and the current slump could be reproduced. Additionally, we have studied dependence of current slump on the impurity densities in the buffer layer and on an off-state drain voltage.

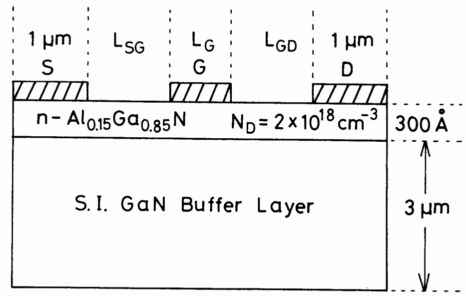

Fig.1. Modeled AlGaN/GaN HEMT analyzed in this study.

2 PYSICAL MODEL

Fig.1 shows a device structure analyzed in this study. 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 – 1.7 eV, E_C – 2.85 eV) are associated with current slump 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 – 1.7 eV for the deep donor. Other experiments show shallower energy levels for the deep donor [9,10], 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 5×10^{16} cm^{-3} and 2×10^{16} cm^{-3}, respectively. The shallow-donor density in the buffer layer N_{Di} is set to 10^{15} cm^{-3}.

Basic equations to be solved are expressed as follows.

1) Poisson's equation

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

2) Continuity equations for electrons and holes

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

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

where

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

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

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

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

3) Rate equations for the deep levels

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

$$\frac{\partial}{\partial t} N_{\mathrm{DA}}^{-} = R_{n,\mathrm{DA}} - R_{p,\mathrm{DA}} \quad (9)$$

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 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 10 V, where the gate voltage V_G is kept constant (0 V). Here, three cases with different $E_C - E_{DD}$ 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 $1/e_{n,\mathrm{DD}}$, which becomes 3.9×10^{-5} s and 9.8×10^{3} s for $E_C - E_{DD} = 0.5$ eV and 1.0 eV, respectively. The above overshoot and undershoot behavior is also reported experimentally in AlGaN/GaN HEMTs [2],[6].

We have next calculated a case when V_D and V_G are both changed abruptly. Fig.3 shows calculated turn-on characteristics ($E_C - E_{DD}$ 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

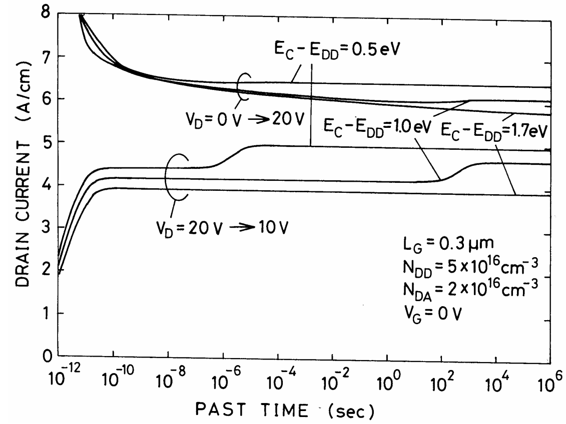

Fig.2. Comparison of drain-current responses of AlGaN/GaN HEMT as a parameter of deep donor's energy level E_{DD} when V_D is raised abruptly from 0 V to 20 V (upper) or when V_D is lowered abruptly from 20 V to 10 V (lower). V_G = 0 V. $N_{DD} = 5\times10^{16}$ cm^{-3} and $N_{DA} = 2\times10^{16}$ cm^{-3}.

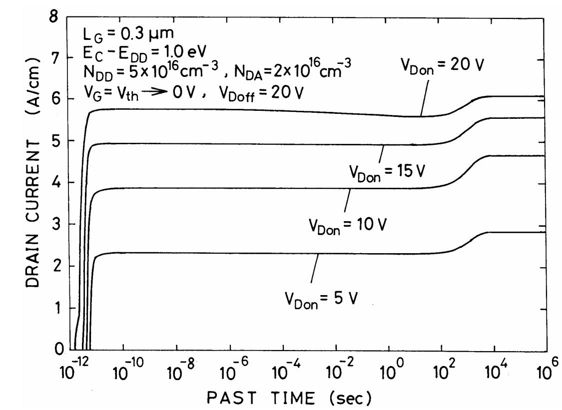

Fig.3. Calculated turn-on characteristics of AlGaN/GaN HEMT when V_G is changed from threshold voltage V_{th} to 0 V, with on-state drain voltage V_{Don} as a parameter. Off-state drain voltage V_{Doff} = 20 V. $E_C - E_{DD}$ = 1.0 eV. $N_{DD} = 5\times10^{16}$ cm^{-3} and $N_{DA} = 2\times10^{16}$ cm^{-3}.

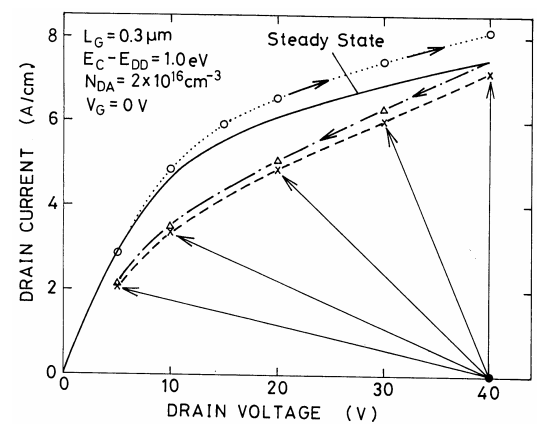

Fig.4. Steady-state *I-V* curve (V_G = 0 V; solid line) and quasi-pulsed *I-V* curves for AlGaN/GaN HEMT. $E_C - E_{DD}$ = 1.0 eV. (x): V_{Doff} = 40 V and $V_{Goff} = V_{th}$ ($t = 10^{-8}$ s), (○): V_D is raised from 0 V ($t = 10^{-9}$ s), (Δ): V_D is lowered from 40V ($t = 10^{-8}$ s).

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Fig.2, and hence the change of V_D is regarded as 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 $t = 10^{-8}$ s after the gate voltage is switched on. This is obtained from the turn-on characteristics, and this curve corresponds to a quasi-pulsed *I-V* curve with pulse width of 10^{-8} s. (We are also plotting other quasi-pulsed *I-V* curves when only V_D is changed, 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 slump 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 AlGaN/GaN HEMTs.

4 CURRENT SLUMP

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. Hence, we will show N_{DA} dependence of the characteristics.

Fig.5 shows calculated I_D-V_D curves of AlGaN/GaN HEMTs with $N_{DA} = 5\times10^{15}$ cm^{-3} or 10^{17} cm^{-3}, where N_{DD} is 2×10^{17} cm^{-3} and $E_C - E_{DD}$ is 1.0 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 channel-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 slump) should become more pronounced for higher N_{DA}. Here, it should be mentioned that for lower N_{DA}, the current slump 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 slump and obtaining sharp current cutoff.

4.2 Dependence on Off-State Drain Voltage

Next, we describe dependence of current slump on the off-state drain voltage V_{Doff}. Fig.6 shows calculated steady-state I_D-V_D curve 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. Here, $N_{DD} = 2\times10^{17}$ cm^{-3}, $N_{DA} = 10^{17}$ cm^{-3}, and $E_C - E_{DD} =$ 1.0 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 slump is more pronounced for higher V_{Doff}. This is understood as follows. 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 the ionized deep-donor density N_{DD}^+ becomes lower (negative space-charge densities are higher) there for higher V_{Doff}. Hence, when V_G is switched on and

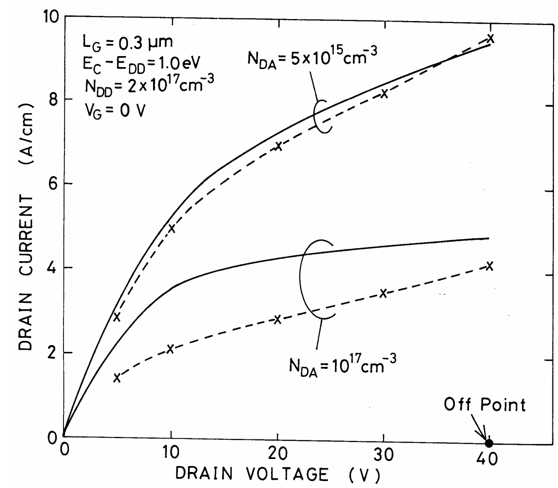

Fig.5. Steady-state *I-V* curves (V_G = 0 V; solid lines) and quasi-pulsed *I-V* curves (x ; $t = 10^{-8}$ s) for AlGaN/GaN HEMTs with different N_{DA} (5×10^{15} cm^{-3} , 10^{17} cm^{-3}). Initial point is shown by (●). $E_C - E_{DD}$ = 1.0 eV and $N_{DD} = 2\times10^{17}$ cm^{-3}.

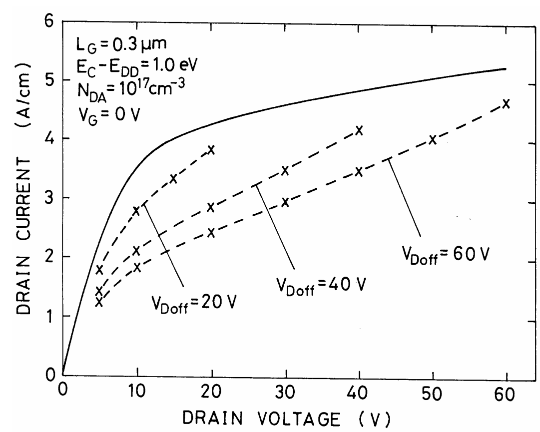

Fig.6. Steady-state *I-V* curve (V_G = 0 V; solid line) and quasi-pulsed *I-V* curves (x ; $t = 10^{-8}$ s) for AlGaN/GaN HEMT, with different off-state drain voltage V_{Doff}. $E_C - E_{DD}$ = 1.0 eV. $N_{DD} = 2\times10^{17}$ cm^{-3} and $N_{DA} = 10^{17}$ cm^{-3}.

V_D is lowered from higher V_{Doff}, the drain current remains at a lower value, resulting in more pronounced current slump. This tendency is also reported experimentally in AlGaN/GaN HEMTs [11].

5 CONCLUSION

Transient simulations of AlGaN/GaN HEMTs 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 lag phenomena and current slump could be reproduced. It has also been shown that the current slump 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. It is suggested that to minimize current slump in AlGaN/GaN HEMTs, an acceptor density in a semi-insulating buffer layer should be made low, although there may be a trade-off relationship between reducing current slump and obtaining sharp current cutoff.

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