Analysis of Buffer-Trapping Effects on Current Reduction and Pulsed *I-V* Curves of GaN FETs

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***Abstract* — Two-dimensional transient analyses 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 included. Quasi-pulsed *I-V* curves are derived from the transient characteristics. It is shown that so called current collapse or current reduction is more pronounced for a case with higher acceptor density in the buffer layer, because trapping effects become more significant. It is also shown that the current reduction is more pronounced when the drain voltage is lowered from a higher drain bias during turn-on.**

I. Introduction

Recently, GaN-based FETs have received great interest 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 AC *I-V* curves become quite different, resulting in lower AC power available than that expected from the DC operation [1],[2]. This is called power slump or current collapse in the GaN-device field. These are serious problems, and there are many experimental works reported on these phenomena. But, 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 is considered, and studied how the current reduction (current collapse) and pulsed *I-V* curves are affected by the deep-level parameters and the applied drain bias.

II. Physical Model

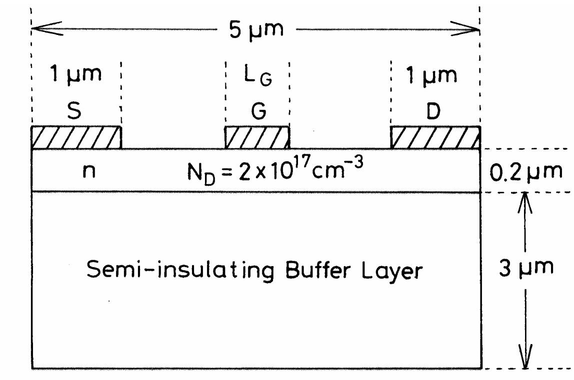

Fig.1 Modeled GaN MESFET analyzed in this study.

Fig.1 shows a device structure analyzed in this study. The donor density in the active layer is 2×10^{17} cm^{-3}, and its thickness is 0.2 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 collapse (or power 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 – 1.75 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, but N_{DA} is varied as a parameter to study its effect on the device characteristics. The shallow donor density in the buffer layer N_{Di} is set to 10^{15} cm^{-3}.

Basic equations to be solved are Poisson's equation including ionized deep-level terms, continuity equations for electrons and holes which include carrier loss rates via the deep levels, and rate equations for the deep levels. These 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.

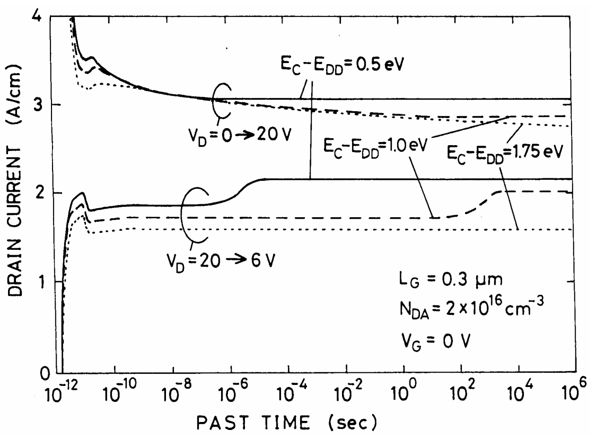

Fig.2 Comparison of drain-current responses of GaN MESFET as a parameter of deep donor's energy level E_{DD} when V_{D} is raised abruptly from 0 V to 20 V (upper) or when V_{D} is lowered abruptly from 20 V to 6 V (lower). $N_{\mathrm{DD}} = 5\times10^{16}$ cm^{-3} and $N_{\mathrm{DA}} = 2\times10^{16}$ cm^{-3}.

III. Drain Lag

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 $E_{\mathrm{C}} - E_{\mathrm{DD}}$ are shown. When V_{D} is raised, the drain currents overshoot the steady-state values, because electrons are injected into the buffer layer, and the 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 the deep donor. It is understood that the drain currents begin to increase as the deep donors begin to emit electrons, so that 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 $E_{\mathrm{C}} - E_{\mathrm{DD}} = 0.5$ eV and 1.0 eV, respectively. The time constant for $E_{\mathrm{C}} - E_{\mathrm{DD}} = 1.75$ eV is estimated as a quite long value of 3.9×10^{16} s. The above overshoot and undershoot behavior is also reported experimentally in GaN MESFETs [2] and AlGaN/GaN HEMTs [3].

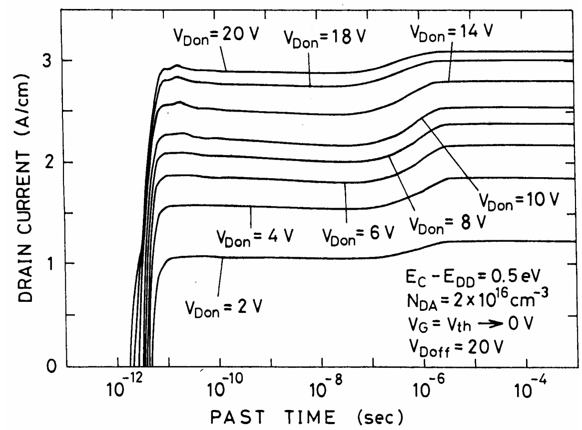

Fig.3 Calculated turn-on characteristics of GaN MESFET when V_{G} is changed from threshold voltage V_{th} to 0 V, with on-state drain voltage V_{Don} as a parameter. Off-state drain voltage $V_{\mathrm{Doff}} = 20$ V. $E_{\mathrm{C}} - E_{\mathrm{DD}} = 0.5$ eV. $N_{\mathrm{DD}} = 5\times10^{16}$ cm^{-3} and $N_{\mathrm{DA}} = 2\times10^{16}$ cm^{-3}.

IV. Current Collapse

We have next calculated a case when V_{D} and V_{G} are both changed abruptly. Fig.3 shows calculated turn-on characteristics ($E_{\mathrm{C}} - E_{\mathrm{DD}}$ is 0.5 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 $t = 10^{-8}$ 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^{-8} s. (We are also plotting other quasi-pulsed *I-V* curves when only V_{D} is changed (cf. Fig.2) , which reflect the 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 indicates that the current reduction (current collapse) or power 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 GaN-based FETs.

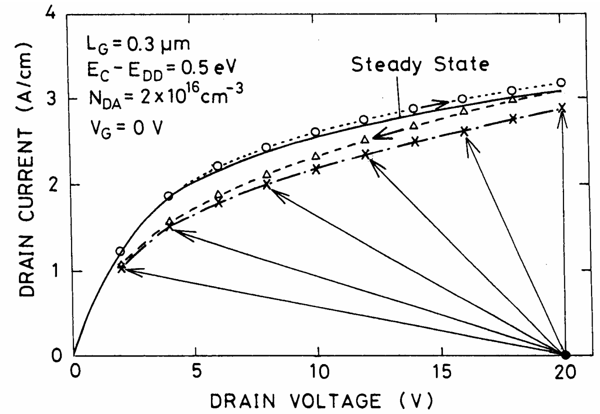

Fig.4 Steady-state *I-V* curve (V_G = 0 V; solid line) and quasi-pulsed *I-V* curves for GaN MESFET. $E_C - E_{DD}$ = 0.5 eV. (x): V_{Doff} = 20 V and $V_{Goff} = V_{th}$ ($t = 10^{-8}$ s; Fig.3), (○): V_D is raised from 0 V ($t = 10^{-9}$ s; Fig.2), (Δ): V_D is lowered from 20V ($t = 10^{-8}$ s; Fig.2).

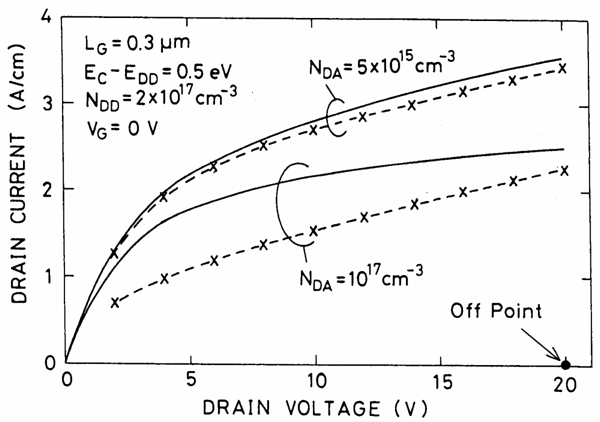

Fig.5 Steady-state *I-V* curves (V_G = 0 V; solid lines) and quasi-pulsed *I-V* curves (x ; $t = 10^{-8}$ s) for GaN MESFETs with different N_{DA} (5×10^{15} cm^{-3} , 10^{17} cm^{-3}). Initial point is shown by (●). $E_C - E_{DD}$ = 0.5 eV and $N_{DD} = 2 \times 10^{17}$ cm^{-3}.

V. Dependence Of Deep-Acceptor Density

Next, we have studied the dependence of deep-level densities (N_{DD}, N_{DA}) in the buffer layer. The above characteristics are found to be almost independent of the deep-donor density N_{DD} under a condition that N_{DD} is higher than 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]. Therefore, we will show N_{DA} dependence of the characteristics. Fig.5 shows the calculated I_D-V_D curves for different N_{DA} (5×10^{15} cm^{-3}, 10^{17} cm^{-3}), where N_{DD} is 2×10^{17} cm^{-3} and $E_C - E_{DD}$ is 0.5 eV. It is seen that the steady-state drain currents are higher for lower N_{DA}, because the current via the buffer layer becomes higher. 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 the trapping effects become more remarkable for higher N_{DA} because of higher N_{DD}^+. It is concluded that the deep-acceptor density in the buffer layer must be made low to minimize the current reduction or current collapse.

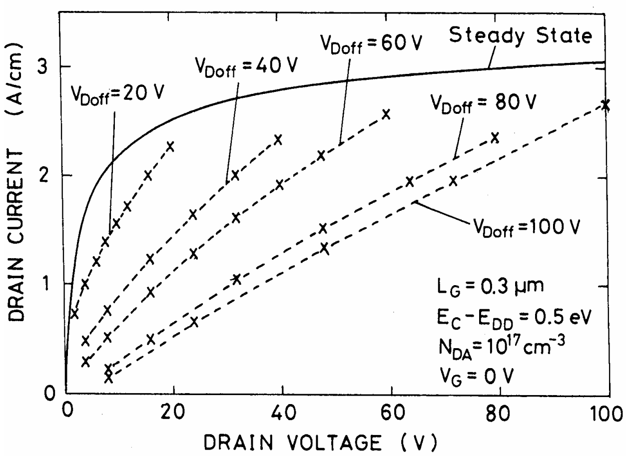

Fig.6 Steady-state *I-V* curve (V_G = 0 V; solid line) and quasi-pulsed *I-V* curves (x ; $t = 10^{-8}$ s) for GaN MESFET, with off-state drain voltage V_{Doff} as a parameter. $E_C - E_{DD}$ = 0.5 eV. $N_{DD} = 2 \times 10^{17}$ cm^{-3} and $N_{DA} = 10^{17}$ cm^{-3}.

VI. Dependence of Off-State Drain Voltage

Finally, we have studied dependence of off-state drain voltage V_{Doff} on the current reduction or current collapse. Fig.6 shows the calculated pulsed *I-V* curves as a parameter of V_{Doff}. Here N_{DD} is 2×10^{17} cm^{-3}, N_{DA} is 10^{17} cm^{-3}, and $E_C - E_{DD}$ is 0.5 eV. It is seen that the current reduction (current collapse) is more pronounced for higher V_{Doff}. This is understood from the fact that in the case of higher drain bias, electrons are injected deeper into the buffer layer and more electrons are captured by the traps. Therefore, when the drain voltage is lowered from higher V_{Doff}, the trapping effects are more pronounced, resulting in the heavier current reduction. This tendency is also reported experimentally in AlGaN/GaN HFETs [11].

VII. Conclusion

Two-dimensional transient analyses of GaN MESFETs have been performed in which a three level compensation model is adopted for the semi-insulating buffer layer, and the pulsed *I-V* curves have been derived from the transient characteristics. It has been shown that the current collapse (current reduction) or power slump becomes more pronounced when the deep-acceptor density in the buffer layer is higher and when the off-state drain voltage is higher, because the trapping effects become more significant. The buffer-trapping effects may be similar to trapping effects in an undoped GaN layer in AlGaN/GaN HEMTs. It is concluded that to minimize the current reduction or current collapse, the acceptor density in the buffer layer should be made low.

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