Simulation of Surface and Buffer Trapping Effects on Gate Lag in AlGaN/GaN HEMTs

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ABSTRACT

Two-dimensional analysis of turn-on characteristics of AlGaN/GaN HEMTs is performed in which both buffer traps and surface states (traps) are considered. It is studied how so-called gate lag is affected by these traps. It is shown that gate lag due to buffer traps can occur because in the off state, electrons are injected into the buffer layer and captured by the traps. It is also shown that gate lag due to an electron-trap-type surface state can occur only when electron's gate tunneling is considered. Dependence of gate lag on buffer-trap parameters is also studied.

Keywords: AlGaN/GaN HEMT, gate lag, trap, surface state, gate tunneling

1 INTRODUCTION

AlGaN/GaN HEMTs are now receiving great attention because of their applications to high-power 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 for 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 the dc operation. This is called power slump or current collapse. The current collapse is a combined effect of drain lag and gate lag. These are serious problems and many experimental works are made [1-5], but relatively small number of theoretical works is reported [6-9].

Theoretically, it is considered that buffer trapping is a cause of drain lag [10], and surface trapping is a cause of gate lag [6,8]. In [6], effects of a donor-type surface state near the valence band, which acts as a hole trap, were studied, and in [8], effects of a donor-type or acceptor-type surface state near the conduction band (which acts as an electron trap) together with electron's gate tunneling were studied.

In this work, we have made two-dimensional transient simulation of AlGaN/GaN HEMTs in which both buffer traps and surface states are considered, and found that the buffer traps can strongly contribute to the gate lag in AlGaN/GaN HEMTs.

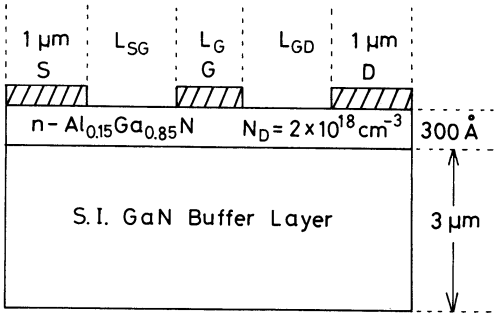

Figure 1: Device structure analyzed in this study.

2 PHYSICAL MODELS

Figure1 shows a device structure analyzed in this study. The gate length L_G is set to 0.3 μm. The source-to-gate length L_{SG} and the gate-to-drain length L_{GD} are 0.5 μm and 1.5 μm, respectively. In a semi-insulating buffer layer, we consider a deep donor and a deep acceptor [10]. The energy level of deep acceptor E_{DA} is set to $E_C - 2.85$ eV ($E_V + 0.6$ eV), and the energy level of the deep donor E_{DD} is typically set to $E_C - 1.0$ eV [10]. When the deep-donor density N_{DD} is higher than the deep-acceptor density N_{DA}, the deep donors donate electrons to the deep acceptors, and hence the ionized (empty) deep-donor density N_{DD}^+ becomes nearly equal to N_{DA} under equilibrium. In this case the deep donors act as electron traps. Here N_{DD} and N_{DA} are typically set to 5×10^{16} cm^{-3} and 2×10^{16} cm^{-3}, respectively. Electron and hole capture cross sections for the deep donor are set to 10^{-13} cm^2 and 10^{-15} cm^2, respectively, and hence the deep-donor's electron-emission time constant, which is given by the inverse of emission rate, becomes 9.8×10^3 sec. As a surface-state model, we adopt Spicer's unified defect model and consider a pair of a deep donor and a deep acceptor ($E_V + 0.6$ eV). As an energy level of the surface deep donor E_{SD}, we use a value of $E_C - 0.5$ eV, because relatively shallow surface states are considered previously [8]. The surface states are assumed to distribute uniformly within 5 Å from the surface, and their densities are typically set to 10^{13} cm^{-2} (2×10^{20} cm^{-3}). Electron and hole capture cross sections for the surface deep donor are both set to 10^{-15} cm^2, and the

surface deep donor's electron-emission time constant becomes $3.9\text{x}10^{-3}$ sec.

Basic equations to be solved are Poisson's equation including ionized deep-level terms, continuity equations for electrons and holes which include electron and hole loss rates via the deep levels, and rate equations for the deep levels [11]. These are expressed as follows.

1) Poisson's equation

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

2) Continuity equations for electrons and holes

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

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

where

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

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

$$R_{n,\mathrm{SD}} = C_{n,\mathrm{SD}} N_{\mathrm{SD}}^{+} n - e_{n,\mathrm{SD}}(N_{\mathrm{SD}} - N_{\mathrm{SD}}^{+}) \tag{6}$$

$$R_{n,\mathrm{SA}} = C_{n,\mathrm{SA}}(N_{\mathrm{SA}} - N_{\mathrm{SA}}^{-}) n - e_{n,\mathrm{SA}} N_{\mathrm{SA}}^{-} \tag{7}$$

$$R_{p,\mathrm{DD}} = C_{p,\mathrm{DD}}(N_{\mathrm{DD}} - N_{\mathrm{DD}}^{+}) p - e_{p,\mathrm{DD}} N_{\mathrm{DD}}^{+} \tag{8}$$

$$R_{p,\mathrm{DA}} = C_{p,\mathrm{DA}} N_{\mathrm{DA}}^{-} p - e_{p,\mathrm{DA}}(N_{\mathrm{DA}} - N_{\mathrm{DA}}^{-}) \tag{9}$$

$$R_{p,\mathrm{SD}} = C_{p,\mathrm{SD}}(N_{\mathrm{SD}} - N_{\mathrm{SD}}^{+}) p - e_{p,\mathrm{SD}} N_{\mathrm{SD}}^{+} \tag{10}$$

$$R_{p,\mathrm{SA}} = C_{p,\mathrm{SA}} N_{\mathrm{SA}}^{-} p - e_{p,\mathrm{SA}}(N_{\mathrm{SA}} - N_{\mathrm{SA}}^{-}) \tag{11}$$

3) Rate equations for the deep levels

$$\frac{\partial}{\partial t}(N_{\mathrm{DD}} - N_{\mathrm{DD}}^{+}) = R_{n,\mathrm{DD}} - R_{p,\mathrm{DD}} \tag{12}$$

$$\frac{\partial}{\partial t} N_{\mathrm{DA}}^{-} = R_{n,\mathrm{DA}} - R_{p,\mathrm{DA}} \tag{13}$$

$$\frac{\partial}{\partial t}(N_{\mathrm{SD}} - N_{\mathrm{SD}}^{+}) = R_{n,\mathrm{SD}} - R_{p,\mathrm{SD}} \tag{14}$$

$$\frac{\partial}{\partial t} N_{\mathrm{SA}}^{-} = R_{n,\mathrm{SA}} - R_{p,\mathrm{SA}} \tag{15}$$

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

These equations are put into discrete forms and are solved numerically. We have calculated the drain-current responses when the gate voltage V_{G} (and the drain voltage V_{D}) is changed abruptly.

3 BUFFER-TRAP EFFECTS ON GATE LAG

Next, we describe calculated results for a case including only buffer traps without surface states. Figure 2 shows calculated turn-on characteristics of AlGaN/GaN HEMT with buffer traps ($N_{\mathrm{DD}} = 5\text{x}10^{16}$ cm^{-3}, $N_{\mathrm{DA}} = 2\text{x}10^{16}$ cm^{-3} and $E_{\mathrm{C}} - E_{\mathrm{DD}} = 1.0$ eV) when V_{G} is changed from the threshold voltage V_{th} to 0 V and V_{D} is changed from 20 V to V_{Don}. It is seen that the drain currents remain at low values for some periods and begin to increase slowly around 10^3 sec. This is due to the slow response of deep donors in the buffer layer. It is understood that the drain currents begin to increase when the deep donors in the buffer layer begin to emit electrons. In Fig.2, we see that some transients arise when only V_{G} is changed (uppermost line: V_{D} = 20 V). This indicates that gate lag occurs due to deep levels in the buffer layer. We will discuss below why this happens.

Figure 3 shows a comparison of (a) conduction-band-edge energy profiles, (b) electron density profiles, and (c) ionized deep-donor density N_{DD}^{+} profiles between the off state (left: $V_{\mathrm{D}} = 20$ V, $V_{\mathrm{G}} = V_{\mathrm{th}} = -9.24$ V) and the on state (right: $V_{\mathrm{D}} = 20$ V, $V_{\mathrm{G}} = 0$ V). From Fig.3(a), in the on state, some linear potential drops are observed between source and gate (and between gate and drain), indicating that source access resistance become important. It is understood that due to this potential drop at the source side, when V_{G} becomes negative and channel is depleted, electrons do not all flow into the source and drain electrodes, but can be injected into the buffer layer as seen in Fig.3(b). These electrons are captured by the deep donors, and hence N_{DD}^{+} decreases in the off state, as seen in Fig.3(c). Because of this increase in negative charges in the buffer layer, even if V_{G} is switched on, the drain current remains at a low value for some periods until the deep donors begin to emit electrons. Therefore, the gate lag arises.

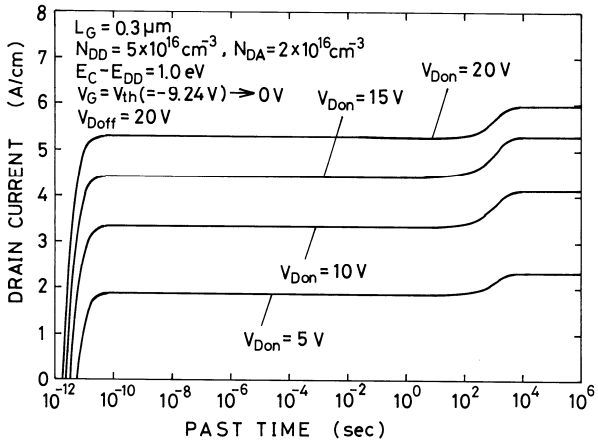

Figure 2: Calculated turn-on characteristics of AlGaN/GaN HEMT with only buffer traps when V_{G} is changed from threshold voltage V_{th} to 0 V and V_{D} is changed from 20 V to V_{Don}.

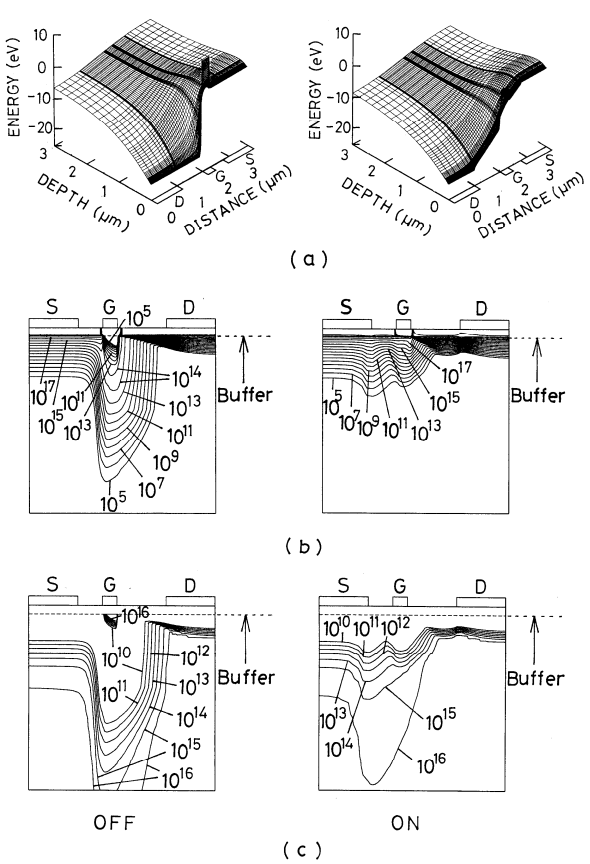

Figure 3: (a) Conduction-band-edge energy profiles, (b) electron density profiles, and (c) ionized deep-donor density N_{DD}^{+} profiles when only V_G is different. The left is for $V_G = V_{th} = -9.24$ V and $V_D = 20$ V (OFF), and the right is for $V_G = 0$ V and $V_D = 20$ V (ON). $N_{DD} = 5\text{x}10^{16}$ cm^{-3}, $N_{DA} = 2\text{x}10^{16}$ cm^{-3} and $E_C - E_{DD} = 1.0$ eV.

4 SURFACE-STATE EFFECTS ON GATE LAG

Next, we describe a case when both the buffer traps and surface states are considered. Figure 4 shows calculated turn-on characteristics of AlGaN/GaN HEMT when V_G is changed from V_{th} to 0 V, where V_D is kept constant at 20 V and electron's gate tunneling is considered. Here, N_{DD} is $2\text{x}10^{17}$ cm^{-3}, $N_{DA} = 10^{17}$ cm^{-3} and $E_C - E_{DD} = 1.0$ eV. Surface-state densities are 10^{13} cm^{-2} or $2\text{x}10^{20}$ cm^{-3}. The surface deep-donor's energy level is $E_C - 0.5$ eV. It is seen that slight current transients occur around 10^{-3} sec. This occurs due to surface states' contribution. It is understood that in the off state, electron tunneling occurs at the drain edge of the gate, and electrons are injected into the surface-state layer and captured by the surface deep donors. Because of this surface negative charge, when V_G is switched on, the drain current remains at a lower value, indicating enhanced gate lag. However, the change rate of drain current due to surface states is not so large here.

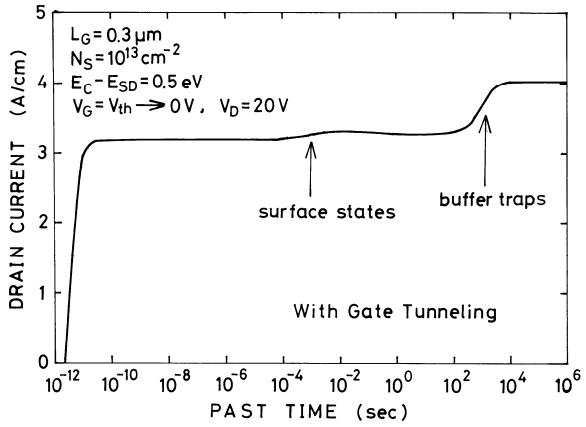

Figure 4: Calculated turn-on characteristics of AlGaN/GaN HEMT including both buffer traps and surface states, where gate tunneling is considered. V_G is changed from V_{th} to 0 V, and V_D is kept constant at 20 V. Surface deep-donor's energy level is $E_C - 0.5$ eV. $N_S = 10^{13}$ cm^{-2}. $N_{DD} = 2\text{x}10^{17}$ cm^{-3} and $N_{DA} = 10^{17}$ cm^{-3}

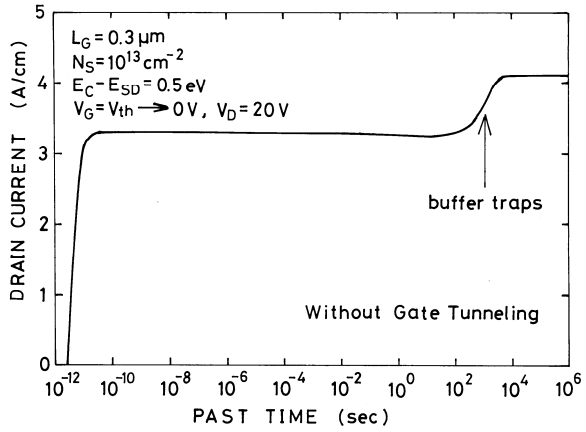

Figure 5: Calculated turn-on characteristics of AlGaN/GaN HEMT including both buffer traps and surface states, where gate tunneling is not considered. Other conditions are the same as in Fig.4.

Figure 5 shows calculated turn-on characteristics of AlGaN/GaN HEMT when only V_G is changed, where the gate tunneling is neglected. The voltage conditions and the trap parameters are the same as in Fig.4. It is seen that transients due to surface states disappear. This indicates that there are no surface-state effects in this case. In fact, as was shown in our previous work on GaAs MESFETs [11], turn-on characteristics showed little gate lag when the dominant surface state acted as an electron trap.

5 TRAP-PARAMETER DEPENDENCE OF GATE LAG

Here, we describe some results on buffer-trap-parameter dependence of gate lag. Figure 6 shows the gate-lag rate $\Delta I_D/I_D$ (ΔI_D: current reduction I_D: steady-state current) as a

function of deep-acceptor density N_{DA} in the buffer layer. The lag rate becomes high with N_{DA}, because the trapping effects should become larger for higher N_{DA} since N_{DA} becomes nearly equal to the ionized (empty) deep-donor density N_{DD}^{+} under equilibrium, which acts as an electron trap. However, the lag rate seems to saturate with N_{DA}. This is understood that for very high N_{DA}, the barrier between the channel and the buffer layer becomes steep to prevent further electron injection. Figure 7 shows the gate-lag rate $\Delta I_D/I_D$ as a function of the deep-donor's energy level E_{DD}. It seems that the lag rate is not so dependent on E_{DD}.

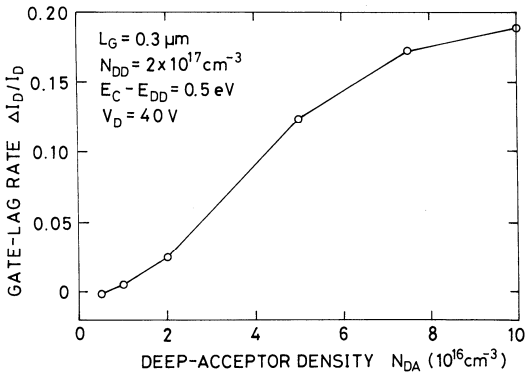

Figure 6: Gate-lag rate versus deep-acceptor density N_{DA}.

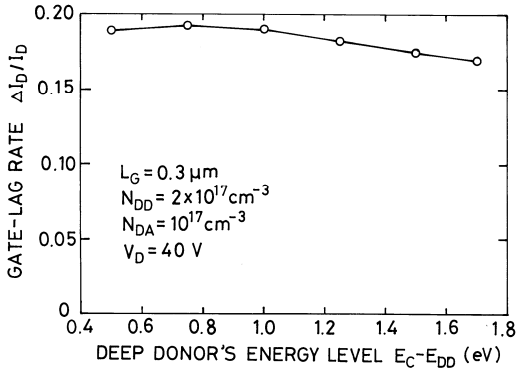

Figure 7: Gate-lag rate versus deep donor's energy level.

6 CONCLUSION

Two-dimensional transient analysis of AlGaN/GaN HEMTs has been performed in which both buffer traps and surface states are considered. It has been shown that gate lag due to buffer traps could occur because in the off state, electrons are injected into the buffer layer and captured by traps, resulting in more negatively charged buffer layer. It has also been shown that gate lag due to the electron-trap-type surface state can arise only when the electron's gate tunneling is included. The gate lag due to buffer traps becomes more pronounced when the deep-acceptor density in the buffer layer is higher.

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