

# Reduction in Lags and Current Collapse in Field-Plate AlGaIn/GaN HEMTs with High Acceptor Density in a Buffer Layer

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## ABSTRACT

We make a two-dimensional transient analysis of field-plate AlGaIn/GaN HEMTs with a semi-insulating buffer layer, where a deep acceptor above the midgap is considered. It is studied how the deep-acceptor density  $N_{DA}$  and the field plate affect buffer-related lag phenomena and current collapse.  $N_{DA}$  is varied between  $10^{17} \text{ cm}^{-3}$  and  $8 \times 10^{17} \text{ cm}^{-3}$ . It is shown that without a field plate the drain lag and current collapse increase with increasing  $N_{DA}$  as expected, although the gate lag decreases when  $N_{DA}$  becomes higher than  $2 \times 10^{17} \text{ cm}^{-3}$ . But with a field plate, surprisingly, the lags and current collapse decrease when  $N_{DA}$  becomes high. This is attributed to the fact that the reduction in drain lag and current collapse by introducing a field plate becomes more significant when  $N_{DA}$  becomes higher.

**Keywords:** GaN, HEMT, deep acceptor, current collapse, field plate

## 1 INTRODUCTION

In AlGaIn/GaN HEMTs, slow current transients are often observed when the gate voltage or the drain voltage is changed abruptly [1]. This is called gate lag or drain lag. The slow transients mean that dc  $I$ - $V$  curves and RF  $I$ - $V$  curves become quite different, resulting in lower RF power available than that expected from dc operation [2]. This is called current collapse. In switching devices, the current collapse appears as an increase in dynamic on resistance. These are serious problems, and many experimental works are reported [1-4], and several theoretical works are made [4-6]. In previous theoretical works, the semi-insulating buffer is treated as undoped, and a deep donor above the midgap is assumed to compensate a deep acceptor below the midgap [5]. Effects of a field plate on lags and current collapse are also studied [7]. By the way, recently, a Fe-doped semi-insulating buffer is often adopted, and Fe acts as a deep acceptor whose energy level is close to the conduction band [8, 9]. Therefore, in this work, we make an analysis of field-plate AlGaIn/GaN HEMTs with a Fe-doped buffer. As a result, we have found that without a field plate, the drain lag and current collapse increase with increasing the deep-acceptor density  $N_{DA}$  as expected, but with a field plate, surprisingly, the drain lags and current collapse are suppressed when  $N_{DA}$  becomes high.

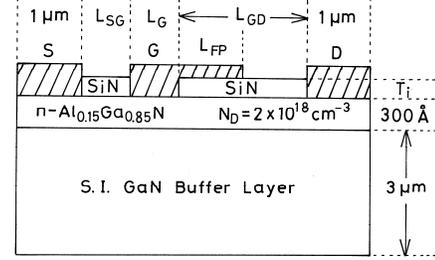


Figure 1: Device structure analyzed in this study

## 2 PHYSICAL MODEL

Figure 1 shows a modeled device structure analyzed in this study. The gate length  $L_G$  and the field-plate length  $L_{FP}$  are typically set to  $0.3 \mu\text{m}$  and  $1 \mu\text{m}$ , respectively. Polarization charges of  $10^{13} \text{ cm}^{-2}$  are set at the heterojunction interface, and the surface polarization charges are assumed to be compensated by surface-state charges, as in [5]. As a buffer layer, we consider a Fe-doped semi-insulating buffer layer. The Fe-level ( $E_{DA}$ ) is set to 0.5 eV below the bottom of conduction band, and it is considered to be a deep acceptor [8, 9]. Here the deep acceptor acts as an electron trap. The deep-acceptor density  $N_{DA}$  is varied between  $10^{17}$  and  $8 \times 10^{17} \text{ cm}^{-3}$ .

Basic equations to be solved are Poisson's equation including an ionized deep-acceptor term, continuity equations for electrons and holes which include carrier loss rates via the deep acceptor and a rate equation for the deep acceptor [10, 11]. These are expressed as follows.

- 1) Poisson's equation

$$\nabla \cdot (\epsilon \nabla \psi) = -q(p - n + N_D - N_{DA}^-) \quad (1)$$

- 2) Continuity equations for electrons and holes

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_n - R_{n,DA} \quad (2)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot \mathbf{J}_p - R_{p,DA} \quad (3)$$

where

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

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

- 3) Rate equation for the deep acceptor

$$\frac{\partial}{\partial t} N_{DA}^- = R_{n,DA} - R_{p,DA} \quad (6)$$

where  $N_{DA}^-$  represents the ionized deep-acceptor density.  $C_{n,DA}$  and  $C_{p,DA}$  are the electron and hole capture coefficients of the deep acceptor, respectively,  $e_{n,DA}$  and  $e_{p,DA}$  are the electron and hole emission rates of the deep acceptor, respectively. These are given as functions of the deep acceptor's energy level and the capture cross sections. The above basic equations are put into discrete forms and are solved numerically.

### 3 DRAIN LAG

Figures 2 and 3 show calculated drain-current responses of AlGaIn/GaN HEMTs with  $N_{DA} = 10^{17} \text{ cm}^{-3}$  and  $8 \times 10^{17} \text{ cm}^{-3}$ , respectively when  $V_D$  is lowered abruptly from 40 V to  $V_{Dfin}$ , where  $V_G$  is kept constant at 0 V. Figures 2(a) and 3(a) show the case without a field plate ( $L_{FP} = 0$ ) and Figs.2(b) and 3(b) show the case with a field plate ( $L_{FP} = 1 \mu\text{m}$ ). Here the thickness of SiN passivation layer  $T_i$  is 0.03  $\mu\text{m}$ . In both cases with and without a field plate, the drain currents remain at low values for some periods and begin to increase slowly, showing drain-lag behavior. It is understood that the drain currents begin to increase when the deep acceptors in the buffer layer begin to emit electrons, because the state of higher  $V_D$  is a state where more electrons are captured by the deep acceptors and the buffer is more negatively charged. It is seen that the change of drain current is smaller for the case with a field plate, indicating that the drain lag is smaller for the field-plate structure. Comparing Fig.2 and Fig.3, the reduction in drain lag by introducing a field plate seems to be more remarkable for higher  $N_{DA}$ , but this point will be described later in section 5. We discuss below why the reduction in drain lag by introducing a field plate arises.

Figure 4 shows (a) electron density profiles and (b) ionized deep-acceptor density  $N_{DA}^-$  profiles at  $V_G = 0 \text{ V}$  and  $V_D = 40 \text{ V}$  when  $N_{DA} = 8 \times 10^{17} \text{ cm}^{-3}$ . The left shows the case without a field plate, and the right shows the case of field-plate structure. In Fig.4(a), it is seen that without a field plate, electrons are injected deeper into the buffer layer under the gate. These electrons are captured by the deep acceptors, and hence  $N_{DA}^-$  increases in the deeper region of buffer layer as seen in Fig.4(b). In the case of field-plate structure, as seen in Fig.4(a), electron injection under the gate is weaker. This is because the electric field at the drain edge of the gate is weakened by introducing a field plate. But electrons are also injected into the buffer layer under the field plate. However, the injection depth is not so deep as compared to the case without a field plate. Hence, the change of  $N_{DA}^-$  by capturing electrons is smaller for the field-plate structure as seen in Fig.4(b). Therefore, the drain lag becomes smaller for the structure with a field plate.

### 4 CURRENT COLLAPSE

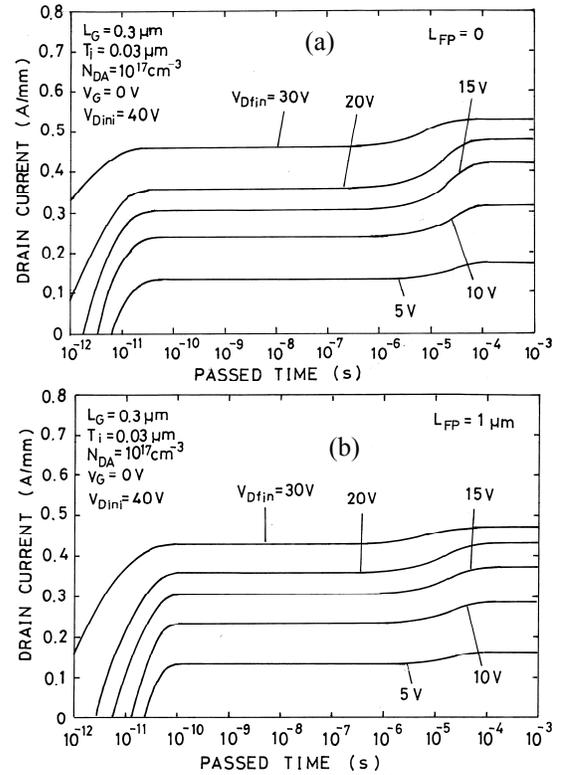


Figure 2: Calculated drain-current responses of AlGaIn/GaN HEMTs when  $V_D$  is changed abruptly from 40 V to  $V_{Dfin}$ , while  $V_G$  is kept constant at 0 V.  $N_{DA} = 10^{17} \text{ cm}^{-3}$  (a) Without field plate, (b) with field plate.

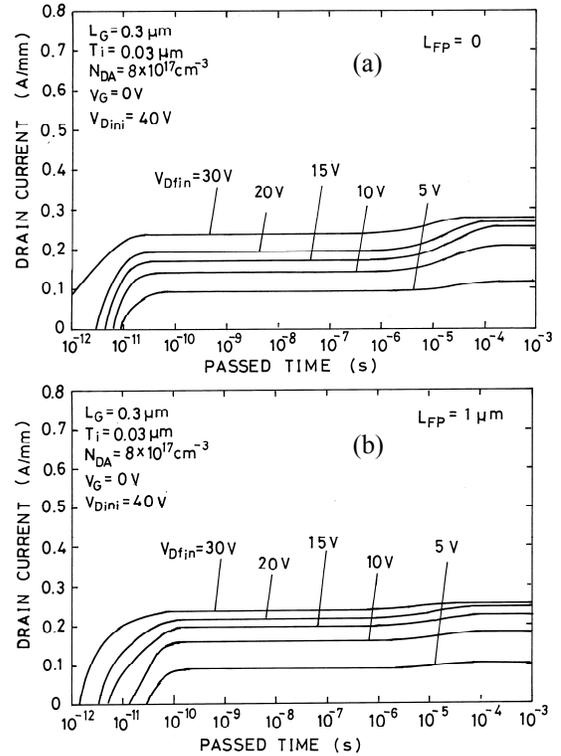


Figure 3: Calculated drain-current responses when  $N_{DA} = 8 \times 10^{17} \text{ cm}^{-3}$ . The rest is the same as in Fig.2. (a) Without field plate, (b) with field plate.

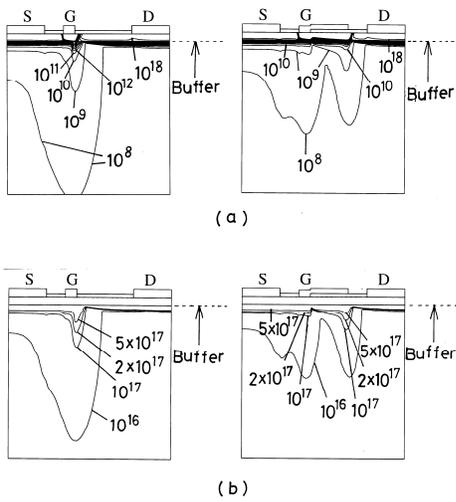


Figure 4: (a) Electron density profiles and (b) ionized deep-acceptor density  $N_{DA}^-$  profiles at  $V_G = 0$  V and  $V_D = 40$  V.  $T_i = 0.03$   $\mu$ m.  $N_{DA} = 8 \times 10^{17}$  cm $^{-3}$ . The left is for the case without field plate, and the right is for the field-plate structure ( $L_{FP} = 1$   $\mu$ m).

Next, we have calculated a case when  $V_G$  is also changed from an off point.  $V_G$  is changed from threshold voltage  $V_{th}$  to 0 V, and  $V_D$  is changed from 40 V to  $V_{Don}$  (on-state drain voltage). The characteristics become similar to those in Figs.2 and 3, although some transients arise when only  $V_G$  is changed (gate lag). From these turn-on characteristics, we obtain quasi-pulsed  $I$ - $V$  curves. In Fig.5, we plot by (x) the drain current at  $t = 10^{-8}$  s after  $V_G$  is switched on. Here,  $N_{DA} = 8 \times 10^{17}$  cm $^{-3}$ . Figure 5(a) shows the case without a field plate, and Fig.5(b) shows the case of field-plate structure ( $L_{FP} = 1$   $\mu$ m). These curves are regarded as quasi-pulsed  $I$ - $V$  curves with pulse width of  $10^{-8}$  s. They stay rather lower than the steady-state  $I$ - $V$  curves (solid lines), indicating gate lag and current collapse behavior. Note that the gate lag is rather large [5]. In Fig.5, we also plot another pulsed  $I$ - $V$  curve ( $\circ$ ), which is obtained from Fig.3 where only  $V_D$  is changed, indicating drain-lag behavior. From Fig.5, we can definitely say that the lag phenomena (drain lag, gate lag) and current collapse become smaller for the structure with a field plate.

## 5 DEPENDENCE ON DEEP-ACCEPTOR DENSITY AND FIELD-PLATE LENGTH

We have next studied dependence of lag phenomena and current collapse on the field-plate length  $L_{FP}$  and the deep-acceptor density  $N_{DA}$ . Figure 6 shows the current reduction rate  $\Delta I_p/I_D$  due to (a) drain lag, (b) gate lag and (c) current collapse as a function of the deep acceptor density  $N_{DA}$ , with the field-plate length  $L_{FP}$  as a parameter. It is seen that without a field plate ( $L_{FP} = 0$ ), the drain lag and current collapse increase as  $N_{DA}$  increases, because the trapping effects should more significant when the deep-acceptor density is higher (the deep acceptors acts as

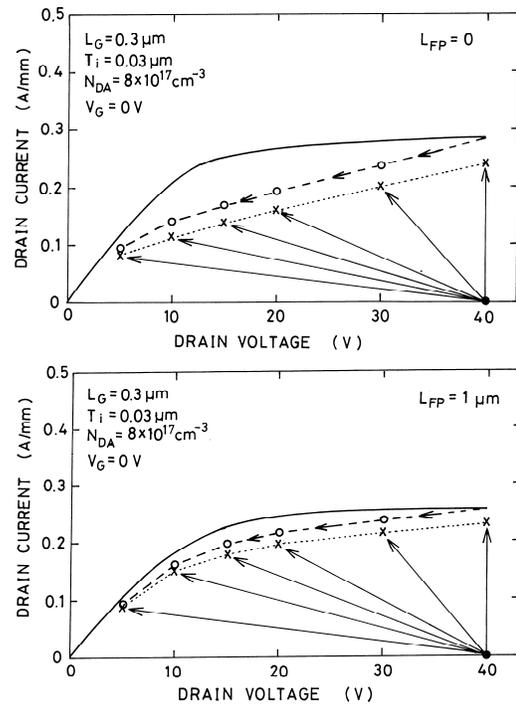


Figure 5: Steady-state  $I$ - $V$  curves ( $V_G = 0$  V; solid lines) and quasi-pulsed  $I$ - $V$  curves (x,  $\circ$ ) of AlGaIn/GaN HEMTs.  $N_{DA} = 8 \times 10^{17}$  cm $^{-3}$ . (a) Without field plate, (b) with 1  $\mu$ m-length field plate. ( $\circ$ ): Only  $V_D$  is changed from 40V, ( $\times$ ):  $V_D$  is lowered from 40 V and  $V_G$  is changed from  $V_{th}$  to 0 V.

electron traps). It is also seen that at a given  $N_{DA}$ , when  $L_{FP}$  becomes long, the lags and current collapse decrease. This is because by introducing a longer field plate, the electric field at the drain edge of the gate is more reduced, and hence electron injection into the buffer layer under the gate is more weakened, leading to less trapping effects as mentioned in section 3. This tendency is more pronounced when  $N_{DA}$  becomes higher, indicating that the field-plate effects are stronger for higher  $N_{DA}$ . Finally, it is clearly seen that with a field plate ( $L_{FP} > 0$ ), the drain lag and current collapse decrease as  $N_{DA}$  increases, suggesting that the trapping effects are smaller for higher  $N_{DA}$  in the field-plate structures. This is a surprising result, because the deep acceptor should act as traps. The reason is now not necessarily clear. But, it is considered that when  $N_{DA}$  is higher, the barrier at the channel- buffer interface become steeper, and electrons are not diffused so deep into the buffer layer. Thus, the effects of field plate set on the device surface to reduce the drain lag and current collapse should become stronger when  $N_{DA}$  is higher. Anyway, this result is attributed to the fact that the reduction in drain lag and current collapse by introducing a field plate becomes more significant when  $N_{DA}$  becomes higher.

## 6 CONCLUSION

A two-dimensional transient analysis of field-plate AlGaIn/

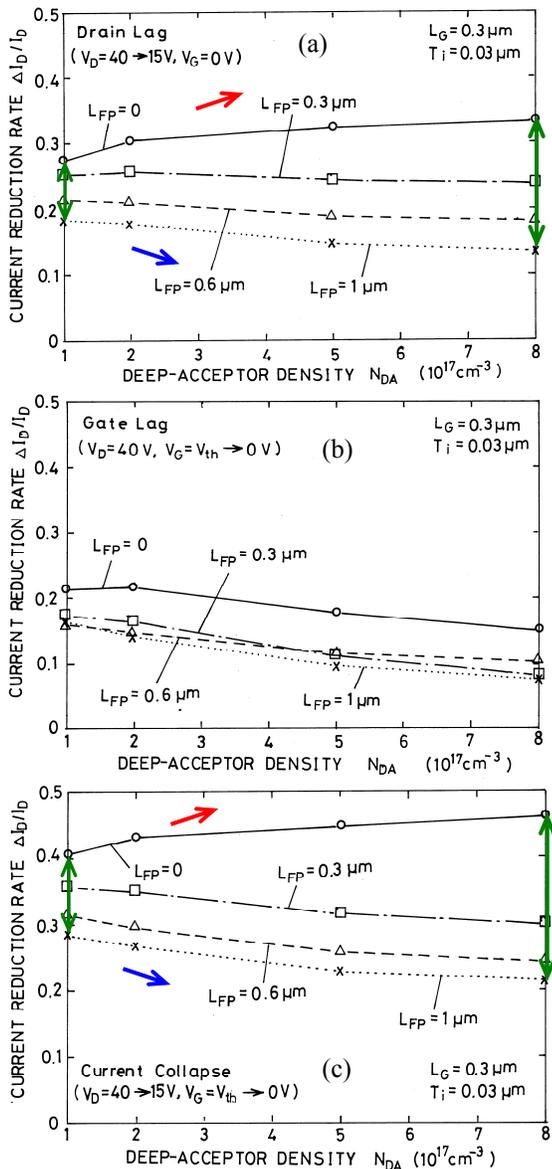


Figure 6: Current reduction rate  $\Delta I_D/I_D$  due to (a) drain lag, (b) gate lag and (c) current collapse as a function of the deep acceptor density  $N_{DA}$ , with the field-plate length  $L_{FP}$  as a parameter.  $T_i = 0.03 \mu\text{m}$ .

GaN HEMTs with a semi-insulating buffer layer has been performed where relatively high densities ( $1 \sim 8 \times 10^{17} \text{ cm}^{-3}$ ) of deep acceptor above the midgap are considered. It has been shown that the drain lag, gate lag and current collapse are reduced by introducing a field plate. This reduction occurs because electron trapping by the deep acceptors in the buffer layer is weakened by the field plate. It has also been shown that without a field plate, the drain lag and current collapse increase with increasing the deep-acceptor density as expected, although the gate lag decreases when the deep-acceptor density becomes higher than  $2 \times 10^{17} \text{ cm}^{-3}$ . On the other hand, with a field plate, surprisingly, the lags

and current collapse decrease when the deep-acceptor density becomes high. This is attributed to the fact that the reduction in drain lag and current collapse by introducing a field plate becomes more pronounced when the deep-acceptor density becomes higher. In other words, this may be explained that when the deep-acceptor density is higher, electrons are not so diffused into the buffer due to the steeper barrier, and hence the effects of field-plate set on the device surface should become stronger.

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