Deep-Donor-Induced Suppression of Current Collapse in an AlGaN-GaN Heterojunction Structure Grown on Si

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SUMMARY TCAD simulation was performed to investigate the material properties of an AlGaN/GaN structure in Deep Acceptor (DA)-rich and Deep Donor (DD)-rich GaN cases. DD-rich semi-insulating GaN generated a positively charged area thereof to prevent the electron concentration in 2DEG from decreasing, while a DA-rich counterpart caused electron depletion, which was the origin of the current collapse in AlGaN/GaN HFETs. These simulation results were well verified experimentally using three nitride samples including buffer-GaN layers with carbon concentration ([C]) of $5 \times 10^{17}$, $5 \times 10^{18}$, and $4 \times 10^{19}$ cm$^{-3}$. DD-rich behaviors were observed for the sample with $[C] = 4 \times 10^{19}$ cm$^{-3}$, and DD energy level $E_{DD}$ of 0.6 eV was estimated by the Arrhenius plot of temperature-dependent $I_D$. This $E_{DD}$ value coincided with the previously estimated $E_{DD}$. The backgate experiments revealed that these DD-rich semi-insulating GaN suppressed both current collapse and buffer leakage, thus providing characteristics desirable for practical usage.

key words: AlGaN/GaN HFETs, deep donor, deep acceptor, GaN, semi-insulating

1. Introduction

The AlGaN/GaN heterojunction field-effect-transistor (HFET) has attracted particular research and industrial attention as a high-power and high-frequency switching device [1]. This trend arises from the unique material property of GaN in that two-dimensional electron gas (2DEG) with high electron mobility is generated by dielectric polarization of GaN in that two-dimensional electron gas (2DEG) with the reference also provided its energy level ($E_{DA}$) of above the mid-bandgap [5], rendering GaN semi-insulating, and the anergy level of the DA ($E_{DA}$) is possibly 0.9 eV above the valence band maximum edge ($E_V$) [6]. Possibly owing to the DA-originated semi-insulating GaN, some references reported that the introduction of highly doped GaN:C buffer layers in HFET devices reduce the leakage current through GaN layers under 2DEG (buffer leakage) [7] and suppress the punch-through effect in short channels [8].

GaN including DA centers is electrically neutral under a zero external electric bias; however, non-zero external biases defy this charge neutrality. The DA captures externally injected electrons by the biases, resulting in a negatively charged film. This charge-state transition with its large time constant owing to a large $E_D$ yields the so-called current collapse, which is a chronic problem in AlGaN/GaN HFETs [9]. Therefore, this problem must be resolved for not only improving device performance but also for assuring reliability [10].

Researchers have investigated the origin of defects in GaN. Uedono et al. reported that the gallium vacancy ($V_Ga$) coupled with multiple nitrogen vacancies ($V_N n$), where n is the number of nitrogen vacancy, $V_N$, denoted as $V_Ga(V_N n)$, could be the primary defect in GaN:C grown on (111) Si with the C concentration ([C]) ranging from $2 \times 10^{16}$ to $9 \times 10^{19}$ cm$^{-3}$ [11]. This defect can act as deep donor (DD), and the reference also provided its energy level ($E_{DD}$) candidates to be approximately 0.2, 0.7, and 1.6 eV below the conduction band minimum edge ($E_C$). Others reported $E_D$ of above the mid-bandgap ranging from 0.5 to 0.7 eV below the $E_C$ [12]–[16]. As such, some reports discussed DDs in GaN, but few have discussed how DDs and large DD concentrations ($N_{DD}$) affect the material properties of highly doped GaN:C.

In this study, we investigate how DDs and DAs in C-doped GaN change the transient conductivity of 2DEG in an AlGaN/GaN heterostructure grown on a Si substrate (AlGaN/GaN) when an external electric field is applied to the structure. First, technology computer-aided design, TCAD (Synopsys Inc.), was used for this research. The AlGaN/GaN structure in TCAD includes a DA-rich or DD-rich GaN, in which the doping situations are created by the doping setup of $N_{DA} > N_{DD} + N_D$ for the former, and...
$N_{DD} + N_D > N_{DA}$ for the latter. The band diagram of the AlGaN/GaN and the transient conductivity of the 2DEG are simulated when the nitride body is negatively biased at the AlGaN, a situation called “backgated” herein. Next, these simulation results are verified experimentally using the structure that reproduces the simulation. Finally, the paper concludes the role of the DA and DD in C-doped GaN.

2. Simulations and Experiments

The AlGaN/GaN structure for TCAD simulation, as shown in Fig. 1, comprises a 10-nm (Al$_{0.3}$Ga$_{0.7}$)N grown on a GaN layer to generate 2DEG at the AlGaN/GaN interface, and a SiN film on top of the AlGaN. The DA-rich model includes $N_D = 1 \times 10^{16}$, $N_{DD} = 5 \times 10^{16}$, and $N_{DA} = 1 \times 10^{17}$ cm$^{-3}$, while the DD-rich model incorporates $N_D = 1 \times 10^{16}$, $N_{DD} = 1.5 \times 10^{17}$, and $N_{DA} = 1 \times 10^{17}$ cm$^{-3}$. These doping conditions generate the schematic zero-biased band diagrams of the GaN, as shown in Fig. 2. In DA-rich GaN, $N_{DA}$ can capture all electrons generated by $N_D$ and $N_{DD}$; electrons except for the electrons captured by $N_{DA}$ must remain in $N_{DD}$ for this DD-rich doping. At any rate, mobile electrons do not exist in the GaN; therefore, $E_F$ is pinned to $E_{DA}$ or $E_{DD}$. No trap state at the AlGaN-SiN interface is introduced for clarifying the role of DAs and DDs. $E_{DA}$ and $E_{DD}$ are adopted to be $E_F + 0.9$ eV, and $E_C - 0.7$ eV, respectively.[6], [11]. An electron and hole capture cross section of $1 \times 10^{-15}$ cm$^2$ was applied in both models[17]–[19].

As shown in Fig. 1, the two Ohmic contacts were formed on the AlGaN, denoting “source” and “drain,” and the Schottky contact, as a substitute of the electrical behavior between GaN and Si, was placed on the backside of the GaN layer, denoting “backgate.” A negative bias applied to the backgate (negative backgating) changed the 2DEG conductivity[5]. The source is always the grounding electrode. The direct-current (DC) voltage from the drain to source ($V_{DS}$) and $V_{GS}$, and that at the backgate are 1 V and −10 V, respectively.

Figures 3 (a) and (c) depict how the $E_C$ profile of the GaN transitions with respect to $E_F = 0$ for the DA-rich and DD-rich cases, respectively. Figures 3 (b) and (d) show the drain-to-source current ($I_{DS}$) normalized by the $I_{DS}$ at $V_{DS} = 1$ V and $V_{GS} = 0$ V ($I_{DS}$norm) as a function of time ($t$), corresponding to the situation of Fig. (a) and (c), respectively. $t = 0$ is defined as the time when a −10 V of $V_{GS}$ is applied.

In the DA-rich model, a negative $V_{GS}$ creates a negatively charged GaN to reduce $I_{DS}$, as shown in Fig. 3 (b), because its consequent hole-emission from DA transforms the charge state of DA from neutral to negative, denoted as $0 \rightarrow -$ in the inserted band diagram of Fig. 3 (a). As shown by the red line in Fig. 3 (a), this negatively charged state remains even at $t = 5000$ s, because the DA requires a longer time to recover from the negative charged state owing to the deep $E_{DA}$. This is the origin of the current collapse typically observed in AlGaN/GaN-HFETs[9].
However, this transient behavior does not appear in the DD-rich model, because a negative $V_{GS}$ consequently stimulates electron emission from DDs, the charge state of which transforms from neutral to positive, denoted as $0 \rightarrow +$ in the inserted band diagram of Fig. 3 (c). This positive charge accumulating near the backgate weakens the electric field strength beneath the 2DEG ($E_{2DEG}$). This is directly signified by the plateau region of the red line in Fig. 3 (c). Since $E_{2DEG}$ decrease to the value of $V_{SG} = 0V$, the $I_{DS}^{norm}$ increases to approximately 1 as shown in Fig. 3 (d). This simulation result implies that DD-rich semi-insulating GaN layers are potentially capable of suppressing current collapse.

Three experimental nitride-film samples were prepared to verify the abovementioned simulation results. The samples are of the same nitride structure comprising 10-nm Al$_{0.3}$Ga$_{0.7}$N, 0.3-μm GaN as the channel layer, 0.7-μm GaN buffer, 0.2-μm Al$_{0.3}$Ga$_{0.7}$N, and 0.2-μm AlN epitaxially grown in this order on a low-resistive (1 - 4 mΩ-cm) $p$-type Si (111) substrate. All these films are grown by the metal-organic chemical vapor deposition method; therefore, the Si substrate itself was used as the backgate electrode. The Si substrate itself was of the same nitride structure comprising 10-nm Al$_{0.3}$Ga$_{0.7}$N, 0.3-μm GaN as the channel layer, 0.7-μm GaN buffer, 0.2-μm Al$_{0.3}$Ga$_{0.7}$N, and 0.2-μm AlN epitaxially grown in this order on a low-resistive (1 - 4 mΩ-cm) $p$-type Si (111) substrate. All these films are grown by the metal-organic chemical vapor deposition method; therefore, the Si substrate itself was used as the backgate electrode.

To adapt $[C]$ in the GaN buffer layers, $R_{III/V}$ of 2300 and $T_g$ of 1070 °C, $R_{III/V}$ of 2300 and $T_g$ of 1010 °C, $R_{III/V}$ of 650 and $T_g$ of 1010 °C were used for samples A, B, and C, respectively; $P_g$ is constant at 13 kPa for all samples. These growth conditions provide samples A, B, and C with $[C] = 5 \times 10^{17}, 5 \times 10^{18},$ and $4 \times 10^{19}$ cm$^{-3}$, respectively. An electron-beam evaporator was used to form the source and drain electrodes consisting of 200-μm wide Ti followed by Al on top of the Al$_{0.3}$Ga$_{0.7}$N layers. The electrodes were annealed at 530 °C to achieve ohmic-contact. The gap length was 15 μm between the electrodes. SiN films passivate the exposed surface of the Al$_{0.3}$Ga$_{0.7}$N between the source and drain, as shown in Fig. 1. The Si substrate itself was used as the backgate electrode.

Figure 4 shows the experimental transient waveforms of $I_{DS}^{norm}$. The same bias conditions as used in the simulation were selected. The $I_{DS}^{norm}$ transient curves of samples A and B behave similarly as numerically predicted for a DA-rich model, whereas sample C clearly shows a monotonic increase as the simulation predicts a similar $I_{DS}$ behavior for a DD-rich model.

Therefore, these experimental results indicate that the prepared GaN films transition from DA-rich to DD-rich at a certain $[C]$ between $5 \times 10^{17}$ cm$^{-3}$ and $4 \times 10^{19}$ cm$^{-3}$. $C_N$ is generally regarded as a DA [6]; therefore, it is reasonable to regard GaN/C as a DA-rich film. Simultaneously, as reported in Ref. [11], a large $[C]$ induces the generation of $V_{Ga(N)h}$ acting as a DD. M. J. Uren et al. has reported that external hole injection from 2DEG region with negative backgate bias also decrease $E_{2DEG}$. Due to non-ohmic hole conduction, in this phenomenon, $E_{2DEG}$ of > 10 MV/m is applied at least [5]. Since $I_{DS}^{norm}$ of sample C increased to approximately 1, this transition does not originate from external hole injection.

To verify this presumption that sample C includes a DD, we measured the temperature-dependent $I_{DS}$ of sample C. Here, we assume that $I_{DS}$ per width ($i_{DS}$) follows the function $i_{DS}(t) = A \exp(-t/\tau) + I_0 - A$ [20], [21]. $\tau$ is a scaling time-constant that is estimated by fitting the measured $I_{DS}$ curves to this equation. $I_0$ is $I_{DS}$ at $t = 0$ when $V_{DS}$ and $V_{GS}$ are applied, and $A$ is the constant amplitude ($A > 0$). Figure 5 includes the measured temperature-dependent $i_{DS}$ curve under the same bias condition as used in Fig. 4, and the Arrhenius plot of ln ($\tau T^2$), the slope of which provides the energy level of a deep center affecting $i_{DS}$ behaviors [22]. The Arrhenius plot exhibits an excellent linear correlation, and its slope is estimated to be 0.6 eV below the $E_C$. This implies that this deep level is a DD. In addition, this estimated $E_{DD}$ value matches well with that as previously reported [11]–[16]. Therefore, we can conclude that the GaN in sample C is DD-rich.

Figure 6 shows how the change in resistance between the source and drain ($R_{DS}$) is associated with the backgate bias. $V_{GS}$ ramps up to -70 V with a -10 V step, and the applied bias maintains for 1000 s at each and every step. At the end, $I_{DS}$ is measured under $V_{GS} = 0V$ and $V_{DS} = 1V$, and $R_{DS}$ is obtained by $I_{DS}$ being divided by $V_{DS}$. Samples

![Fig. 4](image)

\textbf{Fig. 4} $I_{DS}^{norm}$ transition of various [C] samples

![Fig. 5](image)

\textbf{Fig. 5} (a) The time-transient waveforms of $i_{DS}$ of sample C at various ambient temperatures ($T$), (b) Arrhenius plot of ln ($\tau T^2$)
A and B show the \( R_{DS} \) increment, while the \( R_{DS} \) boost is suppressed significantly in sample C. This can be understood if the GaN in sample C is DD-rich because, as mentioned above, DD-rich GaN is positively charged under negatively backgated conditions. This can be another proof for some GaN:C including DDs.

Reference [23] reports that highly C-doped Al\(_{0.1}\)Ga\(_{0.9}\)N buffers reduce vertical leakage current. As discussed above, a high C doping changes the deep-level states in GaN, and we investigated the vertical leakage of our samples. Figure 7 shows the vertical leakage flowing through the unit area from the backgate to source with a positive \( V_{GS} \) being applied. Note that vertical leakage with negative and positive \( V_{GS} \) are limited by AlN/Si barrier and electron trapping effect of GaN buffer layer, respectively [24], [25]. Thus, positive \( V_{GS} \) were chosen to evaluate each semi-insulating GaN layers. As reported in Ref. [23], a denser \([C]\) in GaN films improves the leakage current. These experimental facts indicate that DD-rich semi-insulating GaN is preferable for AlGaN/GaN-HFETs, because such GaN can prevent both current collapse and buffer leakage.

3. Conclusions

TCAD simulation was performed to investigate the material properties of an AlGaN/GaN structure in DA-rich and DD-rich GaN cases. DD-rich semi-insulating GaN generated a positively charged area thereof to prevent the electron concentration in 2DEG from decreasing, while a DA-rich counterpart caused electron depletion, which was the origin of the current collapse in AlGaN/GaN HFETs. These simulation results were well verified experimentally using three nitride samples including buffer-GaN layers with \([C]\) of \(5 \times 10^{17}, 5 \times 10^{18},\) and \(4 \times 10^{19}\) cm\(^{-3}\). DD-rich behaviors were observed for the sample with \([C]\) = \(4 \times 10^{19}\) cm\(^{-3}\), and \(E_{DD} = 0.6\) eV was estimated by the Arrhenius plot of temperature-dependent \(I_{DS}\). This \(E_{DD}\) value coincided with the previously estimated \(E_{DD}\). The backgate experiments revealed that these DD-rich semi-insulating GaN suppressed both current collapse and buffer leakage, thus providing characteristics desirable for practical usage.

References


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