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PAPER

# 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 $5\times10^{17}$, $5\times10^{18}$, and $4\times10^{19}$ cm$^{-3}$. DD-rich behaviors were observed for the sample with [C] $= 4\times10^{19}$ cm$^{-3}$, and DD energy level $E_{\mathrm{DD}} = 0.6$ eV was estimated by the Arrhenius plot of temperature-dependent $I_{\mathrm{DS}}$. This $E_{\mathrm{DD}}$ value coincided with the previously estimated $E_{\mathrm{DD}}$. 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 mismatch at AlGaN/GaN interfaces [2].

The 2DEG in AlGaN/GaN HFETs acts as the channel layer thereof, and many HFET devices typically include a relatively thick GaN layer beneath the 2DEG [2]. This GaN layer must be highly resistive to achieve a low parasitic capacitance and low leakage current during the off state of a HFET. However, intentionally undoped GaN epitaxial films do not exhibit high resistivity in many cases, because the epi layers unavoidably incorporate impurities and defects such as Si, O, and nitrogen vacancies, acting as shallow donor [3], [4]. For these nitride films to achieve substantial insulation, deep acceptor (DA) doping is critical to compensate for the shallow donors. Additionally, its doping concentration ($N_{\mathrm{DA}}$) must surpass the shallow-donor concentration ($N_{\mathrm{D}}$).

A possible DA candidate in GaN is carbon (C) occupying the nitrogen-site ($\mathrm{C_N}$) [5], [6]. The Fermi level ($E_{\mathrm{F}}$) of C-doped GaN films (GaN:C) is reportedly pinned below the mid-bandgap [5], rendering GaN semi-insulating, and the aenergy level of the DA ($E_{\mathrm{DA}}$) is possibly 0.9 eV above the valence band maximum edge ($E_{\mathrm{V}}$) [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 $E_{\mathrm{DA}}$ 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 ($V_{\mathrm{Ga}}$) coupled with multiple nitrogen vacancies ($(V_{\mathrm{N}})_{\mathrm{n}}$, where n is the number of nitrogen vacancy, $V_{\mathrm{N}}$), denoted as $V_{\mathrm{Ga}}(V_{\mathrm{N}})_{\mathrm{n}}$, could be the primary defect in GaN:C grown on (111) Si with the C concentration ([C]) ranging from $2\times10^{16}$ to $9\times10^{19}$ cm$^{-3}$ [11]. This defect can act as deep donor (DD), and the reference also provided its energy level ($E_{\mathrm{DD}}$) candidates to be approximately 0.2, 0.7, and 1.6 eV below the conduction band minimum edge ($E_{\mathrm{C}}$). Others reported $E_{\mathrm{DD}}$ of above the mid-bandgap ranging from 0.5 to 0.7 eV below the $E_{\mathrm{C}}$ [12]–[16]. As such, some reports discussed DDs in GaN, but few have discussed how DDs and large DD concentrations ($N_{\mathrm{DD}}$) 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 filed 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 $N_{\mathrm{DA}} > N_{\mathrm{DD}} + N_{\mathrm{D}}$ for the former, and

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$N_{DD} + N_D > N_{DA}$ 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 $E_V + 0.9$ 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].

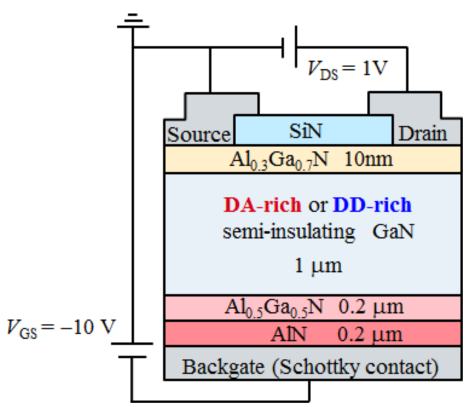


**Fig. 1** Back-Gated HFET for the simulation.

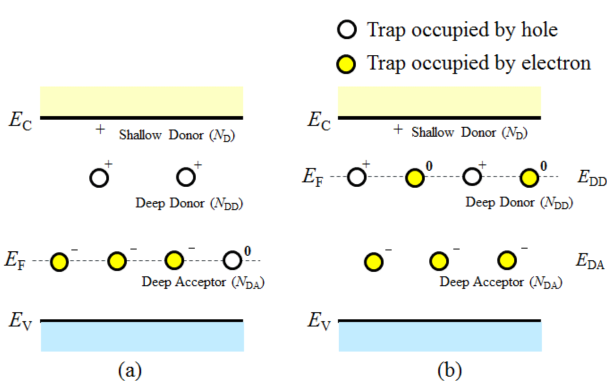


**Fig. 2** Simulation models for GaN layer (a) DA-rich GaN, (b) DD-rich GaN.

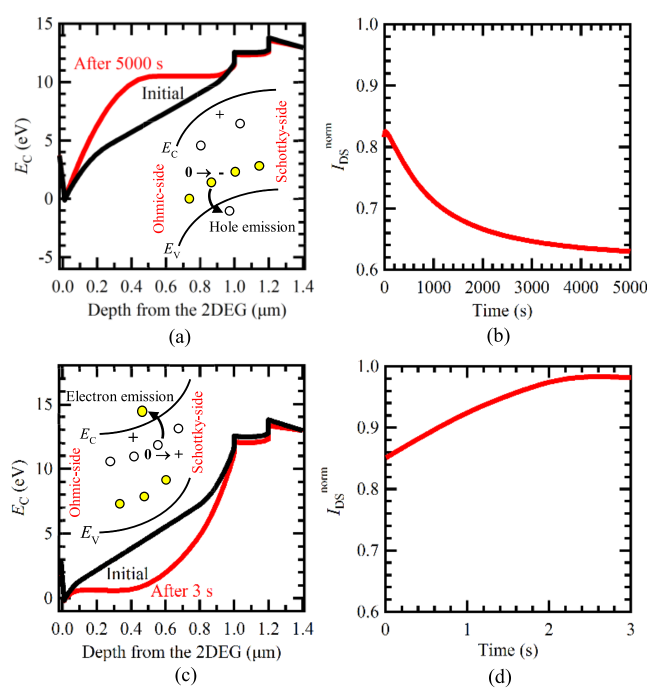


**Fig. 3** (a) $E_C$ profile (b) simulated $I_{DS}{}^{norm}$ transition in DA-rich model, and (c) $E_C$ profile (d) simulated $I_{DS}{}^{norm}$ transition in DD-rich model

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 at $V_{SG}$ = 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-$\mu$m GaN as the channel layer, 0.7-$\mu$m GaN buffer, 0.2-$\mu$m $Al_{0.5}Ga_{0.5}N$, and 0.2-$\mu$m 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 GaN layers unintentionally incorporate C. A growth pressure ($P_g$) of 85 kPa, a III/V molar ratio ($R_{III/V}$) of 2300, and a growth temperature ($T_g$) of 1130 °C were used for the channel GaN layer with [C] = $2 \times 10^{16}$ cm$^{-3}$. [C] is determined by secondary-ion mass spectroscopy.

The only difference among the three samples is [C] in their GaN buffers. To adapt [C] in the GaN buffer layers, $R_{III/V}$ = 2300 and $T_g$ = 1070 °C, $R_{III/V}$ = 2300 and $T_g$ = 1010 °C, $R_{III/V}$ = 650 and $T_g$ = 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-$\mu$m wide Ti followed by Al on top of the $Al_{0.3}Ga_{0.7}N$ layers. The electrodes was annealed at 530 °C to achieve ohmic-contact. The gap length was 15 $\mu$m 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 $V_{Ga}(V_N)_n$ 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 $V_{GS}$ = 0 V and $V_{DS}$ = 1 V, and $R_{DS}$ is obtained by $I_{DS}$ being divided by $V_{DS}$. Samples

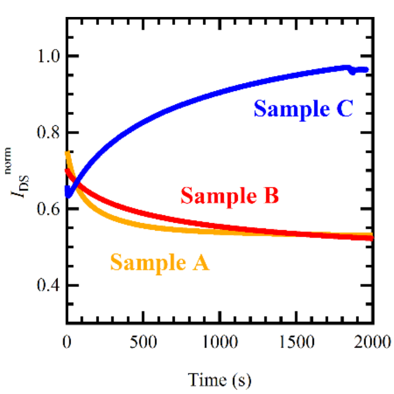


**Fig. 4** $I_{DS}^{norm}$ transition of various [C] samples

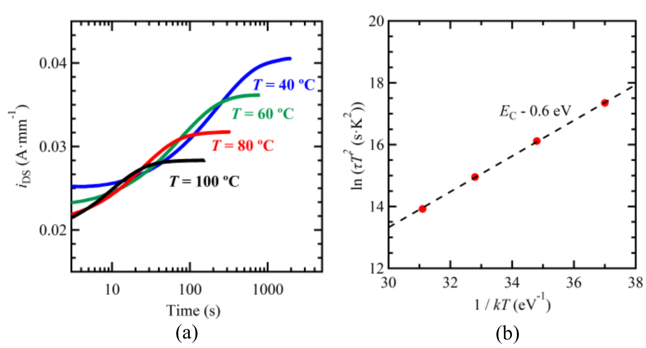


**Fig. 5** (a) The time-transient waveforms of $i_{DS}$ of sample C at various ambient temperatures ($T$), (b) Arrhenius plot of ln ($\tau T^2$)

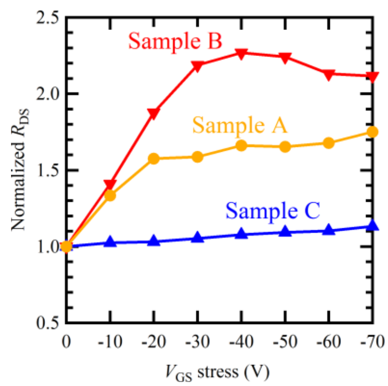


**Fig. 6** $V_{GS}$ induced Current collapse. $R_{DS}$ is normalized by initial $R_{DS}$

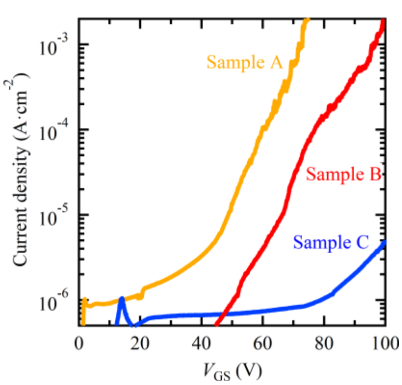


**Fig. 7** Vertical leakage with positive $V_{GS}$. The current density is the source current divided by the source contact area.

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 $V_{GS}$ ware 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.

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