Received 5 June 2018; revised 18 July 2018, 23 August 2018, and 19 September 2018; accepted 22 September 2018. Date of publication 1 October 2018; date of current version 12 October 2018. The review of this paper was arranged by Editor K. Shenai.

Digital Object Identifier 10.1109/JEDS.2018.2872975

High Figure-of-Merit (V_{BR}^2/R_{ON}) AlGaN/GaN Power HEMT With Periodically C-Doped GaN Buffer and AlGaN Back Barrier

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This work was supported in part by the Civil-Military Technology Cooperation Program under Grant 17-CM-MA-03, and in part by the Program of Defense Acquisition Program Administration and Agency for Defense Development, and in part by the 2214-A Coded International Doctoral Research Fellowship Programme from the Scientific and Technological Research Council of Turkey (TUBITAK).

ABSTRACT In this paper, we investigated characteristics of AlGaN/GaN high-electron mobility transistors (HEMTs) with high resistive buffer structure consisted of periodically carbon-doped (PCD) GaN buffer layer and AlGaN back barrier layer. The PCD structure was proposed for reducing undesirable trapping effects, which resulted in effective suppression of the current collapse compared to that in conventional carbon buffer structure. To further improve the dynamic performances of the device and to increase the electron confinement of the 2-D electron gas (2-DEG) channel, AlGaN back barrier was inserted between the GaN channel and the PCD buffer layer, which results in greatly improved current collapse with slightly improved 2-DEG mobility compared to those of the device without back barrier. The OFF-state leakage current of the device with back-barrier is about 2 orders lower in magnitude than that of device without back barrier, which leads to the breakdown voltage of 2 kV and figure of merit of 2.27 $GV^2\Omega^{-1}cm^{-2}$ for the device with L_{GD} of 10 μm, one of the highest values ever reported for the GaN-based HEMTs.

INDEX TERMS AlGaN/GaN, HEMT, periodically carbon-doped GaN, PCD, breakdown voltage, current collapse, MOCVD, low leakage current.

I. INTRODUCTION

AlGaN/GaN-based high-electron mobility transistors (HEMTs) are attractive for high power electronics applications due to superior material properties of the III-nitride semiconductors such as large energy bandgap, high breakdown electrical field, and high saturation velocity [1]. In addition, high-resistivity (HR) buffer layer is required to fully utilize the material advantages of the HEMTs [2]–[5]. The unintentionally doped (UID) GaN buffer layer has an insufficient resistivity due to inevitably introduced background n-type dopants, such as nitrogen vacancy and oxygen impurity, which can induce parasitic leakage paths increasing the OFF-state leakage current. The HR or semi-insulating (S.I.) GaN buffer layers can be achieved by introducing acceptors-like defects or dislocations and doping of deep acceptor impurities (such as Fe or C atoms), which compensates the background donors [2]–[5]. These approaches to obtain the S.I. buffer layer, however, occasionally suffer from a severe current collapse due to undesirable trapping effects related to the deep acceptors [6]–[10]. In our previous work [6], the novel periodically carbon-doped (PCD) GaN buffer structure was proposed instead of conventional thick carbon-doped GaN (C-GaN) buffer structure in order to suppress the undesirable trapping effects related to the deep acceptors. The PCD buffer layer consisted of periodically repeated structure of

6 nm-thick carbon doped GaN (C-GaN) and 12 nm-thick UID GaN. The total thickness of PCD buffer layer was 2 μm. For the case of the conventional C-GaN buffer, some electrons from the 2DEG channel can be captured into many unoccupied neutral deep-acceptors in the buffer layer when large drain voltage applied, which would cause severe current collapse. In the case of PCD buffer layer, residual background electrons ($\sim 5 \times 10^{16}$ cm^{-3}) in UID GaN layer spatially move into the neighboring C-GaN to compensate the deep-acceptor traps in the C-GaN of PCD layer, which would not only make the UID GaN layers fully depleted to increase the resistance of the buffer layer, but also leave much less unoccupied deep acceptors in the C-GaN of PCD layer to decrease the trapping effect into the buffer layer. However, the suppression of the trapping effect in our previous work was not so satisfactory to achieve a reliable dynamic device operation.

In this work, to further improve carrier confinement and to further suppress undesirable trapping effects, we proposed a highly resistive semi-insulating buffer structure with inserting the AlGaN back-barrier layer between the channel layer and the PCD layer. Furthermore, we also optimized conditions of this buffer structure such as carbon concentration and Al mole fraction and thickness in the back-barrier by using numerical simulations. The fabricated device with proposed buffer structure exhibited considerable improvement of device performances such as extremely low leakage current, very high breakdown voltage, greatly reduced current collapse phenomenon, and one of highest figure-of-merit value.

II. SIMULATION

To achieve HR buffer layer, the carbon concentration should be high. However, excessive carbon concentration in HR buffer layer induces the degradation of epitaxial quality and device performance by impurity scattering and buffer-related current collapse [6]–[10]. Therefore, it is necessary to define and optimize the carbon concentration in buffer layer.

Figure 1 (a) shows calculated conduction band energy diagrams for different carbon concentration extracted by using self-consistent solutions of 1D Schrödinger-Poisson equations with *TiberCAD* software and the numerical details are given elsewhere [11], [12]. The simulated device structure consists of 25nm-thick $Al_{0.25}Ga_{0.75}N$ barrier layer, 1 nm-thick AlN interlayer, 100 nm-thick UID GaN channel layer, and 2 μm-thick PCD GaN buffer layer (one periodic structure; 12 nm C-GaN/50nm UID GaN). With increasing carbon concentration, conduction band edge of buffer side is raised, which leads to enhancement of electron confinement and breakdown voltage due to the decrease of the leakage current through the buffer layer [7]. In enlarged view of the conduction band energy, as shown in Figure 1 (b), when the carbon doping concentrations of less than 1×10^{17} cm^{-3} are considered, the distinction between conduction band profiles of C-GaN layer and UID GaN layer in PCD layer is not obvious, but the difference is clearly observable with showing periodic shape of conduction band diagram when the doping concentration exceeds 5×10^{17} cm^{-3}. This result indicates that the total amount of deep acceptros in C-doped GaN of PCD layer is not sufficient to compensate background electrons from UID GaN of PCD layer.

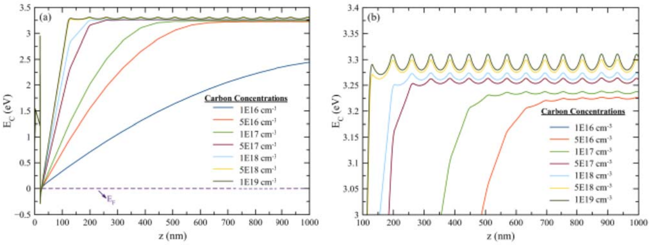

FIGURE 1. Calculated conduction band energy diagrams for different carbon concentrations (a) and the detailed view (b). "z" is distance in growth direction.

Figure 2 shows electron probability distributions for different carbon concentrations. The peak electron probability distribution also rapidly increases when carbon concentration is higher than 5×10^{17} cm^{-3} due to the improved electron confinement as expected. However, as previously stated, high-level carbon concentration in buffer layer gives rise to the increased impurity scattering and the trapping/detrapping effects through the carbon-related defects which degrades the device performances, such as decrease of mobility and current collapse [6]–[10]. For this reason, the doping concentration of carbon of 1×10^{18} cm^{-3} is assumed to be optimized in this work. The experimental results which include XRC FWHM (full width half maximum), extracted dislocation density [13], [14], and buffer resistance are presented according to carbon concentration as shown in Table 1. For carbon concentration of 1×10^{17} cm^{-3}, buffer resistance was relatively low as 1×10^{7} ohm, which is not suitable to prevent leakage current and improve to breakdown characteristics [9]. For carbon concentration of 6×10^{18} cm^{-3}, the XRC FWHM valuses and dislocation density were much higher, which presents very poor crystallinity due to high carbon concentration. For the carbon concentrations of 1×10^{18}cm^{-3}, the PCD layer had both high buffer resistance of 1.6×10^{11} ohm and acceptable crystallinity. These results support our numerical optimization results.

TABLE 1. Measured XRC FWHM, extracted dislocation density and buffer resistance of PCD layer with different carbon concentrations.

Carbon concentration [/cm³]	XRC FWHM [002]	XRC FWHM [102]	Dislocation density [× 10⁸/cm²]	Buffer resistance [ohm]
1×10^{17}	386	667	9.04	4.7×10^{7}
1×10^{18}	419	676	8.92	1.6×10^{11}
6×10^{18}	793	1361	37.50	2.7×10^{12}

Figure 3 shows the calculated conduction band energy diagrams near AlGaN/GaN heterostructure with 5 nm-thick AlGaN back barrier. The back barrier was inserted between

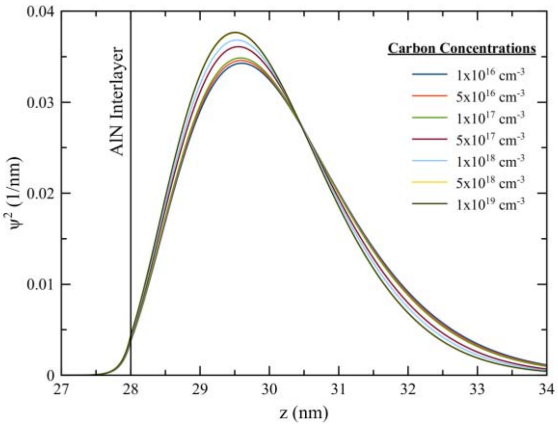

FIGURE 2. Calculated electron probability distributions for different carbon concentrations in AlGaN/GaN heterostructures with PCD buffer.

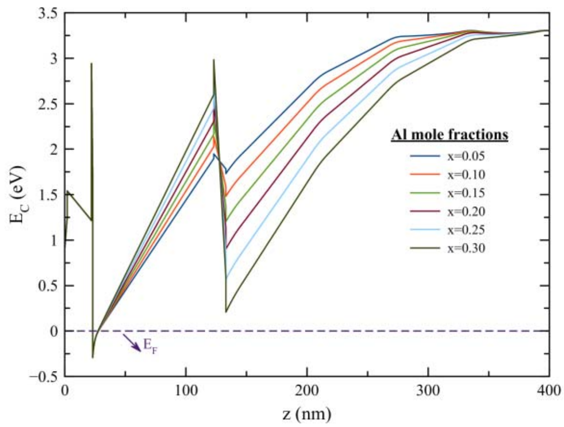

FIGURE 3. Calculated conduction band energy diagrams for different Al mole fractions (x) in AlGaN/GaN heterostructures with PCD buffer and $Al_xGa_{1-x}N$ back-barrier.

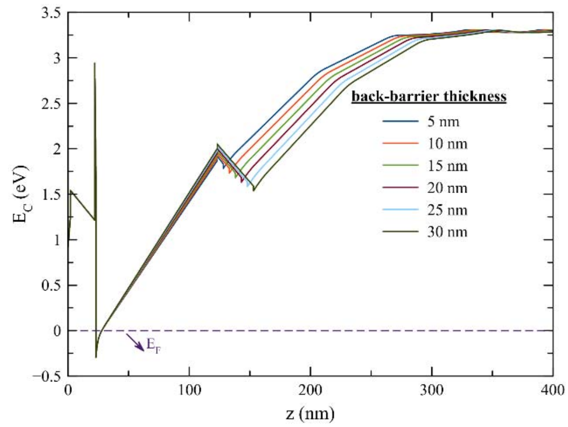

FIGURE 4. Calculated conduction band energy diagrams for different thicknesses of AlGaN back-barrier with 5% of Al mole fraction.

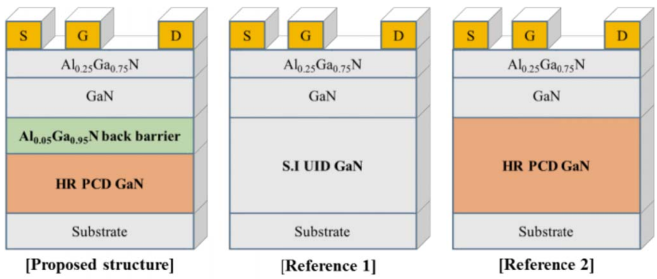

FIGURE 5. Schematic cross-sectional structures of fabricated HEMTs with various buffer structures.

the channel layer thickness of 100 nm and the PCD buffer layer with carbon doping concentration of 1×10^{18} cm^{-3}. Al mole fraction of the AlGaN back barrier was varied from 5 to 30 %. As Al mole fraction is increased, the conduction band bending between the AlGaN back-barrier and the PCD buffer layer is increased. It is generally known, however, that high Al mole fraction in the back barrier can induce additional strain to increase the dislocation density in the channel layer [15] and moreover may also forms the second quantum well at the interface between the AlGaN back barrier and the PCD buffer layer, which would rather increase the leakage current of the device. It is noticed, therefore, that relatively low Al mole fraction of ~ 5 % is desired for the AlGaN back barrier.

Effects of the thickness of AlGaN back-barrier layer with Al mole fraction of 5 % are shown in Figure 4, which shows that the conduction band bending between AlGaN back-barrier and PCD buffer layer increases, but the change is not significant with increasing the thickness of the back barrier. Therefore, sufficiently thick back barrier is desirable because it separates the channel layer from the PCD buffer layer which effectively prevents channel electrons from being captured to the traps in the PCD buffer layer. As a result, the AlGaN back barrier should be designed to have lower Al mole fraction and sufficiently higher thickness to ensure low defect generation in the channel layer and effective separation of the channel layer from the PCD buffer layer.

III. FABRICATION

The epitaxial structure for the propose AlGaN/GaN HEMT consists of 30 nm-thick low-temperature GaN layer, 2 μm-thick PCD buffer layer with carbon doping concentration of and 1×10^{18}/cm^3, 30 nm-thick $Al_{0.05}Ga_{0.95}N$ back barrier, 100 nm-thick GaN channel layer, 1 nm-thick AlN layer, and 25 nm-thick $Al_{0.25}Ga_{0.75}N$ layers, subsequently grown by using metal organic chemical vapor deposition (MOCVD) on the sapphire substrate. The growth for the PCD buffer layer and the AlGaN back barrier was based on the simulation results. For comparison, two different reference HEMT structures were also grown with; 1) conventional S.I. UID-GaN buffer layer without both the PCD layer and AlGaN back barrier, 2) PCD buffer layer without the AlGaN back barrier. The schematic of the fabricated AlGaN/GaN-based HEMTs with three different S.I. GaN buffer layers are shown in Figure 5. The secondary ion mass spectrometry (SIMS) measurement was performed to analyze the carbon concentration in the PCD buffer as shown in Figure 6. The 2-DEG property with various buffer structures are measured by using Hall measurement based on Van der Pauw method, which is shown in Table 2. The 2-DEG mobility and density were measured as 1870 cm^2/V·s and 9.01 × $10^{12}/cm^3$ for the proposed device, respectively, which is comparable to those of the device with conventional S.I.UID GaN buffer. This is because the AlGaN back barrier effectively reduces the scattering effect from carbon impurity in the PCD buffer layer.

For the device fabrication, the isolation process was carried out by using inductively coupled plasma-reactive ion etching (ICP-RIE). Then source and drain contacts were formed by Si/Ti/Al/Ni/Au metal scheme, and followed by rapid thermal annealing (RTA) at 850 °C for 30 sec in nitrogen ambient. Finally, Ni/Au metal was deposited for gate electrode.

TABLE 2. The electrical properties of 2-DEG channel of fabricated AlGaN/GaN HEMTs with various buffer structures.

Buffer structure	[Proposed structure] PCD GaN with AlGaN back barrier	[Ref 1] Conventional S.I. UID GaN	[Ref 2] PCD GaN Without AlGaN back barrier
Sheet resistance of 2DEG [Ω/sq]	369	342	396
Mobility of 2DEG [cm²/V·s]	1870	1900	1810
Sheet concentration of 2DEG [/cm²]	9.01 x 10^{12}	9.58 x 10^{12}	8.69 x 10^{12}

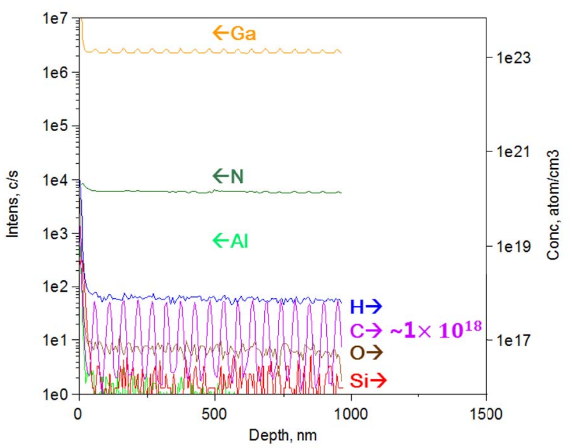

FIGURE 6. Measured carbon concentration in the periodically carbon doped GaN buffer structure by using the secondary ion mass spectrometry (SIMS) measurement. The extracted carbon concentration in C-GaN of PCD buffer layer was 1×10^{18}/cm^3.

IV. RESULTS AND DISCUSSION

The DC characteristics of the fabricated devices are measured by using an Agilent 4156 C semiconductor parameter analyzer at room temperature. Figure 7 shows the transfercharacteristics at saturation region (V_{ds} = 10 V) of the fabricated AlGaN/GaN HEMTs with three different buffer structures. The proposed device with both PCD buffer and AlGaN back barrier shows an very low OFF-state leakage current of ∼2 × 10^{-9} A/mm, which is much lower compared to the values of two reference HEMTs; ∼ 1 × 10^{-5} A/mm and ∼ 2 × 10^{-7} A/mm for the HEMT with S.I UID GaN buffer and for the HEMTs with PCD buffer only, respectively. It is also noticed that the ON-current of the proposed HEMT is comparable to the currents of the reference HEMTs, which results in excellent ON/OFF current ratio of 1.7 × 10^8, even though the OFF-state leakage current of the proposed HEMT is two and four orders lower in magnitude than those of the reference HEMTs with S.I UID GaN buffer and the HEMT with PCD buffer only, respectively. This indicates that the PCD buffer layer eliminates parasitic leakage paths because the carbon-related deep acceptors in C doped GaN of PCD layer compensate the back ground donors in the UID GaN of PCD layer and further the AlGaN back barrier enhances the electron confinement in the channel which effectively prevent electrons from flowing into the buffer layer [16]–[18]. The subthreshold swing of the proposed device was 110 mV/dec on average, which is acceptable value for AlGaN/GaN-based power switching device when comparing with other reported results [19].

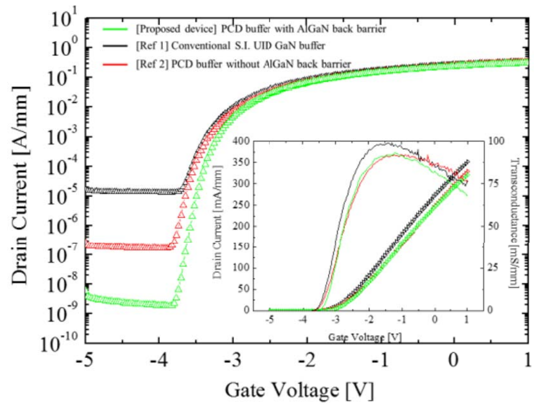

FIGURE 7. Comparisons of measured I_D-V_{GS} characteristics of fabricated HEMTs with different buffer structures.

The pulsed I_{ds}-V_{ds} characteristics were measured at V_{gs} of −0.5 V with several quiescent bias points [$V_{GS,Q}$, $V_{DS,Q}$] = [0 V, 0 V]:black, [−5 V, 0 V]:blue, and [−5 V, 10 V]:red, as shown in Figure 8. Pulse width and period are 50 μs and 1 ms, respectively. The degradation of drain current at quiescent bias points of [$V_{GS,Q}$, $V_{DS,Q}$] = [−5 V, 10 V] was resulted from the current collapse phenomenon. The current collapse in AlGaN/GaN HEMTs is mainly due to the electron trapping effects at surface of the AlGaN barrier (called "gate lag") and in the GaN buffer layer at high drain voltage (called "drain lag") [6]–[10]. The gate lag can be observed by comparing the pulsed I–V with the quiescent bias condition [$V_{GS,Q}$, $V_{DS,Q}$] = [0V, 0V] and [$V_{GS,Q}$, $V_{DS,Q}$] = [−5 V, 0 V].

By comparing pulsed I–V with bias condition [$V_{GS,Q}$, $V_{DS,Q}$] = [−5 V, 0 V] and [$V_{GS,Q}$, $V_{DS,Q}$] = [−5 V, 10 V], the drain-lag can be distinguished because only the drain voltage changed [6]–[8]. Among the devices, the difference of gate lag was negligible, but the proposed device exhibited much smaller drain lag compared to two other reference devices. Two reference HEMTs with the S.I. UID GaN buffer

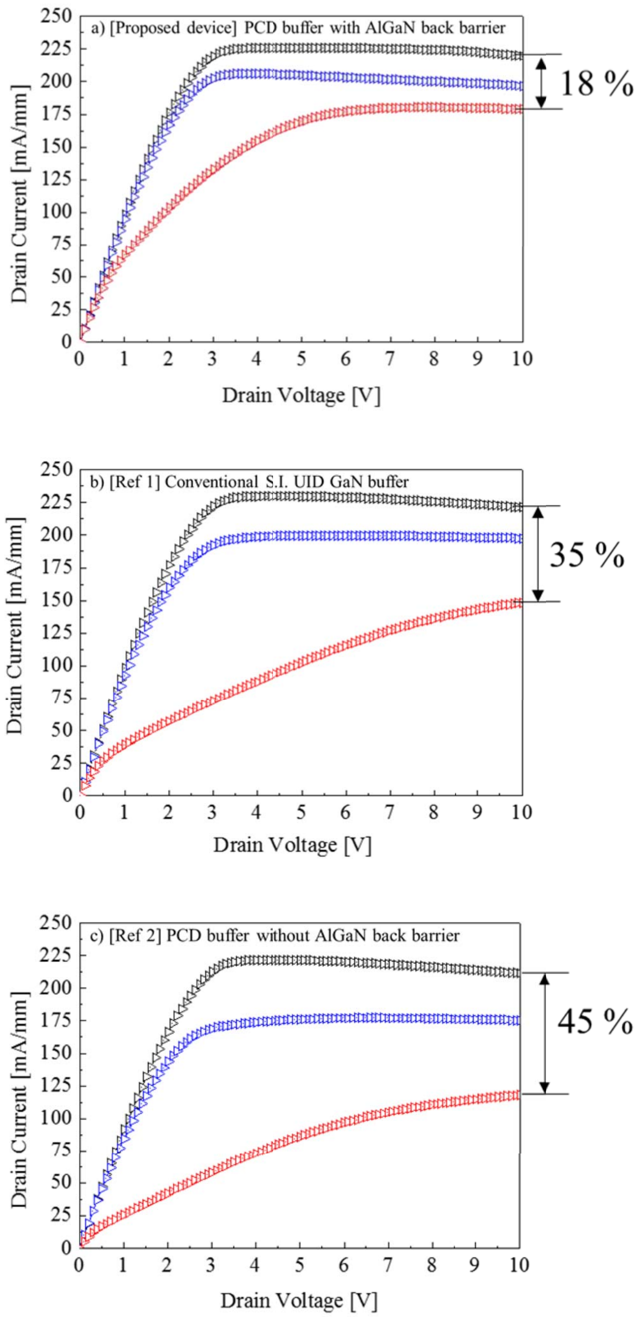

FIGURE 8. Pulsed I–V characteristics of HEMTs with different buffer structures of a) [Proposed device] PCD GaN and AlGaN back barrier, b) [Ref 1] Conventional S.I. UID GaN, c) [Ref 2] PCD GaN without AlGaN back barrier. The black, blue and red triangles correspond to the pulsed I–V at V_{GS} of −0.5 V with quiescent bias of ($V_{GS,Q}$ = 0 V, $V_{DS,Q}$ = 0 V), ($V_{GS,Q}$ = −5 V, $V_{DS,Q}$ = 0 V), ($V_{GS,Q}$ = −5 V, $V_{DS,Q}$ = 10 V).

layer and the PCD buffer layer showed severe current collapse of 35, and 45 %, respectively. However, the proposed HEMT exhibited much less current collapse of 18 %, which indicates that the insertion of the AlGaN back barrier is an excellent way to suppress undesirable trapping effects in buffer layer [16]–[18].

The OFF-state breakdown characteristics of the fabricated HEMTs with a gate-to-drain distance (L_{GD}) of 5 μm were measured by using Keithley model 248 high voltage supply and Keithley 6485 picoammeter as shown in Figure 9. The breakdown voltage (V_{BR}) is defined as the drain voltage when the drain current reaches to 1 mA/mm. For device with L_{GD} of 5 μm, the HEMTs with S.I. UID GaN buffer, with PCD GaN buffer, and with PCD GaN buffer and AlGaN back barrier exhibit V_{BR} of 510 V, 1200 V, and 1320 V, respectively.

High V_{BR} for the HEMTs with the PCD buffer layer is believed to be due to the spatial compensation between the UID and C-doped GaN layer [6]. The compensation makes the UID GaN in PCD layer fully depleted to greatly increase the resistance of the layer, which causes the PCD buffer layer to be semi-insulating. The proposed HEMT exhibited even higher V_{BR} because the AlGaN back barrier effectively blocks electrons flowing to buffer layer [14]–[16], as discussed above.

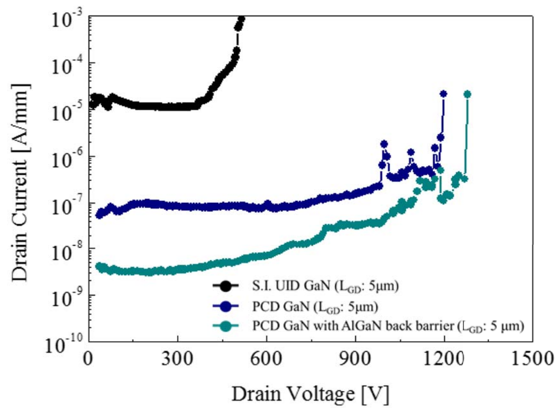

FIGURE 9. Measured OFF-state breakdown characteristics of fabricated HEMTs with different buffer structures at V_{GS} = −4V.

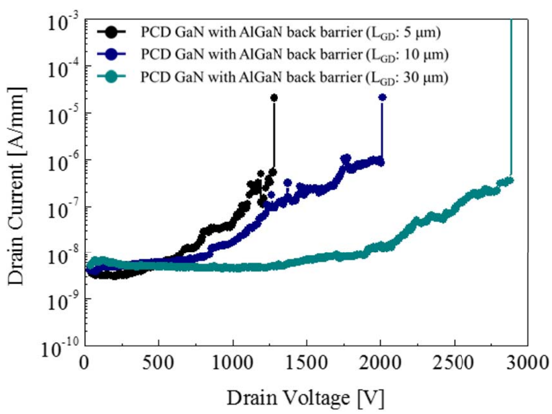

FIGURE 10. Measured OFF-state breakdown characteristics of the proposed HEMTs with different gate-drain distance, L_{GD} at V_{GS} = −4 V.

The OFF-state breakdown characteristics of the proposed HETMs with different L_{GD} are shown in Figure 10. The extremely high V_{BR} of 2020 V, 2900 V were achieved

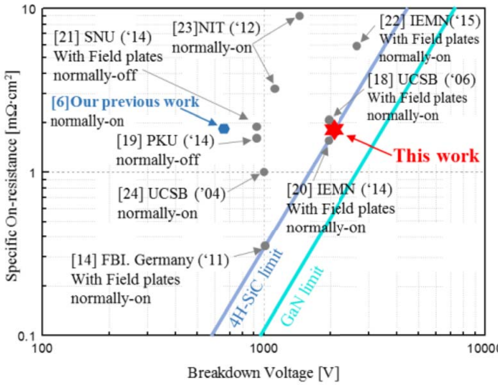

FIGURE 11. Relations between specific on-resistance and breakdown of the fabricated GaN HEMT in this work. Those relations of results reported by other groups are also shown in the graph.

from the proposed HEMT with L_{GD} of 10 μm, 30 μm, respectively.

Figure 11 shows the figure of merits (FOM) for the relationship between the specific on-resistance (R_{ON}) and the V_{BR} of the proposed HEMT with L_{GD} of 10 μm for comparison with previously reported results [16]–[27]. The extracted R_{ON} of the proposed HEMT with L_{GD} of 10 μm in this work is 1.8 mΩ·cm^2 with I_{DS} of 200 mA/mm at V_{DS} of 2V calculated from the method reported by HS Lee *et al.* [20]. A very high FOM of $\sim$ 2.27 GV$^2\Omega^{-1}$cm^{-2} has been achieved for the proposed device with L_{GD} of 10 μm, one of the highest values ever reported for the GaN-based high-electron mobility transistors (HEMTs), even though the proposed HEMT investigated in this work does not have other approaches like field-plated structures. The high FOM value and acceptable subthreshold swing of the proposed devices considered, the switching loss of the proposed device is expected to be low when the device operates under an appropriate condition.

V. CONCLUSION

Characteristics of high-performance AlGaN/GaN HEMTs with high resistive GaN buffer consisted of PCD buffer and AlGaN back-barrier were investigated. Considerable enhancement in OFF-state leakage current and current collapse were observed according to presence of AlGaN back-barrier. A very low OFF-state leakage current of $\sim$2 $\times$ 10^{-9} A/mm and current collapse of 18 % have been achieved, which are about 2 orders lower in magnitude and about 2 times lower than those of reference devices, respectively. Furthermore, a very high FOM of $\sim$2.27 GV$^2\Omega^{-1}$cm^{-2} with V_{BR} of 2020 V has been achieved for L_{GD} of 10 μm. This indicates that the proposed buffer structure consisted of PCD buffer and AlGaN back-barrier is promising for high power device applications.

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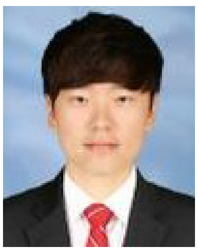

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