**AI/GaN channel high electron mobility transistors (AlGaN HEMTs) show potential for next-generation high-power RF applications with Johnson’s figure of merit, which is four times higher than current GaN HEMTs because of higher breakdown electric fields.** The early work of AlGaN HEMTs demonstrated the remarkable enhancement of the breakdown field with the Al composition in the AlGaN channel layers increase. $^{21}$ Al$_{0.5}$Ga$_{0.5}$N/Al$_{0.38}$/GaN$_{0.62}$N HEMTs yielded a maximum drain current density ($I_{DS}$) of 114 mA mm$^{-1}$, and a breakdown voltage of 1650 V. Al$_{0.85}$Ga$_{0.15}$N/Al$_{0.6}$/GaN$_{0.4}$N HEMTs with 80 nm gates yielded a maximum $I_{DS}$ of 160 mA mm$^{-1}$ and a breakdown voltage ranging from 80 to 250 V.$^{1,3}$ RF characteristics such as a cut-off frequency and maximum oscillating frequency of 28.4 and 18.5 GHz, respectively, have been reported to demonstrate the feasibility of high-power density and high-speed AlGaN HEMTs. The use of AlN barrier layer improves the performance of AlGaN HEMT by maximizing the conduction band offset, increasing two-dimensional electron gas (2DEG) density, suppressing alloy scattering in the barrier layer, and improving the breakdown characteristics because of the high breakdown field of AlN (12 MV cm$^{-1}$).$^{4}$ However, conventional metal stack ohmic contacts on the AlN barrier layer typically suffered from the high contact resistance ($R_C$). The Zr/AI/Mo/Au metal stacks on AlN$_{0.4}$/Ga$_{0.6}$N HEMTs exhibited nonlinear current–voltage characteristics with a high $R_C$ of 85 mm even after the rapid thermal annealing at 950 °C.$^{5}$ Al$_{0.5}$Ga$_{0.5}$N HEMTs with the Ti/Al/Ni/Au metal stacks on the 3 nm thick AlN barrier thinned by inductively coupled plasma (ICP)-reactive ion etching (RIE) yielded a high $R_C$ of 85 Ω mm.$^{9}$ The high thermal stability and wide bandgap nature of AlN hinder tunneling conduction from the ohmic metal stacks to 2DEG through the barrier layer.

The removal of the highly resistive barrier layer and the epitaxial formation of the selective regrowth contact of highly n-type doped GaN in the source-drain regions is a favorable way to reduce the high contact resistance. The regrowth contact strategy for GaN HEMTs is advantageous in RF applications because of its high scalability and low ohmic contact resistance, which is less than 1 Ω mm$^{7,8}$ However, epitaxial regrowth ohmic contacts to AlN/Al$_{0.5}$Ga$_{0.5}$N HEMTs showed nonlinear DC output behaviors with a high $R_C$ of 21 Ω mm.$^{9}$ Despite the excellent 2DEG properties with the sheet charge density of $6 \times 10^{12}$ cm$^{-2}$ and the electron mobility of 250 cm$^2$ V$^{-1}$ s$^{-1}$, the maximum $I_{DS}$ for AlN/Al$_{0.5}$Ga$_{0.5}$N HEMTs was as low as 2 mA mm$^{-1}$ due to an extremely high $R_C$ of 1900 Ω mm even with the regrowth contact.$^{9}$ These results implied the presence of an energy barrier in the electron transport between the regrown n-type GaN and AlGaN channel layers because the AlGaN has a smaller electron affinity than GaN. Thus, the development of epitaxial materials with low electron affinity and low resistivity is highly demanded to improve the ohmic contacts in AlN/AlGaN HEMTs.

Recent progress in the sputtering technique, named pulsed sputtering deposition (PSD), has enabled the growth of heavily Si or Ge-doped degenerate GaN (d-GaN) with a maximum electron concentration of $5 \times 10^{19}$ cm$^{-3}$. The PSD-grown heavily Si-doped GaN with an electron concentration of $3 \times 10^{18}$ cm$^{-3}$ and electron mobility of 100 cm$^2$ V$^{-1}$ s$^{-1}$ has a record low resistivity of $1.6 \times 10^{-4}$ Ω cm. We also found that the Si-doping via PSD in GaN increased the optical bandgap up to 3.7 eV, indicating a high Fermi level position above the conduction band edge with the Burstein–Moss shift.$^{12}$ This degenerate nature in the heavily doped PSD GaN is beneficial for forming low-resistive regrowth ohmic contacts to 2DEG in AlGaN HEMTs. It should be noted that The PSD technique also allows to grow high-quality epitaxial AlN on various substrates at low temperatures.$^{13,14}$ Thus, the total use of PSD in preparing both AlN/AlGaN structures and source/drain d-GaN contacts is promising for low-cost manufacturing of the next-generation HEMTs.

In this letter, we have demonstrated the PSD growth of AlN$_{0.5}$Ga$_{0.5}$N HEMT structures and the epitaxial regrowth formation of highly Si-doped d-GaN contacts with a low resistance to 2DEG in AlN$_{0.5}$Ga$_{0.5}$N HEMTs. Figure 1 shows a cross-sectional schematic of the AlN$_{0.5}$Ga$_{0.5}$N HEMT structure with the regrown d-GaN contacts. The starting materials were commercially available 2 in. AlN(0001)/sapphire(0001) templates. The FWHM values of X-ray rocking curves for 0002 and 10$\bar{1}$2 diffractions

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of the AlN template were 23 and 338 arcsec, respectively. The epitaxial heterostructures were grown on the AlN templates using the PSD apparatus in an Ar/N\textsubscript{2} gas mixture at substrate temperatures of 700 °C–850 °C. The epitaxial growth of AlN/Al\textsubscript{0.5}Ga\textsubscript{0.5}N HEMT structure was initiated with the homoepitaxial growth of a 600 nm thick AlN, followed by the growth of 130 nm thick Al\textsubscript{0.5}Ga\textsubscript{0.5}N channel layer, and 25 nm thick AlN barrier layer. The source-drain region for d-GaN regrowth was defined using 200 nm thick SiO\textsubscript{2} masks deposited by e-beam evaporation and patterned using standard RIE and a photolithographic technique. A chlorine-based ICP RIE process was used to remove the AlN barrier and AlGaN channel layers in the source-drain region. The total etching depth was confirmed to be 100 nm using a surface profiler. The epitaxial wafer patterned with the SiO\textsubscript{2} mask was reintroduced into the PSD chamber. PSD was simultaneously used to grow a heavily Si-doped 150 nm thick GaN layer on both the SiO\textsubscript{2} mask and the etched Al\textsubscript{0.5}Ga\textsubscript{0.5}N surface. The detailed growth procedure of Si-doped d-GaN has already been reported in previous studies.\textsuperscript{10,11} Further, the polycrystalline GaN region grown on the SiO\textsubscript{2} mask was removed through the liftoff process using HF acid. Metal stacks Ti/Al/Ti/Au(30/70/30/50 nm) were prepared on the epitaxial d-GaN source/drain region with e-beam evaporation and the other metal stack Ni/Au(100/200 nm) was deposited as gate electrodes.

Figures 1(b) and 1(c) show the atomic force microscopy (AFM) surface images of the starting AlN template and the AlN/Al\textsubscript{0.5}Ga\textsubscript{0.5}N epitaxial layers grown on the AlN template. We found that the initial AlN homoepitaxial growth improved the surface morphology with a low root mean square (RMS) surface roughness value of 0.1 nm. The AlN/Al\textsubscript{0.5}Ga\textsubscript{0.5}N epitaxial heterostructure was grown on this atomically-flat AlN homoepitaxial layer. One can see

Fig. 1. (Color online) (a) A schematic of the AlN/Al\textsubscript{0.5}Ga\textsubscript{0.5}N HEMT with PSD-regrown highly Si-doped degenerate GaN (d-GaN) ohmic contacts. AFM surface images of (b) the starting AlN template and (c) the AlN/Al\textsubscript{0.5}Ga\textsubscript{0.5}N epitaxial layers grown on the AlN template.

Fig. 2. (Color online) (a) A symmetric XRD 2θ/ω curve and its fitting of the AlN/Al\textsubscript{0.5}Ga\textsubscript{0.5}N/AlN heterostructure. (b) The reciprocal space mapping nearly 10\textsubscript{15} diffractions.

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that the AlN barrier surface consists of atomically-flat stepped-and-terraced structures. The RMS of surface roughness was improved from 0.61 to 0.13 nm through the epitaxial process. The AlN barrier surface was specular and without cracks despite the large compositional difference between the AlN barrier and Al0.5Ga0.5N channel layers. Figure 2(a) shows a symmetric XRD 2θ/θo data and its fit curve of AlN/Al0.5Ga0.5N heterostructure. A clear AlGaN 0002 peak was observed at 35.0° with Pendellösung fringes, indicating that the AlN/Al0.5Ga0.5N heterointerface was abrupt. In Fig. 2(a), the experimental curve was well fit using the structural model shown in Fig. 1. The asymmetric reciprocal space mapping near 1015 diffraction in Fig. 2(b) has revealed that the AlN/Al0.5Ga0.5N heterointerface was coherently grown on the underlying AlN.

Further, we measured the capacitance–voltage (C–V) characteristics of AlN/Al0.5Ga0.5N heterostructure with a 100 μm diameter metal stack Ni/Au (100/200 nm) on the AlN barrier layer. Figure 3 shows the depth profile of the carrier concentration for the AlN/Al0.5Ga0.5N heterointerface, which is determined by the C–V measurement. The carrier concentration peak was positioned at a depth of 25 nm, corresponding to the AlN barrier thickness. The 2DEG concentration at the AlN/Al0.5Ga0.5N heterointerface was calculated to be 1.7 × 10^13 cm^-2.

We also investigated the characteristics of PSD-regrown d-GaN contacts using the Hall-effect measurements and a transfer length method (TLM). In Fig. 4(a), the 60 × 60 μm² van der Pauw geometry with clover-leaf point contacts was defined by the selective area growth of n⁺-GaN. The Hall-effect measurements showed that the electron concentration and electron mobility of n⁺-GaN were 2.6 × 10^20 cm^-3 and 115 cm² V^-1 s^-1, respectively, with low sheet resistance (R_S) of 15 Ω sq. These results indicate that the selectively formed n⁺-GaN was a degenerate semiconductor with a Fermi level (E_F) positioned in the conduction band. Assuming the nonparabolicity in the conduction band and the bandgap renormalization effect, the E_F position is estimated to be 0.63 eV above the conduction band edge. The energy barrier against the 2DEG in the Al0.5Ga0.5N channel layer is effectively reduced by this high E_F position in the selectively formed d-GaN, allowing the formation of low-resistive ohmic contacts. The TLM pattern consists of 2DEG channels of various lengths with d-GaN contacts at both ends. The two-terminal current–voltage (I–V) curves show clear ohmic characteristics. In the inset of Fig. 4(b), the TLM result shows that the R_C and the R_DS are 0.43 Ω mm (4.7 × 10^-7 Ω cm²) and 3.9 kΩ/sq, respectively. The R_DS of 3.9 kΩ/sq was within the range of 2.9–7.0 kΩ/sq, which was previously reported for AlGaN channel layers with a similar Al composition.15,16 Figure 4(c) shows the R_C values reported for the AlGaN HEMTs as a function of the Al composition of the AlGaN channel layer.20,21,23 In Fig. 4(c), conventional ohmic technologies such as regrowth contact (solid diamonds) or metal alloy contact (solid circles) show an exponential increase in the R_C with Al composition. Among the reported values, Zr-based ohmic contacts with graded AlGaN caps on Si-doped Al0.7Ga0.3N/Al0.5Ga0.5N structure yielded a relatively low R_C of 3.9 Ω mm.20 On the other hand, the present study gave further one order of magnitude improvements in the R_C despite the use of the AlN barrier layer. The R_C of 0.43 Ω mm is the lowest value reported for AlGaN HEMTs with this Al content and is comparable to the value of conventional GaN HEMT.23

These results show that PSD-assisted selective regrowth of heavily Si-doped d-GaN is a promising method for addressing the ohmic contact challenge in AlGaN HEMT with high Al composition.

Figure 5(a) shows the scanning electron microscopy (SEM) image of the AlN/Al0.5Ga0.5N HEMT structure with the d-GaN regrown contacts. The source-drain length (L_SD) and the gate length (L_G), was 5.9 and 4.4 μm, respectively. The L_SD was defined by the source to drain edges of regrown d-GaN spacing.

The parasitic resistance related to the regrowth region was negligible with a low order of 10^-2 Ω mm because of the small R_DS of d-GaN. Figures 5(b) and 5(c) summarize the DC output characteristics of the AlN/Al0.5Ga0.5N HEMT with the regrown d-GaN contacts. In Fig. 5(b), drain current and drain voltage (I_DS=V_DS) curves of the AlN/Al0.5Ga0.5N HEMT were plotted with the gate voltage (V_GS) steps of −1 V ranging from 2 to −9 V. The I_DS linearly rises without the V_DS offset, which is a striking contrast to the previous reports.5,6 The maximum current density peaked at 250 mA mm^-1. Figure 5(c) shows that the I_DS was plotted against the V_GS at drain voltage V_DS = 5 V. The threshold voltage V_TH of −8.6 V was extracted from the linear extrapolation of transfer characteristics. A maximum transconductance (g_m) of 32 mS mm^-1 was attained at V_GS = −1.8 V, and the I_DS/I_VTH ratio was higher than 10^3. Figure 6 shows the three-terminal off-state breakdown characteristics of AlN/Al0.5Ga0.5N HEMTs at V_GS = −10 V. The leakage current was less than 0.2 μA mm^-1 for a gate to drain edge of regrown d-GaN spacing of 5.4 μm, and the breakdown voltage was recorded at 1635 V. In the inset of Fig. 6, the average breakdown electric field is determined to be 3.0 MV cm^-1 based on the linear relationship between the gate-drain spacing and the breakdown voltage; this is about three times higher than that of a conventional GaN HEMT.24–26 These outstanding device characteristics were attributed to the high quality of coherently grown AlN/Al0.5Ga0.5N heterostructures and the record low R_C of 0.43 Ω mm, which was achieved using heavily Si-doped PSD d-GaN contacts.

Finally, we will discuss the impact of two-dimensional hole gas (2DHG) formed at the bottom heterointerface. According to our device simulation (FETIS, STR), the bottom heterointerface between the AlGaN channel and...
AlN layers ideally yields the 2DHG with the density of ca. $1 \times 10^{13} \text{cm}^{-2}$. Two parallel 2DEG and 2DHG coexisting in proximity at possibly introduce mutual Coulomb interactions. The previous works on AlN/GaN/AlN quantum well (QW) transistors discussed the possibility of lowering 2DEG mobility by the defective interface and/or the Coulomb drag effect. Compared to the GaN QW channel as thin as 30 nm, the Coulomb drag effect should be minor in our case because the 2DHG was separated to the 2DEG by the 120 nm thick AlGaN channel layers. We may need further investigations on the electromagnetic interaction effects on the RF characteristics.

In summary, AlN/Al$_{0.5}$Ga$_{0.5}$N HEMTs with fully strained AlN/Al$_{0.5}$Ga$_{0.5}$N heterostructures and heavily Si-doped d-GaN regrowth contacts were successfully fabricated via the use of PSD. The atomically-flattened surface and abrupt interface of the AlN/Al$_{0.5}$Ga$_{0.5}$N heterostructure resulted in a 2DEG density of $1.7 \times 10^{13} \text{cm}^{-2}$. The selectively regrown n-type GaN contacts exhibited characteristics of d-GaN with the electron concentration and electron mobility of $2.6 \times 10^{20} \text{cm}^{-3}$ and 115 cm$^2$ V$^{-1}$ s$^{-1}$, respectively. Contact resistance $R_C$ of the highly Si-doped d-GaN regrowth contacts was as low as 0.43 $\Omega$ mm despite using the AlN barrier structure, which is the record low value for Al$_{0.5}$Ga$_{0.5}$N HEMTs. Further, we obtained a maximum $I_D = 250 \text{mA mm}^{-1}$, $g_m = 32 \text{mS mm}^{-1}$, and the $I_D/I_{OFF}$ ratio $>10^6$ for these HEMTs. These results show that the PSD technique can overcome the challenges in ohmic contact formation for high Al composition AlGaN electron devices and for fabricating next-generation high-power density RF transistors.

![Fig. 4.](image) (Color online) (a) SEM image of 60 × 60 $\mu$m$^2$ van der Pauw geometry with clover-leaf four-point contacts. (b) Two terminal current–voltage (I–V) characteristics using TLM patterns with PSD-regrown n$^+$-GaN contact. The inset shows the TLM fitting result (c), and the contact resistance $R_C$ as a function of the Al composition in AlGaN channel layers. The solid diamonds and circles indicate the reported $R_C$ values of the regrowth contacts and metal alloy contacts, respectively.  

![Fig. 5.](image) (Color online) (a) SEM image, (b) DC output curves, and (c) transfer characteristics for the AlN/Al$_{0.5}$Ga$_{0.5}$N HEMT.

![Fig. 6.](image) (Color online) Three terminal off-state breakdown characteristics of AlN/Al$_{0.5}$Ga$_{0.5}$N HEMTs with a gate to drain spacing of 5.4 $\mu$m at $V_{GS} = -10 \text{V}$. The inset shows the relationship between the gate to drain spacing and the breakdown voltage. The linear fit determined the average breakdown field of 3.0 MV cm$^{-1}$.
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Data availability
The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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