High drain-current-density and high breakdown-field Al$_{0.36}$Ga$_{0.64}$N-channel heterojunction field-effect transistors with a dual AlN/AlGaN barrier layer

Akiyoshi Inoue$^{1,2}$, Sakura Tanaka$^{1}$, Takashi Egawa$^{1,2}$, and Makoto Miyoshi$^{1,2}$

$^1$Research Center for Nano Device and System, Nagoya Institute of Technology, Nagoya 466-8555, Japan
$^2$Innovation Center for Multi-Business of Nitride Semiconductors, Nagoya Institute of Technology, Nagoya 466-8555, Japan
$^*$E-mail: a.inoue.328@nitech.jp

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In this study, we fabricated and characterized heterojunction field-effect transistors (HFETs) based on an Al$_{0.36}$Ga$_{0.64}$N-channel heterostructure with a dual AlN/AlGaN barrier layer. The device fabrication was accomplished by adopting a regrown n$^{-1}$-GaN layer for ohmic contacts. The fabricated HFETs with a gate length of 2 $\mu$m and a gate-to-drain distance of 6 $\mu$m exhibited an on-state drain current density as high as approximately 270 mA mm$^{-1}$ and an off-state breakdown voltage of approximately 1 kV, which corresponds to an off-state critical electric field of 166 V $\mu$m$^{-1}$. This breakdown field, as a comparison in devices without field-plate electrodes, reaches approximately four-fold higher than that for conventional AlGaN-channel HFETs and was considered quite reasonable as an Al$_{0.36}$Ga$_{0.64}$N-channel transistor. It was also confirmed that the devices adopting the dual AlN/AlGaN barrier layer showed approximately one order of magnitude smaller gate leakage currents than those for devices without the top AlN barrier layer.

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Wide-bandgap AlGaN-channel heterojunction field-effect transistors (HFETs) are highly promising as future ultra-high-power electronic devices since they can show several times higher off-state breakdown voltages than those for conventional GaN-channel FETs.\textsuperscript{1–23} For the past several years, the authors have conducted intensive research on the growth of AlGaN-channel two-dimensional electron gas (2DEG) heterostructures by metalorganic chemical vapor deposition (MOCVD) and their application to HFETs.\textsuperscript{15–23} Most notable topic in our past research is the proposal of strain-controlled quaternary AlGaN/N barrier layers.\textsuperscript{20–23} That is, the quaternary AlGaN channel layers properly designed and grown can provide smooth surface morphologies and thermal stability in addition to high 2DEG densities\textsuperscript{20} and thereby contributed to the improvement in the device performance.\textsuperscript{21,22} The alloy composition of the quaternary AlGaN/N barriers can optimally be designed in relation to alloy compositions of the underlying AlGaN channels.\textsuperscript{20} Furthermore, most recently, we have reported that the on-state performance of AlGaN/N/Al$_{0.19}$Ga$_{0.81}$N HFETs with AlN mole fractions $x$ of approximately 0.2 was drastically improved by adopting a regrown n$^{-1}$-GaN contact layer formed via the selective-area growth (SAG) process.\textsuperscript{22} The fabricated Al$_{0.19}$Ga$_{0.81}$N-channel HFETs with a gate length of 2 $\mu$m exhibited a high maximum drain current density ($I_{DS,MAX}$) of approximately 300 mA mm$^{-1}$ with a high off-state critical electric field ($E_C$) of 122 V $\mu$m$^{-1}$.\textsuperscript{22,23}

To date, our past research on AlGaN-channel heterostructures and HFETs have mostly been conducted for Al$_{1-x}$Ga$_x$N channels with $x$ around 0.2.\textsuperscript{17,19–22} Regarding AlGaN-channel 2DEG heterostructures and HFETs, we predict that higher-AlN-mole-fraction Al$_{1-x}$Ga$_x$N channels with $x$ around 0.4 may cause a little lower 2DEG mobilities\textsuperscript{16} but much higher breakdown field;\textsuperscript{1,3,21,22} compared with those with $x$ around 0.2 that we have ever studied. Therefore, in this study, we attempted to fabricate AlGaN/N/AlGaN HFETs with $x$ around 0.4 adopting the SAG contacts. Furthermore, to ensure good gate electrode properties with low gate leakage currents and stable off-state characteristics, we investigated an insertion of a thin crystalline AlN barrier layer between the AlGaN/N barrier and the gate electrode. Based on the above, this paper presents the following information in addition to the extended abstract for the 2021 International Conference on Solid State Devices and Materials (SSDM 2021).\textsuperscript{23} That is, the energy band simulation for an MOCVD heterostructure, the microstructure observation results by atomic force microscopy (AFM) and cross-sectional high angle annular dark-field scanning transmission-electron microscopy (HAADF-STEM), the electrical characterization results including the Hall effect, transmission-line model (TLM) and the gate-to-source current–voltage ($I–V$) measurements.

1. Experimental methods

Figure 1 shows a schematic of AlGaN-channel HFETs with a dual AlN/AlGaN/N barrier layer investigated in this study. The heterostructure consists of a 2 $\mu$m thick Al$_{0.36}$Ga$_{0.64}$N channel layer and a 1.5 nm thick AlN/20 nm thick Al$_{0.845}$Ga$_{0.15}$In$_{0.005}$N dual barrier layer, which was grown on an epitaxial AlN/sapphire template by MOCVD.\textsuperscript{15–17,19–25} In accordance with the design concept described in our previous report,\textsuperscript{20} the alloy composition of the quaternary AlGaN/N barrier layer was designed to have a lattice strain of no more than 0.6% in the in-plane tensile direction and a 2DEG density higher than 1.5 $×$ 10$^{13}$ cm$^{-2}$. For comparison, we also prepared another heterostructure sample for HFETs without the top AlN barrier layer. The alloy composition and lattice strain were confirmed by X-ray diffraction (XRD) measurements and Rutherford back scattering (RBS). In addition, to confirm the Schottky contact and the influence of the polarization effect for the dual AlN/AlGaN/N barrier layer, the energy band diagram was investigated using Silvaco© ATLAS. The MOCVD samples

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were characterized by AFM, HAADF-STEM, and Hall effect measurement.

In this study, a regrown $n^{++}$-GaN contact layer formed via the self-aligned SAG process was adopted for ohmic contacts. The details of the SAG process are described in our previous report. The Si concentration in the regrown $n^{++}$-GaN layer was approximately $1.2 \times 10^{20} \text{ cm}^{-3}$ at a peak concentration. After the SAG process completed, the device fabrication was conducted using conventional photolithographic method. The source and drain electrodes were formed on the regrown $n^{++}$-GaN areas via an evaporation of a Ti/Al/Ti/Au (9/100/50/100 nm) film and subsequently annealed at 600 °C for 2 min in a N$_2$ atmosphere. Here, the planer-contact type HFETs without the SAG contacts were also fabricated for comparison, in which the post annealing for ohmic contacts were conducted at 900 °C for 2 min in a N$_2$ atmosphere. The gate Schottky electrodes were formed by evaporating a Pd/Ti/Au (40/20/60 nm) film directly on the barrier layer surfaces. The device dimensions were as follows: the source-to-gate length ($L_{SG}$) was 6 μm; the gate length ($L_G$) was 2 μm; the gate-to-drain distance ($L_{GD}$) was 6 μm; and the gate width ($W_G$) was 20 μm and 200 μm. The $I$–$V$ characteristics were evaluated using a semi-conductor parameter analyzer. To investigate the ohmic contact resistance, $I$–$V$ characteristics for test element patterns with different electrode distances were analyzed in accordance with the TLM method. The electrode size for the TLM measurements was 80 μm × 80 μm.

2. Results and discussion

2.1. Characterization of AlN/AlGaInN/AlGaInN heterostructure grown by MOCVD

In this study, we investigated the applicability of the dual AlN/AlGaInN barrier layer to AlGaN-channel HFETs as another interest. This is an idea using a thin crystalline AlN barrier layer for the gate contacts instead of an atomic layer deposited (ALD) Al$_2$O$_3$ film we have conventionally used as a gate insulator. The reason of this attempt is based on our findings. That is, while it is still under investigation, throughout our recent study on high-breakdown-voltage AlGaN-channel HFETs, we often observed some instability of the non-crystalline Al$_2$O$_3$ films particularly under high electric fields. Thus, we considered that wide-bandgap crystalline films such as an epitaxially-deposited AlN layer might be appropriate to achieve stable gate contacts with low-leakage currents. Figure 2 compares energy band diagrams at an equilibrium state for AlGaInN/AlGaN heterostructures with and without the top AlN barrier layer. Here, the simulation assumed a Schottky contact using a nickel metal with a work function of 5.22 eV. The results indicated that the Schottky barrier height surely increased by adopting the top AlN barrier and that the polarization effect in the thin AlN barrier would not cause any harmful influence. Based on these results, we attempted to grow an
AlN/AlGaN/AlGaInN heterostructure and apply it to the fabrication of HFETs.

Figures 3(a) and 3(b) show surface AFM images for MOCVD-grown AlGaInN/AlGaN heterostructures with and without the top AlN barrier layer. As observed in these images, both samples had highly flat surfaces with clear atomic steps, which we consider were due to the strain-controlled design and growth. The root-mean-square (RMS) roughness was measured to be as small as 0.35 nm and 0.24 nm for samples with and without the top AlN barrier layer, respectively. Figures 4(a) and 4(b) show a HAADF-STEM image for the AlN/AlGaInN/AlGaN heterostructure and its magnified image around the dual AlN/AlGaInN barrier layer, respectively. The STEM images showed that the heterostructure was grown with layer thicknesses almost as designed. Furthermore, the magnified image confirmed that atoms in the thin AlN barrier layer were well-aligned and epitaxially deposited upon the AlGaInN layer. The room-temperature 2DEG density and mobility for the AlN/AlGaInN/AlGaN heterostructure were measured to be $1.6 \times 10^{13} \text{ cm}^{-2}$ and 213 cm$^2$ V$^{-1}$ s$^{-1}$ via the Hall effect measurement, which correspond to a sheet resistance of approximately 1.8 k$\Omega$/sq. In general, 2DEG mobilities in AlGaN-channel heterostructures are limited in lower values than those for GaN-channel ones owing to the alloy disorder scattering occurred in their ternary alloy channels, and its influence becomes far stronger at alloy compositions near Al$_{0.5}$Ga$_{0.5}$N.\(^{16}\) In accordance with the theoretical calculation,\(^{16}\) the room-temperature 2DEG mobility of an Al$_{0.4}$Ga$_{0.6}$N channel heterostructure is derived to be approximately 250 cm$^2$ V$^{-1}$ s$^{-1}$ versus$^{-1}$ at a 2DEG density of $2 \times 10^{13} \text{ cm}^{-2}$, which seems to be relatively close to the experimental value obtained in this study. In addition to the above, we speculate that there is an influence of the interface roughness scattering occurred at the heterointerface.\(^{16}\)

2.2. Electrical characteristics of Al$_{0.36}$Ga$_{0.64}$N-channel HFETs

Figure 5 shows typical two-terminal $I$–$V$ characteristics for TLM patterns formed on the AlN/AlGaInN/AlGaN heterostructure via the SAG process. For comparison, the figure also shows the result for planar TLM contacts formed on the same AlN/AlGaInN/AlGaN heterostructure without the use of the SAG process. From this comparison, it was confirmed that ohmic properties were clearly improved by adopting the SAG contacts. The contact resistance was estimated to be approximately 13–23 $\Omega$ mm and 33–50 $\Omega$ mm for the samples with and without the SAG contacts, respectively. The large

Fig. 3. (Color online) Surface AFM images for AlGaInN/AlGaN HFETs (a) with and (b) without the 1.5 nm thick AlN barrier layer.

Fig. 4. (Color online) (a) Cross-sectional HAADF-STEM image for the AlN/AlGaInN/AlGaN heterostructure and (b) its magnified image around the dual AlN/AlGaInN barrier layer.

Fig. 5. (Color online) Typical $I$–$V$ characteristics for two-terminal ohmic contacts of TLM patterns, which were formed on AlN/AlGaInN/AlGaN heterostructures with (red lines) and without (grey lines) the use of the SAG process.
variation in contact resistance was probably caused by the ohmic contacts that were still insufficient. From the above, while the SAG contacts surely improved the ohmic contact property, the contact resistance is still large compared with our previous result, in which the Al$_{0.19}$Ga$_{0.81}$N-channel heterostructure with the same SAG contacts showed a low value of approximately 2.5 $\Omega \cdot$mm$^2$. As for this, we speculate that the enlarged energy-bandgap offset between the regrown n$^{++}$-GaN layer and the AlGaN channel layer restricted the reduction of the contact resistance. Therefore, we need additional concepts and optimization for further improvements in the contact resistance of AlGaN-channel heterostructures with high-AlN-mole fractions.

Figures 6(a) and 6(b) show typical drain-to-source $I$–$V$ ($I_{DS}$–$V_{DS}$) characteristics and transfer characteristics ($I_{DS}$–$V_{GS}$ and $g_m$–$V_{GS}$), respectively, for 2 $\mu$m $L_G$ and 6 $\mu$m $L_{GD}$ AlN/AlGaN/AlGaN HFETs with and without the SAG contacts. As observed in these figures, the fabricated devices showed good pinch-off characteristics, and the on-state performance was obviously improved by adopting the SAG contacts, in the same way as the Al$_{0.19}$Ga$_{0.81}$N-channel HFETs that we previously reported. The $I_{DS\text{MAX}}$ and the maximum $g_m$ ($g_{m\text{MAX}}$) of the HFET with the SAG contacts were measured to be 270 mA mm$^{-1}$ and 35 mS mm$^{-1}$, respectively, which correspond to approximately two-fold higher values than those for the HFET without the SAG contacts. Furthermore, the $I_{DS\text{MAX}}$ obtained in this study appears considerably high even when compared with AlGaN-channel transistors ever reported. This improvement is probably attributed to the reduction in the source resistance brought along with the reduction in the contact resistance, as described before. To confirm this, we attempted to estimate the source resistance and intrinsic $g_m$ ($g_{m0}$). Although it was just a rough estimation including some variation in the contact resistance, the source resistance reduction was derived to be at least 20 $\Omega$, roughly 50% reduction, at almost the same $g_{m0}$ values of approximately 200–220 mS mm$^{-1}$. On the other hand, the measured transfer characteristics suggested another issue to be solved. That is, we observed a large difference in threshold voltages between the HFETs with and without the SAG contacts, as shown in Fig. 6(b). This might imply that, while it includes the reproducibility problems of the epitaxial growth and device processes, some negative influence existed in the SAG process. Therefore, we consider further careful investigation necessary in the future to elucidate this phenomenon.

Figure 7 shows the three-terminal off-state $I$–$V$ characteristics measured for the AlGaN/AlGaN HFETs with and without the top AlN barrier layer. For these measurements, the $V_{GS}$ was maintained at $-20$ V. As observed in this figure, both devices exhibited high breakdown voltages of approximately 1 kV, which corresponds to an off-state $E_C$ of 166 V $\mu$m$^{-1}$. From this, it was confirmed for this study’s Al$_{0.36}$Ga$_{0.64}$N-channel HFETs that performance balance of
HFETs with (red lines) and without (grey lines) the top AlN barrier layer.

for the device without the top AlN barrier layer. Figure 8 shows two-terminal gate-to-source currents that for the device without the top AlN barrier, which is in good agreement with the results shown in Fig. 7. From this, we understand that the dual AlN/AlGaInN barrier layer surely contributed to the suppression of the two-terminal and three-terminal leakage currents in AlGaN-channel HFETs.

Using the off-state $E_C$ value obtained from Fig. 7, the relationship between $E_C$ and $x$ for Al$_{x}$Ga$_{1-x}$N-channel transistors was investigated and presented in Fig. 9, in which the other researchers’ results are also plotted for comparison. Here, the devices in this figure did not adopt any field-limiting structure such as field-plate electrodes. As shown in this figure, the off-state $E_C$ of 166 V $\mu$m$^{-1}$ obtained in this study is quite reasonable as an Al$_{0.36}$Ga$_{0.64}$N-channel transistor. Moreover, it was confirmed that the $E_C$ value achieved for this study’s Al$_{0.36}$Ga$_{0.64}$N-channel HFETs was approximately four-fold higher than those for conventional GaN-channel HFETs ($x = 0$) and approximately 1.4 times higher compared with Al$_{0.36}$Ga$_{0.64}$N-channel HFETs with $x \approx 0.2$ that we have ever studied. Therefore, in future research, we can expect further improvement in the off-state breakdown voltages by adopting an optimal electrode design.

## 3. Conclusions

In this study, we fabricated and characterized Al$_{0.36}$Ga$_{0.64}$N-channel HFETs with a dual AlN/Al$_{0.25}$Ga$_{0.15}$N$_{0.005}$N barrier layer, in which a highly Si-doped n$^+$-GaN contact layer formed via the self-alignment SAG was applied to ohmic contacts. The fabricated HFETs with a gate length of 2 $\mu$m and a gate-to-drain length of 6 $\mu$m exhibited a high $I_{DSMAX}$ of approximately 270 mA mm$^{-1}$. The fabricated devices also showed a high off-state breakdown voltage of 1 kV, which corresponds to an off-state $E_C$ of 166 V $\mu$m$^{-1}$. This value is approximately four-fold and 1.4 times higher than those for Al$_{0.36}$Ga$_{0.64}$N-channel HFETs with $x = 0$ and $x \approx 0.2$, respectively, as a comparison in devices without field-plate electrodes. Furthermore, it was confirmed that the device adopting the dual AlN/AlGaInN barrier layer showed approximately one order of magnitude smaller gate leakage currents than for the device without the top AlN barrier layer. From this, we understand that dual AlN/AlGaInN barrier layers are effective to suppress gate leakage currents and stabilize off-state characteristics for high-AlN-mole-fraction AlGaN-channel HFETs.

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