Instructions for use

Title
Current linearity and operation stability in Al2O3-gate AlGaN/GaN MOS high electron mobility transistors

Author(s)
Nishiguchi, Kenya; Kaneki, Syota; Ozaki, Shiro; Hashizume, Tamotsu

Citation
Japanese Journal of Applied Physics (JJAP), 56(10), 101001-1-101001-8
https://doi.org/10.7567/JJAP.56.101001

Issue Date
2017-10

Doc URL
http://hdl.handle.net/2115/67316

Rights
This article is published under a CC BY licence. The Version of Record is available online at 10.7567/JJAP.56.101001.

Rights(URL)
https://creativecommons.org/licenses/by/4.0/

Type
article

File Information
Jpn.J.Appl.Phys.56.101001.pdf

Hokkaido University Collection of Scholarly and Academic Papers: HUSCAP
Current linearity and operation stability in Al2O3-gate AlGaN/GaN MOS high electron mobility transistors

Kenya Nishiguchi1,*, Syota Kaneki1, Shiro Ozaki1,2, and Tamotsu Hashizume1,*

1Graduate School of Information and Science Technology and Research Center for Integrated Quantum Electronics (RCiQE), Hokkaido University, Sapporo 060-8628, Japan
2Fujitsu Laboratories Ltd., Atsugi, Kanagawa 243-0197, Japan
*E-mail: nishiguchi@rciqe.hokudai.ac.jp; hashi@rciqe.hokudai.ac.jp

Received June 19, 2017; accepted August 1, 2017; published online September 11, 2017

To investigate current linearity and operation stability of metal-oxide–semiconductor (MOS) AlGaN/GaN high electron mobility transistors (HEMTs), we have fabricated and characterized the Al2O3-gate MOS-HEMTs without and with a bias annealing in air at 300 °C. Compared with the as-fabricated (unannealed) MOS HEMTs, the bias-annealed devices showed improved linearity of $I_D-V_G$ curves even in the forward bias regime, resulting in increased maximum drain current. Lower subthreshold slope was also observed after bias annealing. From the precise capacitance–voltage analysis on a MOS diode fabricated on the AlGaN/GaN heterostructure, it was found that the bias annealing effectively reduced the state density at the Al2O3/AlGaN interface. This led to efficient modulation of the AlGaN surface potential close to the conduction band edge, resulting in good gate control of two-dimensional electron gas density even at forward bias. In addition, the bias-annealed MOS HEMT showed small threshold voltage shift after applying forward bias stress and stable operation even at high temperatures. © 2017 The Japan Society of Applied Physics

1. Introduction

GaN-based high electron mobility transistors (HEMTs) have been making steady progress in high-frequency and high-power performances.1–5 Electron saturation velocity as high as $2 \times 10^7$ cm/s and high two-dimensional electron gas (2DEG) density of over $1 \times 10^{12}$ cm$^{-2}$, originating from spontaneous and piezoelectric polarization fields as well as from large conduction band offset, are well-suited for high power radio frequency (RF) applications. By downsizing of the gate length to sub-100 nm regime in conjunction with state-of-the-art technologies, Shinhara and co-workers2,6 have recently achieved ultrahigh-speed operation with record-high $f_T$ of 454 GHz with accompanying power gain cutoff frequency ($f_{max}$) of 444 GHz on a 20 nm gate HEMT. These are fairly desirable for the fifth generation (5G) communication system where the W-band (75–110 GHz) and the E-band (60–90 GHz) frequency ranges are expected to be used for wireless backhaul of mobile communications.

The 5G wireless system also requires higher efficiency and linearity for RF power transistors. Power amplifiers using Schottky-gate (SG) GaN HEMTs suffer from reduced gain and efficiency with increasing input RF power due to significant gate leakage currents caused by a large input swing that may drive the devices deep into the forward bias regime.7 In addition, such high leakage currents seriously affect the operation stability and large signal linearity of power amplifiers. Moreover, SG-HEMTs suffer from the current collapse issues,8 which persist even after the combined application of field plate structures and surface passivation schemes. A possible reason for this is negative surface charges induced by the tunneling injection of electrons into surface states via the SG edge. Nishiguchi et al.9) and Katsumo et al.10) pointed out that such charging region can extend as far as 0.5 μm from the gate edge toward the drain electrode in SG AlGaN/GaN HEMTs without surface passivation.

A metal–insulator–semiconductor (MIS) structure is very effective to overcome such problems related to SG structure. Kanamura et al.7) demonstrated that gate leakage current was sufficiently controlled in the AlGaN/GaN MIS-HEMT even under high input power operation. Thus, a MIS-HEMT can accomodate a wider range of input signal sweep, resulting in higher maximum output power. Furthermore, Tajima and Hashizume11) pointed out that the current collapse was significantly reduced in Al2O3-gate AlGaN/GaN HEMTs, as compared with SG HEMTs with only surface passivation. In particular, the MIS structure will be absolutely necessary for InAlN/GaN HEMTs. It is known that GaN HEMTs using an MIS structure will be absolutely necessary for InAlN/GaN HEMTs. It is known that GaN HEMTs using an MIS structure is very effective to reduce the gate leakage current in SG InAlN/GaN HEMTs due to the large internal electric field in the InAlN barrier layer. Appropriately, the MIS structure is well-suited for addressing the leakage current issue and therefore promoting the performance of InAlN/GaN HEMTs.15,16

Although various kinds of insulator materials have been applied to improve the performance of GaN-based MIS HEMTs, several problems remain unsolved.17) The most serious problem is the threshold voltage ($V_{TH}$) instability, as schematically shown in Fig. 1(a). Several papers reported that different bias conditions induce varying degrees of $V_{TH}$ shift in MIS HEMTs.18–23) Lu et al.18) and Johnson et al.21) reported that higher positive gate biasing of the MIS HEMTs induces larger $V_{TH}$ shift toward the forward bias direction. There are two possible mechanisms for this issue. Under a high positive gate bias, the Fowler–Nordheim (FN) tunneling mechanism can enhance the gate leakage current. In this case, electrons injected into trap levels in insulators cause excess negative charges, resulting in the $V_{TH}$ shift toward the positive bias direction. The high positive gate bias also
supplies electrons to electronic states at the insulator/barrier (AlGaN or InAlN) interface, and the acceptor-type states produce negative charges when they trap electrons. Due to the long associated time constant for electron emission even at RT, electrons captured at deeper interface states remain trapped during the entire duration of gate sweeping toward the negative bias direction.17,24) This also causes the $V_{TH}$ shift toward the positive bias direction in the $I_D-V_G$ characteristics, as schematically shown in Fig. 1(a).

Another problem is an unexpected degradation of current linearity in GaN-based MIS HEMTs. Although a dynamic range of input signal sweeping is one of advantages in MIS HEMTs, some groups reported on the sudden current saturation at forward bias25,26) as shown in Fig. 1(b). It is likely that a high density of electronic states at the insulator/barrier interface, in particular near the conduction band edge, screens the gate electric field and causes a limited control of surface potential of the barrier layer. This prevents further increase in the 2DEG density, leading to pronounced current saturation at forward gate bias. Such degradation of current linearity can be responsible for gain loss and degradation of large signal linearity in power amplifiers.

Accordingly, this paper presents DC characterization of AlGaN/GaN MOS HEMTs using Al$_2$O$_3$ focusing on the impact of interface states on current linearity and operation stability. To control electronic states at the Al$_2$O$_3$/AlGaN interface, MOS HEMTs were subjected to a bias annealing under air atmosphere.

2. Device fabrication and reverse-bias annealing processes

2.1 Device structure and fabrication process

Figure 2 schematically shows the cross-section of MOS-HEMT device studied in this work. Al$_{0.24}$Ga$_{0.76}$N/GaN heterostructure grown on SiC substrate by metal organic chemical vapor deposition (MOCVD) was used as the starting wafer. The 2DEG density and mobility of the AlGaN/GaN heterostructure were 9.0 × 10$^{12}$ cm$^{-2}$ and 1740 cm$^2$ V$^{-1}$ s$^{-1}$, respectively. Ti/Al/Ti/Au (= 20/50/20/50 nm) source and drain electrodes were deposited on the AlGaN surface, followed by ohmic annealing at 830 °C for 1 min in N$_2$ ambient. As a surface protection layer during ohmic annealing, a 20-nm-thick SiN film was deposited to prevent damage to the AlGaN surface.27) After the ohmic metallization process, the SiN film was removed using a buffered HF solution. An Al$_2$O$_3$ layer with a nominal thickness of 30 nm was then deposited on the AlGaN surface using an atomic layer deposition (ALD) system (SUGA-SAL1500) at 300 °C. In the deposition process, water vapor and trimethylaluminum were introduced into a reactor in alternate pulse forms. Each precursor was injected into the reactor for 15 ms, and the purging time was set to 5 s. In this case, the deposition rate is 0.11 nm/cycle, facilitating the formation of Al$_2$O$_3$ in a layer-by-layer fashion. Finally, the device fabrication was completed by electron beam evaporation of Ni/Au bilayer and subsequent lift-off process to form the gate electrode. The gate length, gate width, and gate–drain distance were 5, 100, and 10 µm, respectively.

2.2 Reverse-bias annealing process

To improve the interface properties of GaN MIS structures, we have carried out various kinds of control processes including post-deposition and post-metallization annealing processes. As described in Ref. 28, a standard post-deposition annealing at 400–700 °C in N$_2$ for 30 min was effective in decreasing state densities at the Al$_2$O$_3$/GaN interface. Even in this case, however, the interface state density of 5 × 10$^{11}$ cm$^{-1}$ eV$^{-1}$ or higher remained, indicating that the post-deposition annealing is insufficient for controlling interface states. We then found that the post-metallization annealing in air at 300 °C for several hours is more effective in achieving better capacitance–voltage (C–V) characteristics than a conventional post-deposition annealing.29) Next, we focused on the occupation condition of interface states during the post-metallization annealing in air, because it can be coupled with change in atomic-bonding configuration at the interface. Then we chose two bias conditions, i.e., an accumulation forward bias (typically +5 V) for occupied interface states with electrons and a deep reverse bias (typically −10 V) for empty interface states. As a result, excellent C–V characteristics with negligible frequency dispersion were observed from the MOS sample after annealing under a reverse bias at 300 °C in air for 3 h.29) The reverse-bias annealing achieved interface state densities less than 8 × 10$^{10}$ cm$^{-2}$ eV$^{-1}$, probably due to the relaxation of dangling bonds and/or reduction of point defects on the GaN surface (Al$_2$O$_3$/GaN interface). We also observed small shifts of flat-band voltage and stable C–V behavior at 200 °C for bias annealed Al$_2$O$_3$/GaN diodes. In this work, we expect that the desirable effects of the reverse-bias annealing can be extended to AlGaN/GaN MOS HEMTs, thereby giving an alternative method in pushing the performance of these devices when applied in high power and high frequency applications.

![Fig. 1. (Color online) (a) Illustrations of $V_{TH}$ shift due to forward bias stress and (b) $I_D$ saturation behavior at forward bias.](image1)

![Fig. 2. (Color online) Schematic cross-sectional view of the Al$_2$O$_3$/Al$_{0.24}$Ga$_{0.76}$N/GaN MOS HEMT structure.](image2)
After bias annealing, the subthreshold slope was decreased to 112 mV/dec. In Fig. 5, a high value of subthreshold slope of MOS-HEMTs from the semi-log scale voltage (V_D) are replotted in Fig. 4(b). The bias-annealing process effectively improved the current linearity, particularly in forward bias, resulting in a broader gm plateau and increased maximum drain current. This effect is important for the MOS-HEMT in terms of the input dynamic range at forward bias. We then calculated the subthreshold slope of MOS-HEMTs from the semi-log scale I_D–V_G characteristics shown in Fig. 5. A high value of subthreshold slope of 148 mV/dec was obtained before the bias annealing. After bias annealing, the subthreshold slope was decreased down to 112 mV/dec. In addition, the V_TH change and significant decrease in gate leakage current were observed in the MOS-HEMT after the bias annealing, as shown in Fig. 5. A possible mechanism for these will be discussed later.

To investigate interface properties of the Al2O3/AlGaN layer connected in series. At forward bias, the nearly flat band condition of the AlGaN layer can lead to the electron spillover from the AlGaN/GaN to Al2O3/AlGaN interfaces. Consequently, the effective capacitance approaches that of the insulator capacitance.

To evaluate the effects of interface states on the C–V characteristics, one-dimensional simulation including self-consistent Poisson–Schrödinger calculations was carried out for the Al2O3/AlGaN/GaN structure, taking into account a state density distribution [D(E)] consisting of acceptor- and donor-like states separated by the charge neutrality level frequency of 1 MHz at RT are shown in Fig. 6(a). Both diodes without and with the bias annealing showed the two-step behavior typically observed in HEMT MOS structures. The first step at reverse bias indicates the depletion of 2DEG at the AlGaN/GaN interface. The following capacitance plateau corresponds to the equivalent capacitance of Al2O3 and AlGaN layers connected in series. At forward bias, the nearly flat band condition of the AlGaN layer can lead to the electron spillover from the AlGaN/GaN to Al2O3/AlGaN interfaces. Consequently, the effective capacitance approaches that of the insulator capacitance.

To evaluate the effects of interface states on the C–V characteristics, one-dimensional simulation including self-consistent Poisson–Schrödinger calculations was carried out for the Al2O3/AlGaN/GaN structure, taking into account a state density distribution [D(E)] consisting of acceptor- and donor-like states separated by the charge neutrality level frequency of 1 MHz at RT are shown in Fig. 6(a). Both diodes without and with the bias annealing showed the two-step behavior typically observed in HEMT MOS structures. The first step at reverse bias indicates the depletion of 2DEG at the AlGaN/GaN interface. The following capacitance plateau corresponds to the equivalent capacitance of Al2O3 and AlGaN layers connected in series. At forward bias, the nearly flat band condition of the AlGaN layer can lead to the electron spillover from the AlGaN/GaN to Al2O3/AlGaN interfaces. Consequently, the effective capacitance approaches that of the insulator capacitance.

To evaluate the effects of interface states on the C–V characteristics, one-dimensional simulation including self-consistent Poisson–Schrödinger calculations was carried out for the Al2O3/AlGaN/GaN structure, taking into account a state density distribution [D(E)] consisting of acceptor- and donor-like states separated by the charge neutrality level frequency of 1 MHz at RT are shown in Fig. 6(a). Both diodes without and with the bias annealing showed the two-step behavior typically observed in HEMT MOS structures. The first step at reverse bias indicates the depletion of 2DEG at the AlGaN/GaN interface. The following capacitance plateau corresponds to the equivalent capacitance of Al2O3 and AlGaN layers connected in series. At forward bias, the nearly flat band condition of the AlGaN layer can lead to the electron spillover from the AlGaN/GaN to Al2O3/AlGaN interfaces. Consequently, the effective capacitance approaches that of the insulator capacitance.

To evaluate the effects of interface states on the C–V characteristics, one-dimensional simulation including self-consistent Poisson–Schrödinger calculations was carried out for the Al2O3/AlGaN/GaN structure, taking into account a state density distribution [D(E)] consisting of acceptor- and donor-like states separated by the charge neutrality level frequency of 1 MHz at RT are shown in Fig. 6(a). Both diodes without and with the bias annealing showed the two-step behavior typically observed in HEMT MOS structures. The first step at reverse bias indicates the depletion of 2DEG at the AlGaN/GaN interface. The following capacitance plateau corresponds to the equivalent capacitance of Al2O3 and AlGaN layers connected in series. At forward bias, the nearly flat band condition of the AlGaN layer can lead to the electron spillover from the AlGaN/GaN to Al2O3/AlGaN interfaces. Consequently, the effective capacitance approaches that of the insulator capacitance.
bands, respectively. Therefore, the charging character of forbidden band (bandgap) from valence and conduction penetration of bonding and anti-bonding states into the insulator surface. In this case, the separation of conduction in atomic-bond arrangement can be induced at the semi-insulator.

For the calculation, we assumed an arbitrary $D_n$ distribution used for calculation. (Color online) Calculated $D_{CT}(E)$ using $t_{\text{meas}} = 100$ s, $\sigma = 1 \times 10^{-16}$ cm$^{-2}$ and $\tau(E)$ obtained from Eq. (2).

\begin{equation}
D_{\text{si}} = D_{\text{si}0} \exp \left( \frac{E - E_{\text{CNL}}}{E_{\text{OA}}} \right)^{n_A}.
\end{equation}

\begin{equation}
D_{\text{si}} = D_{\text{si}0} \exp \left( \frac{E_{\text{CNL}} - E}{E_{\text{OD}}} \right)^{n_D},
\end{equation}

where $D_{\text{si}0}$ is the minimum state density. $E_{\text{OA}}$ and $n$ define the curvature of the $D_{\text{si}}$ distribution, as shown in Fig. 6(b). In addition, we can estimate electron emission time constant $\tau(E)$ from interface states to the conduction band using Shockley–Read–Hall (SRH) statistics:

\begin{equation}
\tau(E) = \frac{1}{v_{\text{TH}} \sigma_{\text{TH}} N_C} \exp \left( \frac{E_T}{kT} \right),
\end{equation}

where $v_{\text{TH}}$, $\sigma_{\text{TH}}$, $N_C$, and $E_T$ are electron thermal velocity, capture cross section of interface states, density of state at the conduction band, and interface state energy, respectively. From $\tau(E)$ and the experimental $C–V$ measurement time ($t_{\text{meas}}$), we calculated the effective emission coefficient $D_{CT}(E)$ of interface states:

\begin{equation}
D_{CT}(E) = 1 - \exp \left[ -\frac{t_{\text{meas}}}{\tau(E)} \right]
\end{equation}

Figure 7 shows the calculated $D_{CT}(E)$ at RT using $t_{\text{meas}} = 100$ s and $\sigma = 1 \times 10^{-16}$ cm$^{-2}$. According to Eq. (2), $\tau(E)$ of interface states near midgap or deeper are too large at RT, resulting in $D_{CT}(E) = 0$. This means that electrons once captured at such deep interface states remain trapped even when large negative bias is applied to the gate electrode. It is estimated from Fig. 7 that interface states at energies below $E_C - 0.8$ eV behave like “frozen states”. By considering $D_{CT}(E)$ and Fermi–Dirac occupation function, we obtained interface state charges (ionized state density) at a given gate voltage $V_G$. Then we calculated $C–V$ curve based on the potential and electron density distributions by numerically solving Poisson–Schrödinger equations, and compared experimental and calculated $C–V$ curves. If we observed the discrepancy between them, then the $D_n$ distribution was modified and the recalculation was repeatedly carried out.

Figure 6 (Color online) (a) $C–V$ characteristics of the Al$_2$O$_3$/AlGaN/GaN MOS diodes. The solid line indicates calculated curves. (b) Schematic illustration of interface state density ($D_n$) distribution used for calculation. (c) $D_n$ distributions determined by the fitting of $C–V$ curves.

$E_{\text{CNL}}$ as schematically shown in Fig. 6(b). Along the insulator–semiconductor interface, the crystalline periodicity of the semiconductor is terminated. In addition, disorder in atomic-bond arrangement can be induced at the semiconductor surface. In this case, the separation of conduction and valence bands becomes insufficient, resulting in the penetration of bonding and anti-bonding states into the forbidden band (bandgap) from valence and conduction bands, respectively. Therefore, the charging character of interface states also reflects those of valence and conduction bands. Namely, a negative charge appears in the conduction band if a state is occupied by an electron (acceptor-like character), while valence band state is positively charged when unoccupied (donor-like character). Thus, it can be assumed that the interface state continuum consists of a mixture of acceptor-like and donor-like states, as schematically shown in Fig. 6(b), and their branch point act as the $E_{\text{CNL}}$. This model is often used as a density distribution of interface states.

For the calculation, we assumed an arbitrary $D_n$ distribution using the following equations:

\begin{equation}
D_{\text{si}} = D_{\text{si}0} \exp \left( \frac{E - E_{\text{CNL}}}{E_{\text{OA}}} \right)^{n_A}.
\end{equation}

\begin{equation}
D_{\text{si}} = D_{\text{si}0} \exp \left( \frac{E_{\text{CNL}} - E}{E_{\text{OD}}} \right)^{n_D},
\end{equation}

where $D_{\text{si}0}$ is the minimum state density. $E_{\text{OA}}$ and $n$ define the curvature of the $D_{\text{si}}$ distribution, as shown in Fig. 6(b). In addition, we can estimate electron emission time constant $\tau(E)$ from interface states to the conduction band using Shockley–Read–Hall (SRH) statistics:

\begin{equation}
\tau(E) = \frac{1}{v_{\text{TH}} \sigma_{\text{TH}} N_C} \exp \left( \frac{E_T}{kT} \right),
\end{equation}

where $v_{\text{TH}}$, $\sigma_{\text{TH}}$, $N_C$, and $E_T$ are electron thermal velocity, capture cross section of interface states, density of state at the conduction band, and interface state energy, respectively.

From $\tau(E)$ and the experimental $C–V$ measurement time ($t_{\text{meas}}$), we calculated the effective emission coefficient $D_{CT}(E)$ of interface states:

\begin{equation}
D_{CT}(E) = 1 - \exp \left[ -\frac{t_{\text{meas}}}{\tau(E)} \right]
\end{equation}

Figure 7 shows the calculated $D_{CT}(E)$ at RT using $t_{\text{meas}} = 100$ s and $\sigma = 1 \times 10^{-16}$ cm$^{-2}$. According to Eq. (2), $\tau(E)$ of interface states near midgap or deeper are too large at RT, resulting in $D_{CT}(E) = 0$. This means that electrons once captured at such deep interface states remain trapped even when large negative bias is applied to the gate electrode. It is estimated from Fig. 7 that interface states at energies below $E_C - 0.8$ eV behave like “frozen states”. By considering $D_{CT}(E)$ and Fermi–Dirac occupation function, we obtained interface state charges (ionized state density) at a given gate voltage $V_G$. Then we calculated $C–V$ curve based on the potential and electron density distributions by numerically solving Poisson–Schrödinger equations, and compared experimental and calculated $C–V$ curves. If we observed the discrepancy between them, then the $D_n$ distribution was modified and the recalculation was repeatedly carried out.

Physical parameters used in the calculation are summarized in Table I.

Using the $D_n$ distributions shown in Fig. 6(c), the calculation well reproduced the experimental $C–V$ data, as indicated by solid lines in Fig. 6(a). As described above, only the acceptor-like traps in the energy range indicated by solid lines in Fig. 6(c) can change their charge state accordingly with the gate voltage sweep at RT. Note, in addition, that it is difficult to evaluate the state density distribution at energies
Table I. Parameters used in the calculations. $m_0$ is the mass of a free electron, \( q \) is the elementary charge, and AlGaN denotes Al$_{0.24}$Ga$_{0.76}$N.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Symbol (unit)</th>
<th>Numerical value (material or interface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap at RT</td>
<td>( E_G ) (eV)</td>
<td>3.4 (GaN)(^{39}), 3.89 (AlGaN)(^{39,39}), 7.0 (Al$_2$O$_3$)(^{41})</td>
</tr>
<tr>
<td>Effective mass of electron ( m_e/m_0 )</td>
<td>( m_e ) (GaN)</td>
<td>0.20, 0.23 (AlGaN)</td>
</tr>
<tr>
<td>Relative permittivity ( \varepsilon )</td>
<td>( \varepsilon ) (GaN)</td>
<td>9.5, 9.2 (Al$<em>{0.24}$Ga$</em>{0.76}$N), 9.0 (Al$_2$O$_3$)</td>
</tr>
<tr>
<td>Band offset ( \Delta E_C ) (eV)</td>
<td>( \Delta E_C ) (AlGaN/GaN)(^{39})</td>
<td>0.34, 2.1 (Al$_2$O$_3$/AlGaN)(^{41})</td>
</tr>
<tr>
<td>Surface barrier height ( \phi_s ) (eV)</td>
<td>( \phi_s ) (Ni/Al$_2$O$_3$)(^{40})</td>
<td>8 ( \times ) 10$^{-12}$ (AlGaN/GaN)</td>
</tr>
<tr>
<td>Charge neutrality level ( E_{CNL} )</td>
<td>( E_{CNL} ) (Al$_2$O$_3$/AlGaN)(^{32})</td>
<td>1.3 eV (Al$_2$O$_3$)</td>
</tr>
<tr>
<td>Capture cross section of interface states</td>
<td>( \sigma ) (cm$^2$)</td>
<td>1 ( \times ) 10$^{-16}$ ( \times ) 30</td>
</tr>
<tr>
<td>C–V Measurement duration ( t ) (s)</td>
<td>( t ) (s)</td>
<td>100</td>
</tr>
</tbody>
</table>

above \( E_C = 0.2 \text{ eV} \) from C–V measurements using frequency of 1 MHz, because electron trapping/detrapping processes at such shallow interface states can respond to the measurement AC signal and accordingly give an inaccurate estimate of capacitance. Therefore, state densities at the energies above \( E_C = 0.2 \text{ eV} \) were not considered for the present C–V calculation.

As shown in Fig. 6(c), the Al$_2$O$_3$/AlGaN interface without annealing showed high interface state densities of order \( 1 \times 10^{13} \text{ cm}^{-2} \text{ eV}^{-1} \). The bias annealing process effectively decreased the state densities, leading to the steeper C–V slope in forward bias shown in Fig. 6(a). The calculated \( V_{TH} \) corresponding to the first step in the C–V curve was \(-7.5 \text{ V} \), very close to that of the MOS-HEMT subjected to bias annealing, as shown in Fig. 6(a). On the other hand, the sample without the annealing showed a \( V_{TH} \) shift toward the negative bias direction, probably due to excess positive charges arising from donor-type interface states and/or defect levels in the bulk Al$_2$O$_3$. When a fixed charge of \( +1.2 \times 10^{13} \text{ cm}^{-2} \) was assumed in the Al$_2$O$_3$ layer or at the Al$_2$O$_3$/AlGaN interface, the calculation reproduced the experimental C–V result for the HEMT without annealing, as shown in Fig. 6(a). A possible candidate for a defect level in Al$_2$O$_3$ is an oxygen-vacancy related defect.\(^{32,43}\) The bias-annealing process decreased such levels, resulting in the \( V_{TH} \) recovery toward the expected value. Zhou et al.\(^{44}\) also reported similar \( V_{TH} \) recovery with a post-deposition annealing in Al$_2$O$_3$/AlGaN/ GaN MOS-HEMTs. As shown in Fig. 5, in addition, we observed decrease in gate leakage current in the MOS-HEMT after the bias annealing. For the GaN-based MIS-HEMTs using Al$_2$O$_3$, Si$_N_4$, and AlTiO, it has been reported that the Poole–Frenkel (PF) emission conduction was dominant for leakage current.\(^{35–48}\) Similarly to the \( V_{TH} \) recovery behavior, there is a possibility the reduction of leakage current arises from decrease in defect levels in the Al$_2$O$_3$ layer, contributing to the suppression of the PF hopping conduction.

The C–V analysis showed that the bias annealing process effectively decreased state densities at the Al$_2$O$_3$/AlGaN interface, leading to the improvement of current linearity, as shown in Fig. 4. To gain a better insight into the relationship between interface states and gate controllability of the MOS-HEMT, we calculated surface potential (\( V_S \)) of AlGaN shown in Fig. 8(a) and the 2DEG density as a function of gate overdrive, taking into account \( D_s \) distributions obtained from the C–V analysis [Fig. 6(c)].

Figures 8(b) and 8(c) show the calculated \( V_S \) as a function of gate overdrive for the MOS-HEMTs without and with bias annealing. In the gate bias range up to 10 V, both devices showed the same \( V_S \) change. This gate voltage corresponds to \( qV_S = 0.8 \text{ eV} \). As mentioned above, interface states at energies below \( E_C = 0.8 \text{ eV} \) are considered to be “frozen states”, i.e., negligible effect on the \( V_S \) control. Beyond \( V_G – V_{TH} = 10 \text{ V} \), acceptor states shown in Fig. 6(c) are active accordingly with the gate voltage sweeping, and the
ionized acceptor charges screen the gate electric field. Thus high-density states prevent $V_g$ modulation (poor potential control) for the MOS-HEMT without the bias annealing. Such $V_g$ behavior is directly related to the control of the 2DEG density, as shown in Fig. 8(c). The limited increase in the 2DEG density with $V_G$ is clearly observed for the MOS-HEMT without the bias annealing. On the other hand, the MOS-HEMT with annealing shows relatively good control of 2DEG by $V_G$. The calculated results shown in Fig. 8(c) are similar to the measured $I_D$--$V_G$ curves of MOS-HEMTs shown in Fig. 4(b), indicating that the effective reduction of interface states is responsible for the improved linearity in MOS-HEMT with bias annealing.

It should be mentioned that some papers reported poor current linearity in MIS-type AlGaN/GaN HEMTs. To investigate current linearity behavior, we tried to plot the full width at half maxima (FWHM) of $g_m$--$V_G$ profiles as a function of the equivalent oxide thickness (EOT) including insulator and AlGaN barrier layers. Figure 9 shows comparison of FWHM of $g_m$ for AlGaN/GaN MIS-HEMTs using SiO$_2$, Al$_2$O$_3$, SiN, HfO$_2$, AlN, and TiO$_2$ dielectric materials. Our data are also included in Fig. 9. It is expected that the FWHM of $g_m$ increases with EOT, and experimental data generally showed this tendency. However, there is a wide scattering of data, indicating that interface properties of insulator/AlGaN structures are not dependent on the insulator material used but on the bond disorder and/or surface defects on the AlGaN surface, probably related to fabrication process conditions including deposition methods.

The broken line is a guide to the eye for the better results reported. Our device with the bias annealing showed high FWHM value, demonstrating excellent current linearity in our AlGaN/GaN MOS-HEMTs.

### 3.2 Operation stability of AlGaN/GaN MOS-HEMTs

To evaluate operation stability of the MOS-HEMT, the $V_{TH}$ shift after applying forward bias stress was also investigated. For fair comparison, the equivalent stress bias with respect to $V_G$ -- $V_{TH}$ was applied to the MOS-HEMTs without and with the bias annealing ($V_G$ -- $V_{TH}$ = 23 V), as shown in Fig. 10. The gate stress time was 10 s, while keeping $V_D$ = 15 V. Then the $I_D$--$V_G$ characteristics were measured from $V_G$ = 0 V toward the negative bias direction, as shown in Fig. 10. The broken lines indicate the transfer curves without the stress bias annealing.

We then measured the transfer characteristics of the devices at a higher temperature of 100 °C. As shown in Fig. 11, both devices showed about 30% reduction in $g_m$ and decreased maximum drain current, as compared with those measured at RT. This is consistent with the results reported by Husna et al. and Suria et al., and mainly due to the reduction of electron mobility attributed to optical phonon scattering at high temperatures. As shown in Fig. 11(a), the MOS-HEMT without the annealing showed a deeper $V_{TH}$ shift at 100 °C.
Husna et al. 68 and Yang et al. 72 reported similar $V_{TH}$ shift at high temperature, and pointed out a possibility that some of donor-like defect levels such as oxygen vacancies in Al$_2$O$_3$ can detrap larger number of electrons at elevated temperatures, resulting in excess positive charges driving the $V_{TH}$ toward the negative bias direction. According to the SRH statistics, in addition, deeper interface states can emit electrons to the conduction band at higher temperatures, relatively increasing the number of positive charges at the Al$_2$O$_3$/AlGaN interface. High densities of states for the MOS-HEMT without the annealing, as shown in Fig. 6(c), enhance this charging effect. On the other hand, the $V_{TH}$ of the MOS-HEMT with the bias annealing remained unchanged even at 100 °C, as shown in Fig. 11(b), probably due to the reduction of defect levels in Al$_2$O$_3$ and interface states.

4. Conclusions

To improve current linearity and operation stability, bias annealing in air at 300 °C was applied to AlGaN/GaN MOS-HEMTs using Al$_2$O$_3$ as gate oxide. The device without annealing showed a sudden current saturation at forward bias. On the other hand, the MOS HEMT with the annealing showed improved current linearity, resulting in the increase in the maximum drain current. Lower subthreshold slope was also observed after the bias annealing. From the precise C–V analysis on the MOS diode fabricated on the AlGaN/GaN heterostructure, it was found that the bias annealing effectively reduced the state density at the Al$_2$O$_3$/AlGaN interface. This led to efficient modulation of the AlGaN surface potential closely to the conduction band edge, resulting in good gate control of 2DEG density even at forward bias. In addition, the MOS HEMT with the annealing showed smaller threshold voltage shift after applying forward bias stress. For the device without annealing, the $V_{TH}$ measured at 100 °C was much deeper than that at RT. On the other hand, such temperature-dependent change in the $V_{TH}$ was not observed for the MOS-HEMT with the annealing. We therefore demonstrated that bias annealing in air is effective in improving current linearity and operation stability of Al$_2$O$_3$/AlGaN/GaN MOS-HEMTs.

Acknowledgments

This work was partially supported by JSPS KAKENHI Grant Number JP16H06421, Strategic International Collaborative Research Program (SICORP), Japan Science and Technology Agency (JST) and Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), “Next-generation power electronics” (funding agency: NEDO).