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# Insulator-semiconductor interface fixed charges in AlGaN/GaN metal-insulator-semiconductor devices with Al<sub>2</sub>O<sub>3</sub> or AlTiO gate dielectrics

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We have investigated insulator-semiconductor interface fixed charges in AlGaN/GaN metalinsulator-semiconductor (MIS) devices with  $Al_2O_3$  or AlTiO (an alloy of  $Al_2O_3$  and TiO<sub>2</sub>) gate dielectrics obtained by atomic layer deposition on AlGaN. Analyzing insulator-thickness dependences of threshold voltages for the MIS devices, we evaluated positive interface fixed charges, whose density at the AlTiO/AlGaN interface is significantly lower than that at the  $Al_2O_3/AlGaN$ interface. This and a higher dielectric constant of AlTiO lead to rather shallower threshold voltages for the AlTiO gate dielectric than for  $Al_2O_3$ . The lower interface fixed charge density also leads to the fact that the two-dimensional electron concentration is a decreasing function of the insulator thickness for AlTiO, whereas being an increasing function for  $Al_2O_3$ . Moreover, we discuss the relationship between the interface fixed charges and interface states. From the conductance method, it is shown that the interface state densities are very similar at the  $Al_2O_3/AlGaN$ and AlTiO/AlGaN interfaces. Therefore, we consider that the lower AlTiO/AlGaN interface fixed charge density is not owing to electrons trapped at deep interface states compensating the positive fixed charges and can be attributed to a lower density of oxygen-related interface donors. *Published by AIP Publishing*. https://doi.org/10.1063/1.5017668

#### I. INTRODUCTION

GaN-based heterojunction field-effect transistors (HFETs)<sup>1</sup> are important devices owing to their high current drive capability and high breakdown voltages. However, there are several disadvantages of GaN-based HFETs; selfheating effects,<sup>2–4</sup> current collapse phenomena,<sup>5,6</sup> and also gate leakage currents are limiting factors for the practical use of these devices. For the suppression of gate leakage currents and the current collapse phenomena in GaN-based devices, it can be effective to employ metal-insulator-semiconductor (MIS) structures, which are also significant to normally off operations,<sup>7</sup> even though GaN-based MIS devices sometimes exhibit unstable characteristics.<sup>8–12</sup> As a gate dielectric of GaN-based MIS devices, high-dielectric-constant (high-k) insulators, such as Al<sub>2</sub>O<sub>3</sub>,<sup>13</sup> HfO<sub>2</sub>,<sup>14,15</sup> TaON,<sup>16</sup> AlN,<sup>17–21</sup> BN,<sup>22,23</sup> and AlTiO,<sup>24</sup> have been investigated. In GaN-based MIS device processing, when an insulator is deposited on a negatively polarized III-N semiconductor surface, such as Ga-face (Al)GaN, positive insulator-semiconductor interface fixed charges tend to be generated and to cancel the negative polarization charges.<sup>25–32</sup> However, the existence of the insulator-semiconductor interface fixed charges is not a necessity.<sup>29,30</sup> Since the interface fixed charges have significant impacts on threshold voltages  $V_{\rm th}$ , we expect that  $V_{\rm th}$ can be controlled by "interface charge engineering,"<sup>29</sup> i.e., by controlling the interface fixed charges. In particular, if the positive interface fixed charge density is sufficiently suppressed, a normally off operation can be expected.<sup>33,34</sup>

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However, despite many reports on the interface fixed charges, their sufficient control is a remaining issue. Moreover, their origin is not fully elucidated even though they are attributed to positively ionized oxygen donors in some cases. Therefore, further investigations on insulator-semiconductor interface fixed charges for GaN-based MIS devices are very necessary and important towards  $V_{\rm th}$  control and normally off operations.

In this work, we investigated insulator-semiconductor interface fixed charges in AlGaN/GaN MIS devices with Al2O3 or AlTiO (an alloy of Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub><sup>35-37</sup>) gate dielectrics, which are deposited on an AlGaN/GaN heterostructure by atomic layer deposition (ALD). AlTiO has, depending on its composition, intermediate physical properties between Al<sub>2</sub>O<sub>3</sub>  $(k \sim 9 \text{ and } E_g \sim 7 \text{ eV})$  and TiO<sub>2</sub>  $(k \sim 60 \text{ and } E_g \sim 3 \text{ eV})$ <sup>37</sup> being useful to balance the trade-off between k and energy gap  $E_{g}$ . Previously, we fabricated AlTiO/AlGaN/GaN MIS devices with excellent characteristics, indicating that AlTiO can be an important candidate for a gate dielectric of GaN-based MIS devices.<sup>24</sup> The present work involves a comparative study on insulator-semiconductor interface fixed charges in Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices. By analyzing linear insulator-thickness dependences of  $V_{\rm th}$ , we evaluated insulator-semiconductor interface fixed charges. As a result, we find that the fixed charge density at the AlTiO/AlGaN interface is significantly lower than that at the Al<sub>2</sub>O<sub>3</sub>/AlGaN interface. In addition, we also discuss the relationship between the interface fixed charges and interface states. It is suggested that the lower AlTiO/AlGaN interface fixed charge density is not owing to electrons trapped at deep interface states.

#### **II. DEVICE FABRICATION**

Using an Al<sub>0.27</sub>Ga<sub>0.73</sub>N(30 nm)/GaN(3000 nm) heterostructure grown by metal-organic vapor phase epitaxy on sapphire(0001), we fabricated AlGaN/GaN MIS devices with Al<sub>2</sub>O<sub>3</sub> or AlTiO gate dielectrics. The device fabrication was started with Ti/Al/Ti/Au Ohmic electrode formation. After surface treatments using organic solvents, oxygen plasma ashing, and an ammonium-based solution, insulator films of Al<sub>2</sub>O<sub>3</sub> or AlTiO as gate dielectrics with several thicknesses  $d_{\rm ins} = 6-29 \,\rm nm$  were deposited on the AlGaN surface by ALD. The Al<sub>2</sub>O<sub>3</sub> films ( $k \sim 9$  and  $E_g \sim 7 \text{ eV}$ ) were obtained by using trimethylaluminum (TMA) and H<sub>2</sub>O as precursors, and the Al<sub>x</sub>Ti<sub>y</sub>O films (x:y=0.73:0.27,  $k \sim 13-14$ , and  $E_{\rm g} \sim 6 \, {\rm eV}$ ) were by using TMA, tetrakis-dimethylamino titanium (TDMAT), and H<sub>2</sub>O. After post-deposition annealing in H<sub>2</sub>-mixed Ar at 350 °C, Ni/Au gate electrode formation completed the device fabrication. As a result, we obtained Al<sub>2</sub>O<sub>3</sub>/ AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices, whose cross sections are schematically shown in Fig. 1(a), with  $70 \,\mu\text{m} \times 70 \,\mu\text{m}$  gate electrodes surrounded by the Ohmic electrodes as shown by top-view optical images in Fig. 1(b).

## III. INSULATOR-SEMICONDUCTOR INTERFACE FIXED CHARGES

In order to investigate insulator-semiconductor interface fixed charges, we examined threshold voltages  $V_{\rm th}$  of the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices, by measuring capacitance-voltage (*C*–*V*) characteristics between the gate and the grounded Ohmic electrodes. Since GaN-based MIS devices sometimes exhibit unstable  $V_{\rm th}$ depending on the sweeping range of the gate voltage  $V_{\rm G}$ ,<sup>8–12</sup> we checked  $V_{\rm th}$  stability; starting from  $V_{\rm G0} \ge 0$ , *C*–*V* characteristics were measured under  $V_{\rm G} = V_{\rm G0} \rightarrow -15$  V with a sweep rate of 0.36 V/s. Figure 2 shows an example of the



FIG. 1. (a) Schematic cross sections and (b) top-view optical images of the fabricated  $Al_2O_3/AlGaN/GaN$  and AlTiO/AlGaN/GaN MIS devices.



FIG. 2. Checking  $V_{\rm th}$  stability of the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices with  $d_{\rm ins} = 19$  nm: *C*–V characteristics measured at 1 MHz under  $V_{\rm G} = V_{\rm G0} \rightarrow -15$  V with a sweep rate of 0.36 V/s, where  $V_{\rm G0} = 0$ , 1, 2, 3, 4, and 5 V.

measurement results for  $d_{ins} = 19$  nm, at 1 MHz frequency with  $V_{G0} = 0, 1, 2, 3, 4$ , and 5 V. Although we find rather stable  $V_{th}$ , weak  $V_{th}$  shifts take place after positive bias applications, probably owing to charging effects of trapped electrons. Thus, to determine  $V_{th}$ , we employ  $V_{G0} = 0$  V to avoid the charging effects. Figure 3(a) shows C-V characteristics of the MIS devices with  $d_{ins} = 6-29$  nm, measured at 1 MHz under  $V_G = 0 \rightarrow -15$  V with a sweep rate of 0.36 V/s. As shown in Fig. 3(b), the sheet concentration of the two-dimensional electron gas (2DEG) under the gate,  $n_s$ , can be obtained by integrating C as a function of  $V_G$ , from which we can determine  $V_{th}$ .

Figure 4 shows the band diagram of AlGaN/GaN MIS devices, considering the interface fixed charges. From this, we obtain

$$\frac{\Delta\sigma_{\rm ins} - qn_{\rm s}}{k_{\rm ins}\varepsilon_0} d_{\rm ins} + \frac{\Delta\sigma_{\rm AIGaN} - qn_{\rm s}}{k_{\rm AIGaN}\varepsilon_0} d_{\rm AIGaN}$$
$$= -V_{\rm G} + \psi/q + E_{\rm F}/q \tag{1}$$

using the elementary charge q > 0, the vacuum permittivity  $\varepsilon_0$ , the insulator-semiconductor interface fixed charge density  $\sigma_{ins}$ , the polarization charge densities  $\sigma_{GaN}$  and  $\sigma_{AlGaN}$ , the dielectric constants  $k_{ins}$  and  $k_{AlGaN}$ , the thicknesses  $d_{ins}$  and  $d_{AlGaN}$ , the 2DEG Fermi energy  $E_F$ , and  $\psi = \phi - \phi - \Delta E_C$  defined in Fig. 4, where  $\Delta \sigma_{ins} = \sigma_{ins} - \sigma_{GaN}$  and  $\Delta \sigma_{AlGaN} = \sigma_{AlGaN} - \sigma_{GaN}$ . For  $V_G = V_{th}$  ( $n_s = 0$  and  $E_F = 0$ ), we find

$$V_{\rm th} = -\frac{\Delta\sigma_{\rm ins}}{k_{\rm ins}\varepsilon_0} d_{\rm ins} - \frac{\Delta\sigma_{\rm AlGaN}}{k_{\rm AlGaN}\varepsilon_0} d_{\rm AlGaN} + \psi/q \qquad (2)$$

giving a linear  $d_{\rm ins}$ -dependence of  $V_{\rm th}$  with a slope of  $-\Delta\sigma_{\rm ins}/(k_{\rm ins}\varepsilon_0)$ . The 2DEG concentration  $n_{\rm s}$  under the gate is approximately given by

$$qn_{\rm s} \simeq C_0 (V_{\rm G} - V_{\rm th}) \tag{3}$$

as experimentally confirmed in Fig. 3(b), where

$$\frac{1}{C_0} = \frac{d_{\text{ins}}}{k_{\text{ins}}\varepsilon_0} + \frac{d_{\text{AIGaN}}}{k_{\text{AIGaN}}\varepsilon_0}.$$
(4)



FIG. 3. (a) C-V characteristics of the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices with  $d_{ins} = 6-29$  nm, measured at 1 MHz under  $V_G = 0 \rightarrow -15$  V with a sweep rate of 0.36 V/s. (b) The 2DEG sheet concentration  $n_s$  obtained by integrating C as functions of the gate voltage  $V_G$ , from which we can determine  $V_{th}$ .



FIG. 4. The band diagram of AlGaN/GaN MIS devices, considering the interface fixed charges.

For  $V_{\rm G} = 0$ ,  $n_{\rm s} = n_{\rm s0}$  is given by

$$qn_{\rm s0} \simeq -C_0 V_{\rm th} = \frac{\Delta\sigma_{\rm ins} d_{\rm ins}/(k_{\rm ins}\varepsilon_0) + \Delta\sigma_{\rm AlGaN} d_{\rm AlGaN}/(k_{\rm AlGaN}\varepsilon_0) - \psi/q}{d_{\rm ins}/(k_{\rm ins}\varepsilon_0) + d_{\rm AlGaN}/(k_{\rm AlGaN}\varepsilon_0)}$$
(5)

which is a nonlinear function of  $d_{ins}$ .

According to Eq. (4),  $1/C_0$  is a linear function of  $d_{ins}$ . Experimentally,  $C_0$  is estimated by C at  $V_G = 0$  V as plotted in Fig. 5(a), where we can confirm the linear relation. From the slopes, we obtain dielectric constants  $k_{ins} = 9.4$  and 13.4 for Al<sub>2</sub>O<sub>3</sub> and AlTiO, respectively, being consistent with separated experimental results using metal-insulator-metal structures (not shown). From the intercept, we obtain  $k_{AIGaN} = 9.5$  (using  $d_{AIGaN} = 30$  nm). Figure 5(b) shows the experimentally determined  $V_{th}$  as functions of  $d_{ins}$ . We find linear dependences obeying Eq. (2), indicating that the interface fixed charges dominate  $V_{th}$  and also rather shallower  $V_{th}$ for AlTiO than for Al<sub>2</sub>O<sub>3</sub>. By fitting using Eq. (2), we obtain  $\Delta \sigma_{ins}/q = 1.5 \times 10^{13}$  cm<sup>-2</sup> and  $7.3 \times 10^{12}$  cm<sup>-2</sup> at the Al<sub>2</sub>O<sub>3</sub>/ AlGaN and AlTiO/AlGaN interfaces, respectively. The latter gives a significantly lower  $\sigma_{ins}$  than the former, which may be attributed to a lower-density of oxygen donors<sup>25,31,32</sup> at



FIG. 5. (a)  $1/C_0$ , (b)  $V_{\text{th}}$ , and (c)  $n_{s0}$  at  $V_G = 0$  of the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices, as functions  $d_{\text{ins}}$  with fitting curves.

the AlTiO/AlGaN interface. This lower  $\sigma_{ins}$  and the higher  $k_{ins}$  of AlTiO lead to rather shallower  $V_{th}$ . Figure 5(c) shows the experimentally obtained  $n_{s0}$  as functions of  $d_{ins}$ , whose non-linear dependences are fitted by Eq. (5). We find that  $n_{s0}$  is a decreasing function of  $d_{ins}$  for AlTiO, whereas being an increasing function for Al<sub>2</sub>O<sub>3</sub>. From Eq. (5), we obtain

$$\frac{\partial n_{\rm s0}}{\partial d_{\rm ins}} = \frac{C_0}{k_{\rm ins}\varepsilon_0} \left(\Delta\sigma_{\rm ins}/q - n_{\rm s0}\right) \tag{6}$$

which implies that  $\Delta \sigma_{\rm ins}/q > n_{\rm s0}$  leads to increasing  $n_{\rm s0}$  with  $d_{\rm ins}$ , while  $\Delta \sigma_{\rm ins}/q < n_{\rm s0}$  leads to decreasing  $n_{\rm s0}$ . Thus, for Al<sub>2</sub>O<sub>3</sub> and AlTiO,  $n_{\rm s0}$  is an increasing and a decreasing function of  $d_{\rm ins}$ , respectively. It should be noted that, in the limit

of a large  $d_{\rm ins}$ ,  $n_{\rm s0}$  in Eq. (5) approaches to  $\Delta \sigma_{\rm ins}/q$ , indicating that a normally off operation can be expected for sufficiently suppressed interface fixed charges, satisfying  $\Delta \sigma_{\rm ins} < 0$ , i.e.,  $\sigma_{\rm ins} < \sigma_{\rm GaN}$ . However, in the both cases, we observe  $\Delta \sigma_{\rm ins} > 0$ , i.e.,  $\sigma_{\rm ins} > \sigma_{\rm GaN}$ .

Even though  $\Delta \sigma_{ins}$  is obtained experimentally, in order to evaluate  $\sigma_{ins}$ , it is necessary to assume  $\sigma_{GaN}$ . Hereafter, we assume  $\sigma_{\text{GaN}}/q = 2.1 \times 10^{13} \text{ cm}^{-2}$  obtained by a theoretical calculation.<sup>38</sup> This leads to  $\sigma_{\text{ins}}/q = 3.6 \times 10^{13} \text{ cm}^{-2}$  and  $2.8\times10^{13}\,\text{cm}^{-2}$  at the Al2O3/AlGaN and AlTiO/AlGaN interfaces, respectively. In addition, these values should be compared with  $\sigma_{AlGaN}/q$ . Although  $\Delta \sigma_{AlGaN}/q = 1.5 \times 10^{13} \text{ cm}^{-2}$ for Al<sub>0.27</sub>Ga<sub>0.73</sub>N/GaN is obtained theoretically,<sup>39</sup> several experiments show lower  $\Delta \sigma_{AlGaN}$ , about 85% of the theoretical one.<sup>40–42</sup> Thus, we assume  $\Delta \sigma_{AIGaN}/q = 1.3 \times 10^{13} \text{ cm}^{-2}$ , i.e.,  $\sigma_{AlGaN}/q = 3.4 \times 10^{13} \text{ cm}^{-2}$ . Based on the assumptions, we summarize  $\sigma_{ins}$  compared with  $\sigma_{AlGaN}$  in Fig. 6, where the dotted line corresponds to neutral insulator-semiconductor interfaces, i.e.,  $\sigma_{ins} + (-\sigma_{AlGaN}) = 0$ . We obtain that the Al<sub>2</sub>O<sub>3</sub>/AlGaN interface is nearly neutral,<sup>25</sup> while the AlTiO/ AlGaN interface is rather negatively charged owing to the lower  $\sigma_{\text{ins}}$ . By fitting  $V_{\text{th}}$  as functions of  $d_{\text{ins}}$  with Eq. (2), we also obtain  $\psi = 2.0$  and 1.3 eV for the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices, respectively. From these, we obtain band diagrams of the AlGaN/GaN MIS devices by Poisson-Schrödinger calculation<sup>43</sup> as shown in Fig. 7, where we can confirm that the AlTiO/AlGaN interface is negatively charged. The directions of the electric fields in Al<sub>2</sub>O<sub>3</sub> and AlTiO at  $V_{\rm G} = 0$  V are opposite, leading to the fact that  $n_{\rm s0}$  is a decreasing function of  $d_{ins}$  for AlTiO, whereas being an increasing function for Al<sub>2</sub>O<sub>3</sub>.

## IV. RELATION WITH INSULATOR-SEMICONDUCTOR INTERFACE STATES

It should be noted that electrons trapped at deep interface states with very long time constants can act as (quasi) negative interface fixed charges.<sup>30</sup> Therefore, the interface fixed charge measurements might be influenced by electrons at deep interface states compensating the positive fixed



FIG. 6. A comparison between the insulator-semiconductor interface fixed charge density  $\sigma_{\rm ans}$  and AlGaN polarization charge density  $\sigma_{\rm AlGaN}$ .



FIG. 7. Band diagrams of the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices at  $V_{\rm G} = 0$  V, obtained by 1D Poisson-Schrödinger calculation.

charges. In particular, there is a possibility that the lower AlTiO/AlGaN interface fixed charge density is owing to electrons trapped at deep interface states. In order to consider this possibility, we examined the interface states at Al<sub>2</sub>O<sub>3</sub>/AlGaN and AlTiO/AlGaN by frequency dependent C-V measurements. Figure 8 shows examples of the measurement results, C-V characteristics at 100 Hz–1 MHz for the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices with  $d_{\rm ins} = 14-19$  nm. In any cases, no frequency dispersion is observed for negative bias voltages, showing that the  $V_{\rm th}$  determination is not affected by the measurement frequency. On the other hand, for positive bias voltages, frequency dispersions are observed, suggesting insulator-semiconductor interface states.

The conductance method<sup>44</sup> was applied to the frequency dependent *C*–*V* characteristics to evaluate the interface state density.<sup>30,45–51</sup> Assuming the equivalent circuit shown in the insets of Fig. 9, which consists of an interface state capacitance  $C_i$ , an interface state conductance  $G_i$ , and an AlGaN capacitance  $C_{AlGaN}$  in parallel, with an insulator capacitance  $C_{ins}$  connected in series, we obtained the frequency dependence of  $G_i$  for the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/ GaN MIS devices. Figure 9 shows examples of obtained  $G_i/\omega$  as functions of frequency f, where  $\omega = 2\pi f$ , exhibiting single-peaked behavior. As shown by the curves in Fig. 9, the single-peaked behavior is well fitted by<sup>52</sup>

$$\frac{G_{\rm i}}{\omega} = \frac{q^2 D_{\rm i} \ln(1 + \omega^2 \tau^2)}{2\omega\tau},\tag{7}$$

where  $D_i$  is the interface state density and  $\tau$  is the trapping time constant, giving the peak frequency  $f_p = 1/(\pi\tau)$  and the peak value of  $G_i/\omega \simeq 0.4q^2D_i$ . The observed peaks are summarized in Fig. 10(a), where we find very similar behavior



FIG. 8. C-V characteristics of the Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices with  $d_{ins} = 14$ -19 nm, measured at 100 Hz-1 MHz.



FIG. 10. (a) The peak value of  $G_i/\omega$  as functions of peak frequency  $f_p$  and (b) the interface state density  $D_i$  as functions of the energy  $(E_C - E)$ , for the Al2O3/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices.

FIG. 9.  $G_i/\omega$  as functions of frequency with fitting curves for the Al<sub>2</sub>O<sub>3</sub>/ AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices. Insets: The small-signal equivalent circuit.

2 V 3 V 4 V 5 V 6 V 7 V

1 V

2 V

3 V 4 V

10<sup>6</sup>

for Al2O3/AlGaN/GaN and AlTiO/AlGaN/GaN and also for different  $d_{ins}$ , suggesting that the behavior is dominated by interface states with very similar densities at Al<sub>2</sub>O<sub>3</sub>/AlGaN and AlTiO/AlGaN. From the peaks, we can obtain the relationship between  $D_i$  and  $\tau$ . Moreover,  $\tau$  for an interface state at the energy E is given by  $\tau = \tau_0 \exp \left[ (E_{\rm C} - E) / k_{\rm B} T \right]$  using the Boltzmann constant  $k_{\rm B}$ , temperature T, and the conduction band bottom energy  $E_{\rm C}$ , where  $\tau_0$  is a time constant determined by the capture cross section of the trap. Thus, using  $\tau_0$ , we can estimate the relationship between  $D_i$  and  $(E_{\rm C}-E)$ . Even though  $\tau_0$  is ambiguous, assuming a wide range of  $\tau_0 = 1-100$  ps, we show  $D_i$  as functions of  $(E_C - E)$ in Fig. 10(b), where the error bars correspond to the wide range of  $\tau_0$  values. This indicates a very similar shallow interface state density  $D_i \sim 2 \times 10^{13} \text{ cm}^{-2} \text{ eV}^{-1}$  of Al<sub>2</sub>O<sub>3</sub>/ AlGaN and AlTiO/AlGaN and suggests that deep interface state densities are also similar, even though the interface fixed charge density  $\sigma_{ins}$  is rather lower at AlTiO/AlGaN. Thus, we should conclude that there is no correlation between the interface fixed charges and the interface states in our case, as reported in Ref. 32. This suggests that the lower  $\sigma_{ins}$  at AlTiO/AlGaN is not owing to electrons trapped at deep interface states, compensating the positive fixed charges. Since interface states generally have a U-shaped density of states, from the shallow interface state density above, we can expect a deep interface state density of  $\leq 10^{13} \,\mathrm{cm}^{-2} \mathrm{eV}^{-1}$  or less. On the other hand, the difference between  $\sigma_{\rm ins}/q$  at Al<sub>2</sub>O<sub>3</sub>/AlGaN and that at AlTiO/AlGaN is  $\sim 0.8 \times 10^{13} \,\mathrm{cm}^{-2}$ . Thus, it is not plausible that the difference is due to trapped electrons at the deep interface states. Although the material origin of the lower  $\sigma_{ins}$  at AlTiO/ AlGaN is not clear, it is possible to tentatively assume a lower density of oxygen-related interface donors, where strong Ti-O bonding may suppress donor formation.

#### **V. CONCLUSION**

We have investigated insulator-semiconductor interface fixed charges in Al<sub>2</sub>O<sub>3</sub>/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices. The AlTiO/AlGaN interface gives significantly lower-density interface fixed charges and rather shallower threshold voltages. The lower interface fixed charge density also leads to the fact that the 2DEG concentration is a decreasing function of the AlTiO thickness, whereas being an increasing function of the Al<sub>2</sub>O<sub>3</sub> thickness. Moreover, we discuss the relationship between the interface fixed charges and interface states. Since the interface state densities are very similar at Al<sub>2</sub>O<sub>3</sub>/AlGaN and AlTiO/AlGaN, it is suggested that the lower interface fixed charge density at AlTiO/ AlGaN is not owing to electrons trapped at deep interface states, compensating the positive fixed charges. Thus, a lower density of oxygen-related donors at the AlTiO/AlGaN interface can be assumed, where strong Ti-O bonding may suppress donor formation. We consider that the results can provide a clue towards  $V_{\rm th}$  control and normally off operations of GaN-based MIS devices.

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