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# AlGaN/GaN metal-insulator-semiconductor heterojunction field-effect transistors using BN and AlTiO high-k gate insulators

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#### 1 Introduction

GaN-based metal-insulator-semiconductor heterojunction field-effect transistors (MIS-HFETs) have been investigated owing to the merits of gate leakage reduction and passivation to suppress the current collapse. Gate insulators, such as  $Al_2O_3$ ,  $HfO_2$ ,  $TiO_2$ , or AlN, have been studied. Further developments of the MIS-HFETs using novel gate insulators suitable according to applications are important. A desired gate insulator should have:

- a wide energy gap  $E_{\rm g}$  and a high breakdown field  $F_{\rm br}$  for high-voltage operations,
- a high dielectric constant k for high transconductance, and
- a high thermal conductivity  $\kappa$  for good heat release suitable for high-power operations.

In particular, boron nitride (BN) exhibits a high  $F_{\rm br}$ , high k, and very high  $\kappa$  [1, 2]. On the other hand, aluminum titanium oxide (AlTiO: an alloy of very high-k TiO<sub>2</sub> and wide- $E_{\rm g}$  Al<sub>2</sub>O<sub>3</sub> [3]), which has intermediate properties between TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, is important to balance k and  $E_{\rm g}$  [4, 5]. Therefore, BN and AlTiO are promising gate insulators for the MIS-HFETs.

In this work, we characterize physical properties of BN thin films obtained by RF magnetron sputtering and AlTiO thin films obtained by atomic layer deposition (ALD) for several Al compositions. Using such films, we fabricate BN/AlGaN/GaN MIS-HFETs (BN MIS-HFETs) and AlTiO/AlGaN/GaN MIS-HFETs (AlTiO MIS-HFETs). Then, we investigate their temperature-dependent characteristics; analyze electron transport properties for channel conduction and gate leakage, and estimate BN/AlGaN and AlTiO/AlGaN interface state densities.

## 2 BN thin films and BN/AlGaN/GaN MIS-HFETs

We characterized physical properties of amorphous BN thin films obtained by RF magnetron sputtering, which have  $E_{\rm g} \sim 5.7$  eV,  $F_{\rm br} \sim 5.5$  MV/cm, and  $k \sim 7$ . Using the BN films, we fabricated BN MIS-HFETs, which exhibit high maximum drain current  $I_{\rm D}$  and no negative conductance, as shown in Fig. 1(a), suggesting good thermal release properties owing to the excellent  $\kappa$  of BN. We obtain very low gate leakage  $I_{\rm G}$ , as shown in Fig. 1(b), indicating good insulating properties of BN. In addition, transconductance  $g_{\rm m}$  shows a slightly high peak, but rapidly decreases for forward biases, indicating a weak gate controllability, suggesting high-density BN/AlGaN interface states near the conduction band.



Figure 1: (a) Output characteristics and (b) transfer characteristics of BN MIS-HFETs at room temperature.

We investigated temperature-dependent channel conduction of the BN MIS-HFETs, where  $I_{\rm D}$  decreases with increase in temperature. In the linear region, the decrease in  $I_{\rm D}$  is attributed to decrease in the electron mobility, while the sheet electron concentration is constant. In the saturation region, the decreased  $I_{\rm D}$  is proportional to the average electron velocity, whose temperature dependence is in-between those of the low- and high-field velocities, as shown by Monte-Carlo simulation [6] and indicated by experiments [7].

In order to elucidate temperature-dependent gate leakage of the BN MIS-HFETs, we carried out a fitting for two-terminal (drain open) gate-source leakage current  $I_{GS}$ , shown in Fig. 2(a), using

$$I_{\rm GS}(V_{\rm GS}, T) = I_0(V_{\rm GS}) \exp\left[-\frac{E_{\rm a}(V_{\rm GS})}{k_{\rm B}T}\right] + I_1(V_{\rm GS}),\tag{1}$$



Figure 2: (a) Two-terminal (drain open) gate-source leakage current  $I_{\rm GS}$  of the BN/AlGaN/GaN MIS-HFETs as functions of gate-source voltage  $V_{\rm GS}$  for several temperatures T. (b) Experimental data is well fitted at large  $V_{\rm GS}$ . (c) Prefactors  $I_0$  and  $I_1$ , and (d) activation energy  $E_{\rm a}$  as functions of  $V_{\rm GS}$ .

with Boltzmann constant  $k_{\rm B}$ , temperature T, activation energy  $E_{\rm a}$ , prefactors  $I_0$  and  $I_1$ , and gate-source voltage  $V_{\rm GS}$ , where the first term is temperature-dependent and the second term is temperature-independent. We obtained good fittings, as shown in Fig. 2 (b). As a result, we observe  $I_0(V_{\rm GS})$  and  $I_1(V_{\rm GS})$  exponentially increase, as shown in Fig. 2(c), while  $E_{\rm a}(V_{\rm GS})$  is almost constant, as shown in Fig. 2(d), with increase in  $V_{\rm GS}$  at large forward biases. These indicate that the temperature-dependent term does not obey Poole-Frenkel (PF) mechanism. In order to explain the behaviors, we propose a mechanism with temperature-independent tunneling, dominant at low temperatures, and temperature-enhanced tunneling, dominant at high temperatures, as depicted in Fig. 3(a). By considering an equivalent circuit for DC limit, as shown in Fig. 3(b) [8], we estimated the BN/AlGaN interface state density, which is  $\gg 10^{12}$  cm<sup>-2</sup>eV<sup>-1</sup>. High-density BN/AlGaN interface states lead to the weak gate controllability for the BN MIS-HFETs.



Figure 3: (a) Conduction band diagram of Ni/BN/AlGaN/GaN for a mechanism with temperature-independent tunneling and temperature-enhanced tunneling. (b) The equivalent circuit for the DC limit with BN capacitance  $C_{\rm BN}$ , AlGaN capacitance  $C_{\rm AlGaN}$ , and BN/AlGaN interface state density  $D_{\rm i}$ .

## 3 AlTiO thin films and AlTiO/AlGaN/GaN MIS-HFETs

We characterized physical properties of  $Al_x Ti_y O$  thin films obtained by ALD, for several Al compositions x/(x + y). We observe increasing  $E_g$  and  $F_{br}$ , and decreasing k with increase in the Al composition [9]. Considering the trade-off between k and  $F_{br}$ , we applied  $Al_x Ti_y O$  with x : y = 0.73 : 0.27, where  $E_g \sim 6$  eV,  $F_{br} \sim 6.5$  MV/cm, and  $k \sim 24$ , to fabrication of AlTiO MIS-HFETs. In comparison with  $Al_2O_3/AlGaN/GaN$  MIS-HFETs, at room temperature, the AlTiO MIS-HFETs exhibit a higher maximum  $I_D$ , as shown in Fig. 4(a) and (b), a higher peak and better linearity of  $g_m$ , and a shallower threshold voltage, but a higher  $I_G$  (still very low), as shown in Fig. 4(c) and (d), suggesting that AlTiO is more favorable than  $Al_2O_3$  for applications to AlGaN/GaN MIS-HFETs. For the AlTiO MIS-HFETs, we observe a bump in  $I_G$  for high drain-source voltages  $V_{DS}$  and high  $I_D$ , indicating increase in channel temperature due to self-heating effects at high-power consumption. This suggests low- $\kappa$  AlTiO due to random effects in alloy materials [10].



Figure 4: (a) and (b) Output characteristics, (c) and (d) transfer characteristics of AlTiO MIS-HFETs and Al<sub>2</sub>O<sub>3</sub> MIS-HFETs, respectively.

We investigated temperature-dependent channel conduction of the AlTiO MIS-HFETs, where  $I_{\rm D}$  decreases with increase in temperature. The behavior is similar to that of the BN MIS-HFETs. In the linear region, the decrease in  $I_{\rm D}$  is mainly due to decrease in the electron mobility, while the contact resistance and the sheet electron concentration are almost constant. In the saturation region, the decreased  $I_{\rm D}$  is proportional to the average electron velocity, whose temperature dependence is in-between those of the low- and high-field velocities.

In addition, we investigated temperature-dependent gate leakage for the AlTiO MIS-FETs by fitting twoterminal (drain open) gate-source leakage current  $I_{\rm GS}$ , shown in Fig. 5(a), using Eq. (1). We obtained good fittings, as shown in Fig. 5(b). As a result, we observe temperature-independent term  $I_1(V_{\rm GS})$  exponentially increases with increase in  $V_{\rm GS}$ , as shown in the inset of Fig. 5(c), suggesting tunneling current through AlGaN and AlTiO barriers. In addition, for temperature-dependent term, we find that  $I_0(V_{\rm GS})$  is a linear function of  $V_{\rm GS}$ , or proportional to  $(V_{\rm GS} - V_0)$  with  $V_0 \simeq 2.9$  V, as shown in Fig. 5(c); and  $E_a(V_{\rm GS})$  is a linear function of  $\sqrt{V_{\rm GS} - V_0}$ , as shown in Fig. 5(d). The behaviors can be explained by the PF mechanism, described by [11]

$$I_{\rm PF}(F,T) \propto F \exp\left[-\frac{1}{k_{\rm B}T}\left(\phi - \sqrt{\frac{q^3 F}{\pi \varepsilon_0 k}}\right)\right],$$
(2)

with electron charge q, vacuum dielectric constant  $\varepsilon_0$ , electric field F in AlTiO, and trap depth  $\phi \sim 0.41$  eV. The temperature-independent tunneling current, dominant at low temperatures, and PF current, dominant at high temperatures, are depicted in Fig. 6(a). By considering an equivalent circuit for DC limit, shown in Fig. 6(b) [8], we estimated AlTiO/AlGaN interface state density, which is  $\sim 2 \times 10^{12}$  cm<sup>-2</sup>eV<sup>-1</sup>. Low-density AlTiO/AlGaN interface states lead to the strong gate controllability for the AlTiO MIS-HFETs.



Figure 5: (a) Two-terminal (drain open) gate-source leakage current  $I_{\rm GS}$  of the AlTiO/AlGaN/GaN MIS-HFETs as functions of gate-source voltage  $V_{\rm GS}$  for several temperatures T. (b) Experimental data is well fitted at large  $V_{\rm GS}$ . (c) Prefactor  $I_0$  as a linear function of gate-source voltage  $V_{\rm GS}$ , or proportional to  $(V_{\rm GS} - V_0)$  with  $V_0 \simeq 2.9$  V. The inset shows  $I_1$  as an exponential function of  $V_{\rm GS}$ . (d) Activation energy  $E_{\rm a}$  as a function of  $\sqrt{V_{\rm GS} - V_0}$ .

# 4 Conclusions

We characterized physical properties of sputtering-deposited BN thin films and ALD AlTiO thin films for several Al compositions. Using such films, we fabricated BN MIS-HFETs and AlTiO MIS-HFETs. We investigated their temperature-dependent characteristics; analyzed electron transport properties for channel conduction and gate leakage, and estimated BN/AlGaN and AlTiO/AlGaN interface state densities.



Figure 6: (a) Conduction band diagram of Ni/AlTiO/AlGaN/GaN with the temperature-independent tunneling and Poole-Frenkel currents. (b) The equivalent circuit for the DC limit with AlTiO capacitance  $C_{AlTiO}$ , AlGaN capacitance  $C_{AlGaN}$ , and AlTiO/AlGaN interface state density  $D_i$ .

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## **Refereed Journals**

- 1. <u>Tuan Quy Nguyen</u>, Hong-An Shih, Masahiro Kudo, and Toshi-kazu Suzuki, "Fabrication and characterization of BN/AlGaN/GaN metal-insulator-semiconductor heterojunction field-effect transistors with sputtering-deposited BN gate dielectric", Physica Status Solidi C **10**, 1401 (2013).
- Son Phuong Le, <u>Tuan Quy Nguyen</u>, Hong-An Shih, Masahiro Kudo, and Toshi-kazu Suzuki, "Lowfrequency noise in <u>AlN/AlGaN/GaN</u> metal-insulator-semiconductor devices: a comparison with Schottky devices", Journal of Applied Physics, *in press*.

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