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Investigation of gate leakage current mechanism in AlGaIn/GaN high-electron-mobility transistors with sputtered TiN

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The gate leakage current mechanism of AlGaIn/GaN Schottky barrier diodes (SBDs) and high-electron-mobility transistors (HEMTs) with sputtered TiN is systematically investigated. The reverse leakage current (J_R) of TiN SBDs increases exponentially with the increase of reverse voltage (V_R) from 0 to -3.2 V (Reg. I). This conduction behavior is dominated by Poole-Frenkel emission from TiN through an interface state of 0.53 eV to the conductive dislocation-related continuum states. The obtained interface state of 0.53 eV may be due to the plasma damage to the surface of the AlGaIn/GaN HEMT structure during the TiN sputtering. When the TiN SBDs are biased with $-20 < V_R < -3.2$ V, J_R saturated due to the depletion of the 2-dimensional electron gas (2DEG) channel (Reg. II). This conduction behavior is dominated by the trap-assisted tunneling through the interface state at ~ 0.115 eV above the Fermi level. The three terminal OFF-state gate leakage current of AlGaIn/GaN HEMTs exhibited an activation energy of 0.159 eV, which is in close agreement with the obtained interface state of ~ 0.115 eV from saturated J_R (Reg. II) of the SBDs. The observation of the negative temperature coefficient (-1.75 V/K) from the OFF-state breakdown voltage (at $1 \mu\text{A}/\text{mm}$) of AlGaIn/GaN HEMTs is due to the trap-assisted tunneling mechanism, which is also well correlated with the conduction mechanism realized from the reverse leakage current of the SBDs. *Published by AIP Publishing.*
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I. INTRODUCTION

AlGaIn/GaN High-Electron-Mobility transistors (HEMTs) have attracted considerable interest in high-voltage power applications due to the excellent intrinsic material properties such as high electron saturation velocity, high density of 2-dimensional electron gas (2DEG), and high breakdown voltage.^{1,2} Recently, the CMOS-compatible fabrication process, which targets to transfer the processing of GaN-based devices from the III-V line to the existing large diameter (e.g., 8-in.) Si foundries, has been intensively investigated as it provides a promising solution for high-throughput and low-cost GaN devices and ICs for the expanding commercial electronic market.^{3,4} In the CMOS-compatible process, the conventional Ni/Au bi-layer gate^{1,2} cannot be used as Au will cause contamination to Si fabrication line and Ni is difficult to be selectively removed by plasma etching. Hence, the Ni- and Au-free gate metal stack is necessary to realize AlGaIn/GaN HEMTs in the Si CMOS process line. So far, many Ni- and Au-free gates, including Ti,⁵ Cr,⁵ Pt,⁶ Pd,^{6,7} WSi,⁷ Ir,^{7,8} TaN,⁹ and ITO,⁹ have been evaluated for the fabrication of AlGaIn/GaN HEMTs and Schottky barrier diodes (SBDs). Compared to other materials, the TiN exhibits many advantages such as large metal work function (~ 5 eV),¹⁰ high thermal stability,¹⁰ and process compatibility to both dry and wet etching

processes. The AlGaIn/GaN HEMTs with TiN-based gate have been demonstrated by other groups.^{11–15} However, these works mainly focused on the improvement of device characteristics such as current collapse,¹⁴ thermal stability,^{11–13,15} and high voltage stress effect.¹⁵ Recently, we have also reported an improved Schottky barrier height (SBH) of ~ 1.1 eV in AlGaIn/GaN HEMTs with sputtered TiN as the gate electrode.^{16,17} So far, the gate leakage current mechanism and energy levels of the interface states of sputtered TiN on AlGaIn/GaN SBDs and HEMTs have not been studied. The leakage current mechanism was commonly observed to associate with the semiconductor material. For example, Schottky (SC) emission was realized in n-type Ge substrates with Pt¹⁸ and Se¹⁹ Schottky contacts, and Poole-Frenkel (PF) emission was widely adopted for the III-nitrides (GaN,²⁰ AlGaIn/GaN,^{20–22} and AlInN/GaN^{22,23}) with Ni-based Schottky contacts by electron beam (e-beam) evaporation. However, TiN gate was commonly deposited by the sputtering process,^{11–17} which may lead to plasma damages to the surface of the AlGaIn/GaN HEMT structure. Hence, it is important to study and understand the gate leakage current mechanism of AlGaIn/GaN SBDs and HEMTs with sputtered TiN. In this paper, we have investigated the gate leakage current mechanism of AlGaIn/GaN SBDs and HEMTs with sputtered TiN using current-voltage-temperature (I-V-T) measurements. Finally, the OFF-state gate leakage current (I_g) and OFF-state breakdown voltage (BV_{OFF}) of AlGaIn/GaN HEMTs as a function of

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measurement temperatures were also measured and correlated with the obtained conduction mechanism from two terminal gate leakage current of SBDs.

II. EXPERIMENTAL DETAILS

The AlGaIn/GaN HEMT structure was grown on a 4-in. high-resistivity Si (111) substrate by Metal Organic Chemical Vapor Deposition (MOCVD). The epitaxial growth layers include a 1.4 μm -thick transition layer, a 0.8 μm -thick unintentionally doped (UID) GaN buffer, an 18 nm-thick UID-Al_{0.26}Ga_{0.74}N barrier, and a 2 nm-thick UID-GaN cap from bottom to top.²⁴ The threading dislocation density (TDD) of the grown AlGaIn/GaN HEMT structure is in the range between $3 \times 10^9 \text{ cm}^{-2}$ and $6 \times 10^9 \text{ cm}^{-2}$. At room temperature, the measured 2DEG sheet carrier density was $9.8 \times 10^{12} \text{ cm}^{-2}$ with an electron mobility (μ_n) of $1450 \text{ cm}^2/\text{Vs}$ and a sheet resistance (R_{sh}) of $440 \Omega/\square$.¹⁷ After the mesa isolation by BCl_3/Cl_2 plasma etching, ohmic patterns were defined by conventional lithography. Prior to the deposition of Ti/Al/Ni/Au (20/120/40/50 nm) ohmic metal stacks by electron-beam (e-beam) evaporation, the surface native oxide was removed by buffered oxide etchant (BOE) for 2 min followed by de-ionized water rinsing. The contact resistance (R_c) of ohmic contacts was measured at $\sim 0.3 \Omega \text{ mm}$ after the rapid thermal annealing (RTA) at 775°C for 30 s in N_2 ambient. Next, 200 nm-thick TiN was sputtered at a DC power of 450 W as Schottky contacts. The gas flow of $\text{N}_2/\text{Ar} = 40/30 \text{ sccm}$ was selected for the sputtering because this N_2/Ar rate yielded an optimum SBH of $\sim 1.1 \text{ eV}$ by the I-V-T measurement.¹⁷ The pre-pressure and deposition pressure of the TiN sputtering were below $\sim 5 \times 10^{-6} \text{ Torr}$ and $\sim 7.7 \times 10^{-3} \text{ Torr}$, respectively. Finally, the sample was passivated with a 120 nm-thick Si_3N_4 layer by Plasma Enhanced Chemical Vapor Deposition (PECVD) at 300°C . The fabricated devices including SBDs and HEMTs were then characterized using an Agilent B1505A power device analyzer. For this study, we used the guard-ring type SBDs with an anode diameter of $50 \mu\text{m}$. The current-voltage characteristics were performed on the fabricated TiN SBDs as a function of measurement temperatures (275 to 400 K, with a step increment of 25 K). To correlate the current transport mechanism with the device breakdown characteristics, AlGaIn/GaN HEMTs were also measured for I_{DS} , I_G , and BV_{OFF} at the OFF-state gate bias for various measurement temperatures ranging from 280 K to 420 K. The measured HEMT device has a source-gate distance (L_{sg}) and a gate length (L_g) of $2 \mu\text{m}$ and a gate-drain distance (L_{gd}) of $6 \mu\text{m}$ with a gate width (W_g) of $80 \mu\text{m}$.

III. RESULTS AND DISCUSSION

A. Conduction mechanisms at reverse biases

Figure 1 shows the reverse current density (J_R)—reverse bias (V_R) characteristics of sputtered TiN SBDs as a function of measurement temperatures. For the case of Reg. I, J_R increases exponentially with the increase of V_R and saturated after V_R increases beyond -3.2 V . The saturated J_R region is defined as Reg. II. The reverse current saturation behavior

FIG. 1. Reverse current-voltage (J_R - V_R) characteristics of the SBD with the sputtered TiN anode at various temperatures.

was associated with a complete depletion of the 2DEG channel. The J_R increases with the increase of measurement temperature in both Reg. I and Reg. II. Similar observations have also been realized by other reports.^{20,22}

In a Schottky contact, the reverse leakage current before saturation (Reg. I in Figure 1) can be explained using either the Schottky (SC) emission model or the Poole-Frenkel (PF) emission²⁵ model. For the Schottky emission model, the carriers absorb the thermal energy and then emit over the potential barrier at the M-S interface, whereas in the Poole-Frenkel emission model, the carrier transport occurs through trap states with the assistance of the applied field.¹⁹ J_R contributed by these two emission models is given by²⁶

For Schottky emission

$$J_R = A^* T^2 \exp \left[-\frac{q}{k_B T} \left(\phi_t - \sqrt{\frac{qE}{4\pi\epsilon_s(h)\epsilon_0}} \right) \right] \propto T^2 \exp \left(\frac{q}{2k_B T} \sqrt{\frac{qE}{\pi\epsilon_s(h)\epsilon_0}} \right). \quad (1)$$

For Poole-Frenkel emission

$$J_R = qn_0\mu E \exp \left[-\frac{q}{k_B T} \left(\phi_t - \sqrt{\frac{qE}{\pi\epsilon_s(h)\epsilon_0}} \right) \right] \propto E \exp \left(\frac{q}{k_B T} \sqrt{\frac{qE}{\pi\epsilon_s(h)\epsilon_0}} \right). \quad (2)$$

In Eq. (1), A^* is the Richardson constant. In Eq. (2), n_0 and μ denote the carrier density and the effective carrier mobility, respectively. The other parameters k_B , T , ϵ_0 , and q are the Boltzmann constant, the temperature, the vacuum permittivity, and the elementary charge, respectively. The high-frequency (optical) dielectric constant ($\epsilon_s(h) = 5.2$) of $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$ is used as the trap emission, which is much faster than the dielectric relaxation.²⁷ $q\phi_t$ is the effective

barrier height for electron emission from a trapped state and E is the electric field at the M-S interface. Hence, the leakage current mechanism can be identified by analyzing the slope of $\ln(J_R/T^2)$ vs. $E^{0.5}$ for Eq. (1) and $\ln(J_R/E)$ vs. $E^{0.5}$ for Eq. (2).^{18,19} Theoretically, the slope of Poole-Frenkel emission (S_{PF}) is exactly two times the slope of Schottky emission (S_{SC}), as expressed by

$$S_{PF} = \frac{d(J_R/E)}{d(E^{0.5})} = 2S_{SC} = 2 \frac{d(J_R/T^2)}{d(E^{0.5})}. \quad (3)$$

The electric field (E) across the barrier can be calculated using the equation $E = q(\sigma_b - n_s)/\epsilon_s \epsilon_0$.²² The bound charge (σ_b) at the hetero-interface, which is the sum of the piezoelectric polarization charge in the barrier and the difference between spontaneous polarization charge in the barrier and the buffer, is estimated to be $1 \times 10^{13} \text{ cm}^{-2}$.²⁸ $\epsilon_s = 10.32$ is the static dielectric constant of $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$. The 2DEG concentration (n_s) at the hetero-interface can be extracted using the capacitance-voltage (C-V) measurement of the fabricated SBD. Figure 2 shows the C-V characteristics of the TiN SBD at 1 MHz for the forward (−6 to 0 V) and reverse (0 to −6 V) voltage sweeps. The negligible hysteresis suggests that the electron charging and discharging by trap centers are insignificant.²⁹ The extracted V_{th} from the C-V plot is −3.2 V.³⁰ Using the method described in Refs. 8 and 28, the SBH of $1.435 \pm 0.029 \text{ eV}$ was extracted from the C-V curves, indicating the improved SBH by using sputtered TiN as reported in Ref. 17. The calculated E as a function of reverse bias is shown in the inset of Figure 2, which will be used for the subsequent analysis of the leakage current mechanism.

The J_R/T^2 vs. $E^{0.5}$ characteristics at various temperatures are shown in Figure 3(a). The measured S_{SC} , which was determined from the linearly fitted slope of J_R/T^2 with $E^{0.5}$, increased gradually with the increase of temperature as predicted by Eq. (1). Figure 3(b) shows the extracted S_{SC} from the reverse J_R - V_R measurement as well as from the theoretical calculation. The error bars are calculated based on the statistical values of 10 measured SBDs. At all temperatures, the measured mean S_{SC} value is ~ 2.6 times of the theoretical value. Therefore, the carrier transport in Reg. I is unlikely

FIG. 2. Capacitance-Voltage characteristics of forward and reverse sweep at 1 MHz and (inset) calculated E -field vs. reverse bias of the TiN SBD.

FIG. 3. (a) J_R/T^2 vs. $E^{0.5}$ and the linear fit to extract S_{SC} (b) S_{SC} measured from the reverse J_R - V_R characteristics and calculated from the theoretical equation.

dominated by Schottky emission. To verify the extracted value of S_{PF} , the J_R/E vs. $E^{0.5}$ characteristics are also plotted in Figure 4(a). Similarly, the measured J_R/E can also be well fitted with $E^{0.5}$ and the larger S_{PF} is observed at higher measurement temperature. Although the measured statistical S_{PF} in Figure 4(b) does not fit well with the theoretical values, the discrepancy is relatively small (Meas. $S_{PF}/\text{Theo. } S_{PF} = \sim 1.11$ – 1.17). Therefore, the conduction mechanism across the M-S interface is most likely due to Poole-Frenkel emission rather than Schottky emission.

Using the Poole-Frenkel emission model (Reg. I), the parameter $\epsilon_{s(h)}$ is obtained by plotting S_{PF} versus $1000/T$ in Figure 5(a). The extracted $\epsilon_{s(h)}$ in this work and other reported $\epsilon_{s(h)}$ values are also included in Table I. To reduce the error, the mean values of S_{PF} are calculated from 10 measured SBDs. $\epsilon_{s(h)} = 5.28$ are obtained from the fitted graph (see Figure 5(a)), which is consistent with the reported values of GaN (5.35) and AlN (4.77).²⁰ This further supports the presence of Poole-Frenkel emission in the Reg. I of Figure 1 as a gate leakage current conduction mechanism.

The parameter $q\phi_t$ of Poole-Frenkel emission is also calculated from the intercept (I_{PF}) of the J_R/E -axis in Figure 4(a) versus $1000/T$, as shown in Figure 5(b). For comparison, the reported $q\phi_t$ values by other researchers are also

FIG. 4. (a) J_R/E vs. $E^{0.5}$ and the linear fit to extract S_{PF} (b) S_{PF} measured from the reverse J_R - V_R characteristics and calculated from the theoretical equation.

FIG. 5. (a) Slope S_{PF} versus $1000/T$ and (b) intercept I_{PF} versus $1000/T$ plots of SBDs with sputtered TiN anode. The linear fit is based on the Poole-Frenkel emission model.

tabulated in Table I. Although this study employed the HEMT structure with similar Al mole fraction ($x = 0.25$ – 0.28) like other reports,^{20–22,31,32} our obtained $q\phi_t$ of 0.53 eV is larger than those of ~ 0.16 – 0.34 eV (see Table I). The observation of high $q\phi_t$ may be due to the plasma damage to the surface of the AlGaIn/GaN HEMT structure during the TiN sputtering process. Other researchers have also observed high $q\phi_t$.^{27,33} Xu *et al.* have realized the Poole-Frenkel emission dominated leakage current across the sloped mesa side walls with $q\phi_t$ of 0.517 eV. The sloped mesa was formed by inductively coupled plasma etching by the Cl_2 plasma.³³ Subsequently, an even higher $q\phi_t$ of 0.65 eV was reported by Ha *et al.* with CF_4 plasma treatment prior to the e-beam evaporation of the Schottky metal.²⁷ The observation of the high $q\phi_t$ value in both works may not be related to the lower Al mole fraction ($x = 0.15$) in the AlGaIn barrier^{27,33} as small $q\phi_t$ (0.38 eV) was also obtained from Ni/Au Schottky contacts on the high Al mole fraction ($x = 0.65$) AlGaIn barrier.³⁴ The reported high $q\phi_t$ values could be related to the plasma damage rather than the Al mole fraction in the AlGaIn barrier. Recently, we have also reported an activation energy of ~ 0.513 eV, which is related

TABLE I. The reported high-frequency dielectric constant $\epsilon_{s(h)}$ and effective barrier height $q\phi_t$ of Poole-Frenkel emission for Schottky contacts on the $Al_{1-x}Ga_xN/GaN$ HEMT structure. [$\epsilon_{s(h)}$ value: GaN(5.35), AlN(4.77)].²⁰

Schottky contacts	HEMT structure	$\epsilon_{s(h)}$	$q\phi_t$ (eV)	Remark	References
Ni	$Al_{0.25}Ga_{0.75}N/GaN$	~ 5.1	~ 0.30	a	20
Ni/Au	$Al_{0.28}Ga_{0.72}N/AlN/GaN$	...	0.3	a	21
Ni/Au	$Al_{0.26}Ga_{0.74}N/AlN/GaN$	...	0.17	a	22
Ni/Au	$Al_{0.28}Ga_{0.72}N/AlN/GaN$	...	0.35	a	31
Ni/Al/Ta	$Al_{0.26}Ga_{0.74}N/GaN$	...	0.33 ± 0.05	a	32
Ni/Au	$Al_{0.15}Ga_{0.85}N/AlN/GaN$	4.85	0.65	a,c	27
Ni/Au	$Al_{0.15}Ga_{0.85}N/GaN$	...	0.517	a,d	33
Ni/Au	$Al_{0.65}Ga_{0.35}N/AlN/GaN$	...	0.38	a	34
TiN	$Al_{0.26}Ga_{0.74}N/GaN$	5.28	0.53	b	This work

^aSchottky contacts deposited by electron beam (e-beam) evaporation.

^bSchottky contacts deposited by sputtering.

^cSurface CF_4 plasma treatment prior to the Schottky contact deposition.

^dMesa sidewall leakage. Mesa was formed by ICP-RIE using Cl_2 plasma.

to the heavy ($^{131}Xe^+$) ion damages to the AlGaIn/GaN HEMT structure.³⁵ From these observations, the obtained high $q\phi_t$ of 0.53 eV is most probably coming from the plasma damage during the TiN sputtering process.

To illustrate the physical origin of $q\phi_t$ in the Poole-Frenkel emission model for the Reg I in Figure 1, the schematic band diagram is drawn for the AlGaIn/GaN HEMT structure with sputtered TiN (See Figure 6). Based on our reported SBH of ~ 1.1 eV,¹⁷ the obtained $q\phi_t$ of 0.53 eV may not be the dislocation-related traps as the commonly observed trap states at ~ 0.3 eV (Ref. 36) (SBH $- 0.3$ eV $\neq q\phi_t$) below the conduction band edge of AlGaIn/GaN do not match with our $q\phi_t$. The conduction along the threading dislocation line is also not possible because the threading dislocation related states are normally near or below the Fermi level.³⁷ The modified Poole-Frenkel emission as suggested by Zhang *et al.*²⁰ is the most likely mechanism for our gate leakage current behavior in Reg. I. For this modified Poole-Frenkel emission, carrier transport from the TiN into the conductive dislocation related-continuum states must be via a trap state at the M-S interface rather than by direct thermionic emission. The trap state could be neither too low nor too high. If the trap energy level is significantly low, the electron emission from TiN directly into conductive dislocation states would be dominant. On the contrary, if the trap energy level is significantly high, electron emission from TiN into the trap states would play a prominent role.²⁰

In the Reg. II of Figure 1, J_R is saturated with V_R but increases with the increase of measurement temperature, suggesting a thermally activated process with an $\exp(-E_A/k_B T)$ functional dependence. Figure 7 shows the Arrhenius plot of J_R to extract the activation energy (E_A). At $V_R = -5$ and -15 V, the extracted E_A is ~ 0.115 eV with negligible differences. Similar E_A values have also been observed and reported by other researchers. Chen *et al.* and Miller *et al.* have reported E_A of ~ 0.129 eV and ~ 0.18 eV for the $Al_{0.65}Ga_{0.35}N/GaN$ HEMT structure³⁴ and for GaN,³⁷ respectively. Fontserè *et al.* also observed an E_A value for $Al_{0.28}Ga_{0.72}N/GaN$ at ~ 0.4 eV in the measurement temperature range of 450–600 K. At lower temperature, the exhibited E_A value is smaller than ~ 0.4 eV in this work.²¹ Figure 8 illustrates the schematic band diagram of the AlGaIn/GaN HEMT structure with sputtered TiN in Reg. II. When the reverse bias is large enough to saturate the leakage current (Reg. II: -20 V $< V_R < -3.2$ V), the electrons are thermally emitted to E_A and then tunnel through the AlGaIn barrier.³⁷

FIG. 6. Schematic band diagram of the AlGaIn/GaN HEMT structure with sputtered TiN at small reverse bias (Reg. I: -3.2 V $< V_R < 0$).

FIG. 7. Arrhenius plots of the SBD with the sputtered TiN anode at the reverse bias (a) $V_R = -5$ V and (b) $V_R = -15$ V. The activation energies (E_A) are extracted by a linear fit.

At high reverse bias, the electron emission from TiN to the dislocation-related continuum through the trap states of 0.53 eV is not possible. The direct tunneling is the dominant mechanism as the effective thickness of the barrier is reduced due to the high electrical field across the AlGaIn layer.

B. OFF-state gate leakage current in the AlGaIn/GaN HEMT

The temperature dependent gate leakage current (I_G) and source-drain current (I_{DS}) are measured from the three-terminal AlGaIn/GaN HEMT at the OFF-state to correlate the device characteristics with reverse leakage current mechanisms. Figure 9 shows high-voltage drain-biased I_G - V_D characteristics of the AlGaIn/GaN HEMT at different temperatures. To avoid hard damage to the device, the gate voltage $V_G = -7$ V and maximum source-drain bias $V_{DS} = 40$ V are imposed for the measurements. A positive temperature dependency of I_G is observed, which is associated with the temperature assisted tunneling conduction.³⁸ The measured I_{DS} and I_G values at $V_{DS} = 40$ V for different temperatures are given in Figure 10(a). The gradually increasing trend of I_{DS} with the increase of temperature is almost the same as that of I_G except for the difference in the magnitude of current. Figure 10(b) shows the Arrhenius plot to extract the activation energy of both I_G and I_{DS} measured at the OFF-state. The activation energy of 0.159 eV and 0.175 eV is fitted for I_G and I_{DS} , respectively.

FIG. 8. Schematic band diagram of the AlGaIn/GaN HEMT structure with sputtered TiN at large reverse bias (Reg. II: -20 V $< V_R < -3.2$ V).

FIG. 9. $I_G - V_{DS}$ characteristics of the AlGaIn/GaN HEMT with sputtered TiN gate for the gate voltage $V_G = -7$ V at different temperatures (280, 300, 320, 350, 380, and 420 K).

Similar activation energies have also been reported by other researchers. Tan *et al.* extracted an $E_A \sim 0.21$ eV from I_G in the temperature ranging from 293 to 473 K (20 to 200 °C).³⁹ Arulkumaran *et al.* observed three different E_A values by the I_G and I_D measurements for the temperature range of 293 to 673 K (20 to 400 °C),³⁸ in which $E_A \sim 0.2$ eV was attributed to the mechanism of surface hopping conduction, the same as that reported in Ref. 39. The hopping conduction is associated with the surface states created by dangling bonds and/or defects or contamination in between gate and drain. However, as our measured devices have been passivated by PECVD Si_3N_4 , the surface hopping of electrons along the surface states is unlikely to occur as these surface states, such as dangling bonds and defects, have been eliminated by the passivation process. Compared to the M-S interface states that are located at ~ 0.115 eV above the Fermi level (see Figure 8), the extracted E_A from AlGaIn/GaN HEMT also fits well. Hence, the reverse gate leakage current of the HEMT device with passivation believes to be dominated by the trap-assisted tunneling mechanism. This mechanism is also in good agreement with other reports.^{21,37}

The temperature dependent OFF-state breakdown characteristics were measured at $V_G = -7$ V, as shown in Figure 11(a). The OFF-state breakdown voltage (BV_{OFF}) is

FIG. 10. (a) Source-drain (I_{DS}) and gate leakage (I_G) current as a function of measurement temperature and (b) Activation energy plot of I_{DS} and I_G of AlGaIn/GaN HEMTs with sputtered TiN gate for $V_{DS} = 40$ V and $V_G = -7$ V.

FIG. 11. (a) OFF-state breakdown characteristics of the AlGaIn/GaN HEMT at the current compliance of $1 \mu A/mm$ and (b) BV_{OFF} at $V_G = -7$ V as a function of measurement temperature.

defined as the voltage at which I_{DS} reaches the current compliance of $1 \mu A/mm$, which is set to avoid the hard breakdown to the measured device. With the increase of measurement temperature, the BV_{OFF} decreases gradually. The linear fit yields a temperature coefficient of -1.75 V/K as shown in Figure 11(b). The negative or positive coefficients have been observed on AlGaIn/GaN HEMTs with much smaller values (-0.15 ,³⁹ ~ -0.13 ,⁴⁰ 0.33 ,⁴¹ and ~ 0.05 V/K (Ref. 42)). Arulkumaran *et al.* have even reported both positive (0.28 V/K) and negative (-0.53 V/K) coefficients from an individual HEMT device at different temperature ranges.³⁸ Zhang *et al.* reported the temperature coefficient of -6.0 ± 0.4 V/K for both AlGaIn and GaN SBDs and speculated that the magnitude and the sign of temperature coefficient were determined by particular defects of the AlGaIn/GaN HEMT structure.⁴³ Compared to other reported values,^{39–43} our temperature coefficient of -1.75 V/K is within the range, suggesting that the OFF-state breakdown mechanism is dominated by the tunneling gate leakage current.^{38,40}

IV. CONCLUSION

In summary, the reverse leakage current mechanisms of AlGaIn/GaN SBDs and HEMTs with sputtered TiN Schottky contacts were systematically investigated. The conduction mechanism of two terminal gate leakage current is dominated by Poole-Frenkel emission rather than by Schottky emission for the reverse voltage range from 0 to -3.2 V (Reg. I). This has also been confirmed by the extraction of $\varepsilon_{s(h)}$ and $q\phi_t$. The obtained interface state of 0.53 eV may be due to the plasma damage to the surface of AlGaIn/GaN HEMT structure during the TiN sputtering. For the reverse voltage -20 V $< V_R < -3.2$ V (Reg. II), the gate leakage current conduction mechanism is dominated by trap-assisted tunneling with the activation energy of 0.115 eV. This is in close agreement with the activation energy (~ 0.159 eV) calculated from the three terminal OFF-state gate leakage current of the AlGaIn/GaN HEMT. The observation of the negative temperature coefficient (-1.75 V/K) from the OFF-state breakdown voltage (at $1 \mu A/mm$) of the AlGaIn/GaN HEMT is due to the trap-assisted tunneling mechanism,

which is also well correlated with the conduction mechanism realized from the two terminal reverse gate leakage current of AlGaIn/GaN SBDs with sputtered TiN.

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