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

Y. Li,1,a) G. I. Ng,1,2,b) S. Arulkumaran,2 G. Ye,1 Z. H. Liu,3 K. Ranjan,2 and K. S. Ang2
1School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798
2Temasek Laboratories@NTU, Nanyang Technological University, 9th Storey, BorderX Block, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553
3Singapore-MIT Alliance for Research and Technology, 1 Create Way, #10-01 Create Tower, Singapore 138602

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The gate leakage current mechanism of AlGaN/GaN Schottky barrier diodes (SBDs) and high-electron-mobility transistors (HEMTs) with sputtered TiN is systematically investigated. The reverse leakage current (Jr) of TiN SBDs increases exponentially with the increase of reverse voltage (VR) 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 AlGaN/GaN HEMT structure during the TiN sputtering. When the TiN SBDs are biased with −20 < VR < −3.2 V, Jr 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 AlGaN/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 Jr (Reg. II) of the SBDs. The observation of the negative temperature coefficient (−1.75 V/K) from the OFF-state breakdown voltage (at 1 μA/mm) of AlGaN/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

AlGaN/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 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 AlGaN/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 AlGaN/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 AlGaN/GaN,20,22 AlInN/GaN22,23) 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 AlGaN/GaN HEMT structure. Hence, it is important to study and understand the gate leakage current mechanism of AlGaN/GaN SBDs and HEMTs with sputtered TiN. In this paper, we have investigated the gate leakage current mechanism of AlGaN/GaN SBDs and HEMTs with sputtered TiN using current-voltage-temperature (I-V-T) measurements. Finally, the OFF-state gate leakage current (Ig) and OFF-state breakdown voltage (BV_{OFF}) of AlGaN/GaN HEMTs as a function of...
measurement temperatures were also measured and correlated with the obtained conduction mechanism from two terminal gate leakage current of SBDs.

II. EXPERIMENTAL DETAILS

The AlGaN/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-Al0.26Ga0.74N barrier, and a 2 nm-thick UID-GaN cap from bottom to top.24 The threading dislocation density (TDD) of the grown AlGaN/GaN HEMT structure is in the range between $3 \times 10^4 \text{cm}^{-2}$ 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 ($\mu_n$) of 1450 cm$^2$/V·s and a sheet resistance ($R_{sh}$) of 440 $\Omega/\square$.17 After the mesa isolation by BCl$_3$/Cl$_2$ plasma etching, 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 $~0.3 \ \Omega \ \text{mm}$ 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 N$_2$/Ar = 40/30 sccm was selected for the sputtering because this N$_2$/Ar rate yielded an optimum SBH of $~1.1 \text{eV}$ by the I-V-T measurement.17 The pre-pressure and deposition pressure of the TiN sputtering were below $~5 \times 10^{-6} \text{Torr}$ and $~7.7 \times 10^{-3} \text{Torr}$, respectively. Finally, the sample was passivated with a 120 nm-thick Si$_3$N$_4$ 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 guardring type SBDs with an anode diameter of 50 μm. 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, AlGaN/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 μm and a gate-drain distance ($L_{gd}$) of 6 μm with a gate width ($W_g$) of 80 μm.

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 $~3.2 \text{V}$. The saturated $J_R$ region is defined as Reg. II. The reverse current saturation behavior 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. J$R$ contributed by these two emission models is given by26

For Schottky emission

$$J_R = A^*T^2 \exp \left[ -\frac{q}{k_BT} \left( \phi_i - \sqrt{\frac{qE}{4\pi\epsilon_s(h)\epsilon_0}} \right) \right]$$

$$\propto T^2 \exp \left( \frac{qE}{2k_BT} \sqrt{\frac{qE}{\pi\epsilon_s(h)\epsilon_0}} \right). \quad (1)$$

For Poole-Frenkel emission

$$J_R = qn_0\mu E \exp \left[ -\frac{q}{k_BT} \left( \phi_i - \sqrt{\frac{qE}{\pi\epsilon_s(h)\epsilon_0}} \right) \right]$$

$$\propto E \exp \left( \frac{q}{k_BT} \sqrt{\frac{qE}{\pi\epsilon_s(h)\epsilon_0}} \right). \quad (2)$$

In Eq. (1), $A^*$ is the Richardson constant. In Eq. (2), $n_0$ and $\mu$ denote the carrier density and the effective carrier mobility, respectively. The other parameters $k_B$, $T$, $\epsilon_0$, 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 Al$_{0.26}$Ga$_{0.74}$N is used as the trap emission, which is much faster than the dielectric relaxation.27 $q\phi_i$ 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). Theoretically, the slope of Poole-Frenkel emission (SPF) is exactly two times the slope of Schottky emission (SSC), as expressed by

$$S_{PF} = \frac{dJ_R/E}{dE^{0.5}} = 2S_{SC} = \frac{2d(J_R/E^2)}{dE^{0.5}}.$$  

(3)

The electric field ($E$) across the barrier can be calculated using the equation

$$E = \frac{q(\sigma_b - n_s)}{\varepsilon_0 e}.$$  

The bound charge ($\sigma_b$) 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 $1 \times 10^{13}$ cm$^{-2}$. The static dielectric constant of Al$_{0.26}$Ga$_{0.74}$N is 10.32. 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. The extracted $V_{th}$ from the C-V plot is $-3.2$ V. Using the method described in Refs. 8 and 28, the SBH of 1.435 ± 0.029 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 $\sim$2.6 times of the theoretical value. Therefore, the carrier transport in Reg. I is unlikely dominated by Schottky emission. To verify the extracted value of SPF, 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 SPF is observed at higher measurement temperature. Although the measured statistical SPF in Figure 4(b) does not fit well with the theoretical values, the discrepancy is relatively small (Meas. SPF/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 $\varepsilon_s(h)$ is obtained by plotting $S_{PF}$ versus 1000/T in Figure 5(a). The extracted $\varepsilon_s(h)$ in this work and other reported values are also included in Table I. To reduce the error, the mean values of $S_{PF}$ are calculated from 10 measured SBDs. $\varepsilon_s(0) = 5.28$ 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). 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 $q\phi_i$ 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 $q\phi_i$ values by other researchers are also

![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.](image-url)

![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.](image-url)

![FIG. 4. (a) $J_R/E$ vs. $E^{0.5}$ and the linear fit to extract SPF (b) SPF measured from the reverse $J_R-V_R$ characteristics and calculated from the theoretical equation.](image-url)
0.65 eV was reported by Ha et al related to the lower Al mole fraction (x < 0.25–0.28) like other reports. Our obtained qϕt of 0.53 eV is larger than those of ~0.16–0.34 eV (see Table I). The observation of high qϕt may be due to the plasma damage to the surface of the AlGaN/GaN HEMT structure during the TiN sputtering process. Other researchers have also observed high qϕt. Xu et al. have realized the Poole-Frenkel emission dominated leakage current across the sloped mesa side walls with qϕt of 0.517 eV. The sloped mesa was formed by inductively coupled plasma etching by the Cl₂ plasma. Subsequently, an even higher qϕt of 0.65 eV was reported by Ha et al. with CF₄ plasma treatment prior to the e-beam evaporation of the Schottky metal. The observed high qϕt value in both works may not be related to the lower Al mole fraction (x = 0.15) in the AlGaN barrier as small qϕt (0.38 eV) was also obtained from Ni/Au Schottky contacts on the high Al mole fraction (x = 0.65) AlGaN barrier. The reported high qϕt values could be related to the plasma damage rather than the Al mole fraction in the AlGaN barrier. Recently, we have also reported an activation energy of ~0.513 eV, which is related to the heavy (¹³¹Xe⁺) ion damages to the AlGaN/GaN HEMT structure. From these observations, the obtained high qϕt of 0.53 eV is most probably coming from the plasma damage during the TiN sputtering process.

To illustrate the physical origin of qϕt in the Poole-Frenkel emission model for the Reg I in Figure 1, the schematic band diagram is drawn for the AlGaN/GaN HEMT structure with sputtered TiN (See Figure 6). Based on our reported SBH of ~1.1 eV, the obtained qϕt 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 ≠ qϕt) below the conduction band edge of AlGaN/GaN do not match with our qϕt. 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. The modified Poole-Frenkel emission as suggested by Zhang et al. 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.

In the Reg. II of Figure 1, JkB is saturated with VkB but increases with the increase of measurement temperature, suggesting a thermally activated process with an exp(-Eₐ/kₐT) functional dependence. Figure 7 shows the Arrhenius plot of JkB to extract the activation energy (Eₐ). At VkB = -5 and -15 V, the extracted Eₐ is ~0.115 eV with negligible differences. Similar Eₐ values have also been observed and reported by other researchers. Chen et al. and Miller et al. have reported Eₐ of ~0.129 eV and ~0.18 eV for the Al₀.65Ga₀.35N/GaN HEMT structure and for GaN, respectively. Fontseré et al. also observed an Eₐ value for Al₀.28Ga₀.72N/GaN at ~0.4 eV in the measurement temperature range of 450–600 K. At lower temperature, the exhibited Eₐ value is smaller than ~0.4 eV in this work. Figure 8 illustrates the schematic band diagram of the AlGaN/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 < VkB < -3.2 V), the electrons are thermally emitted to Eₐ and then tunnel through the AlGaN barrier.

![FIG. 6. Schematic band diagram of the AlGaN/GaN HEMT structure with sputtered TiN at small reverse bias (Reg. I: -3.2 V < VkB < 0).](image)

### Table I

<table>
<thead>
<tr>
<th>Schottky contacts</th>
<th>HEMT structure</th>
<th>εₑ(h)</th>
<th>qϕt (eV)</th>
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<td>Ni</td>
<td>Al₀.26Ga₀.74N/GaN</td>
<td>~5.1</td>
<td>~0.30</td>
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<td>0.3</td>
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<td>Ni/Au</td>
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<td>0.17</td>
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<td>Ni/Au</td>
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<td>0.35</td>
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<td>Ni/Al/Ta</td>
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<td>0.33 ± 0.05</td>
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<td>...</td>
<td>0.517</td>
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<td>0.38</td>
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<td>TiN</td>
<td>Al₀.26Ga₀.74N/GaN</td>
<td>5.28</td>
<td>0.53</td>
<td>*</td>
<td>This work</td>
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*Schottky contacts deposited by electron beam (e-beam) evaporation.

*Schottky contacts deposited by sputtering.

Surface CF₄ plasma treatment prior to the Schottky contact deposition.

*Mesa sidewall leakage. Mesa was formed by ICP-RIE using Cl₂ plasma.
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 AlGaN layer.

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

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

Similar activation energies have also been reported by other researchers. Tan et al. extracted an EA ~ 0.21 eV from IG in the temperature ranging from 293 to 473 K (20 to 200 °C). Arulkumaran et al. observed three different EA values by the IG and ID measurements for the temperature range of 293 to 673 K (20 to 400 °C), in which EA ~ 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 Si3N4, 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 EA from AlGaN/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.

The temperature dependent OFF-state breakdown characteristics were measured at VG = -7 V, as shown in Figure 11(a). The OFF-state breakdown voltage (BV_OFF) is
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 AlGaN/GaN HEMTs with much smaller values ($-0.15, 0.12, 0.33, 0.05 \ V/K$ (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 $-6.0 \pm 0.4 \ V/K$ for both AlGaN and GaN SBDs and speculated that the magnitude and the sign of temperature coefficient were determined by particular defects of the AlGaN/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 AlGaN/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 mechanism of two terminal gate leakage current is dominated by trap-assisted tunneling with the activation energy of 0.115 eV. This is in close agreement with the activation energy ($\sim 0.159 \ eV$) calculated from the three terminal OFF-state gate leakage current of the AlGaN/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 AlGaN/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 AlGaN/GaN SBDs with sputtered TiN.

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