Current transport mechanisms and trap state investigations in (Ni/Au)–AlN/GaN Schottky barrier diodes

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A B S T R A C T
The current transport mechanisms in (Ni/Au)–AlN/GaN Schottky barrier diodes (SBDs) were investigated by the use of current–voltage characteristics in the temperature range of 80–380 K. In order to determine the true current transport mechanisms for (Ni/Au)–AlN/GaN SBDs, by taking the $J_{\text{tunnel}}$, $E_0$, and $R_s$ as adjustable fit parameters, the experimental $J$–$V$ data were fitted to the analytical expressions given for the current transport mechanisms in a wide range of applied biases and at different temperatures. Fitting results show the weak temperature dependent behavior in the saturation current and the temperature independent behavior of the tunneling parameters in this temperature range. Therefore, it has been concluded that the mechanism of charge transport in (Ni/Au)–AlN/GaN SBDs, along the dislocations intersecting the space charge region, is performed by tunneling.

In addition, in order to analyze the trapping effects in (Ni/Au)–AlN/GaN SBDs, the capacitance–voltage ($C$–$V$) and conductance–voltage ($G$–$V$) characteristics were measured in the frequency range 0.7–50 kHz. A detailed analysis of the frequency-dependent capacitance and conductance data was performed, assuming the models in which traps are located at the heterojunction interface. The density ($D_t$) and time constants ($\tau_s$) of the trap states have been determined as a function of energy separation from the conduction-band edge ($E_c - E_t$) as $D_t \approx (5–8) \times 10^{12} \text{eV}^{-1} \text{cm}^{-2}$ and $\tau_s \approx (43–102) \mu\text{s}$, respectively.

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1. Introduction

AlGaN/GaN heterostructures have attracted special interest due to their potential applications in high electron mobility transistors (HEMT) operating at high power and high temperature levels [1,2]. However, room temperature two-dimensional electron gas (2DEG) density and mobility in turn limit the sheet resistance of the channel and maximum HEMT current (1–1.5 A/mm) for AlGaN/GaN heterostructures [1]. Recently, the AlInN/GaN material system has attracted major interest for electronic applications due to its promising electronic properties, polarization effects, and high thermal stability [3]. AllInN/GaN heterostructures can further enhance the 2DEG density and lead to high HEMT current [3]. It was shown that the DC current levels in turn lead to 2.3 A/mm by using AlInN/AlN/GaN heterojunctions [4]. On the other hand, ultrathin all-binary AlN/GaN HEMTs with ultrathin AlN (2–5 nm) barriers offer higher sheet carrier density and a higher mobility 2DEG channel, which show much promise for high power, high temperature applications in telecommunications, power flow control, and remote sensing [5].

Both molecular-beam epitaxy (MBE) and metal organic chemical-vapor deposition (MOCVD) are currently used to grow high-quality AlGaN/GaN and AlInN/GaN heterostructures with excellent transport characteristics [1–6]. However, it is difficult to grow AlN/GaN HEMTs with high transport characteristics by an MOCVD reactor [7]. Alekseev et al. [8] reported on a low-pressure MOCVD technique for GaN/AlN heterojunction field-effect transistor growth. Room temperature electron mobility in an optimized structure with an 11 nm barrier was 320 cm$^2$/V s and the associated 2DEG density was $2.3 \times 10^{13} \text{cm}^{-2}$.

Because of the large mismatches in lattice constants and thermal expansion constants between GaN and all the available foreign substrates (Al$_2$O$_3$, SiC, ZnO, etc.) causes very high dislocation density ($10^7$–$10^{10} \text{cm}^{-2}$) in a hetero epitaxially grown crystalline GaN layer [2]. The high dislocation density constitutes a serious limitation for the efficiency of radiative recombination, and also for device performance and lifetime. Evtropov et al. [13] and Belyaev et al. [12] showed that the current flow in the III–V heterojunctions, with a high dislocation density, is commonly governed by multistep tunneling with the involvement of dislocations even at room temperature.
In the present paper, we grow AlN/GaN HEMT structures in an MOCVD reactor and investigate the current transport mechanisms in a wide temperature range (80–380 K) in (Ni/Au)–AlN/GaN SBDs. Another purpose of this paper is to characterize the density distribution and relaxation time of the interface states in AlN/GaN HEMT structures by using an admittance technique at room temperature.

2. Experimental

The AlN/GaN heterostructures were grown on c-plane (0 0 0 1) Al₂O₃ substrate in a low-pressure metalorganic chemical-vapor deposition (MOCVD) reactor by using trimethylgallium (TMGₐ), trimethylaluminum (TMAI), and ammonia for Ga, Al, and N precursors, respectively. The buffer structures consisted of high temperature (1150°C) 840 nm AlN templates. A 1.6 nm nominally undoped GaN layer was grown on an AlN template layer at 1050°C, which was followed by the growth of a 4 nm thick high temperature AlN (1150°C) barrier layer. The ohmic and Schottky/rectifier contacts were made on top of the sample at approx. 10⁻² Torr, respectively, within a high vacuum coating system. The ohmic contacts were formed as a square van der Pauw shape and the Schottky contacts were formed as 0.8 mm radius circular dots. After cleaning the samples, Ti/Al/Ni/Au (20/180/40/80 nm) metals were thermally evaporated on the sample and were annealed at 850 °C for 30 s in N₂ ambient in order to form the ohmic contact. Schottky contacts were formed by Ni/Au (50/80 nm) evaporation. Room temperature 2DEG density and mobility were found to be 2 × 10¹³ cm⁻² and 485 cm²/V s, respectively.

The current–voltage (I–V) measurements were performed by use of a Keithley 2400 SourceMeter. The frequency dependence of the C–V and G/ω–V measurements was obtained by using an HP 4192 A LF impedance analyzer. The measurements were performed under the sweep of bias voltage from (−6 V) to (+6 V) and a test signal of 40 mV peak to peak.

3. Results and discussion

The reverse and forward bias I–V characteristics of an (Ni/Au)–AlN/GaN SBDs were measured in a wide temperature range (80–380 K). In Fig. 1, the measured reverse and forward bias J–V characteristics of an (Ni/Au)–AlN/GaN SBDs for the temperatures of 80, 200, 300, and 380 K are given. In order to correctly interpret the current transport mechanisms in the (Ni/Au)–AlN/GaN SBDs, we considered the contribution of thermionic emission (TE) current and tunneling current transport mechanisms (see Fig. 2).

The forward bias J–V characteristics, due to thermionic emission (TE), of SBDs with the series resistance (Rₛ) is given by [9,10].

![Fig. 1. The J–V characteristics of (Ni/Au)–AlN/GaN SBDs.](image1)

![Fig. 2. The fitting of the tunneling current expression (Eq. (2)) to the experimental J–V characteristics of (Ni/Au)–AlN/GaN SBDs measured at 80, 200, and 380 K.](image2)
The values of ideality factor $n$ were obtained from the slope of the linear region of the $J$–$V$ plots [10,11]. The change in $n$ with temperature is shown in Table 1. As shown in Table 1, the $n$ determined from semilog-forward $J$–$V$ plots were found to be a strong function of temperature. The ideality factor $n$ was found to increase with decreasing temperature ($n = 18.9$ at 80 K, $n = 4.7$ at 380 K). It is obvious that the ideality factors of the structures are considerably larger than unity.

The tunneling current density through SBDs is given by [9–12],

$$J_{\text{tunnel}} = J_{\text{thermionic}} \left\{ \exp \left( \frac{q(V - IR_s)}{n kT} \right) - 1 \right\}$$

(2)

where $J_{\text{thermionic}}$ is the reverse saturation current derived from the straight line region of the forward bias current intercept at a zero bias. $T$ is the absolute temperature in K, $q$ is the electron charge, $n$ is the ideality factor, $k$ is the Boltzmann constant, $V$ is the applied bias voltage, and $IR_s$ term is the voltage drop across the $R_s$ of structure [9–11].

### Table 1

<table>
<thead>
<tr>
<th>T (K)</th>
<th>$J_{\text{thermionic}} \times 10^{-7}$ (A/cm²)</th>
<th>$R_s$ (Ω)</th>
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<tr>
<td>80</td>
<td>5.7</td>
<td>18.9</td>
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<td>110</td>
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<td>9.1</td>
<td>4.7</td>
</tr>
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</table>

Fig. 3. The temperature dependences of the tunneling saturation current density ($J_{\text{thermionic}}$) and the characteristic energy of tunneling ($E_0$) for (Ni/Au)–AlN/GaN SBDs.

Fig. 4. (a) Typical measured capacitance and (b) conductance data as a function of voltage for (Ni/Au)–AlN/GaN SBDs measured at 0.7, 1, 2, and 3 kHz.
of interface states. At lower frequencies the interface states can follow the ac signal and yield a frequency dependent excess capacitance. In the high-frequency limit, however, the interface states cannot follow the alternating current (ac) signal. This makes the contribution of interface state capacitance to the total capacitance ignorable small [16,18].

The method described by Schroder for MOS capacitor analysis, which was adapted for the interface trap characterization of AlGaN/GaN HEMTs by Miller et al. [15], was used in the interface trap investigation in (Ni/Au)–AlN/GaN SBDs [14–21]. There are four main possibilities to consider for the spatial location of the interface traps in our study. They measured the density and time constant of interface states. At lower frequencies the interface states can follow the ac signal and yield a frequency dependent excess capacitance. At higher frequencies the interface states can follow the ac signal and yield a frequency dependent excess capacitance.

In this study, the analysis of the frequency-dependent capacitance and conductance data was performed assuming models in which traps are present at the heterojunction-interface traps in our study.

The full circuit model in our analysis is shown in Fig. 5a, where $C_b$ is the barrier capacitance (AlN layer), $C_{GaN}$ is the capacitance of the GaN depletion region capacitor, $R_s$ is the series resistance of the ohmic contact, and $C_m$ and $R_m$ are the interface trap capacitance and associated loss term for the traps. The full circuit in Fig. 5a can be shown by the simplified circuit of Fig. 5b. The capacitance and conductance of the Schottky barrier diode were measured simultaneously assuming a parallel combination of $C$ and $G$, as shown in Fig. 5c.

The parallel conductance $G_p / \omega$ can be obtained from the measured $C_m$ and $G_{m\omega}$ curves by using the relation [14–16,21],

$$\frac{G_p}{\omega} = \frac{-\omega^2 C_0^2 (R_s C_b^2 + R_b G_m - G_m)}{\omega^2 C_b C_m R_s^2 + \omega^2 (C_b R_b G_m + C_m) + C_b^2 - 2 C_b^2 R_b G_m - 2 C_m C_b) + \frac{G_m^2}{C_0^2}$$

In the equation, the barrier capacitance $C_b$ was taken as the $C_{GaN}$ capacitance values. In addition, $R_s$ is the series resistance. The $C_b$ value was determined from the plateau in the $C-V$ curves that are associated with the accumulation of electrons in the two-dimensional electron gas channel. The $C_b$ values used as 1600 nF/cm² were measured at 0.1 kHz. $R_s$ and were calculated from the forward bias $I-V$ characteristics in room temperature by fitting the tunneling current expression (Eq. (2)) to the experimental data (Table 1).

The $G_p / \omega$ as functions of frequency, by assuming a continuum of trap levels, can be expressed as [15,17],

$$\frac{G_p}{\omega} = \frac{g_D^2}{2 \omega^{1/2}} \left[1 + \omega^2 x^2 s \right]$$  

Fig. 6 shows the calculated $G_p / \omega$–ln($\omega$) curves of the AlN/GaN heterostructures for a different bias voltage. $G_p / \omega$ versus ln($\omega$) gives a peak for each bias voltage value due to the $D_t$ contribution. The $D_t$ and $\tau_t$ were calculated by fitting Eq. (5) to the experimental $G_p / \omega$ versus ln($\omega$) curves. By use of the appropriate technique, each value of applied bias voltage is converted into a surface potential corresponding to the Fermi level position within the band gap that we are probing [16,22]. This procedure was applied for several values of bias voltage.

Fig. 7 shows the extracted $D_t$ and $\tau_t$ as a function of energy separation from the conduction-band edge ($E_c - E_f$). The resulting calculated parameters of the AlN/GaN HEMTs were $D_t = (5–8) \times 10^{12}$ eV$^{-1}$ cm$^{-2}$ and $\tau_t = (43–102)$ μs for the interface trap states, respectively.

Kordos et al. [20] investigated the trapping effects in an Al$_2$O$_3$/AlGaN/GaN metal–oxide–semiconductor heterostructure field-effect transistor by temperature dependent conductance measurements. They identified two dominant trap states time constant as 1 μs and 10 ms and trap state density of the order of $10^{12}$ eV$^{-1}$ cm$^{-2}$. On the other hand, Wu et al. [19] published a study on the electrical characterization of Al$_2$O$_3$/GaN interfaces.
by photo-assisted capacitance–voltage characterization. They report the average interface trap density $D_{it}$ of $(1–2) \times 10^{12}$ eV$^{-1}$ cm$^{-2}$. In this study, our measured trap state density and time constant $(D_{it} \approx (5–8) \times 10^{12}$ eV$^{-1}$ cm$^{-2}$ and $\tau_t \approx (43–102)$ µs) are consistent with the reported results for the GaN based structures.

4. Conclusions

The mechanism of charge transport in the (Ni/Au)–AlN/GaN Schottky barrier diodes were investigated by the use of current–voltage characteristics in the temperature range of 80–380 K. The true current transport mechanisms for (Ni/Au)–AlN/GaN SBDs were determined by fitting the analytical expressions given for the current transport mechanisms to the experimental $I–V$ data in a wide range of applied biases and at different temperatures, by taking the $J(t)–E_S$ and $R_c$ as adjustable fit parameters. Fitting results show the weak temperature dependent behavior in the saturation current and the temperature independent behavior of the tunneling parameters in this temperature range. Therefore, it has been concluded that the mechanism of charge transport in (Ni/Au)–AlN/GaN SBDs, along the dislocations intersecting the space charge region, is performed by tunneling.

Furthermore, in order to investigate the trapping effects in AlN/GaN heterostructures, the frequency dependent ($C–V$) and ($G–C–V$) measurements were done in the frequency range 0.7–50 kHz. A detailed analysis of the frequency-dependent capacitance and conductance data was performed, assuming the models in which traps are located at the heterojunction interface. The density ($D_{it}$) and time constants ($\tau_t$) of the trap states have been determined as a function of energy separation from the conduction-band edge $(E_c – E_F)$ for (Ni/Au)–AlN/GaN SBDs.

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