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Leakage current by Frenkel–Poole emission in Ni/Au Schottky contacts on $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructures

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In order to determine the reverse-bias leakage current mechanisms in Schottky diodes on $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructures, the temperature-dependent current-voltage measurements were performed in the temperature range of 250–375 K. In this temperature range, the leakage current was found to be in agreement with the predicted characteristics, which is based on the Frenkel–Poole emission model. The analysis of the reverse current-voltage characteristics dictates that the main process in leakage current flow is the emission of electrons from a trapped state near the metal-semiconductor interface into a continuum of states which associated with each conductive dislocation. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3115805]

Because of its promising electronic properties, polarization effects, and high thermal stability, the AlInN/GaN material system has gained major interest for its electronic applications.[1,2] The possibility to grow epitaxial layers that are lattice matched to GaN at an indium content x of approximately 17% is the important feature of the $Al_{1-x}In_xN$ alloy.[3] At the lattice-matched $Al_{0.83}In_{0.17}N/GaN$, the heterostructure interface minimizes strain, and thereby it also minimizes cracking and/or dislocation formation.[3] Because of this, AlInN materials hold great potential for GaN-based optoelectronics. However, a high excess leakage current of the reverse-biased Schottky contact is defined as the most important for high quality device reliability.[2] Several investigations have been conducted for the basic mechanisms of gate leakage current,[4–10] and leakage current reduction.[11] Zhang *et al.*[7] analyzed the leakage current mechanisms in the Schottky contacts of both n-GaN and AlGaN/GaN at different temperatures and concluded that tunneling current dominates at temperatures below 150 K, whereas the Frenkel–Poole emission dominates at temperatures higher than 250 K. Miller *et al.*[8] have shown that the reverse-bias leakage in AlGaN/GaN can be analyzed in a conventional tunneling model. The effects of the dislocations and defects states, in the reverse-bias leakage, have been suggested by several studies for GaN and $Al_xGa_{1-x}N$ heterostructures[4,6,7] wherein defects, in particular dislocations, might play an important role in reverse-bias leakage.[4,7,8] However, to date, no investigation has been made to analyze the leakage current of the mechanisms of Schottky contacts on $Al_{1-x}In_xN/AlN/GaN$ heterostructures. In the present paper, we show the results of our investigation on reverse leakage current through Ni/Au Schottky contacts on $Al_{1-x}In_xN/AlN/GaN$ heterostructures over a temperature range of $250\ K < T < 375\ K$.

The $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure on a c-plane (0001) Al_2O_3 substrate was grown in a low-pressure metal-organic chemical-vapor deposition reactor. The growth was initiated with a 15-nm-thick low-temperature (840 °C) AlN nucleation layer. Then, a 520 nm high-temperature (HT) AlN buffer layer (BL) was grown at a temperature of 1150 °C. A 2100-nm-thick undoped GaN BL was then grown at 1070 °C. Under the GaN BL, a 2-nm-thick HT-AlN layer was grown at 1085 °C. Then, an HT-AlN layer was followed by a 20-nm-thick AlInN ternary layer. This layer was grown at 800 °C. The Ohmic contacts were formed as a square van de Pauw shape and the Schottky contacts formed as 1 mm diameter circular dots, respectively (Fig. 1). After annealing temperature and annealing time optimization study for the Ohmic contact formation, the Ti/Al/Ni/Au (35/200/50/150 nm) metals were thermally evaporated on the sample and were annealed at 850 °C for 30 s in N_2 ambient in order to form the Ohmic contact. Schottky contacts were formed by Ni/Au (40/50 nm) evaporation. The two-dimensional electron gas density and hall mobility at the room temperature in the $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure were measured as $4.2\times10^{13}\ cm^{-2}$ and $812\ cm^2/V\ s$, respectively. Also, the dislocation density of the $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure sample was determined as $5.9\times10^8\ cm^{-2}$ by the methods of high-resolution x-ray diffraction.[12]

The current-voltage (I-V) measurements were performed by the use of an HP 4145 semiconductor parameter analyzer in a temperature range of 250–375 K by using a temperature controlled close-cycle helium cryostat. The sample temperature was monitored by using a copper-constantan thermocouple that was close to the sample and measured with Lake

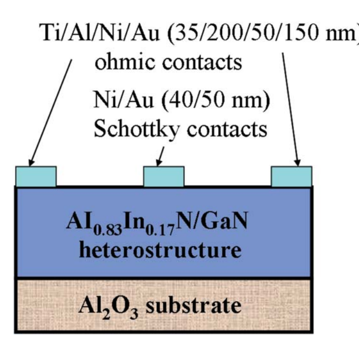

FIG. 1. (Color online) Schematic diagram of the $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure and view of the Ohmic and Schottky contacts on the structures.

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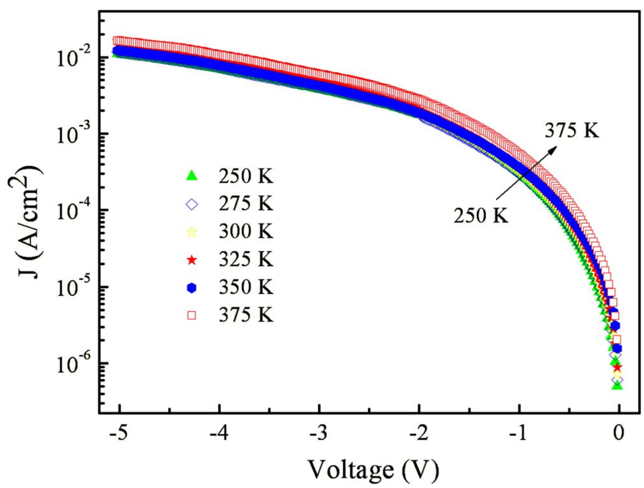

FIG. 2. (Color online) Reverse-bias semilogarithmic current-voltage characteristics of a (Ni/Au)$-Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure at various temperatures.

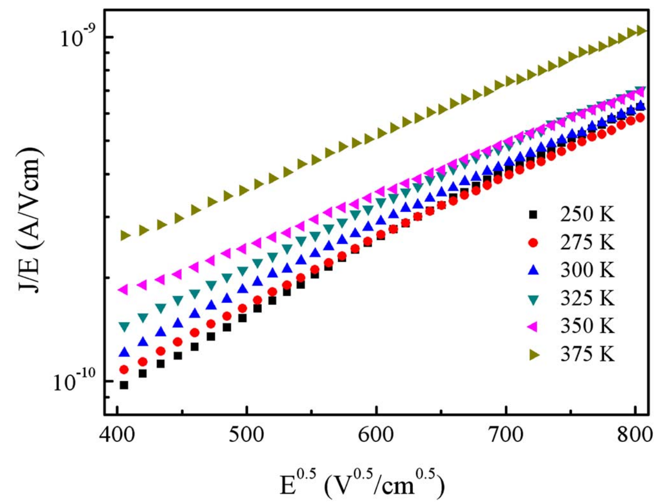

FIG. 3. (Color online) Measured reverse-bias current density divided by electric field vs square root of electric field for Schottky contact on the $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure.

Shore model 331 autotuning temperature controllers with sensitivity better than ± 0.1 K.

Figure 2 shows the current density as a function of bias voltage for the $Al_{0.83}In_{0.17}N/AlN/GaN$ Schottky diodes at temperatures between 250 and 375 K. Measured leakage current values are in comparable range of literature values of Schottky contacts on AlInN/GaN heterostructure.[2,13] For temperatures above 250 K and in the measured macroscopic current densities in $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructures, Schottky diodes were observed to be dependent on an electric field and temperature. As shown in Fig. 3, we observe a linear dependence of $\ln(J/E_b)$ on (E_b), where J is the current density and E_b the electric field at the semiconductor surface. J is also observed to increase with increasing temperature.

Given the large n-type barrier heights that are typical for Schottky contacts to $Al_{1-x}In_xN$, we assume that thermionic emission over the Schottky barrier only makes a negligible contribution to reverse-bias current flow.[4–6,12] In the case of dominant dislocation-related conductivity in the leakage current at room temperature for $Al_{0.83}In_{0.17}N/AlN/GaN$ Schottky diodes, we required in our analysis that a single transport mechanism must accurately describe the current flow. The transport model based on Frenkel–Poole emission satisfied this criterion and gives realistic values for the necessary physical parameters.[7,14]

Frenkel–Poole emission refers to electric-field-enhanced thermal emission from a trapped state into a continuum of electronic states, in which usually, but not necessarily, the conduction band in an insulator. The current density associated with Frenkel–Poole emission is given by[4–9,11,13–16]

$$J = CE_b \exp\left[-\frac{q(\phi_t - \sqrt{qE_b/\pi\varepsilon_0\varepsilon_s}}{kT}\right], \tag{1}$$

where E_b is the electric field in the semiconductor barrier at the metal-semiconductor interface and is calculated assuming that it is constant within the $Al_{1-x}In_xN$ barrier layer, ϕ_t is the barrier height for electron emission from the trapped state, ε_s is the relative dielectric permittivity at high frequency, T is the temperature, ε_0 is the permittivity of free space, and k is Boltzmann's constant. Because the electrons that are emitted from the trapped states do not polarize the surrounding atoms, the relevant dielectric constant is at a high frequency rather than a static dielectric constant.[7,14]

In Eq. (1), the current transport by Frenkel–Poole emission, $\ln(J/E_b)$ should be a linear function of $\sqrt{E_b}$, i.e.,

$$\log(J/E_b) = \frac{q}{kT}\sqrt{\frac{qE_b}{\pi\varepsilon_0\varepsilon_s}} - \frac{q\phi_t}{kT} + \log C \equiv R(T)\sqrt{E_b} + S(T), \tag{2a}$$

$$R(T) = \frac{q}{kT}\sqrt{\frac{q}{\pi\varepsilon_0\varepsilon_s}}, \tag{2b}$$

$$S(T) = -\frac{q\phi_t}{kT} + \log C. \tag{2c}$$

As seen in Fig. 3, the leakage current densities in the $Al_{0.83}In_{0.17}N/AlN/GaN$ diode structures are well described by the electric-field dependence of Eqs. (1). Figure 4 shows

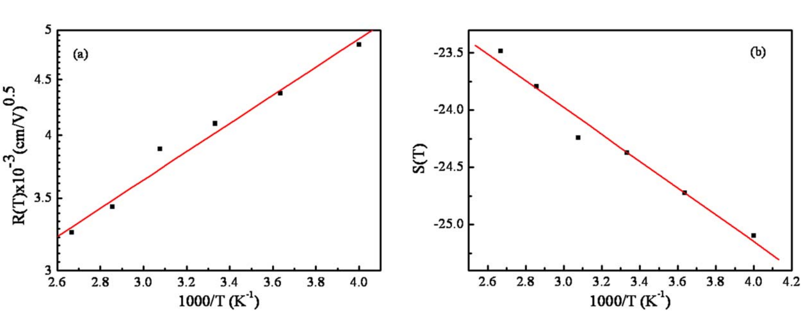

FIG. 4. (Color online) (a) slopes $R(T)$ and (b) intercepts $S(T)$ of the curves shown in Fig. 3 for the Schottky contact on the $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructures.

the functions $R(T)$ and $S(T)$, as defined in Eqs. (2b) and (2c), respectively, plotted as functions of $1/T$. We see from these plots that the measured current densities exhibit both the electric field and the temperature dependence that are expected in Frenkel–Poole emission. Furthermore, the high-frequency relative dielectric constant (ε_s) and the emission barrier height (ϕ_t) values for $Al_{0.83}In_{0.17}N/AlN/GaN$ diode structures can be extracted from these data values. From the slopes of $R(T)$ and $S(T)$ versus $1/T$, as plotted in Figs. 4(a) and 4(b), respectively, we obtain $\varepsilon_s=5.8$ and $\phi_t=0.12$ eV values. The obtained values ε_s for $Al_{0.83}In_{0.17}N$ are in good agreement with the reported values[17] of 5.35 for GaN and 5.8 for InN, and they support the validity of the Frenkel–Poole emission model in describing current transport in these structures.

It can be concluded that emission into or from dislocation-related trapped states, or conduction along dislocation lines, should be the dominant factor determining the electric field and temperature dependence of the leakage current density.[6,7,15] The threading dislocation density for the GaN based high electron mobility transistor structures grown on sapphire substrate are given on the order of 10^8 cm^{-2}.[12] The dislocation density for $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure were measured as 5.9×10^8 cm^{-2} in this study. Measuring the emission barrier height of 0.12 eV would require the relevant trapped state to be located 0.12 eV below the conduction-band edge of $Al_{0.83}In_{0.17}N$.[7]

The electric field and temperature dependence of the current density dictates the Frenkel–Poole emission rather than Schottky emission, in which carrier transport from the metal contact into the conductive dislocation must occur via a trapped state rather than by direct thermionic emission from the metal. Furthermore, the trapped state energy must be close to the metal Fermi level. If the trapped level was significantly lower in energy, the emission of the carriers from the metal directly into conductive dislocation states would most likely dominate, while if the trapped level were significantly higher in energy, the emission of the carriers from the metal into the trapped state would also be a significant factor.[4,7]

The leakage current transport mechanism across the Schottky contacts on $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructures was determined by using temperature dependent reverse-bias current-voltage characteristics in the temperature range of 250 to 375 K. In this temperature range, reverse-bias leakage current is dominated by Frenkel–Poole emission. The analysis of the reverse current-voltage characteristics dictates that the main process in leakage current flow is the emission of electrons from a trapped state near the metal-semiconductor interface into a continuum of states which associated with each conductive dislocation. The measured emission barrier heights for the $Al_{0.83}In_{0.17}N/AlN/GaN$ Schottky diode structures shows that the conductive dislocation states are aligned in the $Al_{0.83}In_{0.17}N$ energy bad gap.

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