Current transport and barrier height evaluation in Ni/InAlN/GaN Schottky diodes

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The current-voltage characteristics of the Ni/InAlN/GaN Schottky diodes were measured at various temperatures in the range of 300–700 K. The experimental data were analyzed considering different current-transport mechanisms. From the analysis it follows that the tunneling current, which might be due to a multistep tunneling along dislocations, is the dominant component at all temperatures in the samples investigated. The barrier height of the Ni/InAlN/GaN Schottky diodes, evaluated from the thermionic emission current, shows a slightly negative temperature coefficient and its value at 300 K is $\geq$1.46 eV. This is significantly higher barrier height than reported before ($<$1 eV). This discrepancy follows from an incorrect evaluation using the intercept and slope of a measured characteristic without separation of the individual current components. © *2010 American Institute of Physics*. [doi:10.1063/1.3442486]

InAlN/GaN heterostructure field-effect transistors (HFETs) are under detailed investigations since recently because of their expected better performance than AlGaN/GaN counterparts. This follows from higher spontaneous polarization in the InAlN with respect to the AlGaN (i.e., higher carrier density and thus higher drain current), as well as from the possibility to grow the InAlN barrier layer (mole fraction of InN of ~17%) lattice matched to GaN.[1] On the other hand, the growth of the InAlN is difficult due to large mismatch between InN and AlN which can lead to phase separation and composition inhomogeneities.[2] Nevertheless, encouraging results have been obtained on InAlN/GaN HFETs, such as current gain cutoff frequency of 102 GHz (Ref. 3) and output power of 10 W/mm at 10 GHz.[4] However, less is known up to now about the current-transport mechanism in the Schottky contacts on InAlN/GaN structures. Predicted barrier height considering known work function of the metal and InAlN should be relatively high, e.g., up to 2.4 eV for Au/InAlN contacts.[5] However, significantly lower barrier heights of only 0.5–0.7 eV and 0.84 eV were evaluated experimentally for the Ni- and Pt-based contacts, respectively.[1] Recently, an increase in the Ni/InAlN barrier height with increased temperature, from 0.20 eV at 80 K to 0.93 eV at 375 K, was reported.[6] It should be noted that similar barrier height dependence on temperature, with room temperature values of 0.96 and 0.65 eV, were reported for Ni/AlGaN/GaN and Ni/GaN contacts too.[7,8] Barrier height inhomogeneity is supposed to be responsible for observed behavior.[7] Leakage current by Frenkel–Poole emission[9] and tunneling current through dislocations[6] have been considered as dominant current-transport mechanisms in the Ni/InAlN/GaN contacts. All these indicate that many questions concerning the Schottky contacts on the InAlN/GaN structures are still open.

In this paper, the current-voltage ($I-V$) characteristics of the Ni/InAlN/GaN Schottky diodes, measured at various temperatures in the range of 300–700 K, are analyzed. Different current-transport mechanisms, such as thermionic emission, generation-recombination, and tunneling and leakage currents, are considered. It is shown that the tunneling current dominates in the Ni/InAlN/GaN Schottky diodes investigated. The barrier height evaluated is $\geq$1.46 eV at room temperature, i.e., significantly higher than reported before, and decreases slightly with increased temperature.

The InAlN/GaN structure used in this study was grown by metal-organic vapor phase epitaxy on SiC substrate at EPFL Lausanne. The layer structure consisted of a GaN buffer layer, followed by a 1 nm AlN spacer layer and a 10 nm thick InAlN ($x_{InN} \cong 17\%$) barrier layer.[2] Conventional field-effect transistor fabrication steps were used for the device preparation at TU Vienna. The processing started with Ar-based reactive ion etching for a mesa isolation. After that Ohmic contacts were prepared by evaporation of Ti/Al/Ni/Au metal stack and subsequent rapid thermal annealing. Finally, Ni/Au gate contacts were patterned by electron-beam lithography. Beside HFET devices with submicrometer gates, also Schottky diodes with a circular (100 μm diameter) and rectangular (50×200 μm^2) geometry were prepared. Parametric semiconductor analyzer Agilent 4155C and cryostat system BIO-RAD DL 8000 were used to measure the $I-V$ characteristics of the Schottky diodes prepared.

The $I-V$ characteristics of the Ni/InAlN/GaN Schottky diodes were measured at various ambient temperatures ranging between 80 and 700 K. However, as it is shown below, only data obtained at higher temperatures are important for the barrier height evaluation in samples used. The typical forward-bias characteristics for the temperatures 300–600 K are shown in Fig. 1. The $I-V$ curves shifted toward the higher bias with decreased temperature. The barrier height and the ideality factor were determined from the intercept

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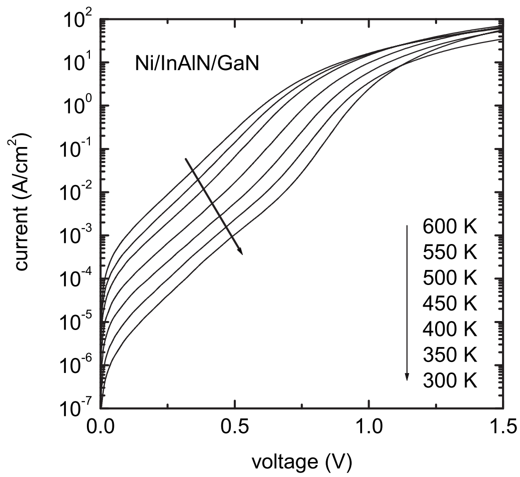

FIG. 1. Experimental forward $I-V$ characteristics of Ni/InAlN/GaN Schottky diode for different temperatures.

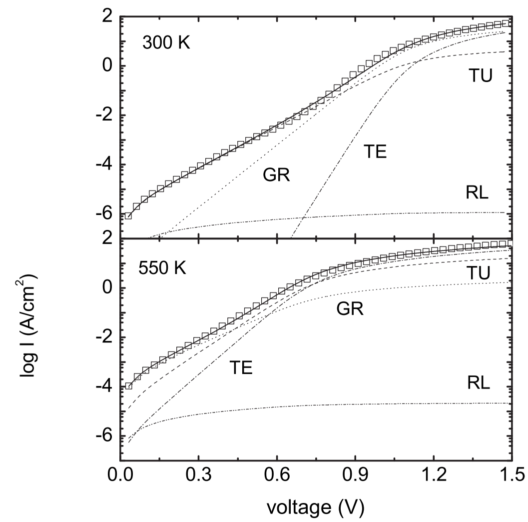

FIG. 3. Fitting result of the forward $I-V$ characteristic of Ni/InAlN/GaN Schottky diode at 300 and 550 K (experimental data—open marks, fitted curve—full line, individual current contributions as described in the text—dashed lines).

and slope of the semilogarithmic $I-V$ plot, as commonly used.[6–8] The effective Richardson constant $A^{**}=55.7\ \mathrm{A\ cm^{-2}\ K^{-2}}$ was used at the calculation. Data obtained for the two diodes with different area of the gate contact and for each used temperature are shown in Fig. 2. A strong increase in the barrier height and simultaneously a decrease of the ideality factor with increased temperature are obtained. The room temperature values of the barrier height and ideality factor are ~0.87 and 2 eV, respectively. These are similar data as reported before for Ni/InAlN/GaN structures[6] as well as Ni/GaN contacts.[8] On the other hand, evaluated barrier height is too low compared with expected values. Moreover, a strong increase in the barrier height with increased temperature cannot be explained theoretically. Therefore we performed detailed analysis of measured $I-V$ characteristics concerning possible current-transport mechanisms.

The current transport in a Schottky diode can be described, in general, as a contribution of the following mechanisms: thermionic emission (TE), generation-recombination (GR), tunneling (TU) and leakage (RL) currents.[10] Detailed description of these mechanisms including corresponding equations can be found in Refs. 8 or 10. A fitting of the experimental $I-V$ characteristics considering all current components as well as series resistance as variable parameters was made for each used temperature. As an example, the fitting results for the data measured at 300 and 550 K are shown in Fig. 3. A good agreement between the experimental and calculated curves was obtained (the fitting error obtained was ≤20%). Concerning a contribution of the individual current components, we can conclude that the RL current can be neglected, as it follows from the fitting. Such a small contribution was found for all temperatures. On the other hand, the TU current dominates at the bias voltages lower than ~1 V, i.e., in the linear part of the log I versus V dependence. This is valid for temperatures around 300 K (see Fig. 3). The TU component is less dependent on temperature, in contradiction to the TE current which depends by square law on temperature. This supports a necessity of high-temperature measurement of Schottky diodes with relatively high tunneling contribution, as it is the case of InAlN/GaN diodes in general (but AlGaN/GaN diodes particularly too). At higher temperatures, as demonstrated for 550 K in Fig. 3, the TE current contributes significantly to the total current with an overlap of the TE and TU components at the bias of about 0.7 V. It should be also mentioned, that a contribution of the GR current cannot be neglected, as follows from our fitting results shown in Fig. 3.

From performed analysis of the current transport in the Ni/InAlN/GaN Schottky diodes, it follows that the tunneling current is the dominant one. The characteristic tunneling energy $E_{00}\cong 27$ meV results from the fitting procedure, which corresponds to the InAlN doping of $2.9\times 10^{18}\ \mathrm{cm^{-3}}$. This is in good agreement with the residual doping of the InAlN layer expected to be around $(1-5)\times 10^{18}\ \mathrm{cm^{-3}}$ (Ref. 2). It has been already reported that the current transport in Ti/GaN Schottky diodes can be described by a multistep tunneling along dislocations.[11] This follows from the well known fact that the dislocation density in GaN is much higher than that in other III-V materials, such as GaAs and InP. However, the InAlN/GaN growth quality is still partially behind that of the AlGaN/GaN,[2] thus higher dislocation density ($10^8-10^{10}\ \mathrm{cm^{-2}}$) can be expected in these structures. This underlines an importance of the tunneling current at an

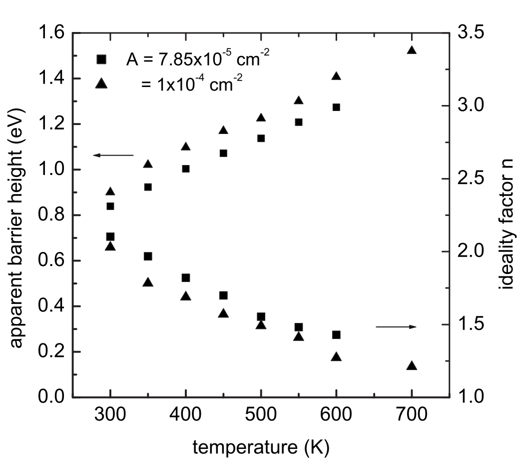

FIG. 2. Apparent barrier height and ideality factor as a function of temperature for two Ni/InAlN/GaN Schottky diodes with different area of the gate contact.

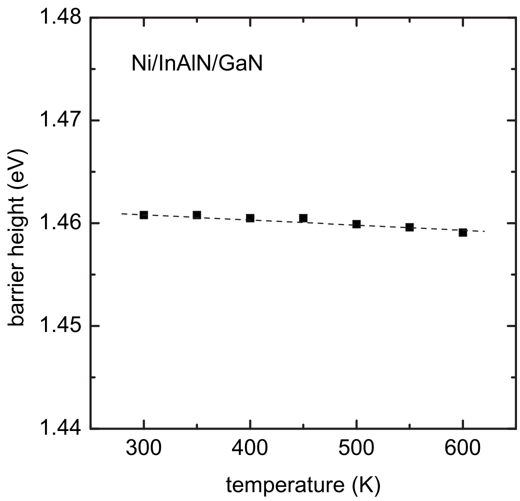

FIG. 4. Barrier height of Ni/InAlN/GaN Schottky diode as a function of temperature. Note that the barrier height evaluated represents only the lower boundary of possible values, as the TU contribution to the total current is relatively high in structures investigated.

analysis of the current transport in InAlN-based Schottky contacts.

The tunneling current needs to be considered mainly at the evaluation of the barrier height. Results obtained by a common procedure, as described above and shown in Fig. 2, do not represent the barrier height which results from the TE current. This is actually cleared by an inspection of Fig. 3. The TE current components, obtained from the fitting procedure of the experimental $I-V$ characteristics at each temperature, were used to evaluate the barrier height of the Ni/InAlN/GaN diodes investigated. The barrier height as a function of temperature is shown in Fig. 4. The barrier height is 1.461 eV at 300 K and exhibits a slightly negative temperature coefficient. Obtained room temperature value of the barrier height is significantly higher than those reported before.[1,6] Moreover, a decrease in the barrier height with increased temperature corresponds to theoretical predictions. However, it should be noted that the barrier heights evaluated are only the lower boundaries of possible true barrier height values, mainly for lower temperatures used. This follows from the fact that the TE current component at bias voltages ≤ 1 V is much lower than the total current. Relatively reasonable fitting might be performed with lower saturation current of the TE contribution, i.e., with higher barrier height than shown in Fig. 4. However, at highest temperatures used the TE contribution to the total current is becoming more significant and the apparent barrier height (Fig. 2) is approaching the values extracted from the complex analysis. Material structure with better structural quality, i.e., with lower TU current contribution to the total current, would be needed for a more exact evaluation of the true barrier height in metal/InAlN Schottky contacts. Nevertheless, this result shows that the barrier height in InAlN-based Schottky contacts is significantly higher than those reported before, if correct evaluation is applied. This conclusion is valid also for some reports on AlGaN/GaN Schottky diodes.

In summary, current transport in the Ni/InAlN/GaN Schottky diodes was analyzed on the base of measured $I-V$ characteristics at various temperatures ranging between 300 and 700 K. From the fitting procedure it follows that the tunneling current is the dominant component in the samples investigated. The barrier height evaluated from the TE current shows a slight negative temperature coefficient and its value at 300 K is ≥ 1.46 eV. This is significantly higher barrier height than 0.5–0.84 eV reported before. This discrepancy follows from an incorrect evaluation of the individual current components. On the other hand, more exact evaluation of the barrier height in a metal/InAlN structure needs that the tunneling current should be lower than in the samples investigated, i.e., high-temperature measurement should be performed and/or the structural quality of InAlN will be improved.

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