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Schottky barrier height on thermally oxidized InAlN surface evaluated by electrical and optical measurements

J. Kováč,[1] R. Šramatý,[1] A. Chvála,[1] H. Sibboni,[2] E. Morvan,[2] M. A. DiForte-Poisson,[2] D. Donoval,[1] and P. Kordoš[1,3,a)]

[1]*Department of Microelectronics, Slovak University of Technology, SK-81219 Bratislava, Slovakia*
[2]*Alcatel-Thales III-V Lab, route de Nozay, 91460 Marcoussis, France*
[3]*Institute of Electrical Engineering, Slovak Academy of Sciences, SK-84104 Bratislava, Slovakia*

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Current transport and Schottky barrier height analysis on InAlN/GaN structures with thermally oxidized InAlN surface (800 °C, 1 min) was performed. From the current-voltage characteristics measured at various temperatures (300–820 K) and their approximation by various current mechanisms, it follows that the tunneling current dominates. Extraction of the thermionic emission yielded the Schottky barrier height of 2.43 eV at 300 K and its slight decrease with increased temperature. Optical method (photoemission current vs photon energy) allows direct barrier height evaluation without analyzing current mechanisms. Comparative analysis using optical method yielded the room-temperature barrier height of 2.57 eV. Obtained barrier heights document significant barrier enhancement due an InAlN oxidation. This result confirms the thermal oxidation procedure as a useful tool at the preparation of reliable InAlN-based devices. © *2011 American Institute of Physics*. [doi:10.1063/1.3583458]

InAlN/GaN heterostructures exhibit two-times higher carrier drift velocity[1] and about three-times higher carrier density[2] than widely studied AlGaN/GaN counterparts. From this it follows that InAlN-based heterostructure field-effect transistors (HFETs) might exhibit better performance for high-frequency and/or high-power applications. Recent results on InAlN/GaN HFETs, such as current gain cutoff frequency of 205 GHz (Ref. 3) and output power of 10 W/mm at 10 GHz (Ref. 4) support it. On the other hand, high gate leakage (RL) current as a serious drawback of these devices is well known. This effect can be significantly suppressed by metal-oxide-semiconductor HFETs on AlGaN/GaN (Ref. 5) and InAlN/GaN.[6] Preferable type of insulator and method of its preparation have been not specified yet but Al_2O_3 prepared by atomic layer deposition seems to be an optimal case.[7] InAlN is usually grown nearly lattice matched to GaN, which means about 83% of AlN in the ternary. Such "high-Al-content" material seems to be a good candidate for simple preparation of an insulator by thermal oxidation. The potential of such approach has been already demonstrated.[8,9] In both studies a suppression of the gate RL current in ox-InAlN/GaN HFETs by thin native oxide is demonstrated. Recently, also study on surface states and barrier height of AlGaN/GaN due thermal oxidation was reported.[10] However, less is known up to now about current-transport and barrier height of the Schottky contact on oxidized InAlN/GaN structures.

In this letter, electrical and optical measurements on InAlN/GaN structures with thermally oxidized InAlN and Ni gate contact are used to characterize their transport properties and Schottky barrier height on Ni. The current-voltage (*I-V*) characteristics were measured at various temperatures in the range of 300–820 K. Simulation analysis shows that tunneling (TU) current dominates in the current transport with partially decreased influence at higher temperatures comparing to thermionic emission (TE). Extracted TE current yielded a barrier height of 2.43 eV at 300 K, which slightly decreased with increased temperature. Internal photoemission method, as more accurate procedure, was used to verify the barrier height on ox-InAlN/GaN. Resulting barrier height of 2.57 eV at 300 K correlates well with that obtained from the electrical characterization. It should be noted, that the barrier height of ~1.46 eV was obtained on intentionally nonoxidized InAlN/GaN Schottky diodes using similar fitting analysis.[11,12] This indicates on high perspective of thermal oxidation procedure in order to enhance the Schottky barrier height on InAlN structures.

The InAlN/GaN structure used in this study was grown by metal-organic vapor phase epitaxy on sapphire substrate. The layer structure consisted of a GaN buffer layer, followed by a 1 nm AlN spacer layer and a 10 nm thick InAlN ($x_{AlN} \cong 82\%$) barrier layer. All layers were unintentionally doped. Composition of the InAlN is chosen to prepare nearly lattice-matched layer to GaN. The device preparation started with an oxidation of the InAlN surface. The oxidation was performed at 800 °C for 1 min in pure oxygen atmosphere at atmospheric pressure. The oxide thickness is estimated from x-ray photoemission spectroscopy to be about 1 nm. After that openings into the ox-InAlN layer before ohmic metal deposition were made by fluorine-based reactive ion etching. The ohmic contacts were prepared by evaporation of Ti/Al and subsequent rapid thermal annealing at 900 °C. Finally, Ni/Pt/Au gate contacts were patterned by optical lithography. The structures with a circular gate contact (400 μm diameter) and surrounding ohmic contact (gate-Ohmic separation 20 μm) were prepared.

Electrical characterization was performed by measurement of *I-V* characteristics at various temperatures in the range 300–820 K using parametric semiconductor analyzer Agilent 4155C and a Carbolite laboratory thermostatic chamber LHT6/30. For optical measurements a halogen lamp (50 W), a monochromator SPM-2 with focused radiation on the

[a)]Electronic mail: elekkord@savba.sk.

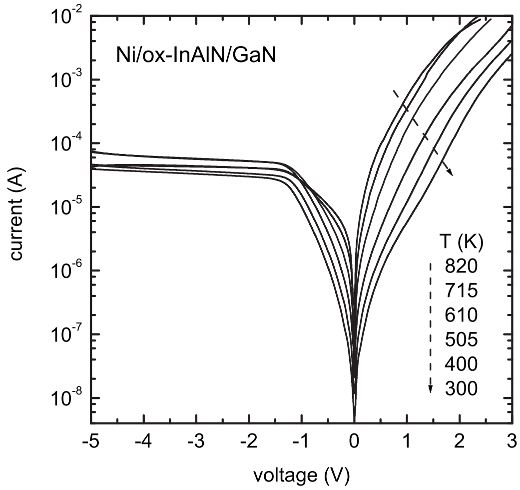

FIG. 1. Experimental *I-V* characteristics of Ni/ox-InAlN/GaN Schottky diode at six selected temperatures.

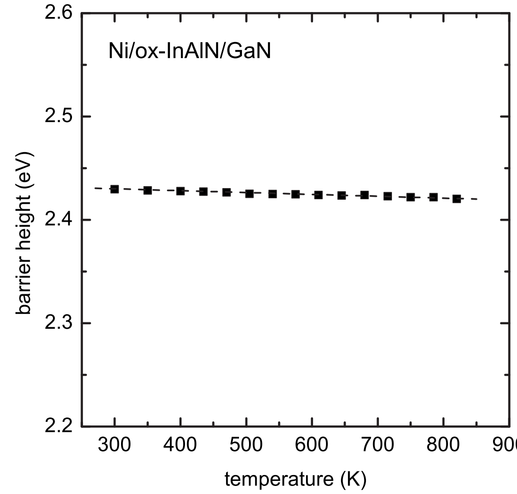

FIG. 3. Temperature dependence of barrier height on Ni/ox-InAlN/GaN Schottky diodes.

sample and calibrated radiation detector were used.

Typical *I-V* characteristics of the Ni/ox-InAlN/GaN Schottky diodes for six selected temperatures (from used 15 temperatures) are shown in Fig. 1. The forward-bias *I-V* curves shifted toward higher current with increased temperature. An influence of temperature on the reverse-biased characteristics is less pronounced and indicates on Frenkel–Poole emission. For an analysis of the current transport in the samples investigated we used similar procedure as reported on Ni/InAlN/GaN Schottky diodes.[11] A fitting of the experimental *I-V* characteristics, considering following transport mechanisms: TE, generation-recombination (GR), TU, and RL currents, was performed. Detailed description of these mechanisms including corresponding equations can be found in Refs. 13 and 14. As examples, the fitting results for data measured at 300 and 820 K are shown in Fig. 2. A good agreement between the experimental (open marks) and calculated (full lines) *I-V* characteristics was obtained. This result shows that TU current dominates in whole temperature range used. However, an impact of TE on the total current increases with increased temperature. This underlines an importance of high-temperature measurements at the characterization of InAlN-based Schottky diodes. The RL current contribution (RL) is rather small and the GR current can be neglected (thus not shown in Fig. 2). We note that the room temperature *I-V* characteristics before and after the heating cycle up to 820 K were slightly different with an indication of a change in the oxide thickness and/or composition. This issue is now under detailed investigations.

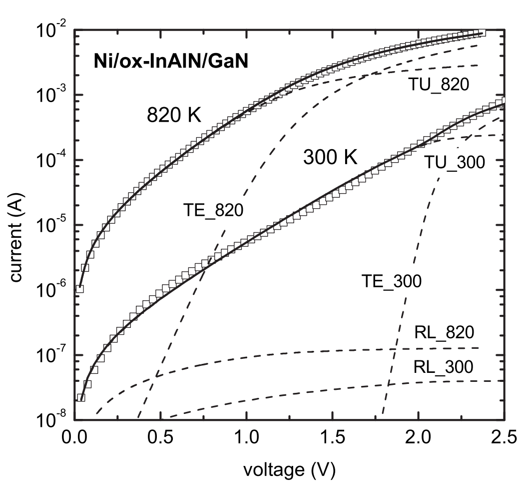

FIG. 2. Fitting result of the forward *I-V* characteristics of Ni/ox-InAlN/GaN Schottky diode at 300 and 820 K (experimental data: open marks, fitted curve: full line, individual current contributions as described in the text: dashed lines).

The TE component, extracted from the fitting procedure for each measurement temperature, was used to evaluate the Schottky barrier height on Ni/ox-InAlN/GaN structures. The result, i.e., temperature dependence of the Schottky barrier height, is shown in Fig. 3. The effective Richardson constant $A^{**}=55.7$ A cm^{-2} K^{-2} was used for the calculations.[15] The barrier height is 2.43 eV at 300 K and decreases slightly with increased temperature to reach 2.42 eV at 820 K. It should be mentioned that the room-temperature barrier height of $\sim$1.46 eV has been reported for nonoxidized Ni/InAlN/GaN Schottky diodes.[11] This indicates an efficient enhancement of the barrier height by thermal oxidation of the InAlN surface. Temperature coefficient of the barrier height $\alpha \cong -2$ meV/100 K is significantly smaller than would be expected according temperature dependence of the InAlN band gap. One possible explanation is that the Fermi level is pinned by interface states. It should be noted that similar temperature coefficient has been found on nonoxidized Ni/InAlN/GaN Schottky diodes with barrier height of 1.47 eV at 300 K.[12]

In order to verify the barrier height on Ni/ox-InAlN/GaN Schottky diodes evaluated by electrical characterization we performed a comparative optical characterization of these structures. The relationship between the photoemission current of a Schottky barrier R and the incident photon energy $h\nu$ can be written as

$$R \sim (h\nu - q\Phi_B)^2,$$

where Φ_B is the barrier height. An optical characterization has various advantages over an electrical one. This method allows direct evaluation of the barrier height, i.e., it is not necessary to separate individual current transport contributions. Additionally, one does not need to know the Richardson constant, gate contact area and sample temperature, as it is the case of TE evaluation. Photoemission current as a function of the photon energy, measured at 300 K, is shown

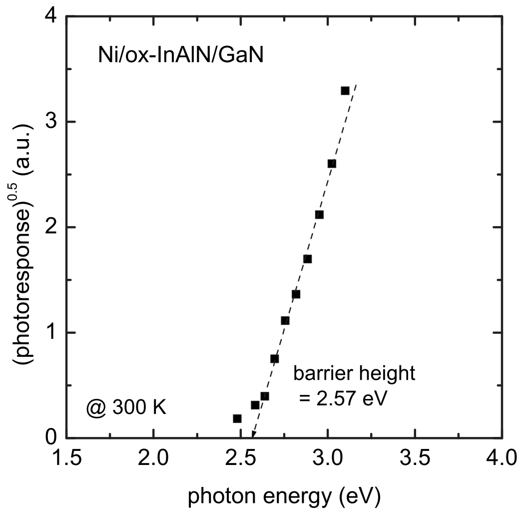

FIG. 4. Square root of photocurrent per incident photon vs incident photon energy at 300 K for Ni/ox-InAlN/GaN structure.

in Fig. 4. The barrier height evaluated on Ni/ox-InAlN/GaN structures is 2.57 eV. This is in good agreement with the barrier height of 2.43 eV at 300 K obtained using electrical (I-V) characterization. Similar partial underestimation of the barrier height from electrical method comparing to optical one is well known and was reported also on relaxed GaN and AlGaN structures.[16] Unfortunately, it does not exists a report on the barrier height on InAlN/GaN structures evaluated using optical method, according our knowledge. On the other hand, the barrier height on oxidized InAlN surface, comparing to ~1.46 eV on nonoxidized one, is enhanced significantly. However, physical and material details of an InAlN oxidation, e.g., formation of the oxide and its correlation to surface states, if an oxidation process affects only near-surface region or also the bulk of InAlN, etc., need to be investigated in the next.

In summary, the analysis of the current transport and Schottky barrier height on the InAlN/GaN structures with thermally oxidized InAlN surface has been performed. From our study it follows that:

(i) The TU current dominates in the current transport of Ni/ox-InAlN/GaN structures.

(ii) The barrier height evaluated using electrical (I-V) and optical (photoemission) characterization at 300 K is 2.43 eV and 2.57 eV, respectively.

(iii) The barrier height enhancement due a thin native oxide on InAlN is significant ($\Phi_B \sim 1.46$ eV on intentionally nonoxidized InAlN/GaN diodes), which documents high perspective of InAlN thermal oxidation for preparation of high-performance InAlN-based devices.

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