Temperature behavior of inhomogeneous Pt/GaN Schottky contacts

Ferdinando Iucolano,[a] Fabrizio Roccaforte, Filippo Giannazzo, and Vito Raineri
CNR-IMM, Stradale Primosole 50, 95121 Catania, Italy

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In this letter, a correlation between the nanoscale localized electrical properties of the Pt/GaN Schottky barrier and the temperature behavior of macroscopic Schottky diodes is demonstrated. Although a significant improvement of the ideality factor of the diodes is achieved after annealing at 400 °C, local current-voltage measurements, performed with a biased tip of a conductive atomic force microscope, revealed the inhomogeneous nature of the barrier. Its nanoscale degree of homogeneity was quantitatively described by means of Tung's model [Phys. Rev. B **45**, 13509 (1992)], allowing the authors to explain the temperature dependence of the electrical characteristics of the macroscopic diodes. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2710770]

Because of its properties such as the wide band gap, the high critical electric field and the high saturation velocity, and the continuous improvement of the crystal quality, the interest on gallium nitride (GaN) for high power and high frequency devices applications is growing.[1] One of the key issues in GaN-based electronics is still the formation of reproducible and reliable rectifying contacts, with a high Schottky barrier and a low leakage current. In particular, due to the submicrometric scaling of the gate dimensions in advanced high electron mobility transistors, an accurate control of the barrier is required to ensure the device reproducibility and ideality. As the Schottky barrier height Φ_B is expected to be dependent on the metal work function, high work function materials (Ni, Pt, Au, Pd,…) are typically used for rectifying contacts on n-type GaN. However, several works reported experimental values of Φ_B much lower than those predicted by the Schottky-Mott relation,[2] with the ideality factor n significantly exceeding the unity.[3–5] In order to explain the current transport through the barrier and the deviations from the ideal behavior, the commonly reported characterization of conventional Schottky diodes is not exhaustive. In this sense, a nanoscale study of the degree of homogeneity of metal/GaN Schottky barriers can improve the understanding of the macroscopic electrical behavior of the contacts and, ultimately, to optimize the device performances.

In this letter, the nanoscale electrical properties of the Pt/GaN Schottky barrier were studied by local current-voltage measurements carried out with the biased conductive tip of an atomic force microscope (AFM). In particular, the contact degree of homogeneity was quantitatively described by Tung's model on inhomogeneous Schottky barriers,[6] demonstrating that the nanoscale electrical properties of the barrier are strongly correlated to the temperature dependence of the Schottky diode electrical characteristics.

n-type Si-doped ($N_D=1\times10^{16}$ cm^{-3}) GaN epilayers, 3 μm thick, grown on Al_2O_3 substrates, were used in this work. In order to study the macroscopic properties of the contact, test Schottky diodes, i.e., circular dots of radius of 150 μm, were fabricated. First, Ohmic contacts (circular crowns of area of 5×10^{-3} cm^2) were formed by the deposition of a Ti/Al/Ni/Au multilayer followed by a rapid thermal annealing at 750 °C.[7] The distance between the Ohmic and the Schottky contacts was 50 μm. Thereafter, the Schottky contact was formed by a Pt/Au bilayer. As previously reported in literature, postdeposition annealing processes can lead, under certain conditions, to an increase of the barrier height and to an improvement of the ideality factor in Pt/Au and Ni/Au contacts on GaN.[4,8] Accordingly, in order to improve the electrical properties of our contacts, the diodes were annealed in Ar for 60 s at several temperatures in the range of 300–500 °C.

The current-voltage (I-V) characteristics of several diodes were measured before and after annealing using a Süss Microtec probe station and an Agilent 4155C parameter analyzer. The forward I-V characteristics representative of the average behavior of the diodes are reported on a semilogarithmic scale in Fig. 1, for the as prepared sample and for the sample annealed at 400 °C, i.e., the annealing process that allowed us to optimize the electrical characteristics in terms of barrier height Φ_B and ideality factor n. The values of Φ_B and n were determined from a fit of the linear region of the forward I-V curves, according to the thermoionic emission model,[2]

$$I=AA^{*}T^{2}\exp\left(-\frac{q\Phi_B}{kT}\right)\exp\left(\frac{qV}{nkT}\right), \tag{1}$$

where A is the area of the Schottky contact, A^* is the Richardson constant of GaN (26.9 A/cm^2 K^2),[9] T is the absolute temperature, and k is the Boltzmann constant.

In particular, the as prepared contact has a Schottky barrier height $\Phi_B=0.79$ eV, with an ideality factor of $n=1.80$. The strong deviation from the ideality of the Pt/GaN barrier after metal deposition can be related to a poor adhesion of the metal on the GaN surface or to the presence of a residual native oxide that ultimately lead to a high concentration of interface states. On the other hand, after annealing at 400 °C, an increase of the barrier height up to 0.96 eV is observed, accompanied by an improvement of the ideality factor n that reached the value of $n=1.16$. This latter can be ascribed to the improvement of the intimate metal/GaN interface quality, arising from the removal of a nonuniform residual thin interfacial oxide (by interface reaction or metal diffusion) and/or from the reduction of the interface state density.[4,8] In spite of the strong improvement achieved after annealing at 400 °C, the reported mean barrier height value

[a]Electronic mail: ferdinando.iucolano@imm.cnr.it

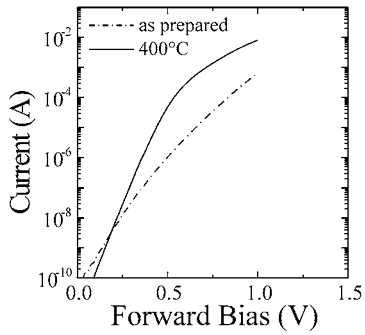

FIG. 1. Forward *I-V* characteristics of the Au/Pt/GaN Schottky diodes before (as prepared) and after annealing at 400 °C.

(0.96 eV) is characterized by a quite large standard deviation, i.e., 0.08 eV.

In order to gain insights on the nanoscale electrical properties of the Pt/GaN Schottky barrier, local *I-V* measurements were performed using a DI-3100 AFM equipped with a biased conductive diamond-coated Si tip. The local *I-V* measurements were carried out on the optimized contact annealed at 400 °C, i.e., where the macroscopic diodes showed an almost ideal behavior ($n=1.16$).

For these measurements, a large area Ti/Al/Ni/Au Ohmic contact was formed on a portion of the sample surface, whereas an ultrathin Pt/Au Schottky contact (~5 nm) was formed by photolithography and lift-off on the remaining part of the surface. A schematic of the experimental setup is reported in the insert of Fig. 2. A bias ranging from −2 to 2 V was applied to the conductive AFM tip, in contact on a nanometric area with the Schottky metal layer. The large area Ohmic contact was connected to a current amplifier, thus enabling us to measure the current flowing through the metal/GaN barrier on the nanoampere scale with a picoampere sensitivity. As demonstrated by Giannazzo *et al.*,[10] the high resistivity of ultrathin metal films, combined with the electric field localization at the apex of the biased tip, allows us to obtain a nanometric localization of the current transport through the Schottky barrier and, hence, to determine the barrier height with a spatial resolution in the order of the tip diameter (10–20 nm). In particular, the value of the local Schottky barrier height can be determined by the parabolic fit of the *I-V* curve around the onset of the current.[10] The parabolic relation can be directly deduced by Taylor series expansion to the second order of the exponential thermoionic emission law.[10]

First of all, a set of 100 local *I-V* measurements was performed with the tip fixed on the same sample position. These *I-V* curves did not exhibit any systematic temporal drift along the bias axis, ruling out the occurrence of stress-induced electrical degradation of the nanoscale contact during the measurements. From the standard deviation of the mean barrier height of these *I-V* curves, an error on the single local barrier measurement of 0.01 eV was estimated.

Thereafter, the local values of the barrier were determined in different positions of the contact, scanning the biased tip over a $5\times5\ \mu m^2$ area, i.e., in a 10×10 matrix. The statistical distribution of the barrier height values determined by this procedure is reported in Fig. 2. The experimental values exhibit a Gaussian distribution with a mean value of 0.84 eV and a standard deviation $\sigma_\Phi=0.11$ eV, in agreement, within the statistic errors, with the values measured in the macroscopic diodes. The fact that the local *I-V* measurements result into a wide distribution of barrier height values demonstrates the formation of a laterally "inhomogeneous" Schottky barrier. Hence, the determined standard deviation σ_Φ represents a direct measure of the lateral homogeneity of the Pt/GaN barrier.

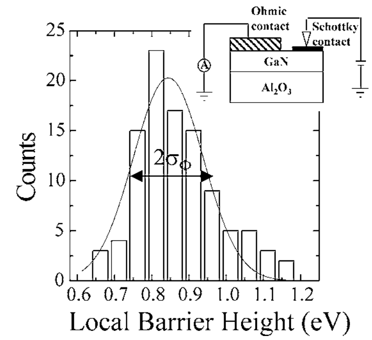

FIG. 2. Statistical distribution of the local barrier height values of the Au/Pt/GaN contact annealed at 400 °C. The relative Gaussian fit curve is also reported. The insert shows the schematic of the experimental setup used for the local *I-V* curves by means of the conductive tip of an AFM.

From a microscopic point of view, according to the model proposed by Tung[6] Sullivan *et al.*[11] an inhomogeneous Schottky contact can be described as a distribution of "patches" with different barrier heights and different areas embedded in a region with an ideal higher barrier Φ_{B0}. In particular, the potential distribution under a low barrier patch is influenced by the surrounding regions with higher barrier height, thus resulting in an "effective" Schottky barrier height Φ_i^{eff} for the local current transport under the ith patch, which can be expressed as[11]

$$\Phi_i^{\mathrm{eff}}=\Phi_{B0}-\gamma_i\left(\frac{V_{\mathrm{bb}}}{\eta}\right)^{1/3}, \tag{2}$$

where γ_i is a parameter describing the inhomogeneity of the barrier and depends both on the patch size and on the deviation of the local barrier Φ_i^{eff} from the ideal higher barrier Φ_{B0}, V_{bb} is the band bending, and $\eta=\varepsilon/qN_D$, being ε the permittivity of the material, q the electron charge, and N_D the carrier concentration in the semiconductor.

As a local *I-V* curve gives the Schottky barrier in a nanometric region, each barrier value can be regarded as the effective barrier height Φ_i^{eff} in a certain interfacial positions of the inhomogeneous barrier.

The ideal barrier height Φ_{B0} in Eq. (2) can be determined from the plot of the barrier height Φ_B versus the ideality factor n of macroscopic diodes at different temperatures, taking as Φ_{B0} the asymptotic value of the barrier extrapolated at $n=1$ (ideal contact).[12,13] In our case, from the values of Φ_B and n determined by the *I-V* curves of the diodes taken at different temperatures [Fig. 3(a)], value of $\Phi_{B0}=1.21$ eV was obtained.

Moreover, it is worth noting that, according to Eq. (2), the standard deviation of the γ_i distribution (σ_γ) can be related to the standard deviation of the local barrier height distribution (σ_Φ) by

$$\sigma_\gamma=\sigma_\Phi\left(\frac{\eta}{V_{\mathrm{bb}}}\right)^{1/3}. \tag{3}$$

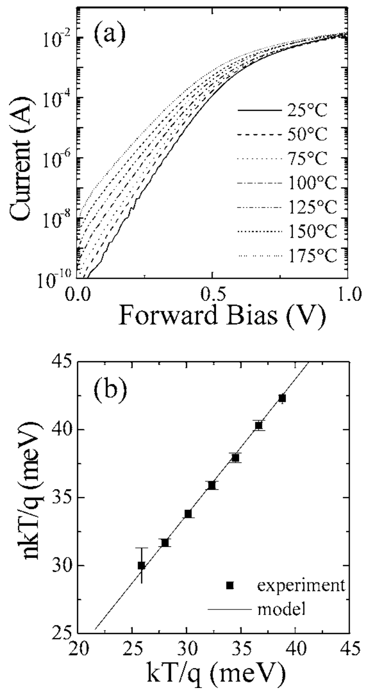

FIG. 3. (a) Forward *I-V* characteristics of macroscopic Au/Pt/GaN Schottky diodes annealed at 400 °C, as function of the measure temperatures. (b) Plot of nkT/q as a function of kT/q of the same diode; the theoretical curve obtained from the nanoscale barrier height distribution is also reported.

From a macroscopic point of view, a direct consequence of the barrier inhomogeneity is the temperature dependence of the ideality factor n of a macroscopic Schottky contact, which can be expressed in the form

$$n = 1 + \frac{T_0}{T}, \tag{4}$$

where T_0 is a constant related to the barrier height distribution.[6] This behavior, which is commonly referred as the "T_0 anomaly," is typical of a real Schottky contact with a distribution of barrier inhomogeneities.

For a Gaussian distribution of the γ_i with a standard deviation σ_γ, T_0 can be expressed as[11]

$$T_0 = \frac{\sigma_\gamma^2}{3\eta^{2/3}V_{bb}^{1/3}}\frac{q}{k} = \frac{q\sigma_\Phi^2}{3kV_{bb}}. \tag{5}$$

This expression relates the nanoscale inhomogeneity of the contact, described by the standard deviation σ_Φ of the Φ_i^{eff} distribution with a value of T_0, that in turn quantifies the deviation from the ideal behavior of macroscopic contacts. Hence, substituting in Eq. (5) the value of $\sigma_\Phi = 0.11$ eV determined by the microscopic measurements, a value of $T_0 = 43 \pm 8$ K was determined.

In order to establish a correlation between the nanoscale electrical properties of the contact and the electrical behavior of the macroscopic diodes, the forward *I-V* characteristics of the Au/Pt/GaN Schottky diodes annealed at 400 °C were carried out at temperatures ranging from 25 to 175 °C [Fig. 3(a)]. Clearly, by increasing the temperature, an increase of the current is observed, as predicted by the thermoionic emission model, accompanied by an improvement of the linearity of the *I-V* curves on a semilogarithmic scale. The temperature dependence of the ideality factor n determined from the *I-V* curves is shown in Fig. 3(b), which reports a plot of nkT/q as a function of kT/q. The theoretical curve obtained using in Eq. (4) the experimental value of $T_0 = 43$ K determined from the nanoscale Schottky barrier height distribution is also reported. As can be seen, the experimental data on macroscopic diodes are very well described by the theoretical behavior obtained from the nanoscale analysis of the local barrier distribution.

In conclusion, a quantitative study of the nanoscale degree of homogeneity of the Pt/GaN Schottky contacts is reported. In spite of the significant improvement of the electrical characteristics obtained after annealing at 400 °C, the inhomogeneous nature of the barrier was demonstrated by local *I-V* measurements carried out by conductive AFM and discussed in terms of Tung's model. In particular, a strong correlation has been demonstrated between the experimental temperature behavior of macroscopic Schottky diodes and the measured nanoscale Schottky barrier height distribution. The results presented in this work can be useful to understand and improve the reproducibility and reliability of electrical properties in Schottky contacts for GaN-based devices.

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