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Poole-Frenkel emission in epitaxial nickel oxide on AlGaIn/GaN heterostructures

Patrick Fiorenza,¹ Giuseppe Greco,^{1,2} Filippo Giannazzo,¹ Raffaella Lo Nigro,¹ and Fabrizio Roccaforte¹

¹Consiglio Nazionale delle Ricerche – Istituto per la Microelettronica e Microsistemi (CNR-IMM), Strada VIII 5, Zona Industriale, 95121 Catania, Italy

²Scuola Superiore di Catania – Università degli Studi di Catania, Via Valdisavio 9, 95123 Catania, Italy

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In this letter, the conduction mechanism through epitaxial nickel oxide (NiO) dielectric films grown by metal-organic chemical vapor deposition on AlGaIn/GaN heterostructures was investigated. In particular, macroscopic current-voltage measurements carried out at different temperatures allowed to demonstrate that Poole-Frenkel (PF) mechanism rules the conduction through the dielectric layer, with an emission barrier of 0.2 eV. Conductive atomic force microscopic measurements were carried out to directly image the presence of preferential current spots on the NiO surface, which have been correlated to the defects responsible for the PF emission. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4761961>]

Gallium nitride (GaN) has excellent physical properties making it a promising material for electronic devices.¹ In the context of GaN research, AlGaIn/GaN junctions are particularly interesting due to the formation of a two-dimensional electron gas (2DEG),² which is the key feature for the fabrication of high electron mobility transistors (HEMTs).

Typically, AlGaIn/GaN HEMTs are based on a Schottky contact as a gate electrode. However, this configuration can be affected by a high gate leakage current, limiting both the off-state performance as well as the maximum of on-state current. In order to overcome this later problem, a dielectric film can be added to insulate the Schottky gate electrode, forming a metal-insulator-semiconductor HEMTs (MIS-HEMTs) structure.³

Different oxides (SiO₂, Al₂O₃, Ga₂O₃, HfO₂, Sc₂O₃, La₂O₃, etc.) have been studied as possible gate dielectrics in GaN transistor technology.^{4–8} In fact, the use of high permittivity dielectric materials can be advantageous to limit the reduction of the gate-to-source capacitance occurring in insulated gate HEMTs, which in turn impact the device transconductance. Furthermore, the understanding of the physical mechanisms involved in the electron conduction through these dielectrics represents a crucial issue for this technology.

Nickel oxide (NiO) can be a promising insulating material for GaN devices, because of its band gap (4 eV) and a relatively high permittivity of 11.9 (i.e., almost three times higher than the commonly used SiO₂).⁹ An interesting aspect also related to NiO is the possibility to tailor its electronic properties by adjusting the material growth conditions.¹⁰ In fact, under certain conditions, p-type semiconducting NiO layers can be obtained and employed for the fabrication of normally off GaN HEMTs.¹¹

Recently, the possibility to growth epitaxial NiO films by metal-organic chemical vapor deposition (MOCVD) on AlGaIn layers has been demonstrated.¹² Although a reduction of the leakage current in NiO/AlGaIn/GaN gate structures was observed compared to a simple Schottky gate contact, the mechanisms involved in the conduction through

the thin epitaxial NiO layer were not clarified. However, the knowledge of the conduction mechanisms in the gate oxide is fundamental to predict and, eventually, to optimize the final performance and reliability of the device.

In this letter, the conduction mechanism of NiO layers grown onto AlGaIn/GaN heterostructures was studied by comparing the temperature behavior of current-voltage characteristics measured on macroscopic diodes with local nanoscale current measurements on the NiO surface.

MIS diodes were fabricated to study the current conduction through the oxide films. First, a 15 nm thick NiO film was grown into a hot-wall horizontal MOCVD reactor onto AlGaIn/GaN heterostructures at a temperature of 450 °C using a 150 sccm Ar flow (carrier gas) and 200 sccm O₂ flow (reaction gas) at 3 Torr pressure for 10 min.¹² Then, the deposited NiO film was patterned by photolithography and wet etched to define MIS structures. Ring-shaped Ohmic contacts were formed by a Ti/Al/Ni/Au stack annealed in Ar at 850 °C.¹³ Finally, Ni/Au metal electrodes were defined by lift-off onto the NiO circular patterns.¹⁴

The current voltage (I-V) characteristics were measured in a Karl-Suss probe station using a HP 4156B parameter analyzer. The temperature dependence was investigated in the range of 298–423 K, using a Lakeshore 331 temperature controller connected to the chuck.

Local nanoscale current measurements were carried out by conductive atomic force microscopy (C-AFM) in a DI3100 Nanoscope® V microscope equipped with the TUNA module under ambient atmospheric conditions. Highly doped diamond coated tips were used to probe the dielectric surface.¹⁵

The deposited NiO films are <111> oriented and the TEM investigation revealed that they epitaxially grew on the (0001) AlGaIn/GaN substrate. The epitaxial growth can be easily explained considering that the deposited films belong to the fcc (face centred cubic) crystal structure; thus, the <111> planes show a hexagonal structure possessing a good lattice mismatch with the hexagonal (0001) AlGaIn planes. Finally, the morphology is characterized by a quite smooth surface with no evident grain shape.

FIG. 1. Forward I - V characteristics of the NiO/AlGaIn/GaN MIS diodes at different temperatures.

Fig. 1 shows the temperature dependence of forward I - V characteristics collected on the NiO/AlGaIn/GaN MIS device. Positive bias has been applied to the gate to keep the n -type AlGaIn substrate in accumulation regime, eliminating the substrate contribution on the conduction; thus, the electric field only drops on the NiO layer.¹⁶

We observed that the current flowing, through the MIS device in accumulation, increases with increasing temperature. This behavior provided insights into the physical mechanism involved in the current conduction.

First, considering the temperature dependent I - V curves in the region around +1 V showed a strong temperature dependence of the current; thus, it was possible to rule out the occurrence of thermionic emission (TE).¹⁷ In fact, the experimental I - V curves could not be fitted by a TE model and the determined ideality factor was meaningless (in 8–12 the range). On the other hand, not even a tunneling mechanism can be used to explain the experimental data, since a weaker temperature variation of the current should be expected.¹⁶

Hence, the current data were drawn as depicted in Fig. 2(a), i.e., reporting the current density (J) divided by the electric field (E) as a function of the square root of the electric field. Accordingly, the experimental data can be fitted considering the Poole-Frenkel (PF) emission mechanism.^{18,19} PF emission refers to electric-field-enhanced thermal emission from a trap state into a continuum of electronic trap states, usually, in the conduction band in an insulator. The current density associated with Poole-Frenkel emission is given by

$$J = CE \exp \left[-\frac{q \left(\phi_t - \sqrt{qE / (\pi \epsilon_0 \epsilon_{NiO})} \right)}{kT} \right], \quad (1)$$

where E is the electric field in the dielectric, ϕ_t is the barrier height for electron emission from the trap states, ϵ_{NiO} is the relative dielectric permittivity at high frequency, T is absolute temperature, ϵ_0 is the permittivity of free space, q is the electron charge, and k is Boltzmann's constant.

FIG. 2. (a) Poole-Frenkel plot: current density divided by the electric field vs the square root of the electric field; (b) m coefficient vs the reverse of the temperature ($1/T$); (c) b coefficient vs the reverse of the temperature ($1/T$).

From Eq. (1), for a current transport ruled by Poole-Frenkel emission, the $\ln(J/E)$ should be a linear function of $(E)^{0.5}$:

$$\ln(J/E) = m(T)E^{0.5} + b(T), \quad (2)$$

$$m(T) = \frac{q}{kT} \sqrt{\frac{q}{\pi\epsilon_0\epsilon_{\text{NiO}}}}, \quad (3)$$

$$b(T) = -\frac{q\phi_t}{kT} + \ln C. \quad (4)$$

As shown in Fig. 2(a), the trend of the current densities in the MIS structures is well explained by the electric-field dependence described by Eq. (2). Figs. 2(b) and 2(c) show the functions $m(T)$ and $b(T)$, as defined in Eqs. (3) and (4), respectively, plotted as functions of $1/T$. It is worth to notice that the measured current densities exhibit both the electric field and the temperature dependences expected in Poole-Frenkel emission. Moreover, from the fit of the experimental data it has been possible to extract the value of the relative dielectric constant and the emission barrier height ϕ_t of the deposited NiO film. In particular, the values $\epsilon_{\text{NiO}} = 10.9 \pm 0.1$ and $\phi_t = 0.20 \pm 0.02$ eV have been obtained. The value of the dielectric constant is in good agreement with the theoretically expected one and with that found by independent capacitance-voltage measurements.¹¹ This latter demonstrates that the PF mechanism describes properly the experimental results.

To better understand the meaning of the emission barrier parameter ϕ_t , a schematic diagram of the conduction band offsets (ΔE_C) in the NiO/AlGaIn/GaN system is reported in Fig. 3, using the values reported in Refs. 9 and 20. Clearly, the emission barrier height ϕ_t is the parameter which quantifies the current in the PF conduction.

The occurrence of the PF mechanism can be associated with material defects responsible for an enhanced current in a certain temperature range. In our case, it is fairly possible that emission either into or from electrically active crystal defects, like grain boundaries, twins, etc., is responsible for the electric field and temperature dependence of the conduction through the NiO layer. The presence of these defects results into localized states at 0.2 eV below the NiO conduction band edge.

In order to directly visualize the current conduction and have an idea of the spatial distribution and density inside NiO of the states responsible for the PF emission, two-dimensional C-AFM measurements were carried out in our sample. By this investigation, it was possible to correlate the morphological features on the bare NiO surface with the current map at a fixed electric field applied by the AFM tip (from 1 MV/cm up to 1.14 MV/cm).

The surface morphology of NiO is shown in Fig. 4(a) and clearly demonstrates that the film is free from

FIG. 3. Schematic of the conduction band offsets in the NiO/AlGaIn/GaN system. The PF emission barrier ϕ_t is also reported.

FIG. 4. Surface morphology of the NiO film (a), and two-dimensional current maps collected at different values of the electric field (b) 1 MV/cm, (c) 1.07 MV/cm, and (d) 1.14 MV/cm.

macroscopic defects, i.e., cracks, pits, etc. The current maps acquired in the same region at different values of the applied electric field are reported in Figs. 4(b)–4(d). In these maps, the darker regions indicate a higher current value. As can be seen, some weak darker spots (higher current flow) are visible. However, it was not possible to establish a correlation between their spatial distribution and the surface morphology shown in Fig. 4(a). It must be pointed out that the density of these spots was estimated to be $\sim 6 \times 10^8 \text{ cm}^{-2}$, and it did not change with increasing applied field (Figs. 4(b)–4(d)), while the current value in these regions increases, as can be seen from their darker contrast in the C-AFM maps. Due to the fact that the density of such weak spots remains constant with increasing tip bias (electric field), they cannot be associated with the occurrence of local breakdown events.²¹ Hence, these spots may be rather correlated to electrically active material defects that are responsible for the PF conduction through the dielectric layer. Clearly, it could be difficult to draw a conclusion on the nature of these defects inside the NiO film. However, considering the values of their density determined by the C-AFM maps, it cannot be ruled out that a correlation exists with the conducting dislocations typically present in the underlying substrate.²² As a matter of fact, it has been already reported that the presence of conducting dislocations can justify a PF mechanism in Ni/AlGaN/GaN Schottky contacts.¹⁷

In conclusion, in this letter it has been demonstrated that the current conduction through epitaxial NiO layers on AlGaN is ruled by a Poole-Frenkel emission associated with electronic states at $\sim 0.2 \text{ eV}$ below the NiO conduction band. A nanoscale characterization of the electrical conduction through the oxide allowed to visualize the presence of localized conducting spots on the NiO surface (with a density of $\sim 6 \times 10^8 \text{ cm}^{-2}$) reasonably correlated to the presence of electrically active defects present into the epitaxial NiO layer.

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