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Interface state effects in GaN Schottky diodes

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ABSTRACT

Current voltage (I-V) and capacitance voltage (C-V) measurements have been performed versus temperature on GaN Schottky diodes. The results show an increase of the Schottky barrier height ϕ_b and a decrease of the ideality factor n both with the increase of the temperature. We show that this behavior originates in the existence of an interface state density distribution, which is determined via the analysis of the temperature dependence of the I-V measurements, and allows the tunneling of the carriers from the semiconductor to the metal. Those interface states are shown to be responsible for interface inhomogeneities which result in two Gaussian voltage dependent Schottky barrier distributions. We show also that, in the presence of this interface state distribution, C-V measurements, without the correction of the built in voltage by taking into account the effect of both the high values of the ideality factor and series resistance, lead to erroneous values of the Schottky barrier height ϕ_b.

1. Introduction

Group III nitride wide band gap semiconductors have attracted considerable interest owing to their applications for optical devices operating in the blue and ultraviolet wavelength regions. These materials and especially gallium nitride (GaN), were also found to be suitable for operation at high electrical and optical power levels, high temperatures and in harsh environments [1–8]. Schottky contact on n type GaN, which is critical for the realization of all these electronic and optoelectronic devices, has been extensively studied [9,2,3,5,10,11,6,12–17]. The ideality factor n and more especially the barrier height ϕ_b are the most important characteristics of metal-semiconductor Schottky barrier contacts, which should be optimized to achieve high performance devices. As seen in Table 1, several values of the Schottky barrier heights and ideality factors have been reported in the literature, depending on the metal used (Pt, Au, Ni and Pd) for the Schottky contact and the active layer growth technique and conditions. The values of the Schottky barrier height (SBH) ϕ_b and ideality factor n were found to range between 0.51 eV and 1.13 eV and 1.03 and 2.96, respectively. This large spread of the values, except those of Schmitz et al. [10] who have obtained values of the ideality factor that are independent of the metal type used, indicates that both the metal type of the Schottky contact and the technique used for the growth of the active layer, and thus the interface between them, play an important role for the achievement of a high quality Schottky diode. It is to be noticed that Schottky contacts realized with Pt are the most often used in the literature. Many authors [12,16,18,19] have also reported an increase of the value of ϕ_b with increasing temperature. This unexpected temperature dependence was attributed to some inhomogeneities of the Schottky barrier [18,19] or to the tunneling effect in a highly defective material [12].

All these results show that in spite of the numerous studies for the realization of electrical contacts on GaN materials, the debate concerning the conduction mechanisms which govern the current flow in the nitride GaN based structures is still open. Additional works are thus suitable for a better control of this kind of contact and for a unified interpretation of the conduction phenomenon.

In this work, Pt/n–GaN Schottky diodes have been realized and current-voltage (I-V) as well as capacitance-voltage (C-V) measurements versus temperature have been performed and analyzed. The results show that the structures under test present an important interface states distribution which is temperature dependent. These interface states act as centers favoring the tunneling of the carriers in a more important way than the tunneling through the top of the barrier. Their overall effect can be seen as the effect of an interfacial layer explaining the temperature dependence of both the barrier height ϕ_b and the ideality factor n. At last, values of the barrier height ϕ_b derived from I-V and C-V measurements, respectively, are shown to be consistent if, in the case of C-V measurements, the value of the built in voltage is corrected to take into account the interface state effect.

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Table 1
Values of the Schottky barrier and ideality factor in GaN, obtained by different authors using different metals and growth techniques of the active layer (LPMOCVD [10], MOVPE [2,14], MOCVD [3,16,18,20], MBE [11]).

Metal type	Barrier height ϕ_b (eV)	Ideality factor n
Pt	1.03–1.04 [2]	1.21 [2]
	0.52–1.13 [3]	1.05–2.96 [3]
	1.08 [10], 0.88 [14]	1.04 [10],1.1 [14]
	0.99 [18]	1.42 [18]
Au	0.88 [3,10]	1.06 [3], 1.04 [10]
	0.82 [16]	1.15 [16]
	0.844 [9], 1.1 [11]	1.03 [9], 1.4 [11]
Ni	0.99 [10], 0.61–0.69 [12]	1.04 [10], 1.19 [12]
	0.75 [18], 0.82 [20]	1.98 [20]
Pd	0.91–0.94 [2],1.05–1.11 [3]	1.14 [2],1.02–1.2 [3]
	0.92 [10], 0.69 [18]	1.04 [10],1.58 [18]
	0.51–0.97 [21]	2 [21]

2. Experimental procedures

2.1. Samples preparation

The samples used in this study are 3.5 μm thick n-GaN layers grown by metalorganic vapor phase epitaxy (MOVPE) on sapphire substrates supplied by LUMILOG with a nominal doping concentration ranging between 1×10^{18} cm^{-3} and 3×10^{18} cm^{-3}. Before metallization, the samples were cleaned in acetone and etched in HCl (3 mol/l) solution for 5 min to remove the native oxide. The Schottky diodes were fabricated on the cleaned surface using photolithography technique. For ohmic contact, Ti/Al/Ti/Au (15/200/15/200 nm) layers were deposited by thermal evaporation and then annealed at 500 °C for 15 min in a flowing N_2 atmosphere. A 150 nm Pt thick layer was deposited (using an e-beam evaporation system) to form a circular Schottky contact with a surface equal to 7.07×10^{-4} cm^2. I-V and C-V measurements were performed versus temperature from 77 K to 300 K, using a Keithley Source Measure Unit 2602 and a HP 4192 impedance analyzer, respectively.

2.2. I-V measurements

Fig. 1 shows the voltage dependence of the current density J obtained in a Pt/n-GaN Schottky diode at different temperatures. For relatively large voltage ($>0.7V$) the current saturates due to effect of the series resistance [22]. For lower voltage, the characteristic exhibits two regimes characterized by two different slopes corresponding to different transport mechanisms. The one taking place in the intermediate voltage range ($0.2-0.6V$) was shown [5] to be driven by the thermionic emission (TE) and is preponderant at high temperatures. By contrast, in the low voltage range ($0-0.45V$), the current flow is dominated by the thermionic field emission (TFE). This is especially the case for highly doped materials.

The TE and TFE transport mechanisms can be described respectively [22,23] by:

$$J_{TE}=A^*T^2\times exp\left(-\frac{q\phi_b}{kT}\right)\times exp\left(\frac{q(V-R_sI)}{nkT}\right)\times\left[1-exp\left(\frac{-q(V-R_sI)}{kT}\right)\right] \quad (1)$$

and

$$J_{TFE}=A^*T\frac{\sqrt{\pi E_{00}q(\phi_b-V-\xi)}}{kcosh(E_{00}/kT)}\times exp\left[\frac{q(V-R_sI)}{E_{00}coth(E_{00}/kT)}\right]\times exp\left[-\frac{q\xi}{kT}-\frac{q(\phi_b-\xi)}{E_{00}coth(E_{00}/kT)}\right]. \quad (2)$$

The total current is then the sum of both. A^* is the Richardson constant equal to 26.4 Acm^{-2}K^{-2} for n-type GaN [16], k is the Boltzmann constant, T is the absolute temperature, q is the electronic charge, ϕ_b is the effective Schottky barrier height, n is the ideality factor, E_{00} is the tunneling factor, ξ is the energy of the Fermi level of the semiconductor with respect to the bottom of its conduction band, R_s is the series resistance and V is the applied bias voltage.

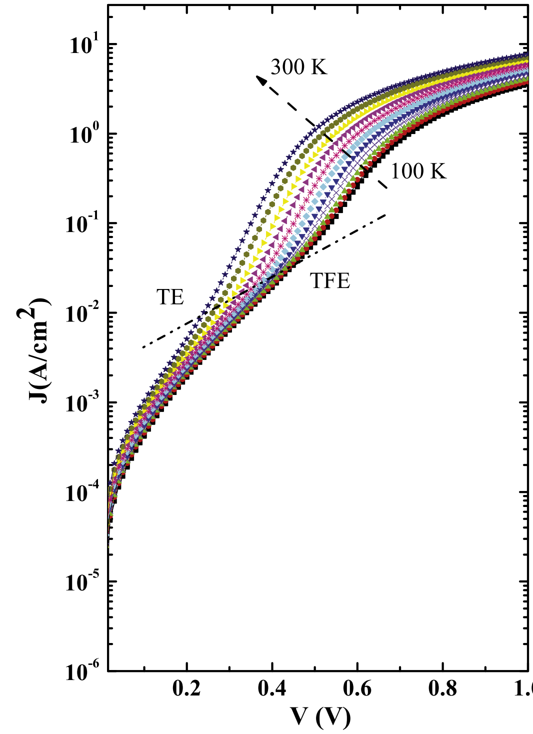

Fig. 1. Temperature dependence of the J-V characteristics in a Pt/n-GaN Schottky diode. Temperature increases by step of 20K in the arrow direction. The dot-line indicates the separation between the two regimes: behind this line the TFE is preponderant, above this line the TE takes place.

2.3. C-V measurements

Fig. 2 shows an example of C-V and $1/C^2-V$ curves obtained in a Pt/n-GaN Schottky diode at different temperatures and a frequency of 500 kHz using a parallel RC model. The data of $1/C^2-V$ in Fig. 2 show a linear behavior of the $1/C^2$ plot versus V, indicating a uniform doping concentration profile whatever the temperature.

This doping concentration can be obtained from the slope of the $1/C^2-V$ plot by the following relationship, where ϵ_0 and ϵ_{SC} are the vacuum dielectric permittivity and the semiconductor relative dielectric permittivity respectively:

$$N_D=-\frac{2}{q\epsilon_0\epsilon_{SC}}\times\frac{dV}{d(S^2/C^2)}. \quad (3)$$

The value of the doping density, at room temperature, was found equal to 5×10^{18}cm^{-3}. However, this value must be corrected [24,25] to take into account the higher-than-one value of n, as we will see in the next section. After correction using the mean values of n (see next section), the values of N_D becomes equal to 3.9×10^{18}cm^{-3}.

3. Series resistance and ideality factor

The series resistance R_s is an important parameter in the characterization of Schottky barrier diodes because it limits the conduction process particularly in large band gap semiconductor materials such as GaN. This parameter has been determined using the Cheung and Cheung [26] technique. The obtained values of R_s are then used to