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Electrical characterization of (Ni/Au)/$Al_{0.25}Ga_{0.75}N$/GaN/SiC Schottky barrier diode

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In this work we report on the characteristics of a (Ni/Au)/AlGaN/GaN/SiC Schottky barrier diode (SBD). A variety of electrical techniques, such as gate current-voltage (I-V), capacitance-voltage (C-V), and deep level transient spectroscopy (DLTS) measurements have been used to characterize the diode. The behavior study of the series resistance, R_S, the ideality factor, n, the effective barrier height, Φ_b, and the leakage current with the temperature have emphasized an inhomogeneity of the barrier height and a tunneling mechanism assisted by traps in the SBD. Hence, C-V measurements successively sweeping up and down the voltage have demonstrate a hysteresis phenomenon which is more pronounced in the temperature range of 240 to 320 K, with a maximum at ~300 K. This parasitic effect can be attributed to the presence of traps activated at the same range of temperature in the SBD. Using the DLTS technique, we have detected one hole trap having an activation energy and a capture cross-section of 0.75 eV and $1.09 \times 10^{-13} cm^2$, respectively, seems to be responsible for the appearance of the hysteresis phenomenon. © *2011 American Institute of Physics*. [doi:10.1063/1.3600229]

I. INTRODUCTION

Gallium nitride–based devices are of great current interest because of their capability to operate at high temperature, high power, and high frequency and in adverse environments. In particular, the AlGaN/GaN heterostructure has a narrow and high-mobility channel due to a two-dimensional electron gas (2DEG) produced at the hetero-interface. Excellent device characteristics have been reported for high electron mobility transistors (HEMTs) employing these structures.[1] However, these characteristics are not always reproducible, because the device performances at high frequencies can be limited by the presence of deep level defects in the AlGaN/GaN heterostructure.[2] Indeed, electrical charges trapped by the deep levels modify the 2DEG concentration in the channel and limit the switching characteristics of the devices.

Hence, the Schottky contact's quality with a sufficient height barrier, Φ_b, and low leakage current are critical factors for the realization of GaN-based HEMTs. In fact, the barrier height, Φ_b, is a key parameter of the junction, controlling both the width of the depletion region in the semiconductor and the electron current across the interface. Although Schottky barrier diodes (SBDs) have already been studied for more than four decades, the fundamental mechanisms that determine the barrier height are still not fully understood.[3,4] It has only been in the past decade that an inhomogeneous contact has been considered as an explanation for a voltage- dependent barrier height.[5,6] Nowadays, many studies take into account the Schottky barrier height (SBH) inhomogeneities and reveal that the experimentally observed dependences of the effective barrier heights and ideality factors of metal semiconductor contacts could be explained by lateral inhomogeneities in the barrier height.[7–9] The correlation between effective SBHs and ideality factors may be approximated by using a linear relationship.[10] Besides, high gate leakage-current is a drawback for AlGaN/GaN HEMTs, which should be reduced to suppress their power consumption and noise. The mechanisms of the gate leakage current of these devices such as trap- and defect-assisted tunneling, barrier-thinning caused by charge trapping, and hopping through dislocations among others have been considered to be responsible for this excessive gate leakage. According to these explanations, the existence of traps located within the barrier height of the AlGaN barrier acts as the facilitator in tunneling through the barrier[11,12] and threading dislocations extending from the GaN layer.[13] Therefore, it is necessary to perform basic investigations of deep-level defects in AlGaN/GaN heterostructures. For that, many characterization techniques have been employed, such as charge-based deep level transient spectroscopy,[14] current deep level transient spectroscopy,[15,16] deep-level transient spectroscopy (DLTS),[17,18] and deep-level optical spectroscopy.[19]

As a preliminary study of parasitic effects in AlGaN/GaN HEMT, we will start by studying AlGaN/GaN Schottky barrier diode SBD.

The relationship between the unusual behavior of n, Φ_b, Rs and the leakage current parameters with temperature, the

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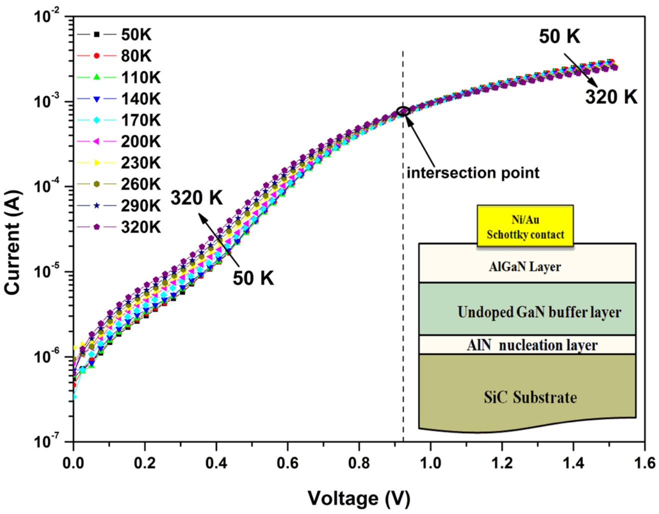

FIG. 1. (Color online) Forward bias semi-logarithmic I -V characteristics for the (Ni/Au)/AlGaN/GaN/SiC diode at various temperatures. The inset shows the schematic cross-section of (Ni/Au)/AlGaN/GaN/SiC SBD adopted for this work (not to scale).

trap-assisted tunneling mechanism, and the hysteresis phenomena in a (Ni/Au)/AlGaN/GaN SBD grown on a silicon carbide substrate (SiC), will be established.

II. EXPERIMENTAL

The AlGaN/GaN heterostructure was grown by metal organic chemical vapor deposition on the SiC substrate. The epilayers consist of a 100 nm AlN nucleation layer followed by a 1.2 μm unintentionally doped GaN layer, and a 30 nm thick $Al_{0.25}Ga_{0.75}N$ barrier Si-doped layer (3×10^{18} cm^{-3}). The device has a gate width of 200 μm and a gate length of 200 μm. The Schottky contact was made with an optimized metallization of Ni/Au with respective thicknesses of 200 and 2000 Å. The schematic cross-section of the AlGaN/GaN/SiC SBD is shown in the inset of Fig. 1.

The C-V and DLTS measurements were performed by a capacitance meter at a frequency of 1 MHz (model 410 C-V Plotter) with high resolution mode. To vary the filling pulse width, a pulse generator (Philips PM 5771) was used. The temperature measurement was varied in the range of 20–325 K by using a closed-cycle liquid helium cryostat with a Lakeshore 330 autotuning temperature controller. For this system, the DLTS signal peak takes place at a temperature where the lock-in frequency, f, is related to the emission rate by $e_n = 2.13$ f.[20]

III. GATE CURRENT-VOLTAGE MEASUREMENTS

The current-voltage (I-V) characterization is among the most common experimental techniques in the physics of semiconductors. Indeed, from the analysis of the I-V data, it is possible to draw conclusions about the presence of defects, the good quality of the contacts, the potential barriers governing the transport of charge, the presence of hetero-interfaces, etc.

In this context, we have measured the gate current after applying a range of forward and reverse voltages on the $(Ni/Au)/Al_{0.25}Ga_{0.75}N/GaN/SiC$ structure for different temperatures.

A. Forward current–voltage characteristics

The forward $I_g - V_g$ characteristics (Fig. 1) were analyzed using the standard thermionic emission relation (1) for electron transport from a metal-semiconductor with low doping concentration and the equation is given by,[21,22]

$$I_d = I_s \exp\left(\frac{qV_d}{nkT}\right)\left[1 - \exp\left(\frac{-qV_d}{kT}\right)\right], \tag{1}$$

where V_d is the voltage across the diode ($V_d = V_g - I_g R_S$), R_S is the series resistance, n is the ideality factor, and I_s is the reverse saturation current derived from the straight line intercept of the current at a zero bias and is given by Eq. (2),

$$I_s = AA^* T^2 \exp\left(\frac{-q\phi_b}{kT}\right), \tag{2}$$

where A^* is the effective Richardson constant [34.2 A cm^{-2} K^{-2} for $Al_{0.25}Ga_{0.75}N$ (Ref. 23)] that can be given in an experimental way by measuring the current according to the temperature and in a theoretical way according to Eq. (3),

$$A^* = \frac{4\pi q m^* k^2}{h^3}, \tag{3}$$

where m^* is the effective mass for $Al_{0.25}Ga_{0.75}N$: $m^* = 2.50 \times 10^{-31}$ kg, A is the diode area, q is the electronic charge, T is the temperature, k is the Boltzmann constant, h is Planck's constant ($h = 6.6261 \times 10^{-34}$ J s) and ϕ_b is the effective barrier height from the metal to the semiconductor. From Eqs. (1) and (2), the barrier height, ϕ_b, and the ideality factor, n, can be written respectively as,

$$\phi_b = \frac{kT}{q} \ln\left(\frac{AA^*T^2}{I_s}\right), \tag{4}$$

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln I_d}\right). \tag{5}$$

The experimental values of the barrier height (ϕ_b) and the ideality factor (n), that have been determined from slopes and intercepts of the linear region of the forward-bias ln(I) versus V plot at each temperature using Eqs. (4) and (5), for the $(Ni/Au)/Al_{0.25}Ga_{0.75}N/GaN/SiC$ Schottky structure change from 0.28 eV and 6.45 (at 50 K) to 0.99 eV and 1.81 (at 320 K), respectively.

Thus, the experimental values of n [Fig. 2] decrease with the increase in temperature, and are all greater than one indicating that the thermionic emission is not the dominant conduction mechanism, but it is rather a tunneling mechanism assisted by traps at the metal/semiconductor interface. Hence, the ϕ_b values increase with temperature, as can be seen in Fig. 2, which is an unusual behavior of the Schottky barrier dependence temperature.

Fei *et al.*[24] have explained this phenomenon by the fact that, when the temperature increases, more and more electrons have sufficient energy to surmount the higher barrier.

Some of the thermally activated metal electrons which are tunneled into the AlGaN semiconductor are nullified by

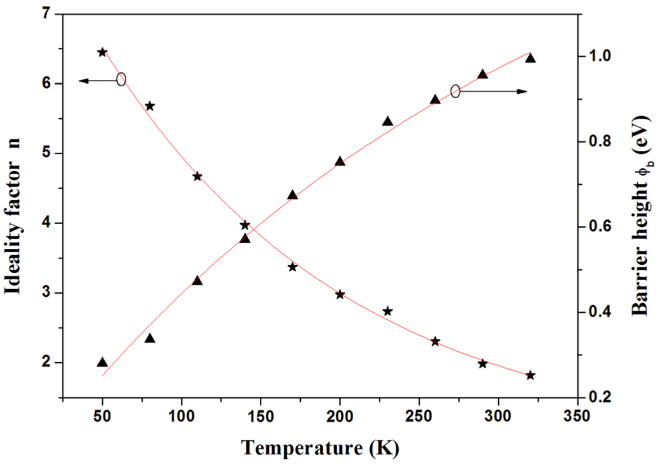

FIG. 2. (Color online) The barrier height, ϕ_b, and the ideality factor, n, as a function of temperature for the (Ni/Au)/AlGaN/GaN/SiC Schottky barrier diode.

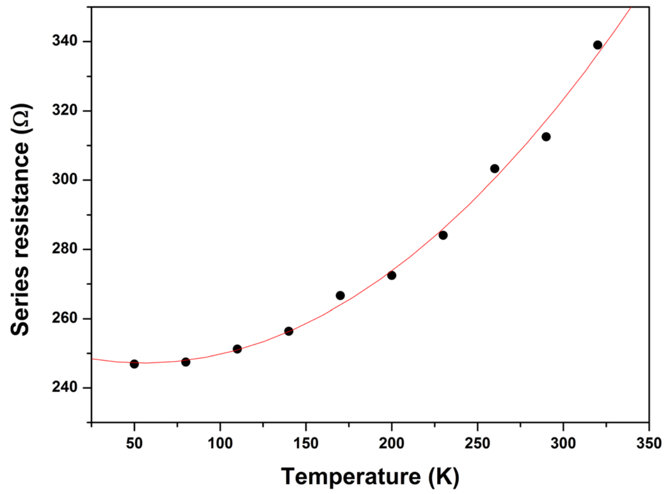

FIG. 4. (Color online) The temperature dependence of the series resistance, R_S, for the (Ni/Au)/AlGaN/GaN/SiC Schottky barrier diode.

the induced polarization positive charges, while the others are transported into the two-dimensional electron gas formed at the AlGaN/GaN interface. The AlGaN donor atoms are thus ionized by the increase in temperature, and the free electrons are drifted into the quantum well. The metal/semiconductor depletion region is consequently widened and the Schottky barrier height is enlarged. Figure 3 shows the experimental barrier height versus the ideality factor plot of the (Ni/Au)/$Al_{0.25}Ga_{0.75}N$/GaN/SiC Schottky structure in the temperature ranging from 50 to 320 K. This explanation may not be suitable to explain this phenomenon since the width of the depletion region is given by Poisson's equation and for the same barrier height the depletion width is different and depends on the electric charge. Further investigations should be held in order to approve or deny this model.

However, the linear relationship (Fig. 3) between the experimentally effective barrier heights (ϕ_b) and ideality factors (n) of the Schottky diode, can only be explained by the lateral inhomogeneities of the barrier heights in the SBD.[25–28] After fitting the experimental ϕ_b versus n plot, its extrapolation to $n=1$ has given a homogeneous barrier height of approximately 1.094 eV. Thus, the significant decrease of ϕ_b and the increase of n, especially at low temperature, are possibly caused by the barrier height inhomogeneities.[29,30] In addition, as can be seen in Fig. 1, an interesting feature of the forward bias I-V curves is the almost common intersection point of all the curves for a certain voltage point (≈0.92 V) where the current through the diode is temperature-independent. Similar results have been obtained by the simulation of forward bias I–V curves of Schottky diodes.[31–34] It was found that the presence of series resistance in the diode causes bending due to current saturation and plays a subtle role in keeping this crossing hidden. Hence, Chand[31] reported that this crossing of forward bias I-V curves for a homogeneous Schottky diode can only be realized in curves with zero series resistance. Osvald[35] theoretically showed that the presence of the R_s is a necessary condition of the intersection of I-V curves. The extraction of the R_s values from the forward I-V plot for $V \geq 0.92$ V, at each temperature, shows an abnormal dependence with temperature, as seen in Fig. 4, where R_s increases

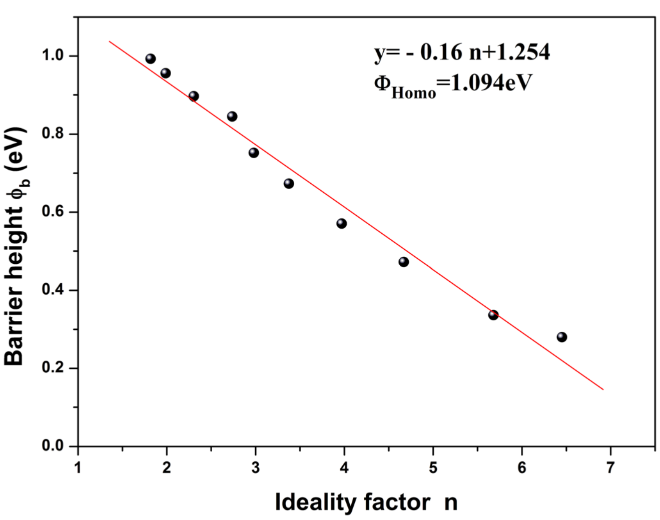

FIG. 3. (Color online) Plot of ϕ_b vs n showing a linear correlation between these parameters; the extrapolation at $n=1$ gives a value of the homogenous barrier $\phi_{Homo} = 1.094$ eV.

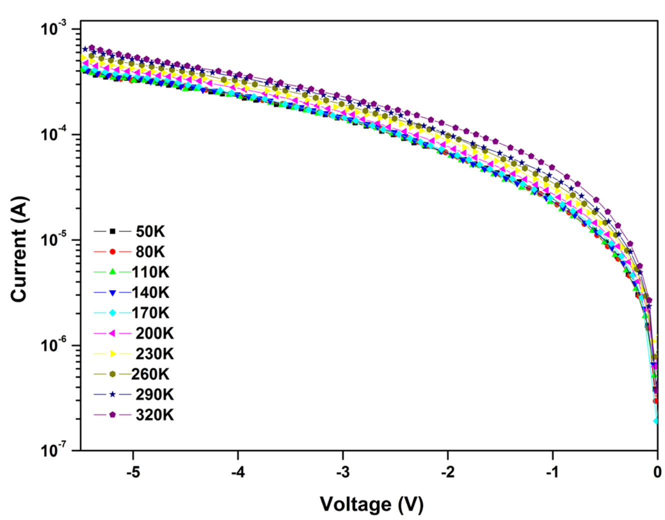

FIG. 5. (Color online) Reverse bias semi-logarithmic I-V characteristics for the (Ni/Au)/AlGaN/GaN/SiC Schottky barrier diode at various temperatures.

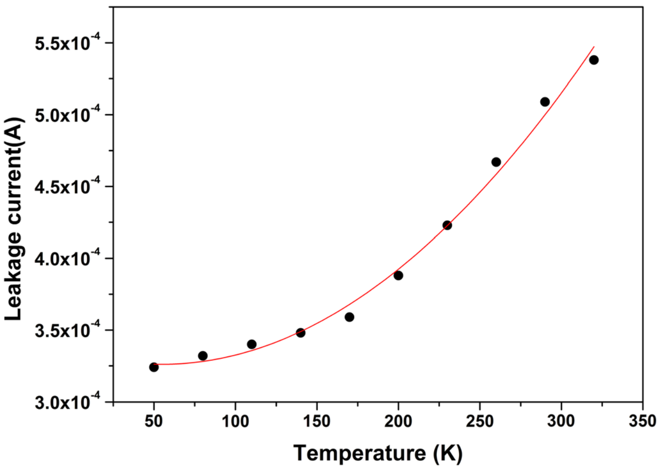

FIG. 6. (Color online) The leakage current at −5 V of a (Ni/Au)/AlGaN/GaN/SiC SBD obtained from the reverse bias I-V data at various temperatures.

with temperature. According to Tekeli *et al.*,[30,36] the R_s variation with the temperature can be expected for semiconductors in the temperature range when there is no freezing behavior of the carriers.

B. Reverse current–voltage characteristics

Figure 5 shows the reverse bias semi-logarithmic I-V characteristics (up to −5.5 V) for this diode at various temperatures. For Vgs = −5 V, the measured leakage current of the (Ni/Au)/AlGaN/GaN/SiC Schottky barrier diode is 3.25×10^{-4} A at 50 K while it is 5.38×10^{-4} A at 320 K. The increase of the leakage current with temperature [Fig. 6] is due to the tunneling through the surface and bulk states.[37] This mechanism was already proved based on the ideality factors extracted from the forward I-V-T plots which are more than the unity.

The reverse current leakage is related to the tunneling mechanism; this theory has been supported by Kim *et al.*[38] who reports that the tunneling mechanism was assisted by some Ni/AlGaN interface states such as dislocations or/and possibly nitrogen vacancies. Also, Huang *et al.*[13] have found that the leakage current is caused by the threading dislocations (TDs) extending from the GaN layer, for a (Ni/Au)/$Al_{0.25}Ga_{0.75}N$/GaN SBD with an AlN interlayer. These TDs provide a preferential paths for the leakage current and were identified by Roccaforte *et al.*[39] as the major cause of the temperature dependencies of n and ϕ_b.

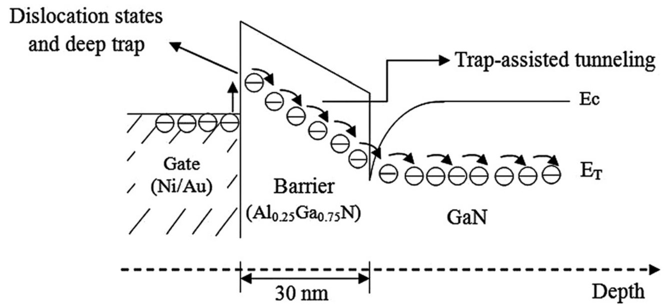

FIG. 8. A schematic diagram showing the possible conduction mechanism in the (Ni/Au)/AlGaN/GaN Schottky diode.

IV. CAPACITANCE-VOLTAGE CHARACTERISTICS AND DLTS MEASUREMENTS

Capacitance-voltage (C-V) measurements of the (Ni/Au)/$Al_{0.25}Ga_{0.75}N$/GaN/SiC structure were performed between 50 and 320 K at a frequency of 1 MHz (an example at 300 K is given) by sweeping voltage successively down (Vg from 1.5 to −7 V) and up (Vg from −7 to 1.5 V); the directions of the voltage sweep are shown in Fig. 7. A hysteresis phenomenon, expressed by a shift toward high reverse bias during the return sweep, has been observed. The hysteresis curves can be explained as follows: (A) emission of electrons, (B) total depletion of electrons, (C) injection and trapping of electrons, and (D) accumulation of electrons. Thus, we attribute this phenomenon to electron charging and discharging by trap centers.

As shown by Chikhaoui *et al.*,[40] this phenomenon indicates an increase in the built-in negative charge, either in the

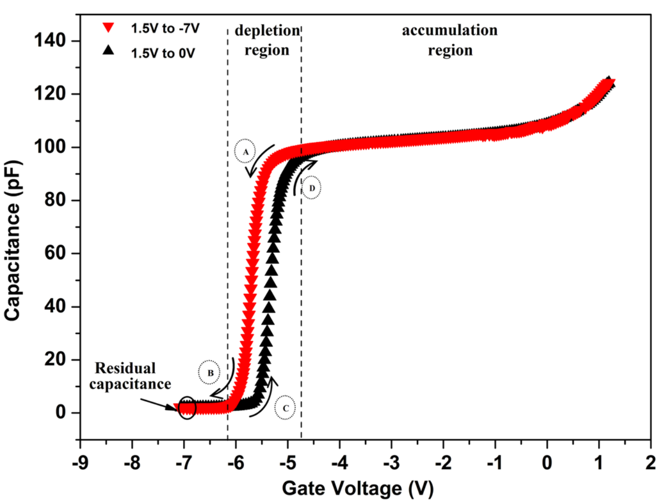

FIG. 7. (Color online) C-V static characteristics of a (Ni/Au)/AlGaN/GaN/SiC SBD recorded at 300 K, after successively sweeping up and down the voltage.

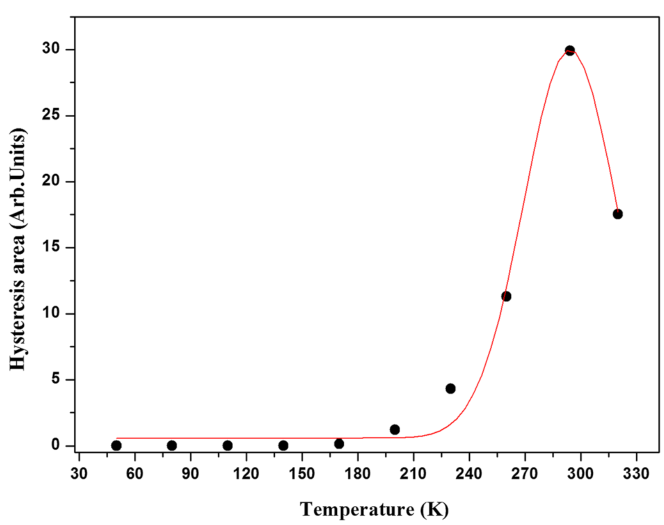

FIG. 9. (Color online) C-V hysteresis area as a function of the temperature for the (Ni/Au)/AlGaN/GaN/SiC Schottky barrier diode.

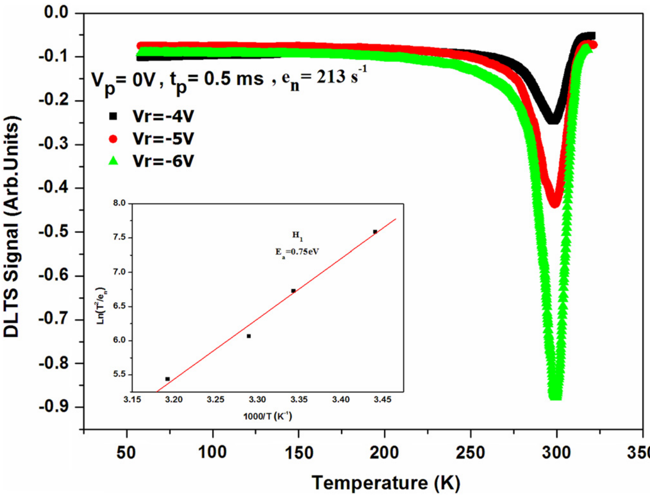

FIG. 10. (Color online) DLTS spectra measured with a reverse bias of −4 V, −5 V and −6 V, a pulse filling time of 0.5 ms and for an emission rate (e_n) of 213 s^{-1}. The inset shows the Arrhenius diagram for the H_1 hole trap observed in the (Ni/Au)/AlGaN/GaN/SiC SBD with DLTS measurements.

AlGaN barrier or in the GaN layer. The defects promote the injection of electrons from the gate into the AlGaN barrier layer, as shown in Fig. 8, through a trap-assisted tunneling mechanism at high reverse bias. This effect was mitigated by adding an Al_2O_3 dielectric layer between the Ni/Au metal and the AlGaN barrier because the electrons are not able to cross the Al_2O_3 layer, as reported by Zheng *et al*;[41] also, the exhibition of the gate leakage current is lower compared to the conventional AlGaN/GaN HEMT.

To understand the evolution of the hysteresis phenomena as function of the temperature, we have determined the hysteresis area at each temperature (from 50 to 320 K). As shown in Fig. 9, we note that the hysteresis area is more significant in the temperature range from 240 to 320 K with a maximum at ∼300 K, which leads us to consider that this phenomenon is thought to be caused by deep defects activated in the same range of temperatures. For that, deep level transient spectroscopy (DLTS) measurements have been realized.

The DLTS spectra (Fig. 10) reveals the presence of one negative peak corresponding to a hole trap called H_1, after applying a reverse voltage, $V_R = -6$ V, a pulse filling time, $t_p = 0.5$ ms, and an emission rate, $e_n = 213\ s^{-1}$. The apparent activation energy, E_a, and the capture cross-section, σ_n, are deduced from the Arrhenius diagram of $\ln(T^2/e_n)$ versus 1000/T (see the inset in Fig. 10).

The hole trap H_1, activated at 300 K, is observed with an activation energy of 0.75 eV and a capture cross-section of 1.09×1^{-13} cm^2. The density of this level was estimated to be 2.93×10^{17} $cm^{-3.}$ To our knowledge, this defect is observed for the first time. Its exact origin remains an open question. Even if the exact microscopic nature of level H_1 cannot be undoubtedly established, the interesting point is that we can conclude that this level may be associated with an extended defect, such as threading dislocations. This idea is demonstrated by the appreciable drop of the H_1 peak height by changing the reverse bias from −6 to −4 V (Fig. 10) with a decrease in the trap density from 2.93×10^{17} cm^{-3} to 4.72×10^{16} cm^{-3}, respectively. This defect, extended from the GaN layer to the Ni/AlGaN interface, seems to be responsible for the appearance of the hysteresis phenomenon on the C-V characteristics occurring due to the electron tunneling from the Schottky gate into this trap state at high reverse bias.

V. CONCLUSION

In summary, the (Ni/Au)/$Al_{0.25}Ga_{0.75}N$/GaN/SiC Schottky barrier diode has been characterized by the I-V-T, C-V-T, and DLTS measurements.

The experimental forward bias I-V characteristics measured at various temperatures reveal an increase of ϕ_b and a decrease of n with increasing temperature. Such behavior is attributed to the inhomogeneities of the barrier height in the SBD. From the reverse bias I-V characteristics, we note an important leakage current which increases with temperature and is due to the tunneling through the surface and bulk states.

Capacitance-voltage characteristics measured at various temperatures, sweeping successively up and down the voltage, show a hysteresis phenomenon which is more pronounced in the temperature range from 240 to 320 K. This phenomenon is attributed to the hole trap, detected by DLTS measurements, which has an activation energy of 0.75 eV. This trap is a threading dislocation extending from the GaN layer to the (Ni/Au)/AlGaN interface.

Finally, a correlation between the abnormal behavior observed in I-V and C-V characteristics and the presence of the hole trap, H_1, has been discussed. This study will allow us to understand the influence of defects in the transport of 2DEG in the AlGaN/GaN/SiC HEMT's structures based on the same materials where the preliminary study of the Schottky diode is crucial.

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