Analysis of the current-voltage characteristic of the Schottky diode based on free-standing GaN substrate

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The current–voltage (I–V) characteristics of Schottky diodes on free-standing GaN substrate are investigated by using electrical characterization and analytical modelling calculation. We have calculated the electrical parameters from experimental current-voltage curve by two methods: ln(I) and Cheung. So, we calculated different electrical parameters using experimental I-V curve such as saturation current, ideality factor, series resistance and barrier height. We have found from the first method, the ideality factor n (1.02), the barrier height ϕ_b (0.65 eV) and a series resistance R_s (84 Ω). From the second method, we have found, n (1.09), ϕ_b (0.79 eV) and R_s (79.58 Ω - 79.73 Ω). Using analytical approach, we plotted the theoretical curves for comparison with the experimental characteristic and also to determine the dominant current transport mechanism. The results found support an assumption that the dominant current mechanism in Au/n-GaN (free-standing substrate) Schottky diode is the thermionic current.

Keywords: I-V characteristics, Gallium nitride free-standing, Schottky diode, Analytical modeling.

1. INTRODUCTION

Wide band-gap nitride semiconductors continue to attract attention as materials for novel optoelectronic and electronic devices. From these semiconductors, we find the GaN and related nitride compounds which show great promise for applications in optical devices (LEDs), laser diodes (LDs), metal-oxide-semiconductor field effect transistors (MOSFETs), high electron mobility transistor (HEMTs), THz detectors etc.

Metal–semiconductor (MS) contact is one of the most widely used rectifying contacts in electronic industry [1-3]. Much work has been done on developing Schottky and ohmic contacts to n-GaN [4]. For realized these contacts a high contact resistance has plagued many contact metallizations to GaN, leading to poor device performance [5]. Also, GaN can be used for high temperature devices and hence the contacts need to with stand elevated temperatures without breaking down. Free-standing GaN substrates [6-8] are thus expected to open the way to explore the intrinsic performance of GaN and its related alloys.

In addition to previous studies on the Au/GaN (free-standing) structure [8-10] we have found it useful to analyze its current-voltage characteristic to provide more information. The objective of this work is to use this substrate for the realization of other structures such as the Hemts transistors and the THz detectors which exploits the Gunn effect in the GaN substrate. So, we report on the study of the electrical behavior of Schottky diode realized on free-standing GaN substrate (Au/n-GaN). We have extracted the electrical parameters of experimental I-V curve by two methods (lnI-V and Cheung) and then we plotted the theoretical characteristics using analytical modeling in order to determine the dominant current in this type of structure.

2. EXPERIMENTAL METHOD

The samples GaN (type n) unintentionally doped were manufactured by the company Lumilog who used the HVPE growth technique (Hydride vapor phase epitaxy). The thickness of the GaN substrate is 200 μm and it's free-standing (Fig.1).

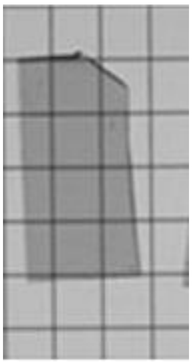
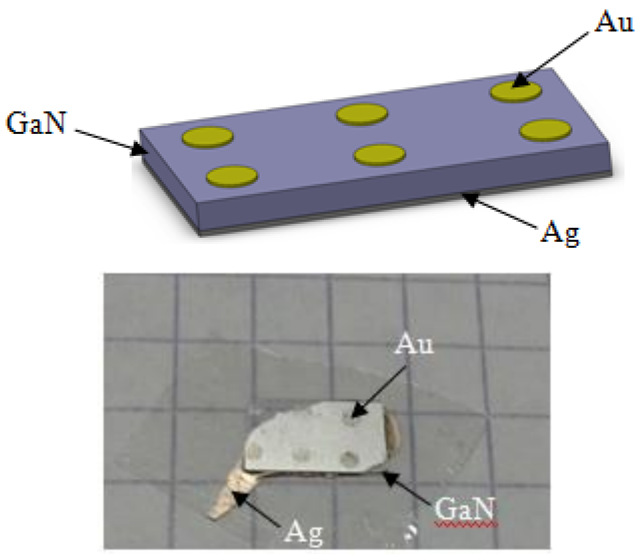


Figure 1 free-standing GaN substrate.

The contact Schottky used is the gold (Au), was carried out by sputtering (substrate carrier at a temperature ≤ 300°C), with area contact equals to 1.96×10^{-3} cm^2. The ohmic contact is formed on the rear face using the silver (Ag). The schematic diagram of vertical Au/n-GaN structure (SBD*:* Schottky Barrier Diode) is shown in Fig. 2.



a. Schematic of vertical Au/n-GaN structure

b. Presentation of vertical Au/n-GaN structure

Figure 2 Schematic and presentation of Au/n-GaN structure (SBD).

To characterize our samples electrically, we used the measurements of current with a measuring instrument "HP 4155 B, Semiconductor Parameter Analyzer". The current-voltage (I-V) measurements of Au/GaN Schottky diode are illustrated in Fig. 3. The experiments are taken at room temperature.

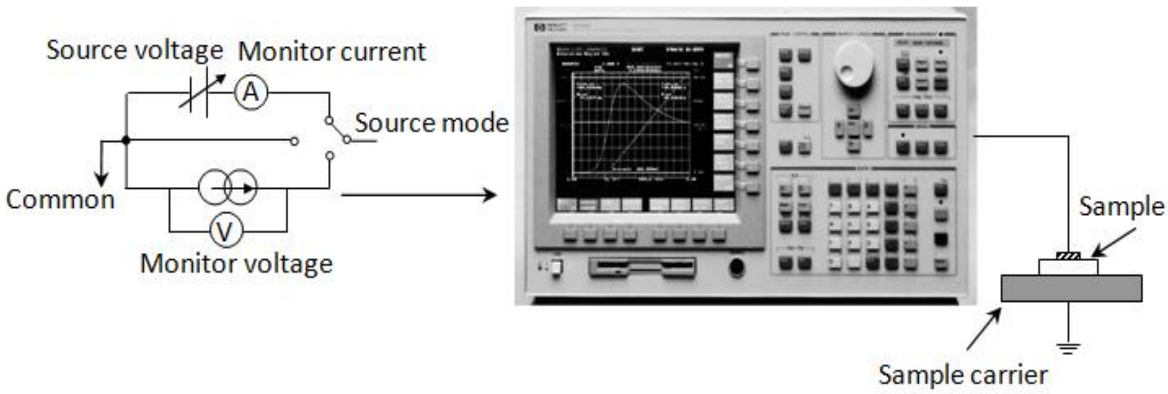


Figure 3 I-V measurements

3. RESULTS AND DISCUSSION

3.1 Experimental study

The current-voltage (I-V) curve is illustrated in Fig. 4. We observed that the structure presents a rectifier behavior for forward bias voltage and the reverse current shows a weak voltage dependence. The change in the slope of this characteristic for high forward bias is caused by the effect of the series resistance.

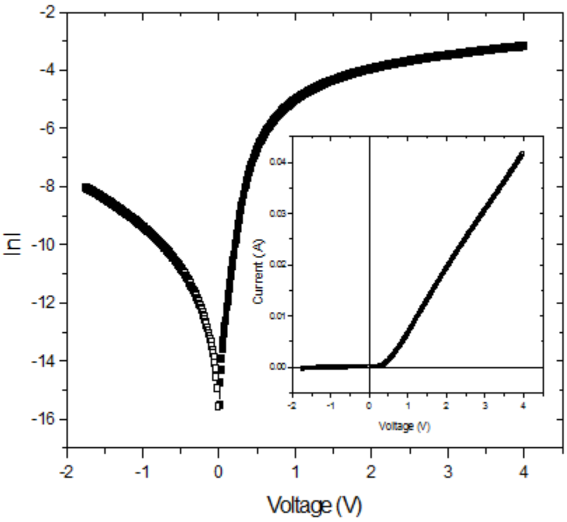


Figure 4 Experimental I-V characteristic of the Au/n-GaN Schottky diode (SBD) at room temperature [8].

The current through a Schottky barrier diode (Au/n-GaN SBD) with R_s at the forward bias, according the thermionic emission (TE) theory, is given by the relation [11]:

$$\mathrm{I_{TE}} = \mathrm{I_{TE0}} \exp\left(\frac{\mathrm{q(V\text{-}R_SI)}}{\mathrm{nkT}}\right) \; I_{TE} = I_{TE0} exp\left(\frac{q(V-R_SI)}{nkT}\right) \quad (1)$$

where I_{TE0} is the saturation current, q is the electron charge, R_s is the series resistance of structure, n is the ideality factor, k is the Boltzmann constant and T is the absolute temperature in Kelvin.
The saturation current I_{TE0} derived from the straight line region of the forward-bias current intercept at a zero bias and is given by:

$$\mathrm{I_{TE0}} = \mathrm{AA^*T^2} \exp\left(\text{-}\frac{\mathrm{q\phi_b}}{\mathrm{kT}}\right) \; I_{TE0} = AA^*T^2 exp\left(-\frac{q\phi_b}{kT}\right) \quad (2)$$

where A is the contact area, A* is the effective Richardson constant (by using an effective mass of 0.22 m_e for n-GaN [12, 13], the calculated value of A* is 26.4 A cm^{-2} K^{-2}) and ϕ_b is the barrier height.
The value of I_{TE0} determined from the forward lnI-V characteristic is found equals to 1.98×10^{-7}A [8].
The ideality factor n is calculated from the slope of the linear region of the lnI–V curve and can be written, as:

$$\mathrm{n} = \frac{\mathrm{q}}{\mathrm{kT}}\frac{\mathrm{d(V\text{-}R_SI)}}{\mathrm{d(lnI)}} \; n = \frac{q}{kT}\frac{d(V-R_SI)}{d(lnI)} \quad (3)$$

The series resistance can be evaluated in this region of high voltage by:

$$R_s = \frac{dV}{dI} \; R_s = \frac{dV}{dI} \tag{4}$$

The values of n, ϕ_b and R_s determined from experimental forward lnI-V characteristic [8] are shown in table 1.

The Schottky diode parameters were achieved also using a method developed by Cheung [14] which is also used in other works [15, 16]. Cheung's functions can be written as follows:

$$\frac{dV}{d(\ln I)} = R_s I + n\frac{kT}{q} \; \frac{dV}{d(lnI)} = R_s I + n\frac{kT}{q} \tag{5}$$

$$H(I) = V\text{-}n\frac{kT}{q}\ln\left(\frac{I}{SA^*T^2}\right) \; H(I) = V - n\frac{kT}{q}ln\left(\frac{I}{SA^*T^2}\right) \tag{6}$$

and

$$H(I) = R_s I + n\phi_b \; H(I) = R_s I + n\phi_b \tag{7}$$

Experimental dV/d(lnI) vs. I and H(I) vs. I plots of the Au/GaN SBD are presented in Fig. 5 at room temperature.

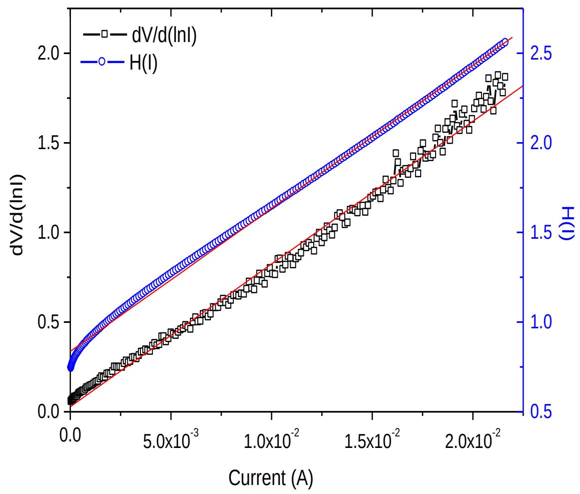


Figure 5 H(I) and dV/d(ln(I)) vs I plots of Au/n-GaN Schottky diode (SBD).

The values of n, ϕ_b and R_s determined by Cheung's method are shown in table 1.

Table 1 Calculated parameters of the studied sample.

Method	**Parameter**		
	n	ϕ_b (eV)	R_s (Ω)
lnI [8]	1.02	0.65	84
	1.09	/	dV/d(lnI): 79.58

Cheung	/	0.76	H(I):	79.73

It can be seen obviously that the values of n, ϕ_b and R_s obtained from lnI-V characteristic (Fig. 4) are in close agreement with the value obtained from dV/d(lnI)-I and H(I)-I curves (Fig. 5). The analysis of the experimental curve-voltage characteristic showed that the Au / GaN structure has a good ideality factor and a low series resistance. This indicates that the GaN substrate has fewer defects at the surface or at the interface. So, this substrate can be used for the realization of other structures such as Hemts transistors and THz detectors in the future.

3.2 Analytical modeling

In this paper, we have developed analytical codes, using Turbo Pascal software, to determine the current–voltage characteristics of a Au/GaN Schottky diode. The analytical calculations are based on the resolution of the equations giving the current according to the bias voltage. From I-V plots we determined the dominate current in the studied structure. The current transport in a Schottky diode can be described, in general, as a contribution of the following mechanisms [11]: thermionic emission (TE), generation-recombination (GR), and leakage (LK) currents. Thus, the total current can be expressed as:

$$\mathrm{I} = \mathrm{I}_{\mathrm{TE}} + \mathrm{I}_{\mathrm{GR}} + \mathrm{I}_{\mathrm{LK}} \quad I = I_{TE} + I_{GR} + I_{LK} \tag{8}$$

The individual contributions of current are:

$$\mathrm{I}_{\mathrm{TE}} = \mathrm{I}_{\mathrm{TE0}}\left\{\exp\left[\frac{\mathrm{q(V\text{-}R_sI)}}{\mathrm{kT}}\right]\text{-}1\right\} \quad I_{TE} = I_{TE0}\left\{exp\left[\frac{q(V-R_sI)}{kT}\right]-1\right\} \tag{9}$$

$$\mathrm{I}_{\mathrm{GR}} = \mathrm{I}_{\mathrm{GR0}}\left\{\exp\left[\frac{\mathrm{q(V\text{-}R_sI)}}{\mathrm{2kT}}\right]\text{-}1\right\} \quad I_{GR} = I_{GR0}\left\{exp\left[\frac{q(V-R_sI)}{2kT}\right]-1\right\} \tag{10}$$

$$I_{LK} = \frac{V-R_sI}{R_{LK}} \tag{11}$$

The generation-recombination saturation current I_{GR0} is written by [17]:

$$\mathrm{I}_{\mathrm{GR0}} = \frac{\mathrm{qAWn_i}}{2\tau} \quad I_{GR0} = \frac{qAWn_i}{2\tau} \tag{12}$$

where W is the depletion width, n_i is the intrinsic carrier concentration and τ is the carrier lifetime.

The leakage component of the current is given by (11) [18], where R_{LK} is the shunt resistance corresponding to the leakage current which represents the inhomogeneities and defects at the metal-semiconductor interface. The parameters chosen for a data fit at 300 K are shown in table 2:

Table 2 Simulation parameters values.

Parameters	**Values**
I_{TE} (A) [8]	6.46×10^{-8}
ϕ_b (eV) [8]	0.65
R_s (Ω) [8]	84

R_{LK} (Ω) [8]	4.68×10^{4}
I_{GR0} (A)	3.38×10^{-9}

Fig. 6 shows the effect of the thermionic current, generation-recombination current and leakage current on the final relationship.

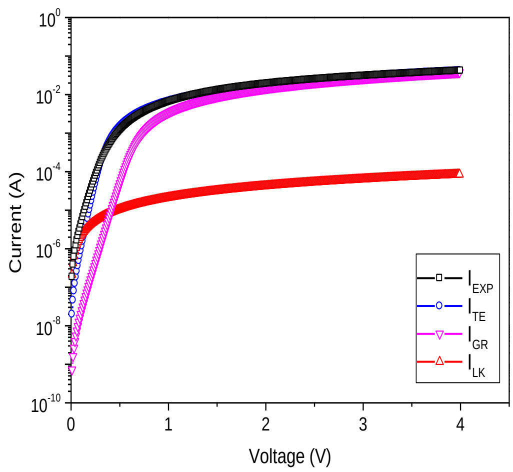


Figure 6 I-V characteristics according to the contribution of each current for the Au/n-GaN structure (SBD).

As can be seen in Fig. 6, the curve of the thermionic current joins the experimental curve for the entire range of polarization. The characteristic of the generation-recombination current moves away from the experimental curve for bias voltages below 2 V and beyond this voltage the two curves approach. The characteristic of the leakage current coincides with the experimental characteristic for low voltages. Fig. 5 represents the I-V characteristics of the sum of two current (thermionic + leakage) and the experimental current of Au/n-GaN structure (SBD).

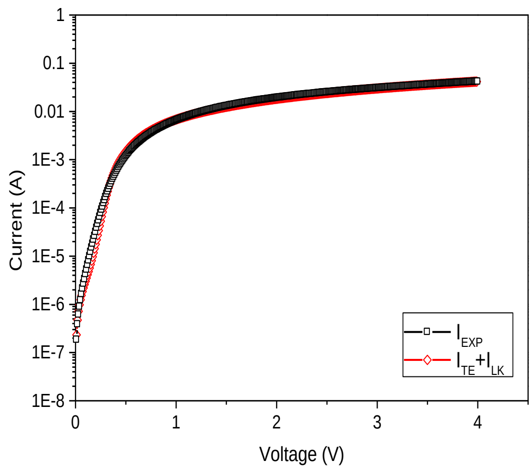


Figure 6 Experimental (I_{EXP}) and theoretical (simulated with I_{TE} + I_{LK}) I-V characteristics of Au/n-GaN structure (SBD).

From this figure, the curve of the theoretical current (I_{TE} + I_{LK}) joins the experimental curve for all bias voltage. Figure 7 represents the I-V characteristics of the sum of two currents (thermionic + generation-recombination) and the experimental characteristic of the Au/n-GaN structure (SBD).

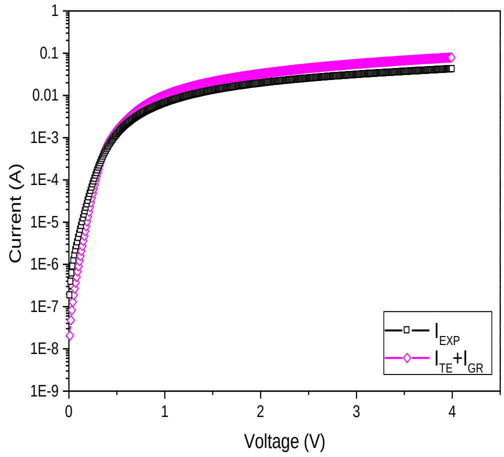


Figure 7 Experimental (I_{EXP}) and theoretical (simulated with I_{TE} + I_{FU}) I-V characteristics of Au/n-GaN structure (SBD).

Starting from this figure, a slight difference is observed between the two curves in the range of low and high voltage.
These results support an assumption that the dominant current mechanism in Au/n-GaN (free-standing substrate) Schottky diode is the thermionic current.

4. CONCLUSIONS

The current–voltage (I-V) characteristics of Schottky barrier diodes on free-standing GaN substrate were both experimentally and computationally investigated. We have calculated the electrical parameters from experimental current-voltage curve by two methods (lnI-V and Cheung) and they are found almost the same. We have found from the first method, the ideality factor n (1.02), the barrier height ϕ_b (0.65 eV) and a series resistance R_s (84 Ω). From the second method, we have found, n (1.09), ϕ_b (0.79 eV) and R_s (79.58 Ω - 79.73 Ω). Using analytical modeling, we traced the theoretical curves for a comparison with the experimental characteristic. From these theoretical characteristics, we have confirmed that the dominant mechanism in this type of the structure is the thermionic current. In general, one can say that the Schottky diode based on free-standing GaN substrate presents good electrical parameters.

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