Extraction of physical Schottky parameters using the Lambert function in Ni/AlGaN/GaN HEMT devices with defined conduction phenomena*

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Abstract: Electrical characterization analyses are proposed in this work using the Lambert function on Schottky junctions in GaN wide band gap semiconductor devices for extraction of physical parameters. The Lambert function is used to give an explicit expression of the current in the Schottky junction. This function is applied with defined conduction phenomena, whereas other work presented arbitrary (or undefined) conduction mechanisms in such parameters' extractions. Based upon AlGaN/GaN HEMT structures, extractions of parameters are undergone in order to provide physical characteristics. This work highlights a new expression of current with defined conduction phenomena in order to quantify the physical properties of Schottky contacts in AlGaN/GaN HEMT transistors.

Key words: GaN; Schottky junction; conduction mechanisms; Lambert function; parameters extraction

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1. Introduction

Wide band gap semiconductors have been partially integrated in high frequency applications since the beginning of the 21st century, bringing numerous advantages over their silicon counterparts. These new devices allow an increase in power density and frequency. The growth of these markets follows an exponential expansion for GaN material, promising an intensive demand in the forthcoming years.

Reliability and robustness are an issue for new technologies lacking maturity in process fabrication. This point has been an important concern for academic researchers. Many methods for Schottky parameters' extraction were built[1−7] in order to correlate macroscopic electrical data and microscopic physical parameters. Each of these methods has advantages and disadvantages[7]. Some are more appropriate for specific cases or strongly dependent on the data set, i.e. numbers of points or current level/voltage range and precision. Moreover, some require high-level algorithm development or may be very demanding in computation resources. To sum up, the main extraction strategies are: (1) Linear parts extrapolation of I and ln I versus V plots[8, 9]; (2) Derivative of the current with respect to voltage [2, 3]; (3) Use of an auxiliary function and a computer-fitting routine[1, 2, 4, 5]; (4) Direct vertical or horizontal optimizations by minimizing the vertical or horizontal quadratic error[7, 10].

An otherwise powerful mathematical function has been extensively used in science[11] in order to deal with the implicit feature of function such as $I = f(V)$: The transcendental Lambert function[12]. The main interest of this function is to enable changing an implicit function to an explicit one, thus allowing an easy solution for mathematical computation and modeling. Recently, Munoz *et al.*[13] proposed using an explicit multi-exponential model based on the simple single-exponential Shockley equation to model any bipolar or Schottky contact junction with arbitrary conduction mechanisms. Furthermore, the literature is very proficient with the use of double-diode models (or more), and additional series resistance with the alternative Lambert model. This model is very interesting in order to fit measurements with an explicit current but is not enough to extract physical parameters in the component since only phenomenological conduction mechanisms are considered.

In this paper, a physical model using the Lambert function with defined conduction phenomena is proposed. This physical approach with Lambert function allows studying the evolution of the Schottky curve as a function of physical parameters and not phenomenological ones. Finally, we present an example of extraction in Ni/AlGaN/GaN HEMT devices. These results have been compared with the literature.

2. Explicit writing of I–V equation for defined conduction phenomena

Munoz *et al.*[13] presented an explicit expression of the Schottky current $I = f(V)$ in order to have a better extraction of its parameters. However, the conduction phenomena were phenomenological ones. Here, we present the different explicit expressions of physical Schottky conduction phenomena. Then, the contributions of thermionic and tunneling physical parameters on the direct Schottky curve are presented.

In order to explain the Schottky diode measurement with physical transport mechanisms, it is possible to use the Lambert function with different conduction phenomena.

· Tunneling mechanism

Beginning by the standard tunneling equation and using the Lambert function, we easily find the corresponding expression:

$$I_{\mathrm{tu}} = \frac{E_0}{qR_{\mathrm{s}}} W_0 \left[\frac{qR_{\mathrm{s}}}{E_0} I_{\mathrm{t}} \exp \frac{q(V + I_{\mathrm{t}} R_{\mathrm{s}})}{E_0} \right] - I_{\mathrm{t}}, \tag{1}$$

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where E_0 is given by:

$$E_0 = E_{00} \coth \frac{E_{00}}{kT}. \quad (2)$$

E_0 is the tunnel energy (eV), E_{00} is a constant related to the WKB expression for the transmission of the barrier (eV), I_t is the tunnel saturation current (A), R_s is the on-state resistance, T is the absolute temperature, q is the elementary electronic charge and k is the Boltzmann constant.

· Thermionic emission

Following the same equation development for thermionic emission:

$$I_{te} = \frac{nkT}{qR_s} W_0 \left[\frac{qR_s}{nkT} I_s \exp \frac{q(V + I_s R_s)}{nkT}\right] - I_s, \quad (3)$$

where I_s is:

$$I_s = A^* A T^2 \exp\left(-\frac{q\Phi_b}{kT}\right). \quad (4)$$

Φ_b is the effective barrier height between the metal and the n-type semiconductor (eV), A^* is the Richardson constant and A the effective area of the diode.

· Generation Recombination

We obtain the same equation type for this phenomenon:

$$I_{g-r} = \frac{2kT}{qR_s} W_0 \left[\frac{qR_s}{2kT} I_r \exp \frac{q(V + I_r R_s)}{2kT}\right] - I_r, \quad (5)$$

I_r is given by:

$$I_r = A\frac{qn_i W}{2\tau}, \quad (6)$$

where n_i is the intrinsic carrier concentration, W the depletion width and τ denotes the effective carrier lifetime. In Eq. (5), the slope of the linear part in logarithmic scale will be equal to 2 at any temperature (the denominator being $2kT$ in the exponential). This particular case is then easy to identify on I–V-T measurements. Furthermore, the generation-recombination current is very low compared to other currents. Therefore, we ignore this contribution in our calculations.

Eqs. (1), (3), and (5) are the expressions of explicit current as $I = f(V)$ and not $I = f(V, I)$ with defined conduction mechanisms in a Schottky diode.

The total explicit current expression in the Schottky diode is then:

$$I_{total} = I_{te} + I_{tu} + I_{g-r} + VG_{sh}. \quad (7)$$

This expression can be represented by an electrical equivalent model with defined conduction phenomena as proposed in Fig. 1.

From Eq. (7), it is possible to analyze the influence of each parameter on the I–V curve. For this purpose, we simulated an arbitrary characteristic with a tunnel and a thermionic current using Eqs. (1) and (3), the shunt and generation–recombination contribution being ignored. The barrier height, the ideality factor and the series resistance are fixed to respectively 1 eV, 1.4 and 0.8 Ω, these values are chosen in order to be close to real measurements. As for the tunneling characteristic, E_0 and I_t are fixed to 0.08 eV and 10^{-8} A/cm^2 for the same reasons. The total gate surface is fixed at 8×10^{-5} cm^2. Each parameter is changed in a range around the fixed values. It is then easy

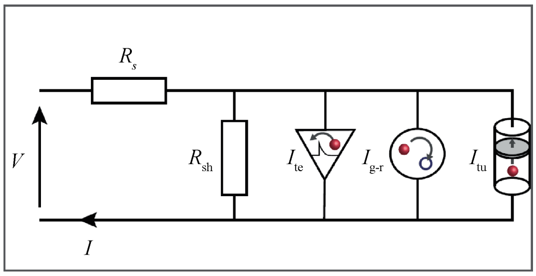

Fig. 1. Electrical equivalent model with all the defined conduction phenomena.

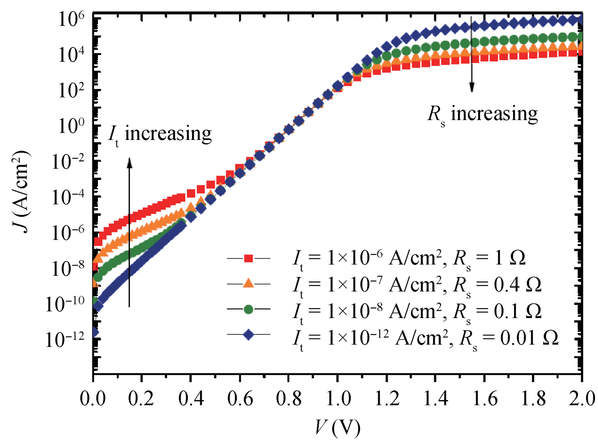

Fig. 2. (Color online) Evolution of the simulated Schottky curve by changing I_t and R_s.

to show their influence on the characteristic. On the following figures, the physical parameters R_s, I_t, E_0, n and Φ_b vary and the temperature is fixed at 293 K.

From Fig. 2, we can observe that increasing R_s will lower the saturation part of the curve. The series resistance effect is only visible in the nonlinear region, at high voltages. This resistance is linked to the ohmic contact and the bulk semiconductor of the diode, giving a voltage drop across the MS interface. Its value depends on the quality of the contact (interface states density)[9].

By modifying I_t, we change the height of the first knee. The parameter E_0 (Fig. 3) will change the slope of the tunneling curve in logarithmic scale. These parameters may vary depending on dislocation density for example[14], as tunnel current may occur through dislocations.

As shown in Fig. 4, the ideality factor affects the slope of the superior part of the characteristic. For $1 < n < 1.02$, it may be linked to a homogeneous contact with image-force lowering. If $n > 1.03$, it may be attributed to an inhomogeneous contact with interface states[9].

Finally, the Schottky barrier height will horizontally shift the superior part of the characteristic (Fig. 5). This parameter can be modified by the aluminum mole fraction in the AlGaN[15] or by a physical modification of the junction like the inter-diffusion of Au-Ni in a Au/Ni/AlGaN/GaN Schottky diode[16].

The Lambert function is then well suited for the simulation of these physical conduction phenomena which may occur in Au/Ni/AlGaN Schottky diodes. An explicit expression of the

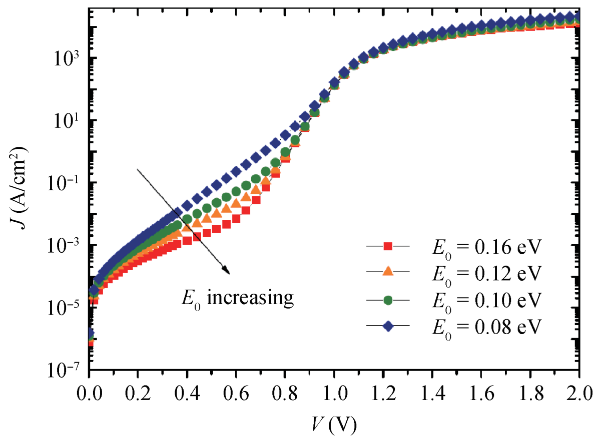

Fig. 3. (Color online) Modification of the I–V curve by changing E_0.

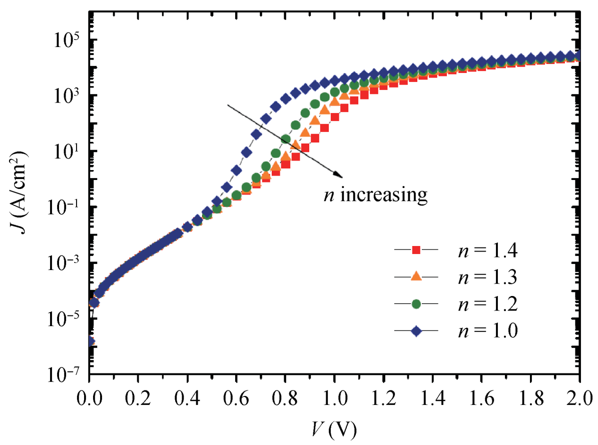

Fig. 4. (Color online) Impact of the ideality factor on the Schottky curve.

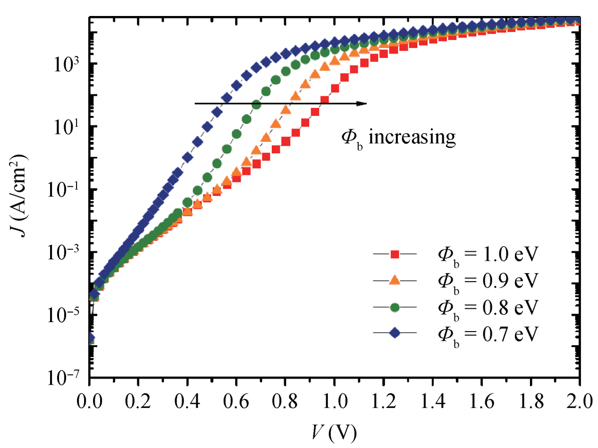

Fig. 5. (Color online) Impact of the barrier height on the Schottky curve.

Schottky current has been developed with defined conduction phenomena. It is thereby possible to analyze the influence of each physical parameter on the curve. From I–V–T measurements, it is now possible to make hypotheses on the conduction phenomena occurring in the component. Using the explicit current expression (7), the physical parameters can be extracted for different temperature measurements, the Lambert function

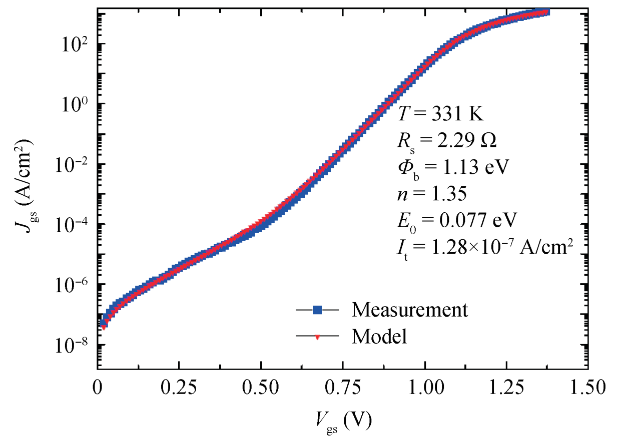

Fig. 6. (Color online) Extraction of all the Schottky parameters for the forward curve at 331 K: density of current versus gate voltage.

being a good candidate for Schottky parameter extraction[17].

3. Application on AlGaN/GaN HEMT

Eq. (7) was used in order to find a physical model for a Schottky diode in a HEMT device (NPTB00050 from Nitronex, total gate surface of 8 $\times 10^{-5}$cm^2, Ni/Al$_{0.26}$Ga$_{0.74}$N/GaN junction). The Richardson constant was theoretically evaluated for Al$_{0.26}$Ga$_{0.74}$ N at 152.1 A·cm^{-2}·K^{-2}[15]. From I–V–T measurements, two conduction phenomena are identified. The first one is dominant at high temperatures and high voltages ($V > 0.6$ V). This phenomenon is most likely of thermionic nature (with a series resistance appearing at the highest currents) due to its temperature behavior and the voltages associated ($V \gg kT/q$). The second phenomenon is assumed to be of tunneling origin because the reverse curve at low voltages (which is of tunneling nature) in absolute coordinates overlaps the lowest part of the forward curve.

Considering these hypotheses, we used Eqs. (1) and (3) in order to extract the physical parameters in a range of temperature from 125 to 331 K and compared them with the literature. An extraction example is shown in Fig. 6.

The results are summarized in Table 1. The differences of extracted R_s are mainly due to our measurements: the range in voltage was not high enough hence the imprecision on R_s extraction.

Barrier heights and ideality factors measurements of Ni/AlGaN Schottky junctions were provided by a few studies. The comparison between our results and the literature shows similar behavior (Figs. 7 and 8). The barrier height is increasing and the ideality factor is decreasing with temperature as seen in Refs. [18, 19]. In literature, different methods were used to extract these parameters (7): least square fit[18] and logarithmic method[19]. The extracted value of barrier height is varying from 0.76 eV (125 K) to 1.13 eV (331 K). These values are in agreement with other work on Ni/AlGaN junctions (1.02 eV for Ni/Al$_{0.23}$Ga$_{0.77}$N junction[15] and 0.92 eV for Ni/Al$_{0.25}$Ga$_{0.75}$N junction[19] at 300 K). Since the aluminum fraction differs slightly between the literature and our work[18, 15, 19]: 0.23, 0.22, and 0.25 (0.26 in our case), it can explain the difference in Φ_b. Furthermore, this is consistent with

Table 1. Summary of Ni/AlGaN Schottky parameters extraction using the Lambert function in AlGaN/GaN HEMT devices with defined conduction phenomena.

T (K)	Φ_b (eV)	n	R_s (Ω)	I_t (A/cm^2)	E_0 (eV)
125	0.76	1.81	3.71	1.23×10^{-8}	0.09
142	0.9	1.63	3.23	1.24×10^{-8}	0.088
166	0.97	1.5	1.52	1.24×10^{-8}	0.079
249	1.09	1.38	3	3.62×10^{-8}	0.076
331	1.13	1.35	2.28	1.29×10^{-7}	0.077

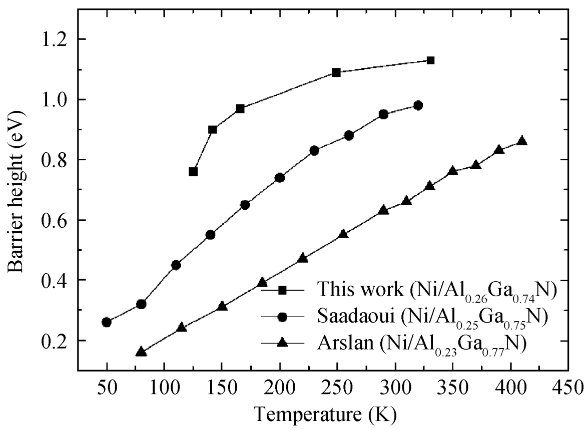

Fig. 7. Evolution of the barrier height with temperature and comparison with the literature.

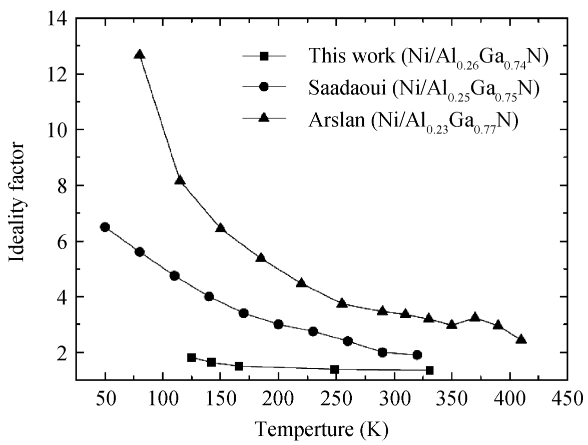

Fig. 8. Evolution of the ideality factor with temperature and comparison with the literature.

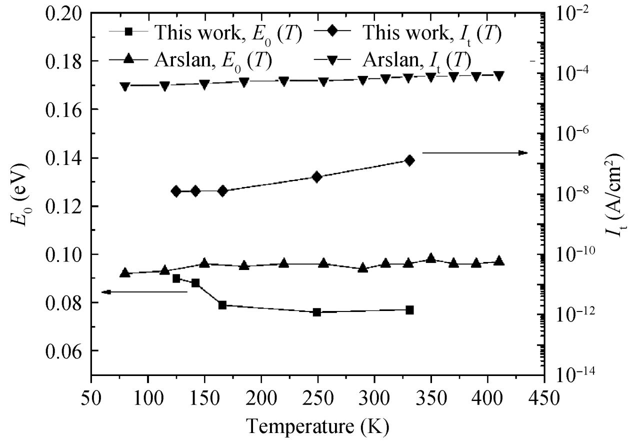

Fig. 9. Evolution of the tunnel parameters with temperature and comparison with the literature.

Qiao *et al.*[15] as the barrier height increases with the aluminum fraction in AlGaN. The ideality factor is changing from 1.81 (125 K) to 1.35 (331 K). Our values of n are then lower than those of literature as illustrated in Fig. (8). The ideality factor hinges on interface states which depends on density of defects (dislocations and traps for example) in the junction or in the space charge region in doped materials. This parameter is then very dependent on the quality of materials and may change between two different technologies.

The tunneling parameters extracted by our method as a function of the temperature are given in Fig. 9: E_0 is almost constant and I_t increases slightly with temperature. This behavior is the same as the one observed by Arslan *et al.* [18].

4. Conclusion

Within this paper, an explicit writing of the Schottky current with defined conduction phenomena was proposed, using the Lambert function. Starting from I–V–T measurements, it is possible to make hypotheses on the conduction phenomena occurring in a component and use them to form an explicit physical-linked current model. Previous studies have shown the utilization of the Lambert function (with undefined conduction phenomena) and gave phenomenological parameters with arbitrary conduction mechanisms. Here, the influence of a given physical parameter on a forward I–V characteristic was presented for two conduction phenomena (thermionic and tunneling). Also, an example of the application of this model on the Schottky junction of the HEMT-GaN device from Nitronex demonstrates an agreement with Ni/AlGaN/GaN junctions found in the literature. All the physical parameters of the junction were extracted from 125 to 331 K.

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