Analysis of Barrier Inhomogeneities in AlGaN/GaN HEMTs' Schottky Diodes by I-V-T measurements

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***Abstract*— Gate design and process is a major reliability issue in AlGaN/GaN HEMTs, arousing the setup of accurate tools and models to determine the Schottky diode parameters. This paper proposes the study of the Schottky diode on a set of two HEMT structures featuring different gate pad connections: as some electrical differences can be found out from the behavior of leakage currents (and associated reliability consequences), it is of prime importance to detect if the extrinsic design of the gate pad impacts the Schottky barrier behavior and hence the physical and electrical parameters. Therefore, forward gate I-V measurements in the temperature range of 100K-400K are presented: the ideality factor and the Schottky barrier height are extracted. An investigation on the Schottky barrier height by using the conventional Richardson plot from the well known physical equations gives an effective Richardson constant (A*) value far from the theory. The model can be greatly improved by applying Werner's model which leads to A* in good agreement with the theory. A small difference is found between the structures, due to a weak difference between the real effective masses. The study reveals a spatial barrier inhomogeneity under the gate at the metal-semiconductor interface on the two sets of devices featuring an extrinsic difference at the interconnection between the gate finger and the pad. However, the Schottky parameters are the same for all tested devices using Werner's model, instead of that from the classical physical equation of the Schottky diode.**

Keywords*— *AlGaN/GaN HEMT, Schottky diode, ideality factor, Schottky barrier height inhomogeneity, Richardson constant, Werner's method, effective mass

I. INTRODUCTION

AlGaN/GaN HEMTs are already at the stage of integration in RF power modules. Reliability and associated security operating areas need to be accurately determined for improved designs. Gate conduction mechanisms that specifically appear at the Schottky diode level and at the metal-semiconductor (M-SC) interface are known to be a key point in reliability improvements of HEMT devices. This interface is very sensitive to structural and electrical properties. In this paper, forward gate I-V-T measurements are exploited to extract the Schottky diode parameters such as the ideality factor (n), the Schottky barrier height (SBH) and the effective Richardson constant (A*). Different techniques are proposed, and are performed on two devices featuring differences on the extrinsic gate pad design (at the interconnection between the gate finger and the pad, Fig. 1). Different methods are proposed to investigate on the Schottky diodes, and to determine if the differences found on the two sets of transistors can be attributed to technological variations of the barrier height.

The paper is organized as follows. In section II, we briefly describe the device structure and the electrical measurements. Section III, reports the electrical parameters extraction versus temperature and their correlation. Section IV develops the application of the conventional Richardson method and Werner's method on devices from each set, leading to the extraction of the SBH and A* values. Section V sets the conclusions drawn from the two techniques.

II. DEVICES UNDER TEST AND EXPERIMENTAL CONDITIONS

AlGaN/GaN HEMTs (1 finger×100µm×0.5µm) under study are grown on SiC substrate and feature 18% of Al content. The surface is SiN passivated. The Schottky contact is formed by deposition of Ni/Pt/Au. Two devices #A and #B are tested, featuring an extrinsic difference at the interconnection between the gate finger and the pad (Fig. 1). The two sets of devices respectively associated to #A and #B structures are statistically homogeneous, and the results are next proposed on a single device from each set.

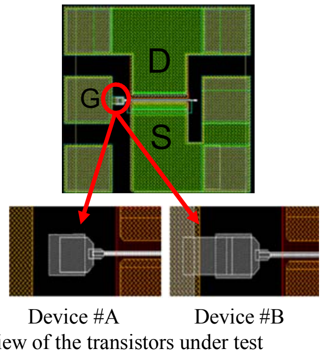


Fig. 1. Mask top view of the transistors under test
Device #A: without the interconnection between the gate and the pad
Device #B: with the interconnection between the gate and the pad

On wafer DC I_G-V_{GS} measurements in the temperature range of 100K to 400K are performed using Agilent 4156C and a Cryoprober. Fig. 2 shows $I_G(V_{GS})$ characteristics of the

Schottky diodes for devices #A and #B. The physical parameters are first extracted according to equations 1a and 1b [2-3]:

$$I_G = I_S \exp\left(\frac{qV_{GS}}{nkT}\right) \tag{1a}$$

$$\text{with } I_S = SA^*T^2 \exp\left(-\frac{q\phi_B}{kT}\right) \tag{1b}$$

where I_S is the saturation current, q is the electron charge, n is the ideality factor, k is Boltzmann constant, T is the temperature, S is the effective area of the diode, A^* is the effective Richardson constant found to be 32 $AK^{-2}cm^{-2}$ from A^*=0.266A (where A= 120 $AK^{-2}cm^{-2}$ and $m^*=0.266m_0$ is the effective mass) for the AlGaN and ϕ_B is the Schottky barrier height [4].

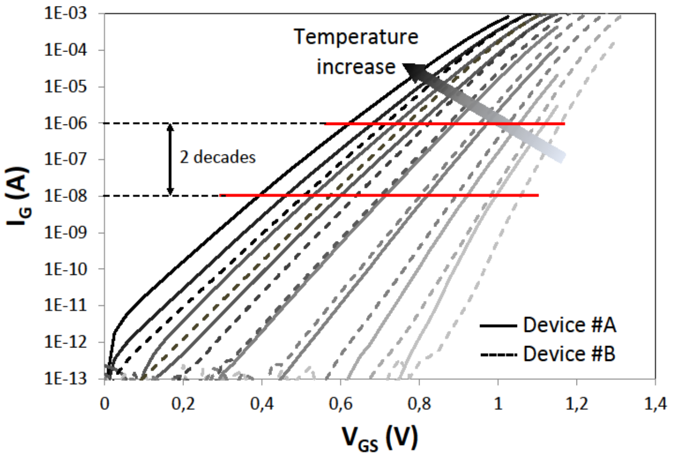


Fig. 2. Forward gate current-voltage characteristics of AlGaN/GaN HEMTs, open drain configuration versus temperature ranging from 100K to 400K.

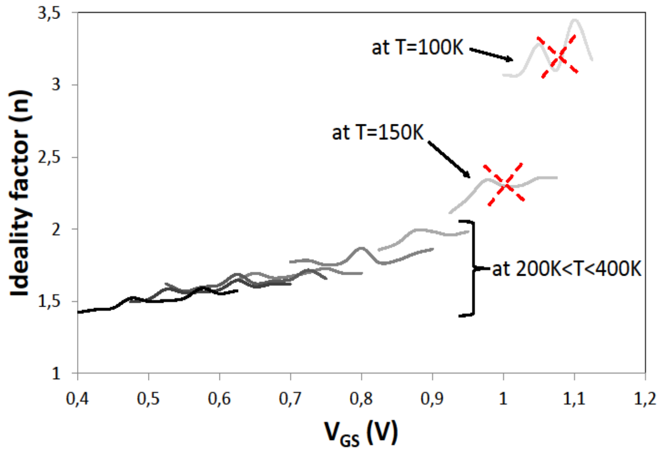
III. Electrical Parameters Extraction

A. *Ideality factor dependence of forward bias*

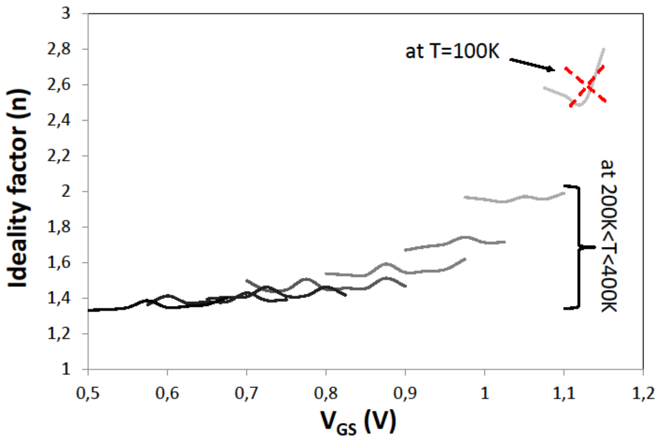
Fig. 2 displays a constant current region [5] where the I-V-T characteristics can be fitted. If these measurements feature a linear relation for all the temperatures (100K to 400K), a variation appears when studying the ideality factor variations versus V_{GS} using (2).

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln(I/I_s)}\right) \tag{2}$$

Therefore, to choose and validate the linear segments for fitting the diode characteristics, it is essential to observe the ideality factor variations versus the applied bias V_{GS} for all temperatures: n must have a quasi-constant value versus V_{GS} as shown in Fig. 3a and 3b (respectively for the transistors #A and #B). The large variation of the ideality factor at 100K and 150K for #A have no physical sense and are thus excluded from the study (also for #B at 100K), as proposed in the next paragraphs. Hence, the best fitting and analysis of the data are in the temperature range of 200K-400K for #A and 150K-400K for #B. The same procedure has been tested for a current range of 5 decades, displaying higher non-linear deviations on the ideality factor: thus, reducing the current range (here taken at 2 decades) improves the accuracy of the extraction method.



(a) Device #A



(b) Device #B

Fig. 3. Ideality factor (n) versus forward bias (V_{GS}) for device #A and device #B within a constant current range of 2 decades (cf. fig.2). The red deletions indicate which measurements have to be excluded from the study (100K and 150K for device #A and at 100K for device #B).

B. *Ideality factor and Schottky barrier height dependences of the temperature*

The first electrical/physical parameters indicators of Schottky barrier homogeneity are the ideality factor and the Schottky barrier height (SBH). By combining (1a) and (1b) and plotting equation (3), it is possible to extract the SBH temperature dependency of n and ϕ_B in fig. 4.

$$\ln\left(\frac{I}{SA^*T^2}\right) = f(V) \tag{3}$$

A marginal decrease of the Schottky barrier height (SBH) and a marginal increase of the ideality factor are observed in the lower temperature range, in comparison with the higher temperature range. These variations are early indicators of deviation from the conventional Richardson behavior: the assumption of homogeneous Schottky barrier could be wrong. According to Werner and *al.* [1], these variations can be attributed to interface states at the thin oxide between the metal and the semiconductor, extra current caused by tunneling through the barrier, generation-recombination current within the space charge region and edge related currents.

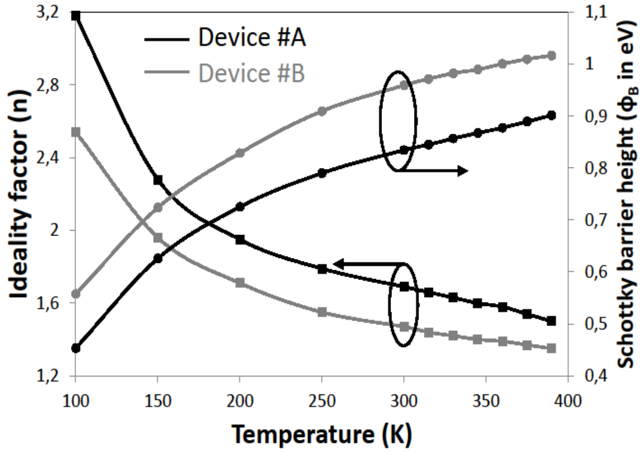


Fig. 4. Temperature dependence of the ideality factor (n) and Schottky barrier height for device #A (black plots) and device #B (grey plots)

The SBH becomes smaller as the ideality factor increases [2-3]. This phenomenon is represented in Fig. 5. Plotting ϕ_B versus n allows to extract the barrier heights for an ideal study case (considering n=1) of the Schottky diode. The extracted values of the SBH at n=1 are 1.1eV for #A, and 1.2eV for #B.

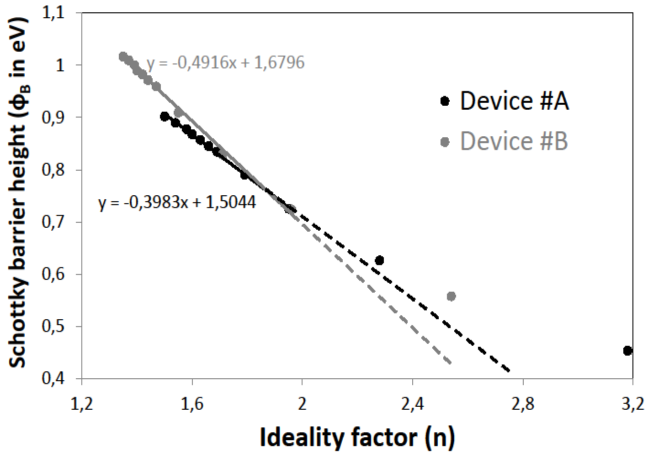


Fig. 5. Schottky barrier height versus ideality factor for device #A (black plot) and device #B (grey plot) featuring the equations of the trends for each device

IV. Potential Fluctuation Model Application

A. *Effective barrier height and its standard deviation*

The model proposed by Werner and Guttler in [1] is designed to analyze the transport properties and the roughness at the interface between the metal and the semiconductor. This analytical model does not require any computer simulation. A Gaussian distribution with a standard deviation is presented in equation (4):

$$P(\phi_B) = \frac{1}{\sigma_s\sqrt{2\pi}} \exp\left(-\frac{\left(\overline{\phi_B} - \phi_B\right)^2}{2\sigma_s^2}\right) \tag{4}$$

by using (1a) and (4), we obtain:

$$\phi_B(T) = \overline{\phi_B} - \frac{\sigma_s^2}{2kT/q} \tag{5}$$

Where $\overline{\phi_B}$ is the mean barrier height, and σ_s is the standard deviation that represents the barrier inhomogeneity (the lower the standard deviation, the better the barrier height homogeneity). By using (5) and by plotting ϕ_B versus 1/T (Fig. 6), the negative slope and the y-intercept allows to extract σ_s and $\overline{\phi_B}$. Table 1 synthesizes the extracted values for the two transistor's configurations #A and #B. Fig. 6 also illustrates the barrier inhomogeneity for both devices; in a case of homogeneous barrier, the plot of SBH versus 1/T should exhibit an horizontal trend parallel to the x-axis, featuring a constant ϕ_B value, which is not the case for these two diodes.

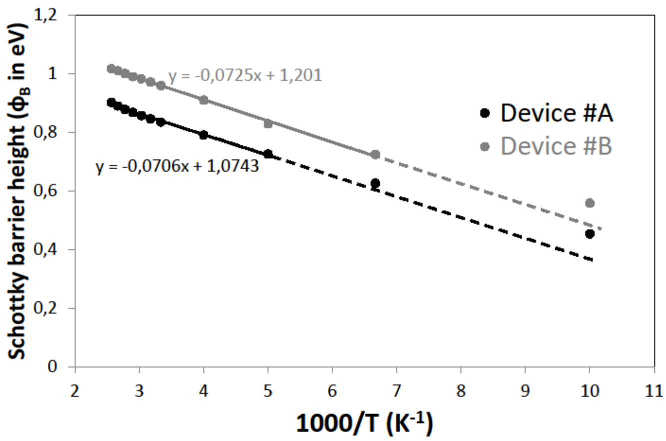


Fig. 6. Schottky barrier height calculated from I-V-T measurements versus 1/T for device #A (black plot) and device #B (grey plot)

B. *Schottky barrier height anomalies evidenced by Richardson constant values*

The constant SBH and the effective Richardson constant can be extracted using (1b) as presented in (6):

$$\ln\left(\frac{I_S}{T^2}\right) = \ln(SA^*) - \frac{q\phi_B}{kT} \tag{6}$$

The plot of *ln(I$_s$/T²)* versus *1/T* from (6) (as shown in Fig. 7 with filled squares) must correspond to a straight line where the slope and the y-intercept are used to extract ϕ_B and A^* respectively.

The Richardson plot should exhibit linearity in the whole temperature range, but it is noticeable that the linear portion is reduced between 250K and 400K (non-linearity at low temperatures). By fitting the plots, a ϕ_B and an A* of 0.6 eV and $2.8.10^{-3}$ $AK^{-2}cm^{-2}$ for transistor #A and 0.7 eV and $1.3.10^{-3}$ $AK^{-2}cm^{-2}$ for transistor #B are extracted. Deviation in

Richardson plots leads to a strong deviation in A*, thus the interface M-SC is considered as inhomogeneous. According to Werner and Guttler's model [1], the SBH in (1b) and (6) should be replaced by (5):

$$\ln(\frac{I_S}{T^2}) = \ln(SA^*) - \frac{q\bar{\phi}_B}{kT} + \frac{q^2\sigma_s^2}{2k^2T^2} \qquad (7)$$

The Richardson plot modified by Werner's model can be written as follows:

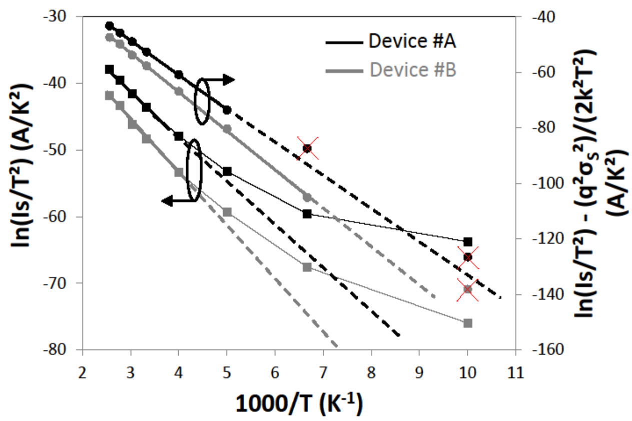


Fig. 7. Conventional and modified Richardson plots of AlGaN/GaN HEMTs.
Conventional Richardson plots with the y-axis on the left.
Modified Richardson plots by Werner's model with y-axis on the right.
Device #A : black lines and dots
Device #B : grey lines and dots

$$\ln\left(\frac{I_S}{T^2} - \frac{q\sigma_s^2}{2k^2T^2}\right) = f\left(\frac{1}{T}\right) \qquad (8)$$

and shown in Fig. 7 with filled circles.

Table 1 synthesizes the Schottky diode parameters extracted from the conventional Richardson method and from the modified Richardson plot using Werner's model.

TABLE I
PHYSICAL AND ELECTRICAL PARAMETERS OF ALGAN/GAN HEMTS

Electrical parameters	Device #A	Device #B
Results of the conventional Richardson method		
T range (K)	250 to 400K	250 to 400K
Φ_B (eV)	0.6	0.7
A* ($AK^{-2}cm^{-2}$)	$2.8.10^{-3}$	$1.3.10^{-3}$
Results of the modified Richardson method by Werner's model		
T range (K)	200 to 400K	150 to 400K
$\bar{\phi}_B$ (eV)	1.1	1.2
σ_S (meV)	111	113
A* ($AK^{-2}cm^{-2}$)	29.8	42
m* (kg)	$0.25m_0$	$0.35m_0$

The temperature range is reduced according to the non constant values of the ideality factor versus V_{GS} for some temperatures (cf. Fig. 3) The new values obtained for A* from our experiments are in close agreement with the theoretical value (26.4 $AK^{-2}cm^{-2}$). The small difference keeps the effective Richardson constant as a questionable parameter! But according to Horvath [6], this is due to the real effective mass that is not always equal to the theoretical value ($m^*=0.22m_0$) calculated at the pure thermoionic emission (9). Hence, the A* value obtained from I-V-T measurements could be affected by lateral inhomogeneities of the barrier. The new values of m* are also presented in table 1.

$$A^* = \frac{4\pi q m^* k^2}{h^3} \qquad (9)$$

Where h is Planck's constant.

Lastly, the inhomogeneities revealed in this paper have been correlated to the presence of defects under the gate finger by means of EBIC measurement technique.

V. CONCLUSIONS

The paper presents an original approach based on the study of the barrier inhomogeneities of the Schottky diodes in AlGaN/GaN HEMTs. The variations of the ideality factor and of the Schottky barrier height are early indicators of barrier inhomogeneities. Then, the applications of the conventional and modified Richardson method consolidate the assumption: the difference in Richardson's constant after applying Werner's model on Richardson's equation is applied to the devices under study, and is physically related to the real effective mass. The transistors – in spite of the extrinsic difference on the gate pad connection mode – show the same behavior. Hence, the defects are localized under the gate, and the pad connection has no influence on the technological parameters, even if a difference is found on electrical signatures between the investigated devices: computed physical parameters A* and m* are very close to theoretical values.

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