GaN Schottky Diodes Parameter Extraction Model from *S*-Parameters Measurement

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***Abstract* — GaN-on-sapphire Schottky barrier diodes (SBDs) have been fabricated for frequency multiplier applications. A complete set of characterization has been done, including DC and RF measurements. A model to extract the Schottky parameters from *S*-parameters measurements in small diodes is proposed, obtaining good capacitance agreement compared with that extracted from capacitance-voltage (*C-V*) measurements carried out in large-area diodes where the parasitic effects are not significant.**

***Keywords* — Schottky, GaN, capacitance, frequency multiplier.**

I. INTRODUCTION

Terahertz technology has considerably been pushed forward during the last decades, however there are still technological challenges to achieve, including powerful compact solid-state devices to generate terahertz signals [1,2].

Schottky barrier diodes (SBDs) can be used as detectors, mixers or frequency multipliers [3,4]. GaAs SBDs are used in heterodyne receivers, not only as the mixer or detector element but also at the local oscillator system based on frequency multipliers [5]. The main drawback of GaAs technology is the limited mm-wave/THz generated power due to the low breakdown field and thermal conductivity [6].

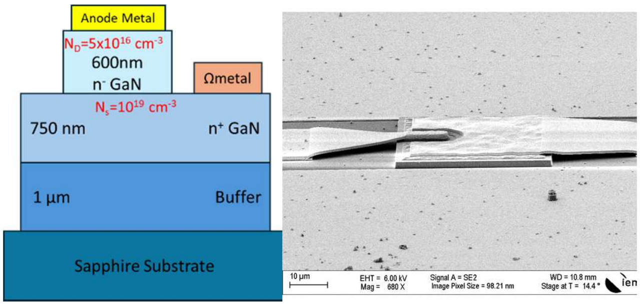
In the last years, GaN SBDs have been studied with great interest due to their properties such as wide band-gap, high mobility, good thermal conductivity, high breakdown field and high electron saturation velocity [7], which makes this semiconductor a promising candidate for high frequency and high power applications [8].

The key parameter of the SBD for the frequency multiplier is the nonlinearity of the capacitance-voltage (*C-V*) characteristic [9], with a limiting factor being the series resistance of the SBD. The equivalent circuit of a Schottky diode is well known and consists, in a first approximation, of a capacitance and a resistance in parallel. This simple equivalent circuit can be used for large diodes at low frequencies and is commonly employed for *C(V)* measurements and material studies. However, for high-frequency applications, the area of the Schottky contact is notably reduced, and the use of an air-bridge technique to electrically connect the diode becomes necessary [10], introducing significant parasitic effects [11]. In this case, other elements should be considered in the equivalent circuit, which are typically estimated by fitting the *S*-parameters measurements [12,13]. A compact and robust model is needed to extract the parasitic parameters of Schottky diodes but it has not yet been developed.

In this work, we present a complete characterization of GaN-on-sapphire SBDs, including DC and RF measurements as well as the extraction of Schottky parameters. Using *S*-parameters measurements, we have estimated the intrinsic and parasitic elements of a simplified small signal equivalent circuit (SSEC). By comparing the capacitance extracted with this model and the one measured in large samples (*C-V* curves), a good agreement has been obtained.

II. DEVICE DESCRIPTION

The GaN epitaxial layers were grown by metal organic chemical vapor deposition (MOCVD) on sapphire substrate, see Fig. 1(a). First a GaN buffer layer with a thickness of 1 µm was grown, then a n^+ GaN thick layer of 750 nm (doped at 10^{19} cm^{-3}) to achieve a low series resistance and finally, a 600 nm n^- GaN layer (doped at $5x10^{16}$ cm^{-3}) known as drift layer.



(a) (b)

Fig. 1. (a) Scheme of the SBDs; (b) SEM image of a fabricated diode with air-bridge.

Metal and SiO_2 hard mask have been used to define the mesa by using a Cl_2-based dry plasma etching. Then, a negative resist layer together with a SiO_2 hard mask were used to define isolation patterns by Cl_2-based ICP dry etching. The ohmic contact Ti/Al/Ni/Au was deposited by evaporation on the n^+ GaN surface and afterwards, a rapid thermal annealing was carried out at 850ºC for 30s. The Schottky contact based on Pt/Au metal stack was deposited on the n^- GaN layer by e-beam evaporation, followed by an annealing process at 400 ºC during 15 min. Finally, the air bridges are made in two steps to connect the coplanar access with the metal contacts. The air bridge metallization consists of Ti/Au deposited by e-beam evaporation. The results reported in this work correspond to two different types of diodes: large circular surface diodes and microwave diodes where an air-bridge is needed, as the one shown in Fig. 1(b).

The *I-V* measurements were carried out using a semiconductor characterization system Keithley 4200-SCS which has three source measure units (SMU). On the other hand, the *C-V* curves were measured using a precision impedance analyzer Agilent 4294A. Furthermore, the *S*-parameter measurements were performed with a vector network analyzer (VNA) Agilent E8361A PNA.

III. SCHOTTKY DIODE PARAMETERS EXTRACTION

A. I-V characteristics

The *I-V* characteristics of circular diodes with different surfaces have been measured. In this section we will present the *I-V* characteristics of a 221 μm diameter diode. Fig. 2 shows the measured forward *I-V* curve, where the internal diode voltage is $V_d = V - IR_s$, with R_s representing the diode series resistance.

By using the thermionic emission theory, the current expression is given by the following equation [15]:

$$J = A^{*}T^{2} exp\left(\frac{q\phi_B}{K_B T}\right) exp\left(\frac{q(V-IR_s)}{\eta K_B T}\right), \tag{1}$$

where A^* is the Richardson constant, T is the temperature ϕ_B the Schottky barrier height, q is the electron charge, η the ideality factor and K_B is the Boltzmann constant. From the forward *I-V* curve we have extracted the value of R_s, ϕ_B and η by using the equation (1), which are 0.6 Ω, 0.66 eV and 1.05, respectively. The low values of η indicates the good quality of the Schottky contacts.

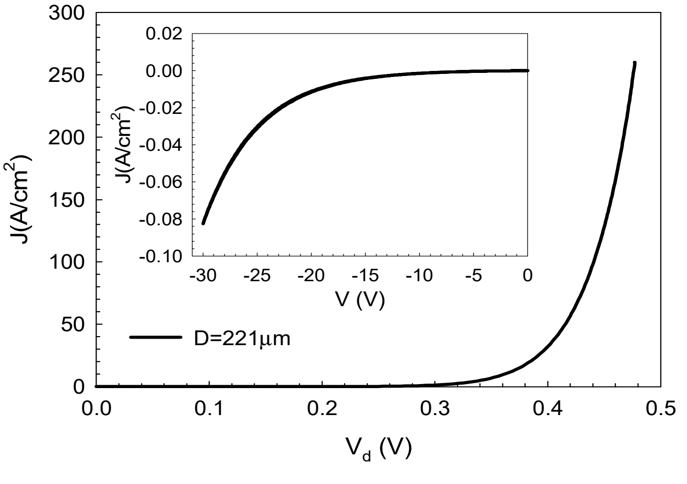


Fig. 2. Measured *I-V* curves in forward bias for a diode of 221 μm of diameter. Inset: Reverse *I-V* characteristic up to -30V.

The inset of Fig. 2 represents the reverse *I-V* measurement, obtaining a current density of less than 0.1 A/cm^2 at -30V. From measurements, the diode current is shown to scale in proportion to the surface area for diodes of different diameters, indicating that the leakage current mechanisms are mainly located in the volume of the diode.

B. C-V characteristics

In this section we present the *C-V* measurements of a diode of the same size, performed at 1 MHz. At 0V the capacitance (C_{j0}) of this diode is around 25pF.

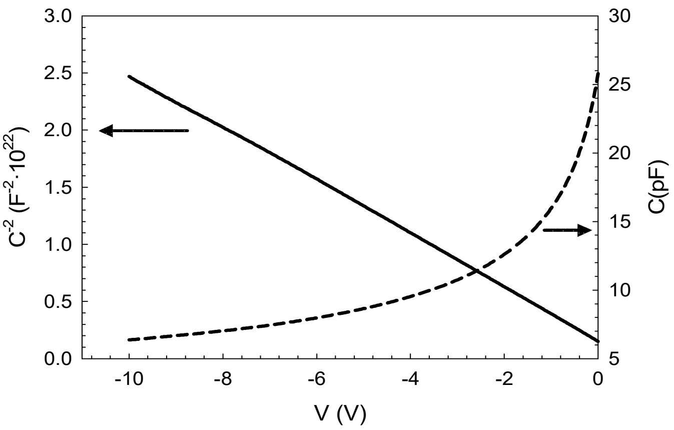


Fig. 3. Representation of the measured *C-V* curve and C^{-2}-*V* in reverse bias for a 221 μm diameter diode.

The ideal capacitance in a SBD is well known [14]. As expected, the representation of C^{-2} as a function of the voltage shows a linear behavior.

Therefore, from the C^{-2}-*V* curve, N_D and V_B can be calculated. Once the value of V_B has been obtained, we can estimate ϕ_B using the following equation [16]:

$$\phi_B = V_B - \frac{K_B T}{q} \ln \frac{N_D}{N_C}, \tag{2}$$

with $N_C = 2[2\pi m^{*} K_B T/h^2]^{3/2}$ the states density of the conduction band. The extracted values of ϕ_B and N_D are 0.77 eV and 4.55x10^{16} cm^{-3}, respectively. The Schottky barrier height extracted from the *C-V* curves is slightly higher than the one extracted from the *I-V* measurements, as has been often observed in the literature, typically attributed to non-ideal interfaces such as barrier inhomogeneities, interfacial charges, etc [17].

IV. SCHOTTKY DIODE EQUIVALENT CIRCUIT MODEL

A. *DC characterization*

The *I-V* characteristics of a small circular diode (12 μm diameter) fabricated with two coplanar waveguide accesses (CPW) has been measured, see Fig. 4. Using the equation (1), the Schottky parameters have been extracted, being R_s=16 Ω, ϕ_B=0.56 eV and η=1.28.

The reverse *I-V* characteristic is shown in the inset of Fig. 4. Around -30V a current density of around 1.5 A/cm^2 is obtained. In comparison with the current density obtained for a large-area diode (221 μm diameter, see inset of Fig. 2), this SBD presents a higher current density, which can be related to edge effects provoking additional leakage current mechanisms [18].

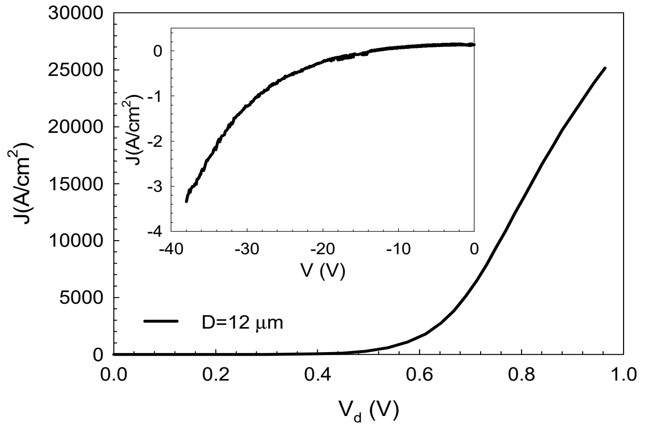


Fig. 4. Measured *I-V* curves in forward bias for a 12 µm diameter diode. Inset: Reverse *I-V* characteristic up to around -40V.

B. *RF characterization*

Due to the smallest dimensions of the microwave diode, the parameters are too small to measure with a precision impedance analyzer like the Agilent 4294A. Then *S*-parameters measurements are required to estimate the diode capacitance and parasitic elements. The calibration used is a standard line-reflect-reflect-match (LRRM) performed with a Formfactor Impedance Standard Substrate (ISS). Furthermore, open and short structures with the same dimensions of the diodes have been measured to carry out access de-embedding [19]. *S*-parameters measurements have been performed from 250 MHz up to 67 GHz.

As we have mentioned previously the parasitic effects become important for small diodes, so the model of a capacitance and a resistance in parallel is no longer valid. Thus, a more complex equivalent circuit is needed. The SSEC considered in this work is shown in Fig. 5.

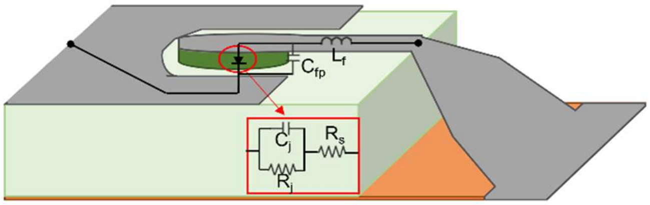


Fig. 5. Scheme of the Schottky diode including the SSEC.

The SSEC can be described by the intrinsic elements, which are the capacitance C_j, the junction resistance R_j and the series resistance R_s, and the parasitic elements: the bridge inductance L_f and the capacitance C_{fp} [19,20].

For the estimation of the different elements of the SSEC, an extraction model based on the comparison of calculated and measured *S*-parameters is used. We used here Quite Universal Circuit Simulator (QUCS) software to calculate the *S*-parameters of the SSEC and by comparison with the *S*-parameters measurements the circuit elements are obtained. Firstly, the C_{j0} normalized by the surface in the large-area circular diodes is mainly the same and equal to 6.7x10^{-4} F/m^2. Thus, for 0V the capacitance C_j will be equal to 75 fF. To estimate the parasitic capacitance C_{fp}, two assumptions are considered. Firstly, for lower GHz frequency range the inductance can be neglected with respect to the capacitances [19]. Secondly, in reverse the series resistance R_s is negligible as compared to R_j. Therefore, in this case the equivalent circuit consists of three elements (R_j, C_j and C_{fp}) in parallel, giving the *Y*-parameters:

$$Y = \frac{1}{R_j}\begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} + j\omega \begin{pmatrix} C_j + C_{fp} & -(C_j + C_{fp}) \\ -(C_j + C_{fp}) & C_j + C_{fp} \end{pmatrix}, \quad (3)$$

Using the Y_{12} parameter at 0V, as we have already calculated that C_j is 75 fF, we can estimate C_{fp} using the equation $C_{Tot}=C_j+C_{fp}=Im[-Y_{12}]/\omega$. C_{fp} is independent of the voltage and equal to 6 fF.

Then, R_s is extracted from a forward bias where C_{j0} is considered to be negligible. Calculating the *Y*-parameters of the equivalent circuit, we obtain that $R_{tot}=1/Re[-Y_{12}]=R_s+R_j$. A value of 15 Ω has been obtained for R_s, very close to the one extracted from the DC measurements (R_s=16 Ω).

Last, the assumption about the inductance being negligible is not valid for all the frequency range. Observing the frequency dependence of the *Y*-parameters, L_f is estimated to be 22 pH.

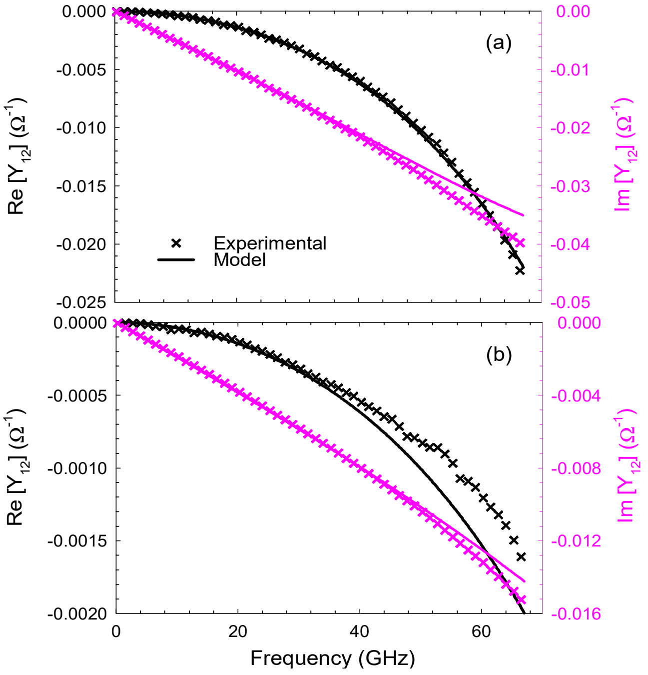


Fig. 6. Y_{12} parameters as a function of the frequency obtained from the measurements (symbols) and the model (solid lines) for two different voltages, (a) 0 V and (b) -5.5 V. The real part of the *Y*-parameters is represented in black and the imaginary part in pink.

C_j and R_j depend on the voltage. For each bias point the model has been used to determine these two parameters. In Fig. 6, a comparison between the experimental and the model *Y*-parameters is represented for two different voltages, 0V and -5.5V, obtaining a good agreement between them. R_j reaches values of MΩ for reverse bias and is reduced to the order of Ω near forward bias.

The aim of this model is to extract the capacitance of the junction for small size diodes. As we have explained, C_j has been estimated with the model for the different voltages. The values obtained from 0 V to -5.5 V are included in Fig. 4.

Representing the inverse of the square capacitance as a function of the voltage, we can calculate the doping level. This representation is also shown in Fig. 4 together with the *C-V* measurements carried out in the 221 μm diameter diode.

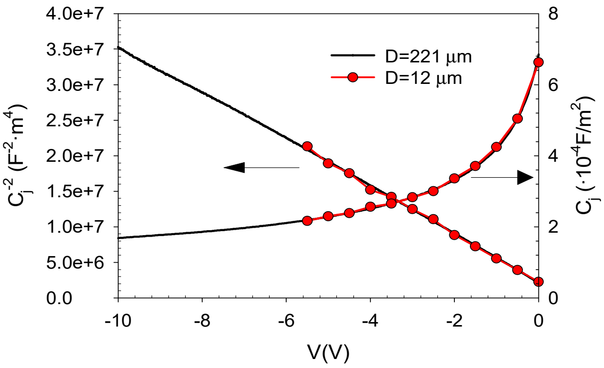


Fig. 7. The junction capacitance (C_j) extracted using the model (red symbols) in a diode of 12 μm of diameter and *C-V* measurement carried out in a large diode of 221 μm of diameter (black solid line).

From the characteristic C^{-2}-V, the doping level has been obtained, N_D=4.67x10^{16} cm^{-3}, which is really similar to the one obtained from *C-V* measurements (4.55x10^{16} cm^{-3}). These results validate the proposed model, that can be used to estimate the doping level in small diodes. On the other hand, we can also calculate ϕ_B [using equation (2)] which is equal to 0.75 eV, which is also really similar to the one obtained from *C-V* measurements on large diode (0.77V).

V. CONCLUSION

A complete characterization of Pt/Au GaN-on-sapphire SBDs have been carried out in this work. The extraction of Schottky parameters from the *I-V* characteristic using the thermionic emission theory is presented. A model based on the *S*-parameters calculated from an equivalent circuit has been used to estimate the capacitance of small diodes. A comparison between the results obtained with the measurement of microwave diode and the *C-V* measurements of a large area diode has been performed, which reveals a good agreement between them and validates the parameter extraction model, paving the way for use of GaN diodes in frequency multiplier designs.

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