Capabilities of GaN Schottky Multipliers for LO Power Generation at Millimeter-Wave Bands

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***Abstract*— Gallium Nitride (GaN) is a very promising material for either electronic and optoelectronic devices because of its high breakdown field, and peak and saturated electron drift velocity. Hence, despite of its lower electron mobility, GaN Schottky diodes might represent a good alternative to GaAs Schottky diodes for LO power generation at millimetre-wave bands due to a much better power handling capabilities. Results from numerical simulations for a 200 GHz doubler predict a ~25 % lower conversion efficiency for GaN Schottky multipliers when compared to GaAs Schottky multipliers. However, higher power handling capabilities, an order of magnitude higher than GaAs with same anode sizes, are predicted for GaN diodes.**

I. Introduction

In the recent years, GaN has emerged as a very promising material for either electronic and optoelectronic devices mainly due to its wide direct bandgap (3.4 eV), which results in a high breakdown field, and its high peak and saturated electron drift velocity [1]. High breakdown voltage materials increase the power handling capabilities of the devices. Hence, GaN Schottky diodes might represent a good alternative to GaAs Schottky diodes for LO power generation at millimeter-wave bands in a near future, when solid-states sources can provide larger amounts of LO power at frequencies around 100-150 GHz. The potential capabilities of GaN Schottky diodes are not in the frame of the design of high frequency multiplier circuits, well within the submillimeter-wave region, but in the early stages of high-frequency multiplier chains where the excellent power handling capabilities of GaN can be exploited. However, GaN has the inconvenient of a lower electron mobility than GaAs, which results in an increase in the series resistance, and thereby, in lower efficiencies.

The objective of this paper is to investigate the capabilities of GaN Schottky diodes for LO power generation at millimeter-wave and submillimeter-wave bands as an alternative to the widely used GaAs Schottky diodes. For this task, we have included the GaN material in an already available in-house CAD tool for Schottky diode-based circuits design. This simulator incorporates an accurate physics-based Drift-Diffusion model for Schottky diodes and has demonstrated very good results for the analysis of GaAs Schottky diodes at millimetre and submillimeter-wave bands [2]. Firstly, the electrical properties of both GaN and GaAs diodes are compared, paying special attention to those with a major impact on the frequency multiplying process, such as the breakdown voltage, the electron mobilities and the nonlinear capacitance. Nevertheless, the key point of the comparison lies in the much higher power handling capabilities of GaN diodes. This is due to the excellent characteristics of GaN in terms of breakdown voltage, which represents the real advantage of this material over GaAs. Moreover, the enhanced power handling capabilities of GaN diodes will lead to simplified designs at the early multiplication stages of THz LO chains, allowing the use of either single-diode configurations or 2-diodes balanced configurations. Current designs with GaAs Schottky diodes employ at least 4-6 anodes balanced configurations for the low frequency multiplication stages [3].

II. Description of the Simulation Tool

The simulation environment couples a Schottky diode physical model with a circuit simulator using appropriate harmonic-balance techniques (see Fig. 1). This allows the concurrent design of circuits taking into account both the device structure (doping and length of the epitaxial layer, and area of the device) and the embedding circuit (bias, available power, and loads at different harmonics).

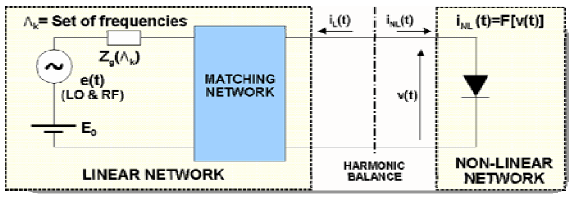

Fig. 34 General scheme of the numerical Harmonic Balance simulator for the design and optimization of Schottky- diode-based circuits at millimeter and submillimeter-wave bands.

The Schottky diode model consists of a physics-based drift-diffusion numerical device simulator [4], which incorporates accurate boundary and interface conditions for self-consistent treatment of tunnelling transport, image-force effects, impact ionization, and non-constant recombination velocity. This physics-based simulator accounts for limiting mechanisms such as avalanche breakdown, velocity saturation, and increase in the series resistance with the input power [4].

This CAD tool has already been validated in previous works [2,4-5], and very good agreements between simulation results and measurements have been obtained not only for GaAs Schottky multipliers [2], but also for GaAs Schottky mixers [5].

III. Electrical Properties of GaN vs. GaAs

In order to evaluate the potential capabilities of GaN Schottky diodes for millimeter and submillimeter-wave applications, a comparative study for GaN and GaAs Schottky diodes has been carried out from DD simulation results in DC at room temperature. The characteristics of the Schottky diode taken as a reference for this study are: An ideal barrier height of 0.99 V for GaAs and 1.2 V for GaN, an anode area of 36 μm², an epilayer thickness of 350 nm, an epilayer doping in the range 0.3 to $5{\cdot}10^{17}$ cm^{-3}, and a substrate doping (n^{++} layer) of $2{\cdot}10^{18}$ cm^{-3}.

The major disadvantage of GaN in comparison to GaAs lies in its lower electron mobility. As can be appreciated in Fig. 2, for typical epilayer doping employed for GaAs Schottky multipliers (N_D = 1 to $5{\cdot}10^{17}$ cm^{-3}), GaAs mobility is in the order of 6-8 times higher than GaN mobility. This has a high impact on the series resistance of GaN Schottky diodes since it is inversely proportional to the mobility. It can be derived from Fig. 2 that GaN resistivity will experience a higher increase with the doping than GaAs resistivity due to the faster decrease of GaN mobility with the doping level. Note that GaN resistivity is 6 times higher than GaAs resistivity for a $1{\cdot}10^{17}$ cm^{-3} doping level, and 11 times higher when the doping is increased up to $2{\cdot}10^{18}$ cm^{-3}. Hence, once the doping levels of the Schottky diode are fixed, worse relative performances for GaN diodes with respect to GaAs diodes will be obtained for high dopings.

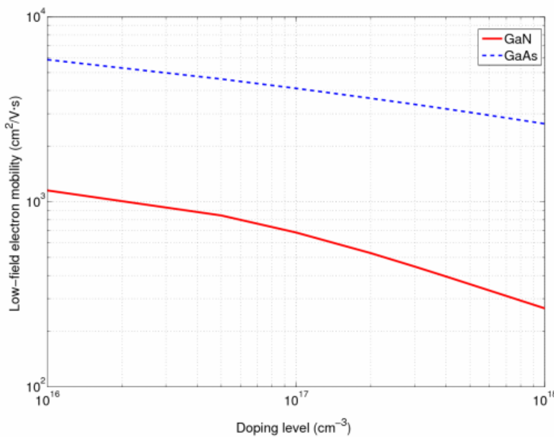

Fig. 35 Low-field electron mobility for GaAs and GaN as a function of the epilayer doping.

The higher series resistance of GaN does not necessary imply a proportional degradation of the conversion efficiency in GaN multipliers in comparison to GaAs multipliers. It is shown in Fig. 3 that the zero junction capacitance (C_{j0}) corresponding to the GaN diode is around a factor of 1.3 lower than the one for the GaAs diode. It can be demonstrated that the effective voltage in the junction nonlinear capacitance (responsible for the frequency multiplication in the varactor mode of operation of the Schottky diode) is inversely proportional to the junction capacitance. Higher multiplication efficiencies are obtained when this effective voltage is maximized as a result of the higher modulation of the nonlinear capacitance. It is obvious that a high series resistance will negatively affect the capacitance sweep. However, the already discussed inconvenience of the increase in the series resistance of GaN can be somewhat compensated by its lower capacitance, as can be seen in Eq. 1. Thus, the joint effect of the series resistance and the capacitance might not result in dramatically lower efficiencies in GaN Schottky multipliers.

$$V_C = -j \cdot \sqrt{\frac{2P_{av}}{R_S}} \cdot \frac{1}{\omega \cdot C_J} \tag{1}$$

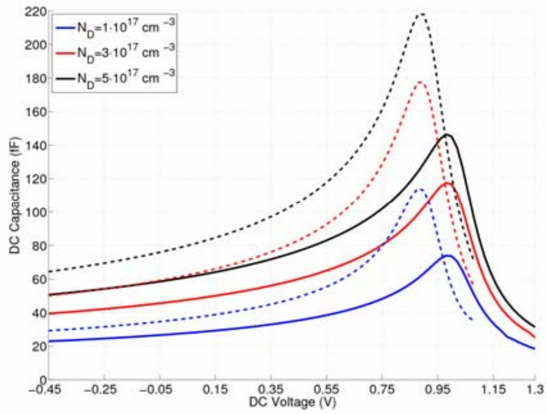

Fig. 36 DC capacitance curves for GaAs (dashed lines) and GaN (solid lines) as a function of the epilayer doping.

However, the real advantage of GaN Schottky diodes comes from its higher critical electric field. This leads to much higher breakdown voltages in GaN diodes than in GaAs diodes, and therefore, to much better power handling capabilities in GaN. Figs. 4 and 5 show the comparison of the breakdown voltages for both materials as a function of the doping level and thickness of the epitaxial layer.

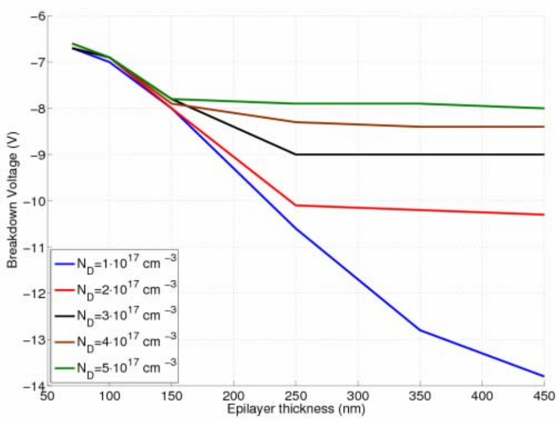

Fig. 37 DC breakdown voltage as a function of the epilayer length and doping for GaAs Schottky diodes.

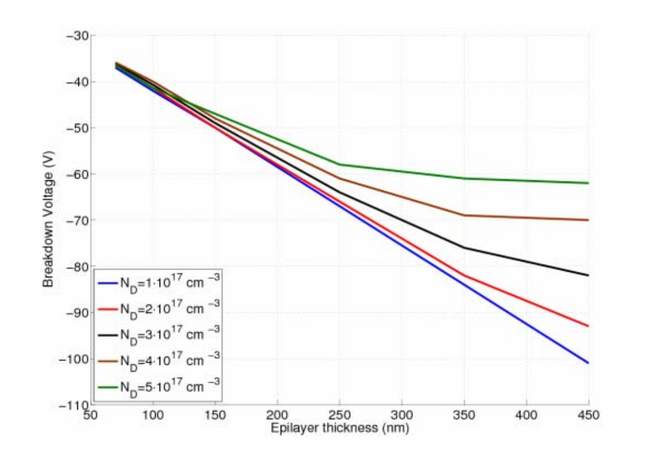

Fig. 38 DC breakdown voltage as a function of the epilayer length and doping for GaN Schottky diodes.

IV. Optimization of a 200 GHz GaN Schottky Doubler

In order to establish a performance comparison between both GaN and GaAs Schottky multipliers, the design of a 200 GHz Schottky doubler is presented in this section, assuming a nominal input power of 150 mW at 100 GHz and a unique anode. This value for the input power is typically considered in practice for the first stages of LO sources at THz frequencies [3].

The optimization of the 200 GHz GaN Schottky doubler was performed by means of our physics-based in-house CAD tool. The results are presented in Figs. 6 and 7. It can be seen that the optimum doping level for the epilayer is 3-5·10^{16} cm^{-3}. For higher dopings, the important decrease of the mobility leads to lower conversion efficiencies.

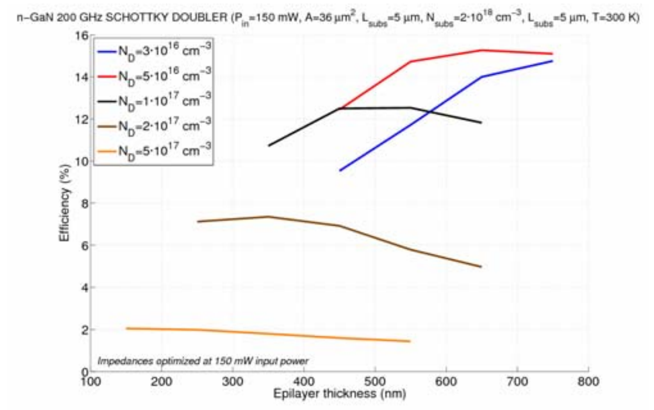

Fig. 39 Simulated performance of a 200 GHz GaN Schottky doubler as a function of the epilayer thickness and the doping level (anode area is 36 μm^2).

Regarding the epitaxial layer, thicknesses between 500-800 nm are necessary for the selected doping levels in order to support the 150 mW input power, as shown in Fig. 6. Reverse bias voltages between -15 and -20 V are also necessary to maximize the voltage swing in the capacitance, and thereby, the efficiency. It can be derived from Fig. 5 that the breakdown voltage will be below -100 V. Hence, the doubler will operate in safe conditions, with no risk of reaching the breakdown regime.

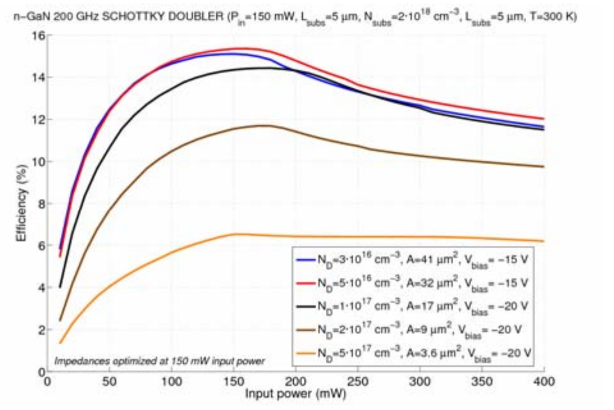

Fig. 40 Simulated performance of a 200 GHz GaN Schottky doubler as a function of the input power and the epilayer doping level. Bias and anode areas have been optimized for a 150 mW input power.

The last step of the optimization process consists in selecting the adequate value for the anode area so that the maximum efficiency is achieved at the available input power. For a 5·10^{16} cm^{-3} doping level in the epilayer, a 15 % peak efficiency is achieved for a 150 mW input power when a 32 μm^2 anode area is selected (see Fig. 7).

It is important to address that for all the simulations in this section, a mobility-field characteristic according to the representative fit in Fig. 8 has been considered for GaN. This fit was proposed by F. Schwierz in 2005, and is based on a large amount of experimental data on low-field electron mobilities for GaN [1].

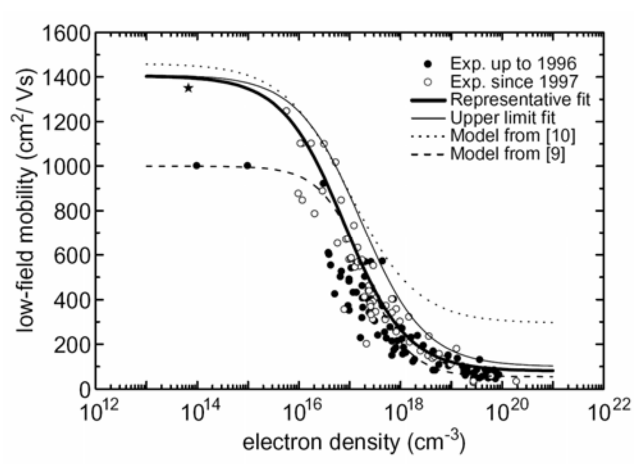

Fig. 41 Measured low-field mobility for wurtzite n-GaN as a function of doping density (reprinted from [1]).

V. GaN vs. GaAs Schottky Multipliers

Fig. 9 shows a comparison between the 200 GHz GaN Schottky doubler optimized in the previous section (featuring a single anode), and a 200 GHz GaAs Schottky doubler with similar anode areas to that considered for the GaN doubler. For the GaAs doubler, 8 anodes are necessary for a 150 mW available input power as a consequence of the lower power handling capabilities of GaAs diodes with respect to GaN diodes.

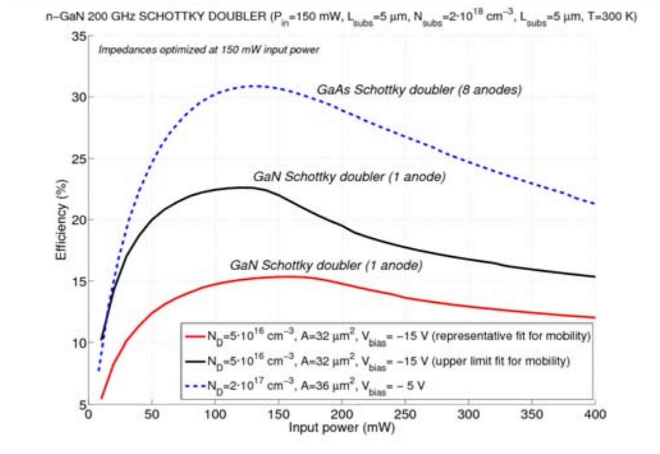

Fig. 9 Performance comparison between a 200 GHz GaAs Schottky doubler (featuring 8 anodes with a 350 nm epilayer) and a 200 GHz GaN Schottky doubler (featuring 1 anode with a 650 nm epilayer).

On the one hand, if the representative fit for the low-field mobility is considered (see Fig. 8), the conversion efficiency of the GaN Schottky doubler is approximately half the obtained with the GaAs doubler. On the other hand, if the upper limit fit in Fig. 8 is used, which is based in the most recent results regarding measured low-field GaN mobilities, a 23 % efficiency is predicted, which is just a 25 % lower than that obtained with the GaAs Schottky doubler. However, the most remarkable result comes from the fact that only one diode has been considered for the GaN doubler.

Typical balanced configurations employed in low frequency multiplication stages (around 200 GHz) include up to 6-8 diodes pumped with around 150-200 mW at 100 GHz. The effective input power per anode yields around 25-30 mW, which is an adequate value for GaAs Schottky diodes in order not to require excessively high anode areas and to prevent the diode from entering the breakdown regime. Balanced configurations are therefore necessary in order to reduce the input power per diode. But great advances are being made in solid-state sources so the available input power at frequencies around 100 GHz is rapidly increasing. This will result in a need for employing more GaAs Schottky diodes in the first multiplication stages or in an increase of the anode areas in order to raise the power handling capabilities of the GaAs diodes. In both cases, it will represent an increase in the length of the chips containing the Schottky diodes. However, the maximum length is limited by the dimensions of the transmission wave-guide, fixing an upper limit to the maximum diode dimensions or number of supported diodes. In addition, the higher the number of diodes, the more difficult it is to achieve a good and equitable power coupling among all the diodes, as there is a major risk for the presence of asymmetries in the circuit due to the fabrication process. This can be catastrophic for the resultant performance. GaN Schottky multipliers might solve part of these problems in the near future when the available input power at frequencies around 100 GHz is high enough to guarantee good output power levels in spite of the lower efficiencies of GaN multipliers. Moreover, the possibility of employing single-diode or 2-diode configurations, with the subsequent reduction in the technological complexity of the circuitry, may represent an extra motivation that encourages the use of GaN Schottky multipliers.

CONCLUSIONS

The potential capabilities of GaN Schottky diodes, according to the results presented in this work, are not in the frame of high frequency multipliers (well within the submillimeter-wave region), but in the first stages of high-frequency multiplier chains where the excellent power handling capabilities of GaN can be exploited, i.e. in the upper part of the millimeter-wave region (100-300 GHz).

The simulation results presented in this work showed that excellent power handling capabilities can be achieved with GaN Schottky diodes at these. Moreover, GaN multipliers can provide good efficiencies (just a 25 % lower than those obtained with GaAs multipliers) at 200 GHz. The efficiency of GaN multipliers might be even closer to that obtained with GaAs multipliers if GaN mobility were slightly improved, which can be possible as new advances on fabrication technologies are constantly going on.

ACKNOWLEDGMENT

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