Harmonic Generation and Noise in GaAs and GaN Schottky Diodes

Diego Pardo[1*], Jesús Grajal[2], Beatriz Mencía[3], Susana Pérez[4], Javier Mateos[5] and Tomás González[6]
[1, 2, 3] *Universidad Politécnica de Madrid, Dept. Señales, Sistemas y Radiocomunicaciones, Madrid, Spain*
[4, 5, 6] *Universidad de Salamanca, Dept. Física Aplicada, Salamanca, Spain*
*Contact: dpardo@gmr.ssr.upm.es, phone +34 91-336- 73-58

*Abstract***— A semiconductor simulation tool based on Monte Carlo techniques has been used to analyse the performance of frequency multipliers in the millimetre-wave frequency range. Both power generation and noise properties have been compared for GaAs and GaN-based doublers. GaN could be an interesting option for frequency multiplication: efficiencies around 15 % can be reached for state-of-the-art carrier mobilities and noise performance is better than in GaAs-based doublers.**

I. Introduction

Development of terahertz technologies is being conditioned by the small number of compact, powerful and tunable THz sources working at room temperature. GaAs Schottky multiplier chains have been widely used for LO power generation at millimeter wave band. However, to obtain the power levels required for applications in the terahertz region, several GaAs Schottky barrier diodes (SBDs) must work in a balanced configuration in the first multiplication stages, to prevent a single diode from entering into a breakdown regime. The set of SBDs that can be integrated in a microstrip line suspended within a transmission wave-guide supposes a limit in the available power in multiplication stages at higher frequencies.

In recent years GaN has become a promising material for high power, high temperature and high frequency applications, mainly due to its wide direct band gap, which results in a high breakdown field, and its high peak and saturated electron drift velocity. The main inconvenient of GaN in comparison to GaAs is its lower electron mobility.

The objective of this paper is to compare noise properties and harmonic generation of GaAs and GaN SBDs for multipliers by means of Monte Carlo (MC) simulations. This method is fundamental in high frequency and high power regimes of non-linear devices, where predictions of other simulation techniques differ from experimental results. As a reference to this study, a 200 GHz doubler is considered. In section II, we described the structure of the simulated diode and the main features of our MC simulator. Section III is devoted to the analysis of the electrical characteristics and the intrinsic noise sources in static conditions. In section IV, we analyse the RF and noise performance of a 200 GHz doubler based on GaAs and GaN diodes. Section V summarizes the main conclusions and future trends of our work.

II. Device Structure and Monte Carlo Simulator

The simulated Schottky diode selected has an epilayer length of 350 nm with a doping concentration of $1\text{x}10^{17}$ cm^{-3}. The length of the substrate is 500 nm, with a doping concentration $2\text{x}10^{18}$ cm^{-3}. The length of the substrate has been shorter as compared to the typical values of fabricated devices in order to reduce the computational cost of the Monte Carlo method. The anode area is 36 μm^2. The ideal barrier height is 0.99 V for GaAs and 1.20 V for GaN diodes, respectively. The performance of the diodes has been evaluated at 300 K.

Calculations are performed by using an ensemble MC simulator three dimensional in momentum space, which is self-consistently coupled with a one dimensional Poisson solver. The effect of degeneracy is accounted for by locally using the classical rejection technique, where the electron heating and nonequilibrium screening effects are introduced by means of the local electron temperature. The ohmic contact is modelled as a surface that injects carriers in thermal equilibrium with the lattice (in order to maintain the neutrality in the region very close to the contact), according to Fermi- Dirac statistics; in addition any carrier reaching the contact leaves the device. On the other hand, Schottky contact is simulated as a perfect absorbent surface. Scattering mechanism included in the Monte Carlo simulation are ionized impurities, acoustic phonons, polar and non-polar optic phonons and intervalley mechanism, for both semiconductors materials. The band structure is modelled as a conduction band with three spherical non-parabolic valleys. The charge density is updated every 0.5 *fs* and devices are divided into equal cells of 20Å long. The number of simulated carriers is around 10^5.

Noise study is carried out from the analysis of the noise spectra of current fluctuation calculated from the Correlation Function (CF) and Fast Fourier Transform method (FFT) as reported in [1].

III. Static Characterization

In this section we analyse the diode configuration presented previously under forward bias conditions. Firstly, current-voltage (I-V) and capacitance-voltage (C-V) characteristics are presented. Secondly, we study the intrinsic noise behaviour.

A. I-V and C-V relations

Fig. 1 shows GaAs and GaN I-V curves. Two main regions are observed in these curves. Accordingly to the thermionic emission theory, a non-linear conductance region is found for voltages lower than the built-in potential, (V_{bi}, around 0.95 V for GaAs and 1.11 V for GaN diodes); and a purely resistive region for higher bias voltages.

By comparing GaAs and GaN curves, we conclude that the I-V non-linearity is similar for both semiconductor diodes. In fact, an approximation of these curves to the exponential rule $I(t) \sim \exp(\alpha V)$ gives $\alpha \sim 27$, (ideality factor $n \sim 1.4$) for GaAs and $\alpha \sim 23$ ($n \sim 1.7$) for GaN diodes.

References [2] and [3] present simulations and measurements of electron transport for these semiconductors, showing higher mobility values for GaAs than GaN.

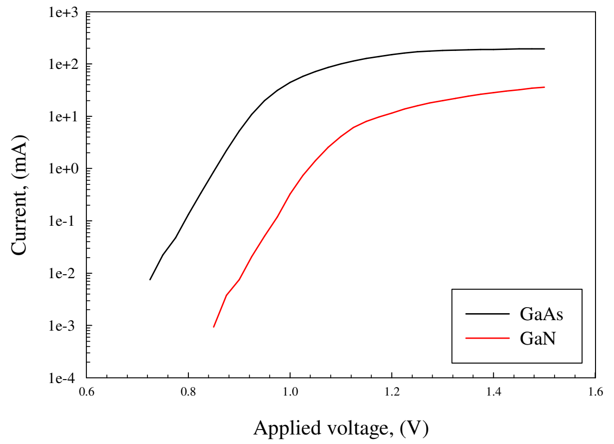

Fig. 1 Current-voltage curves for GaAs and GaN Schottky diodes, calculated with MC method

Fig. 2 shows capacitance-voltage curves, obtained as variations in the average number of carriers inside the diode with the applied voltage.

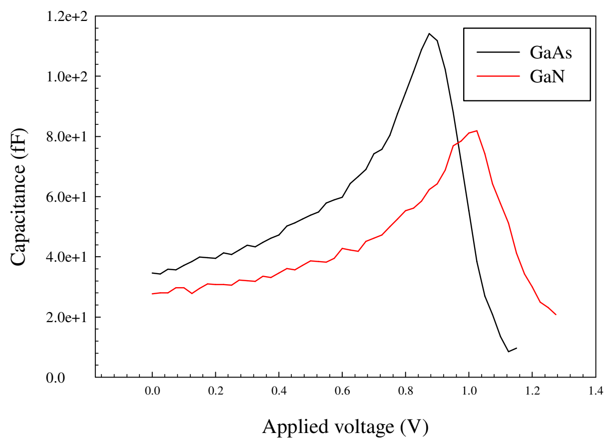

Fig. 2 Capacitance-voltage relation for GaAs and GaN Schottky diodes, obtained from MC method

For $V<V_{bi}$, C-V curves follow the known law $C/C_g = 1/(1-V/V_{bi})^{1/2}$, where $C_g = \varepsilon A/L$ is the SBD geometric capacitance. Differences between GaAs and GaN SBDs capacitance are originated by differences in relative permittivity $(\varepsilon_r(GaAs)/\varepsilon_r(GaN) \sim 1.45)$.

B. Noise under forward bias conditions

Spectral density of current fluctuations for GaAs and GaN diodes is shown in fig. 3 and fig. 4 respectively, under forward bias.

Three main features are observed in the spectral density of these Schottky diodes: a low frequency plateau and two high frequency peaks.

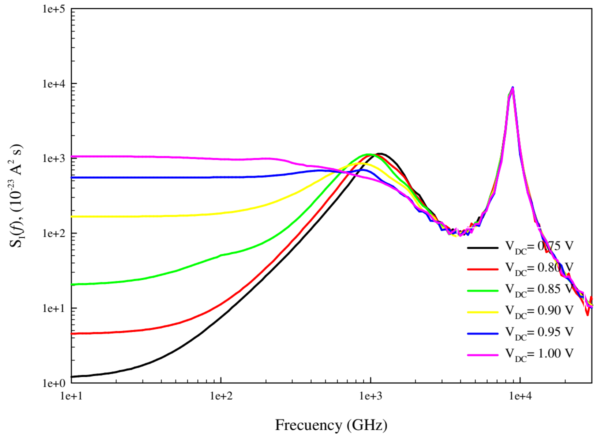

Fig. 3 Spectral density for current fluctuations in GaAs Schottky diode

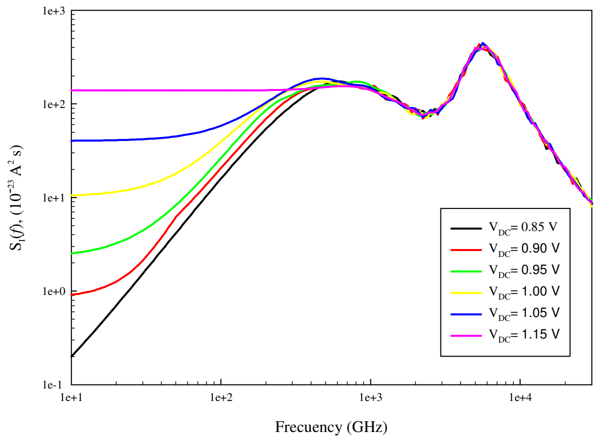

Fig. 4 Spectral density for current fluctuations in GaN Schottky diode

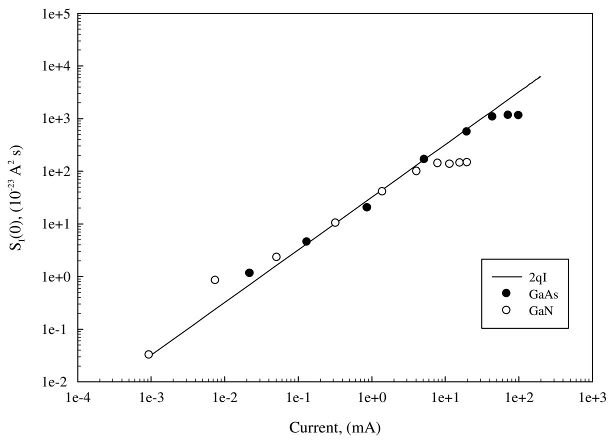

Fig. 5 Low frequency spectral density for GaAs and GaN diodes, as a function of current

The low frequency plateau observed under barrier-limited transport is in good agreement with the shot-noise law $S_I(0)=2qI$, as is shown in fig. 5. This noise component is due to carriers crossing randomly the Schottky barrier. With the increase of DC bias over flat-band regime, shot noise is replaced by thermal noise, [1].

The first high-frequency peak is related to returning carriers, i.e. carriers that approximate the Schottky barrier with insufficient kinetic energy to surmount it, and come back to neutral region of the semiconductor. According to the analytic theory presented in [4], the noise of these carriers is zero at zero frequency, rising as f^2, reaches a maximum, and then disappears. This peak displaces slightly to lower frequencies as DC bias increases. Although the low frequency plateau due to shot noise takes lower values for GaN than GaAs diodes, this peak is located at about 0.6 THz for GaN and about 1 THz for GaAs, resulting in an excess noise influence over the level of the plateau for GaN diodes in the sub- THz region, under barrier transport.

The frequency associated to these carriers is defined by the inverse of the characteristic time of a carrier entering into the space-charge region and returning to the neutral region. So, a reduction in the depletion region by, for example, an increase in the doping of the epilayer translates this peak to higher frequencies.

The second high-frequency peak observed in the spectral density is caused by fluctuations in the carrier's velocity for the in-homogeneity of the n-n$^+$ (epilayer-substrate) homojunction, which lead to electric field fluctuations via Poisson equation. The frequency of this peak is found between the plasma frequencies of the epilayer and the substrate, [5]. So, it is placed about 8.8 THz and 5.7 THz for the GaAs and GaN diodes respectively. From fig. 6, when the doping of the substrate is the same of the epilayer, so the n-n$^+$ in-homogeneity does not exist, the plasma peak disappears. Since plasma peak is independent of DC bias, results of fig. 6 have been obtained for V_{DC}= 0.75 for GaAs and V_{DC}= 0.90 V for GaN.

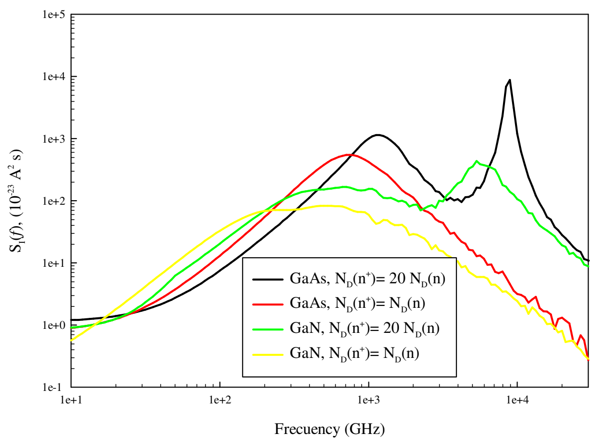

Fig. 6 Spectral density for GaAs and GaN diodes, with and without n-n$^+$ in-homogeneity

IV. 200 GHz Doubler

Frequency doubler operation based on GaAs and GaN diodes is analysed in this section.

A. Harmonic generation

To generate harmonics, GaAs and GaN diodes are excited with a sinusoidal voltage $V(t)= V_0+V_1 \sin(2\pi f t)$, of frequency f= 100 GHz. The breakdown voltage for the GaAs diode is V_{bd} ~ 12.5 V, [6]. In order to prevent a single diode from entering into the breakdown regime, the bias point for the GaAs diode is V_0= -5 V. The amplitude V_1 is 6 V, to avoid the conduction regime at the maximum voltage swing. The time domain response I(t) obtained from the simulation can be transformed into the frequency domain by means of Fourier Transform, and the impedance of the GaAs diode at the fundamental frequency evaluated: $Z(f_0)$= (6.38- 91.43j) Ω. This correspond to an input power of $P(f_0)$= 13.7 mW. To evaluate the efficiency of the 200 GHz GaAs doubler we need to known the impedance at the second harmonic imposed by the external circuit, and this value it is not obtained directly for our calculations. By this end, harmonic balance simulations are used and a result for the impedance of the second harmonic for optimum harmonic extraction is obtained: $Z(2f_0)$= (11.4+44j) Ω. So, the power deliverd at the second harmonic is $P(2f_0)$= 3.7 mW. The efficiency of the doubler is evaluated as $\eta= P(2f_0) / P(f_0)$= 27%, similar to the efficiency presented by [6].

For GaN diode, the breakdown voltage is over 82 V, [6]. This is one of the advantages of GaN versus GaAs diodes, because now the biasing of a single GaN diode can be V_0= -15 V. At 100 GHz enough power is available and the amplitude of the sinusoidal excitation is chosen at V_1= 16.2 V, to maximize the non linear capacitance swing. The impedance of the GaN diode at the fundamental frequency and the power available are $Z(f_0)$= (6- 167j) Ω and $P(f_0)$= 28.3 mW, respectively. Also to calculate the impedance for the second harmonic the harmonic balance simulations are used, given a value of $Z(2f_0)$= (8.49+78.05j) Ω. Finally the calculated conversion efficiency of a single GaN doubler is η= 2.3 mW/28.3 mW= 8.1%.

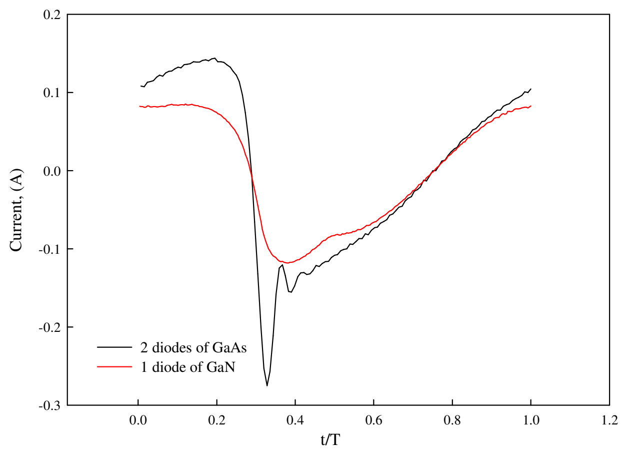

Fig. 7 Time dependence of the current response for the 100 GHz periodic excitation, for two GaAs diodes in parallel configuration and a single GaN diode

These values of conversion efficiencies for both diodes are in good agreement with the results presented in [6] using a drift-diffusion model coupled to a harmonic balance simulator. Optimized structures for the GaN-based doubler with state-of-the-art experimental mobility characteristics suggest that efficiencies above 15% can be reached for 200GHz doublers.

Two GaAs diodes are required to support an input power of 28 mW (power delivered to the GaN doubler based on one diode). To simplify the following analysis, we suppose that the two GaAs diodes are arranged in a parallel configuration. Fig. 7 and fig. 8 show current response and harmonic amplitude for two GaAs diodes in parallel configuration and a single GaN diode. Thanks to the high breakdown potential of GaN, high power excitations can be applied to a single diode, resulting in amplitudes for the second (m=2) and third (m=3) harmonics of the current of the same order of magnitude as the two GaAs diode configuration.

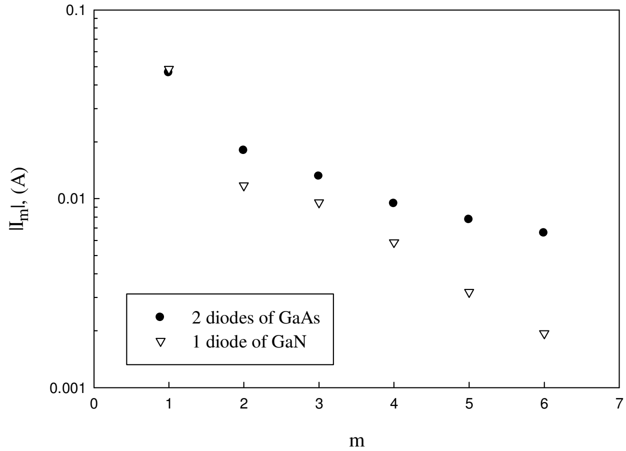

Fig. 8 Harmonics amplitude of the current for two GaAs diodes in parallel configuration and a single GaN diode, at frequency f= 100 GHz. M represents the order of the harmonic.

B. Intrinsic noise for the 200 GHz doubler

Fig. 9 shows the main features of spectral density of current fluctuations for the two GaAs diodes in parallel configuration and the single GaN diode, under periodic large-signal operation. Additionally to the noise spectrum, the fundamental and second harmonics are also included. It is important to take into account that the two peaks represent the power of the fundamental and second harmonic, measured in dBW, while the noise level represents power per Hertz, so to obtain the noise power delivered to an impedance, it must be integrated in a given frequency range. According to power values presented in previous subsection, the relative power of two GaAs diodes in parallel configuration respect to a single GaN diode, delivered to the second harmonic is 5.1 dB.

The noise spectral density for the two GaAs diodes configuration has been obtained as two times the noise spectrum of a single GaAs diode, supposing incorrelation between both GaAs diodes.

Noise properties for the GaN-based doubler are better than for the GaAs-based doubler. Only near GaN plasma peak, about 4 THz, GaN spectral density is higher than GaAs.

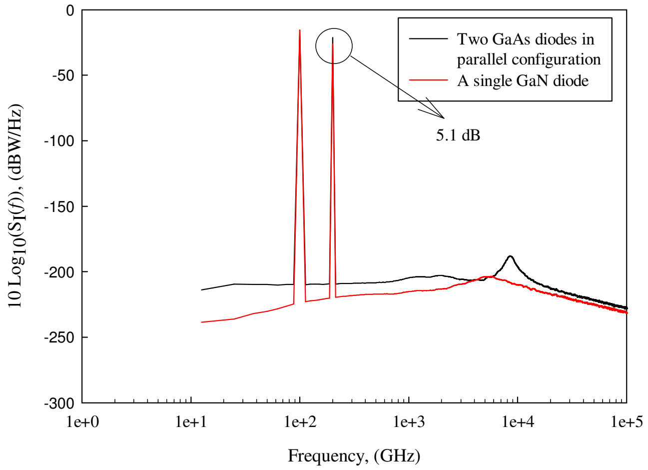

Fig. 9 FFT of fluctuations in current history obtained from MC method, together power for the fundamental and second harmonics

V. Conclusions

We have presented an analysis on noise features and harmonic generation for GaAs and GaN multipliers based on Monte Carlo method. This study presents electric considerations, which can be obtained with other semiconductor simulation models like drift-diffusion, but in addition Monte Carlo simulation let us analyse also the noise properties of devices and circuits.

Noise performance obtained from Monte Carlo method indicates that GaN presents lower levels of noise than GaAs in all frequency spectrum. In future works, analysis of noise in mixers, and the optimisation of the Schottky device structure for noise reduction will be performed.

Acknowledgment

This work was supported by the Junta de Castilla y Leon, Spanish National Research and Development Program under projects GR270, SA019A08, TEC2007-61259/MIC, TEC2008-02148, TeraSense (Consolider- Ingenio 2010, CDS2008-00068), RooTHz (Eurpean Comission- ICT-2009-243845).

References

[1] S. Pérez , T. González , P. Shiktorov, E. Starikov, V. Gruˇzinskis, L. Reggiani, L. Varani and J. C. Vaissière, “Noise in Schottky-barrier diodes: from static to large-signal operation,” in *Proc. of the SPIE*, 2004, vol. 5470, pp. 322-36.

[2] B. E. Foutz ,S. K. O’Leary, M. S. Shur and L. F. Eastman, “Transient electron transport in wurtzite GaN, InN and AlN,” *J. Appl. Phys.* vol. 85, no. 11, pp. 7727-7734, 1999.

[3] F. Schwierz, “An electron mobility model for wurtzite GaN,” *Solid-State Electronics*, vol. 48, no. 6, pp. 889-895, June 2005.

[4] M. Trippe, G. Bosman and A. Van Der Ziel, “Transit-time effects in the noise of Schottky-barrier diodes,” *IEEE Trans. Microwave Theory Tech*, vol. 34, no. 11, pp. 1183- 1192, 1986.

[5] E. Starikov, P. Shiktorov, V. Gruˇzinskis, L. Varani, J. C. Vaissière, J. P. Nougier and L. Reggiani, “Monte Carlo calculation of noise and small-signal impedance spectra in submicrometer GaAs n^+nn^+ diodes,” *J. Appl. Phys.* vol. 79, no. 1, pp.242-252, Jan. 1996.

[6] J. V. Siles and J. Grajal, “Capabilities of GaN Schottky multiplier for LO power generation at millimeter-wave bands,” in Proc. *ISSTT*, 2008, pp.504-507.