Correlation between low-frequency current-noise enhancement and high-frequency oscillations in GaN-based planar nanodiodes: A Monte Carlo study

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We present a spectral analysis of time sequences of current, calculated by means of Monte Carlo simulations, in GaN-based asymmetric nanodiodes, devices that are potential candidates to exhibit Gunn oscillations. It is found that the low-frequency noise increases significantly for biases close to the threshold voltage of Gunn oscillations, taking place at much higher frequencies of hundreds of gigahertz. Due to the inherent difficulty in detecting so fast fluctuations, the measurement of the low-frequency noise can be a quite useful tool for predicting current oscillations at sub-terahertz frequencies in these devices. © *2011 American Institute of Physics*. [doi:10.1063/1.3613956]

Gunn-phenomena based devices have been investigated as a source of microwave and millimetre wave radiation since almost 50 yr. Most of the research works have been directed to improve power, oscillation frequency, and heat dissipation of Gunn diodes, which in the last years reveal GaN as a promising material in this field. The search for materials with high electrical strength to allow high power generation points to GaN as compared to GaAs because of its higher energy gap. The second point is the high frequency issue in which the higher peak and saturation velocity, and lower energy relaxation time of GaN provide also better performances.[1] Finally, heat dissipation has been realized to be a big problem for fabricating GaN Gunn oscillators. Planar topologies as those proposed in Ref. 2, allowing for more efficient heat dissipation, are a promising alternative to the so far unsuccessfully explored vertical GaN structures.[3] The approach we follow in this work for the case of GaN is the use of parallel arrays of planar asymmetric nanodiodes. The device, so-called self-switching diode (SSD), proposed by Song *et al.*[4] in 2003 was intended for logic circuit design. Soon after, InGaAs SSDs demonstrated detection capability up to 110 GHz at room temperature[5] and up to 2.5 THz at 10 K.[6] Monte Carlo (MC) simulations have been used to study the SSD static, dynamic, and noise properties (see Refs. 7 and 8 and references therein). Recently, the functionality of this seemingly simple device has reached one more step: the ability of power generation based on Gunn oscillations.[9] Our research goes towards a compact, cheap, room temperature source above 1 THz using GaN-based SSDs. Experimental results of Gunn oscillations in these devices have not been reported yet but numerical MC simulations predict their presence at very high frequency.[10]

It is still quite tricky to carry out experimental measurements at hundreds of gigahertz. For that reason, alternative methods of analysis become crucial into the field of terahertz (THz) or sub-THz electronic devices, in particular, to detect the presence of oscillations in this frequency range. A first possible indicator is related to the kinks that sometimes appear in the *I-V* curves for applied voltages at which the onset of instabilities take place, indicating the transition from a passive- to a generation-state. In the case of the MC simulations of GaN-based SSDs, below presented in detail, no kink is exhibited by the *I-V* curve even though clear Gunn oscillations in the current sequences together with negative values of the small-signal admittance within several frequency bands are observed. Another prediction method already suggested by Starikov *et al.*[11] consists in the use of the low-frequency noise in the current $S_I(0)$ as indicator of the onset of oscillations, since it exhibits a significant enhancement for voltages approaching the threshold for their appearance.

The aim of this work is to check, by means of MC simulations, if this behavior takes place in the GaN SSDs under study, since they are promising devices for room temperature THz emission by exploiting Gunn effect. Thus, we analyze the possibility of indirectly detecting the presence of current oscillations by the enhancement of low-frequency noise.

The onset of current oscillations in GaN-based SSDs has been analyzed by means of an ensemble MC simulator self-consistently coupled with a 2D Poisson solver. The conduction band of GaN is modelled by three non-parabolic spherical valleys (Γ_1, U, and Γ_3), and the considered scattering mechanisms are acoustic, optical, and intervalley phonons, ionized impurities, and piezoelectric scattering. Since the simulation tool (code developed by our group) is a 2D solver, just "top-view" simulations of the channel have been performed.[12] In order to account for the 3D real topology, we include the fixed charges of the whole layer structure as a "virtual" net doping N_{Db} to the channel, considered when solving Poisson equation but ignored as a source of scattering. We also include a negative surface charge density σ at the semiconductor-air interfaces. More information about the simulation model can be found in Ref. 12.

To perform a frequency analysis of electrical fluctuations and to detect the presence of current oscillations, the time-domain current sequences obtained from the MC simulations are Fourier transformed (once subtracted the average dc value) into the frequency domain to determine the current noise spectral density $S_I(f)$. The current-noise calculated at

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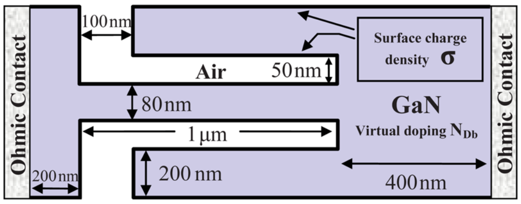

FIG. 1. (Color online) Scheme of the top-view simulations of the channel with the involved parameters, N_{Db} and σ, and the considered dimensions of the diode.

zero frequency $S_I(0)$, corresponding to the noise measured in experiments in the plateau beyond 1/f and g-r noise, will be used as the indicator for the occurrence of oscillations. Both noise and current values reported in the results have been normalized in such a way that just multiplying them by the value of the sheet electron density in the channel of a real device S_I and I are obtained in units of A^2s and A, respectively.

The typical top-view geometry of the SSD channel is shown in Fig. 1, where the dimensions used in our simulations are indicated. Two favorable conditions for the onset of Gunn oscillations take place in this structure: (1) the electric field is well focused at the cathode side of the channel because of the presence of the vertical trenches and (2) the electron concentration is increased by the side field effect when biasing the anode with a positive voltage.

In the following, we present the results for three SSDs with the same value of the virtual doping, $N_{Db} = 2 \times 10^{17}$ cm^{-3}, and different values of the surface charge density, since this parameter is decisive for achieving current oscillations that present harmonics from 100 GHz up to 1 THz. A large value of σ contributes to deplete the channel and higher voltages are necessary for obtaining oscillations. In the first diode, we have set $\sigma/q = -0.25 \times 10^{12}$ cm^{-2}, in the second one $\sigma/q = -1.0 \times 10^{12}$ cm^{-2}, and $\sigma/q = -1.5 \times 10^{12}$ cm^{-2} in the last one.

Figure 2 shows the low-frequency current noise as a function of the applied voltage for the first diode, the one with the lower value considered for the surface charge density, i.e., $\sigma/q = -0.25 \times 10^{12}$ cm^{-2}. Current sequences and noise spectra are also plotted as insets in order to get more information about what happens in the diode for several voltages at which $S_I(0)$ exhibits significant variations. We note that at such voltages, there are no kinks in the I-V curve, shown in Fig. 3(a). As can be observed, the threshold for the onset of Gunn oscillations is about 36 V. Below this voltage, starting from the Nyquist value at equilibrium, the noise exhibits a slight increase with the bias due to electron heating. For voltages higher than 36 V, a remarkable enhancement of the low-frequency noise is detected, in parallel to the transition from a passive- to a generation-state as evidenced by the current sequence and its corresponding spectral density at 45 V. Once the oscillations are well established (voltages above 45 V), $S_I(0)$ decreases and then, at around 53 V, it increases again because of the onset of further frequency components, as observed for 60 V. For higher voltages, we find once more the previously explained behavior, i.e., a drop in the noise up to 75 V due to the presence of clear oscillations followed by another rise according to the incorporation of more harmonics, as occurs at 100 V.

In order to confirm that the enhancement of the low-frequency noise is certainly due to the onset of current oscillations and further spectral components, simulation results for the two other SSDs are presented in Fig. 3. The sole variation with respect to SSD1 made in these diodes, called SSD2 and SSD3, is considering $\sigma/q = -1.0 \times 10^{12}$ cm^{-2} and $\sigma/q = -1.5 \times 10^{12}$ cm^{-2}, respectively. A higher value of σ leads to a stronger channel depletion that makes necessary higher voltages to achieve, first, current conduction through the diode, and then Gunn oscillations, as shown in Fig. 3(a). In SSD2, oscillations are more difficult to be obtained than in SSD1, being necessary the application of a voltage around 80 V, while for SSD3, the effective width of the channel is not enough to achieve current oscillations even at 100 V. In fact, the current level is much lower than in the other diodes.

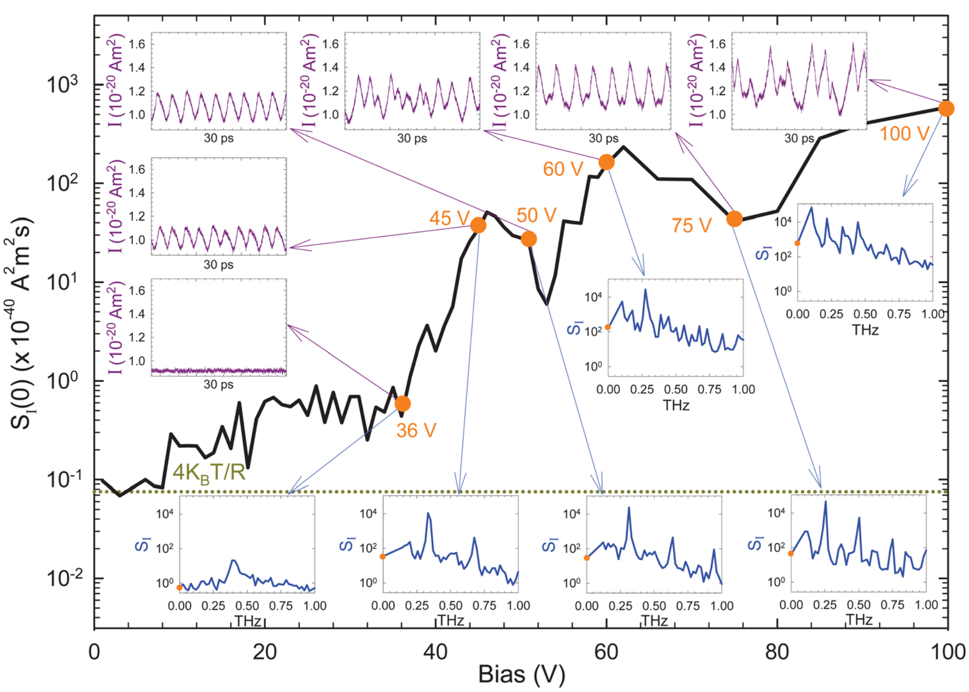

FIG. 2. (Color online) Low-frequency value of the current spectral density as a function of the bias for SSD1, where $\sigma/q = -0.25 \times 10^{12}$ cm^{-2}. The insets show current sequences and spectral density as a function of frequency for several significant applied voltages.

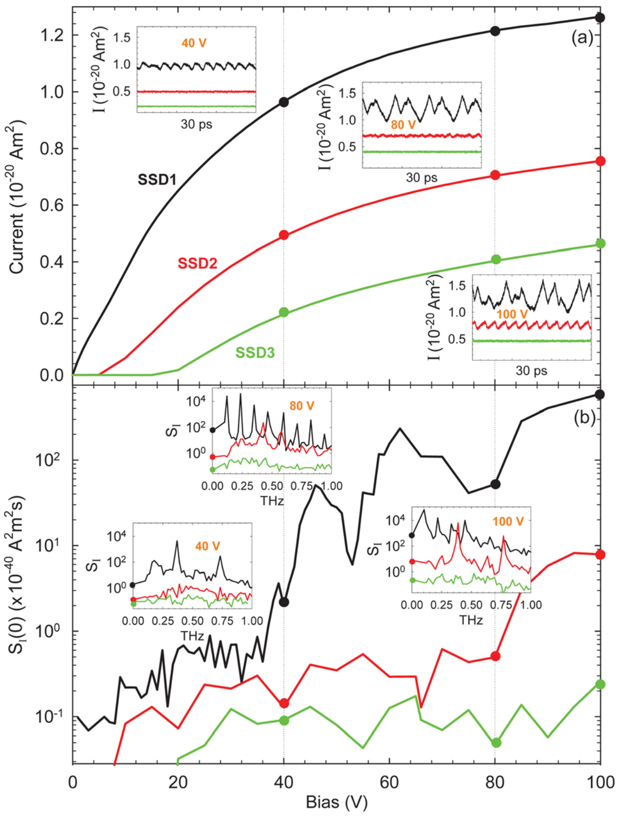

FIG. 3. (Color online) (a) *I-V* curves and (b) low-frequency value of the current spectral density for SSD1 (same as in Fig. 2), that has $\sigma/q=-0.25\times10^{12}$ cm^{-2}, and two more diodes, SSD2 and SSD3, with $\sigma/q=-1.0\times10^{12}$ cm^{-2} and $\sigma/q=-1.5\times10^{12}$ cm^{-2}, respectively. The insets in (a) show current sequences for some applied voltages and in (b) the corresponding noise spectra.

With regard to the low-frequency noise [see Fig. 3(b)], the curve corresponding to SSD2 exhibits a more or less constant value up to 80 V (with a slight increase due to electron heating) and then rises considerably, coinciding with the onset of oscillations at that voltage. For a lower value of σ, which is the case of SSD1 presented before, such a bump takes place at lower bias, at 36 V, while for a higher value of σ, as occurs for SSD3, $S_I(0)$ remains practically constant since no oscillation is achieved.

In summary, in this work, we propose to make use of the low-frequency noise spectral density in order to infer if Gunn oscillations take place in GaN SSDs. MC results exhibit a clear enhancement of the low-frequency noise just for voltages corresponding to the onset of current oscillations and also when higher harmonic components emerge. Thus, the measurement of $S_I(0)$ could be useful to identify the presence of oscillations in structures where they take place at very high (sub-THz) frequencies, like the GaN SSDs analyzed here, and thus circumvent the well known difficulties of experimental measurements in this frequency range.

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