Gunn Oscillations in Asymmetric Nanodiodes Based on Narrow and Wide Band-Gap Semiconductors: Monte Carlo Simulations

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Abstract

By means of Monte Carlo simulations we show the feasibility of asymmetric nonlinear planar nanodiodes for the development of Gunn oscillations. For channel lengths about 1 μm, oscillation frequencies around 100 GHz are predicted in InGaAs diodes, being significantly higher, around 400 GHz, in the case of GaN structures. By simulating two diodes in parallel, we analyze the possible improvement/loss of efficiency due to the coupling between adjacent oscillating channels and the dispersion in the channel lengths.

Keywords: InGaAs, GaN, Gunn oscillations, Monte Carlo simulations, THz devices

1. INTRODUCTION

In recent years the field of Terahertz science has gained international interest due to its broad potential applications, ranging from ultra high speed optical transmission systems to medical diagnostic, industrial quality control or security-screening tools [1]. The development of compact and low-cost semiconductor devices covering the *THz gap* is one of the challenges of nanoelectronics in a medium term future. Great efforts are being made to build compact THz emitters and detectors operating at room temperature [2]. A recently developed planar asymmetric non-linear nanodevice, called self-switching diode (SSD), seems to be a promising candidate to fulfill these requirements [3]. Indeed, operation as detector up to 110 GHz at 300 K, and even up to 1-2 THz at low temperature, has been recently observed in experiments performed with diodes based on InGaAs channels [4, 5].

The SSD is fabricated with just one lithographic step, by simply etching L-shaped insulating grooves onto a semiconductor layer, thus defining a narrow channel with broken symmetry, as shown in Fig. 1. This asymmetry in the topology provides an attractive rectifying *I-V* characteristic. The high speed of operation is mainly due to its planar architecture. The electrodes are connected side by side to the active semiconductor layer rather than placed on top of each other, as in conventional multilayered vertical-structured devices, so that parasitic capacitances are very small. Microwave detectors and frequency multipliers can be achieved by straightforward integration of arrays of SSDs in parallel in order to reduce the overall impedance, without a need for interconnects between the devices [4].

Apart from detectors, the development of active devices, particularly THz emitters, is also necessary. Gunn oscillations are typically used to produce microwave emitters. Increasing the oscillation frequency to enter the THz range is a challenging issue. Materials exhibiting negative differential mobility and high saturation velocity (at which the domains drift) are appropriate to this end. GaN, with a saturation velocity about $2\text{x}10^7$ cm/s and a short energy relaxation time about 0.15 ps, is a good candidate. However, despite big efforts performed in the last years [6-11], only very recently Gunn oscillations were experimentally confirmed in GaN diodes [12]. Mainly vertical structures were explored so far.

The asymmetry in the channel of SSDs is especially appropriate for the development of Gunn oscillations, as demonstrated in [13] for the case of a diode with an InGaAs channel. For a 1.25 μm long channel, oscillations at about 130 GHz at 300 K were predicted by Monte Carlo (MC) simulations. In the case of GaN, by virtue of its superior saturation velocity, higher frequencies are expected. SSDs could be quite useful to this end. Particularly, because of their planar design, heat dissipation, a technological challenge in GaN Gunn diodes, could be managed in an efficient way by a correct design of the channels and their separation.

MC simulations have proved to be quite useful for the analysis of the static, dynamic and noise behavior of SSDs [14-17], and have been also commonly used to study Gunn oscillations in vertical GaN diodes [7, 8, 11]. The objective of this work is to demonstrate, by means of MC simulations, the feasibility of SSDs for the development of Gunn oscillations, both in narrow and wide band-gap materials, taking as examples InGaAs and GaN channels, respectively.

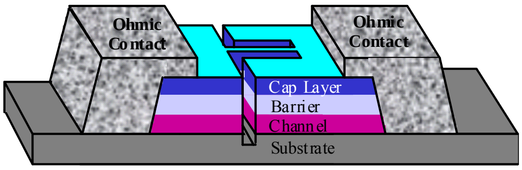

Fig. 1. Three-dimensional geometry of the SSD.

2. MONTE CARLO MODEL

A semiclassical MC simulator self-consistently coupled with a Poisson solver is used for the analysis [18]. The modeling of SSDs would require a 3D simulation to exactly describe the influence of the lateral surface charges and the actual layer structure. To avoid the complexity of 3D models, here instead we perform 2D simulations only in the channel, and the influence of the fixed charges present in other layers is accounted for by means of a "background doping" N_{Db}. In order to include the effect of the depletion originated by charges present in surface states originated in the etching process during the fabrication, a negative charge density σ is considered at the semiconductor-dielectric boundaries of the insulating trenches. Details of the model can be found in [18].

In the case of the InGaAs structure, we have considered $N_{Db}=10^{17}$ cm^{-3} and σ =-0.2x10^{12} cm^{-2}, while for the GaN one N_{Db}=2x10^{17} cm^{-3} and σ =-0.2x10^{12} cm^{-2}. The non-simulated dimension Z, which allows to determine the value of the current provided by a single SSD, is estimated as $Z=n_s/N_{Db}$, taking values of 2x10^{-5} and 4x10^{-5} cm in the InGaAs and GaN SSDs, respectively (for n_s=2x10^{12} and 8x10^{12} cm^{-2}, typical values of sheet electron density in InGaAs and GaN channels, respectively). All the simulations are performed at room temperature.

3. RESULTS AND DISCUSSION

3.1. InGaAs SSDs

Initially, we analyze the case of an SSD with InGaAs channel. Fig. 2(a) shows the geometry of the diode with the values of the main parameters. The channel length is L_C=1425 nm and the width is W_C=60 nm. It has been found that to ease the development of Gunn oscillations a wide vertical trench should be used, W_v=200 nm in our case. The length of the anode access region [right contact in Fig. 2(a)] has been chosen to be long enough (625 nm) to allow electrons thermalize before reaching the contact, process which is rather slow and takes a long distance in InGaAs because of the low density of states in the Γ valley.

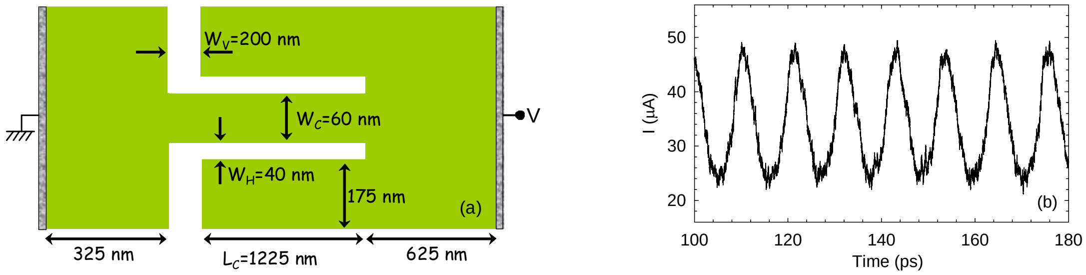

Fig. 2. (a) Geometry of the InGaAs SSD under analysis. (b) Current sequence for V=2.5 V.

For applied voltages higher than 2.0 V, oscillations are observed in the current. Fig. 2(b) shows a current sequence for the case of an applied voltage of 2.5 V. Clear self-sustained oscillations are observed, with a frequency of about 100 GHz, similar to that reported in [13]. The origin of these oscillations is the formation of domains of higher-valley electrons near the entrance of the channel (where the field is higher due to the asymmetry of the diode) and their subsequent displacement along it, eventually evolving into dipoles. The oscillation frequency basically corresponds to the saturation velocity of InGaAs (about 10^{7} cm/s) divided by the distance covered by the domains (about 1 μm).

3.2. GaN SSDs

In the case of GaN SSDs, we have analyzed three different structures, depicted in Fig. 3. Firstly a single diode with channel length L_C=900 nm and width W_C=75 nm. Then, to check if the interaction between close channels has an influence on the observed oscillations, two identical diodes placed in parallel, separated 400 nm, have been simulated (double symmetric structure). Finally, to detect the possible loss of efficiency originated by the dispersion in the device dimensions associated to the technological fabrication processes, two diodes with different channel length (900 and 1200 nm) placed in parallel have been studied (double asymmetric structure). Fig. 3(a) shows the rectifying I-V curves obtained for the three structures. As expected, the double-diode structures provide practically the same current, twice the value obtained in the single diode. The rectifying behaviour is due to electrostatic effects caused by the asymmetry of the structure [3, 14]. When the applied voltage exceeds 30 V, oscillations are observed in the current. Fig. 3(b) shows current sequences for the three structures at an applied voltage of 50 V.

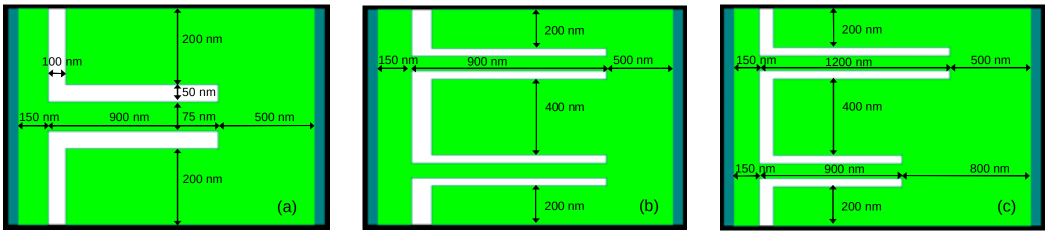

Fig. 3. Geometry of the GaN structures under analysis. (a) Single diode, (b) double symmetric structure, and (c) double asymmetric structure. The width of the channels and trenches in (b) and (c) are the same as in (a).

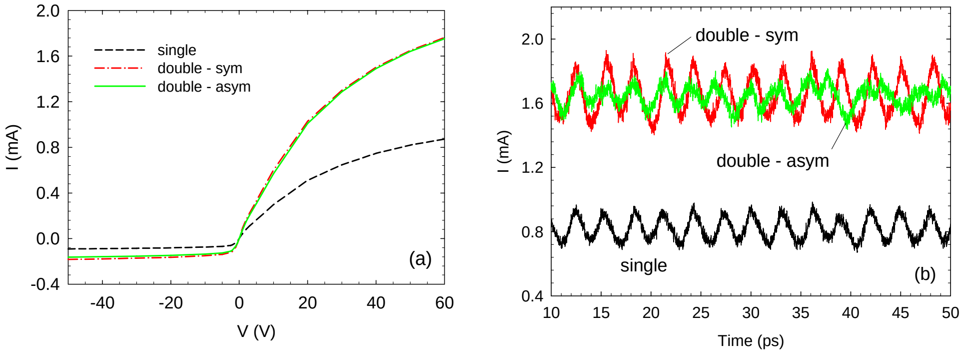

Fig. 4. (a) *I-V* characteristics of the GaN structures of Fig. 3. (b) Current sequences for an applied voltage of 50 V.

Clear and coherent oscillations take place in the single diode, even if their amplitude with respect to the dc current is smaller than in the InGaAs case. To understand the origin of the oscillations, Fig. 5 shows profiles of several microscopic quantities along the center of channel obtained at different time moments during one period. As observed, a high-field domain shifts along the channel, coinciding with and accumulation of slow electrons in the upper U-valley. The accumulation is originated at the entrance of the channel, where the electric field takes high values due to the presence of the vertical trench. This feature of the SSDs architecture is especially appropriate for the development of the Gunn oscillations.

In the case of the double symmetric structure, the behavior of the current is similar, the oscillations showing a double amplitude with respect to the single diode, which indicates that for the separation of 400 nm between channels considered here, oscillations in both channels are in phase and no improvement or loss of efficiency takes place. In contrast, in the case of the two channels with different lengths, oscillations are of lower amplitude and not so clear, thus indicating a loss of efficiency due to diphase effects between both channels. Note that to clearly observe these effects we have considered lengths differing in more than 30%. The frequency and amplitude of the peak found in the current power spectra due to Gunn oscillations are shown in Fig 6 as a function of the applied voltage. Frequencies around 400 GHz are obtained (much higher than in the InGaAs SSD), decreasing with the increase of the applied voltage due to a lower drift velocity. As concerns the amplitude, the expected factor of about 4 is found between the single and double symmetric structures, thus confirming the in-phase oscillations in both channels. In contrast, a clear loss of efficiency takes place in the case of two channels of different length, providing an amplitude even smaller than the single diode.

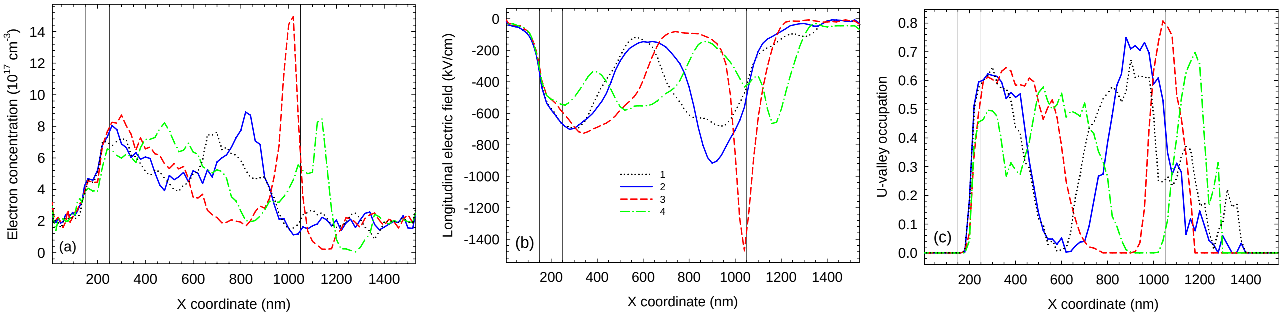

Fig. 5. Profiles of (a) carrier concentration, (b) electric field and (c) U-valley occupation along the center of the channel in the single diode for an applied voltage of 50 V at four equidistant time moments during one period of the oscillation.
Vertical lines indicate the position of the vertical trench and the end of the channel.

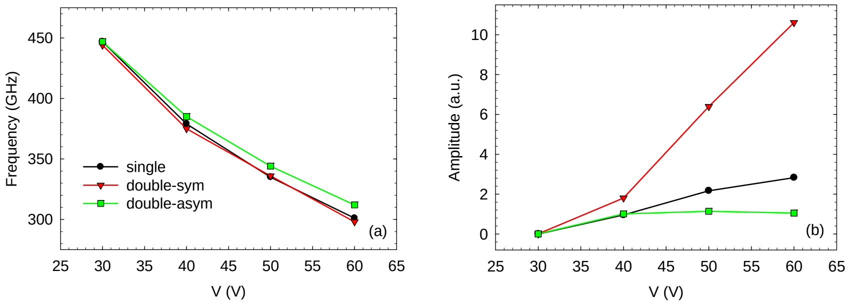

Fig. 6. (a) Frequency and (b) amplitude of the peak in the power spectra as a function of the applied voltage for the diodes of Fig. 3.

4. CONCLUSIONS

The suitability of SSDs for the development of Gunn oscillations has been demonstrated both in narrow and wide band-gap semiconductors. In the case of GaN SSDs, oscillations at frequencies of several hundreds of GHz can be achieved. Arrays of SSDs in parallel can provide levels of current high enough for practical applications. Attention must be paid to the separation between channels and the dispersion in the channel lengths to avoid losses of efficiency. Inclusion of SSDs in resonant circuits should reinforce the observed oscillations and will be the subject of further investigations.

5. ACKNOWLEDGMENT

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