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Monte Carlo analysis of Gunn oscillations in narrow and wide band-gap asymmetric nanodiodes

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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. The DC to AC conversion efficiency is found to be higher than 1% for the fundamental and second harmonic frequencies in GaN diodes.

1. Introduction

Gunn oscillations (GOs) 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 are appropriate to this end. GaN, with a saturation velocity about 2×10⁷ cm/s and a short energy relaxation time about 0.15 ps, is a good candidate. However, despite big efforts spent in the last years [1,2], mainly focused on vertical structures, only very recently promising indications of GOs were experimentally observed in GaN diodes [3]. In the case of planar structures, GOs in GaAs/AlGaAs heterodiodes were also recently measured [4].

The asymmetry in the channel of a self-switching diode (SSD), a lately developed planar nonlinear nanodevice with the topology shown in figure 1 [5], is especially appropriate for the development of GOs, as demonstrated numerically in [6] for the case of a diode with an InGaAs channel. Higher frequencies are expected in SSDs with GaN channels by virtue of its superior saturation velocity and the reduction of the dead space needed for the onset of the oscillations. Moreover, because of the planar design of SSDs, heat dissipation, a technological challenge in power devices, could be managed in an efficient way by a correct design of the channels and their separation.

Monte Carlo (MC) simulations have proved to be quite useful for the analysis of the static, dynamic and noise behavior of SSDs [7,8], and have been commonly used to study GOs in vertical GaN diodes [9]. In this work we demonstrate, by means of MC simulations, the feasibility of SSDs for the development of GOs, both for narrow (InGaAs) and wide (GaN) band-gap channel materials.

Figure 1. Three-dimensional geometry of the SSD. The SSD is fabricated with just one lithographic step, by simply etching L-shaped insulating grooves onto a semiconductor layer to define a narrow channel with broken symmetry.
2. Monte Carlo model

A semiclassical MC simulator self-consistently coupled with a 2D Poisson solver is used for the analysis. To account for the 3D nature of the diodes, a background doping $N_{D\text{b}}$ is considered when solving Poisson equation and a negative charge density $\sigma$ is placed at the semiconductor-dielectric boundaries of the insulating trenches. Details of the model can be found in [10].

In the case of the InGaAs structure, we have considered $N_{D\text{b}}=10^{17}$ cm$^{-3}$ and $\sigma=-0.2\times10^{12}$ cm$^{-2}$, while for the GaN one $N_{D\text{b}}=2\times10^{17}$ cm$^{-3}$ and $\sigma=-0.2\times10^{12}$ cm$^{-2}$. The non-simulated dimension $Z$, which allows to determine the value of the current provided by a single SSD, is estimated as $Z=n_s/N_{D\text{b}}$, taking values of $2\times10^{-5}$ and $4\times10^{-5}$ cm in the InGaAs and GaN SSDs, respectively (for $n_s=2\times10^{12}$ and $8\times10^{12}$ 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. Figure 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 GOs a wide vertical trench should be used, $W_V=200$ nm in our case. The length of the anode access region [right contact in figure 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 $\Gamma$ valley.

![Figure 2](image)

**Figure 2.** (a) Geometry of the InGaAs SSD. (b) Current sequence for $\Delta V=0.5$ V applied every 50 ps.

Figure 2(b) shows the current sequence obtained when the voltage applied to the SSD is incremented in steps of 0.5 V every 50 ps. Oscillations arise for voltages higher than 2.0 V. In particular, clear self-sustained oscillations are observed for 2.5 V, with a frequency of about 100 GHz, similar to that reported in [6]. The origin of the oscillations is the formation of domains of U-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 $\mu$m).

![Figure 3](image)

**Figure 3.** (a) Geometry of the GaN SSD. (b) $I$-$V$ characteristic.
3.2. GaN SSDs

In the case of GaN SSDs, we have analyzed the structure depicted in figure 3(a): a diode with channel length $L_C=900$ nm and width $W_C=75$ nm. Figure 3(b) shows the $I$-$V$ curve obtained for this diode. The rectifying behavior is due to electrostatic effects caused by the asymmetry of the structure [5,7]. Current sequences at several applied voltages are plotted in figure 4(a). As observed, when the applied voltage exceeds 30 V, current oscillations appear. The main frequency of such oscillations is represented in figure 4(b). Values 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 of the domains.

![Figure 4](image-url)

**Figure 4.** (a) Current sequences calculated in the diode of figure 3(a) for several applied voltages. Each sequence is displaced 0.25 mA with respect to the previous one in order to be clearly distinguished. (b) Frequency of the current oscillations vs. applied voltage.

To evaluate the DC to AC conversion efficiency ($\eta = P_{AC}/P_{DC}$) a standard procedure is used [9]: a single-tone sinusoidal potential with amplitude $V_{AC}$ is superimposed to a DC bias $V_{DC}$ (50 V in our case). Under such conditions, the dissipated DC power $P_{DC}$ and the time-average AC power $P_{AC}$ are evaluated. Positive values of $\eta$ correspond to resistive behavior of the diode, while negative values of $\eta$ indicate AC generation from DC. Figure 5(a) shows $\eta$ as a function of the frequency of the AC excitation for three different amplitudes. Negative values higher than 1% are achieved around 340 GHz (frequency of the oscillation taking place when only DC bias is present) and, interestingly, even larger efficiencies (about 2%) are obtained at around half such a frequency. As expected, by increasing the amplitude of the AC signal, the efficiency is enhanced. In figure 5(b), the phase shift between the current response and the AC excitation leading to negative values of $\eta$ at 340 GHz can be observed.

To identify the origin of the oscillations, figure 6 shows profiles of several microscopic quantities along the center of the channel obtained at different time moments during one period of the AC signal for the case $V_{DC}=50$ V, $V_{AC}=10$ V and $f=340$ GHz. As observed, high-field domains shift along the

![Figure 5](image-url)

**Figure 5.** (a) DC to AC conversion efficiency $\eta$ as a function of frequency for the different amplitudes of the AC excitation. (b) Current and voltage waveforms for an excitation frequency of 340 GHz.
channel, coinciding with accumulations of slow electrons in the upper U-valley. The accumulations are 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 SSD geometry is especially appropriate for the development of the GOs. At this particular frequency, two domains coexist in the structure, which indicates that the oscillations observed under DC bias, taking place at 340 GHz for 50 V (figure 4), correspond to the second harmonic of the fundamental frequency of the diode. Indeed, the high efficiency observed in figure 5(a) at around 150 GHz corresponds to the presence of just one domain in the diode (fundamental frequency), which, in addition to the DC bias, requires an external AC component to be excited.

4. Conclusions
By means of MC simulations, the suitability of planar asymmetric nanodiodes for the development of GOs both in narrow and wide band-gap semiconductors has been demonstrated. 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.

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Figure 6. Profiles of (a) carrier concentration, (b) electric field and (c) U-valley occupation along the center of the channel for $V_{DC}=50$ V, $V_{AC}=10$ V and $f=340$ GHz at five equidistant time moments during one period of the excitation. Vertical lines indicate the position of the vertical trench and the end of the channel.