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On the geometrical tunabililty of THz Gunn-like oscillations in InGaAs/InAlAs slot diodes

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Abstract. By using an ensemble Monte Carlo simulation we study the influence of the bias, the recess-to-drain distance, recess length and δ-doping on the frequency of the ultra-fast Gunn-like oscillations f_G found in InGaAs/InAlAs slot diodes. A minimum carrier concentration is needed under the recess for the process to start up. Thus, a δ-doping larger than $5\text{x}10^{12}$ cm^{-2} is necessary, but too high values of this parameter reduce the oscillation frequency. As expected, by shortening the devices (small recess and recess-to-drain lengths) f_G increases. As concerns the DC voltage, the optimum conditions correspond to biases exceeding as less as possible the threshond voltage for the onset of intervally transfer.

1. Introduction

The THz frequency range lies between microwaves and infrared light in the electromagnetic spectrum; thus, the technology for producing T-ray sources is at the limits of electronics from one side and optical systems from the other. Indeed, no powerful radiation sources in this range have been available until the past few years [1]. Even nowadays it does not exist yet a compact source working at room temperature able to generate CW THz fields with a relatively high output power.

In a recent work [2] we showed the possibility to generate ultrafast (in the THz range) Gunn-like oscillations in InGaAs/InAlAs slot diodes (ungated recessed heterostructures, see figure 1). Monte Carlo simulations predict that when the bias surpasses a threshold voltage, associated to the Γ-L intervalley energy, the current exhibits an oscillatory behaviour at extremely high frequency (much higher than that obtained by the 'classical' Gunn effect).

In this work, we present a detailed MC study of the dependence of the oscillation frequency on applied bias, recess-to-drain length, recess length and δ-doping. For this sake, we perform calculations of the current noise spectra, which can give precise indications on the onset of Gunn oscillations. At the same time the instantaneous values of electron velocity, electric potential profile, valley occupations, etc. are monitored in order to optimize the parameters allowing to tune the frequency of the ultrafast Gunn-like oscillations f_G.

2. Device topology and Monte Carlo simulations

The layer structure of the simulated slot diodes is shown in figure 1. Note that it is the same used for the realization of lattice-matched InGaAs HEMTs [3]. The device of reference has a source-to-recess distance (L_S) of 200 nm, a recess length of (L_R) 200 nm and a recess-to-drain distance (L_D) of 550 nm.

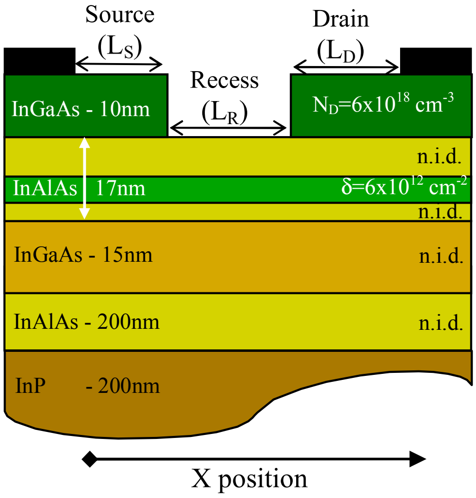

Figure 1. Geometry of the simulated InAlAs/InGaAs slot diode

Calculations are performed by using an ensemble MC simulator at room temperature, which is self-consistently coupled with a two dimensional Poisson solver. The material parameters based on a three valley system are reported in [3]. Ohmic boundary conditions are considered at the source and drain contacts, which are vertically placed adjacent to different materials. Accordingly, nonuniform potential and concentration profiles are considered along these contacts: those that would be obtained if real top electrodes were simulated [3]. The effect of degeneracy is accounted for by locally using a simple rejection technique, where electron heating and nonequilibrium screening effects are introduced by means of the local electron temperature. No other quantum effects are considered in the simulation in order to have reasonable CPU times. The validity of this approach, especially under high-field conditions, and that of the whole MC model was confirmed in previous works [3]. In order to detect the presence of ultrafast Gunn oscillations, special attention is devoted to the calculation of the current noise spectra due to their extreme sensitivity to microscopic features of carrier dynamics and the possibility to easily perform a frequency analysis of the electrical fluctuations.

3. Results

As explained in a recent work [2], a necessary condition for the onset of an oscillatory behaviour within the slot diode is the presence of two types of carriers in the channel: fast electrons in the Γ-valley and slow electrons in the upper valleys. Therefore, the Gunn-like phenomenon can only start when the bias applied to the slot diode surpasses a threshold voltage given by the Γ-L intervalley energy (around 0.6 V). When such voltage drop is reached within a small region at the drain side of the recess, the L valley concentration increases at this point and a zone depleted of Γ electrons appears nearby [see figure 2(a)]. The width of this depleted zone increases rapidly, following the motion of the fast Γ electrons, while only L electrons are injected into the drain region, thus leading to a decrease of the current flowing through the device. This evolution of the depletion region makes the resistance of the recess-drain region increase. When it becomes comparable to that of the region under the recess, it absorbs a part of the voltage drop, not allowing the electrons to gain the intervalley energy while moving under the recess. When this occurs, Γ-valley electrons start to be injected into the drain region,

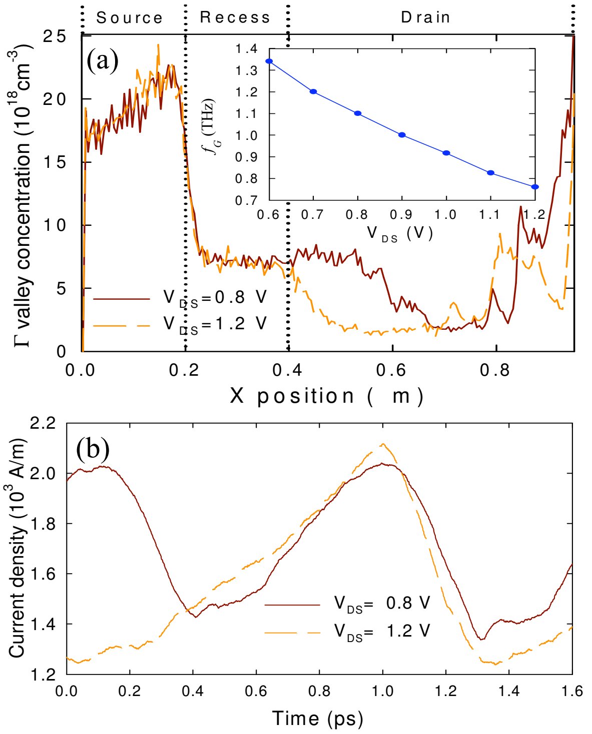

Figure 2. (a) Instantaneous profile of Γ valley electron concentration inside the device for different V_{DS}; the inset shows f_G as a function of V_{DS}. (b) Time dependent current for the same V_{DS}.

filling the previously created depletion and providing a net increase of total concentration and current. The period of this ultra-fast Gunn oscillation is mainly determined by the transit time of Γ-valley electrons through the recess-drain region, and depends on the applied voltage, length of the recess, recess-drain distance and δ-doping. These dependencies will be studied in the following sections.

3.1. Influence of the bias voltage

The inset of figure 2 shows how f_G decreases when increasing the bias from 1.34 THz for V_{DS}=0.6 V to 0.76 THz for V_{DS}=1.2 V. This is mainly due to the fact that for lower voltages L-valley electrons are not injected just at the drain side of the recess, but somewhat inside the drain region, thus decreasing the traveling time of the depletion/filling region (figure 2). However, the current modulation achieved under these conditions (amplitude of the oscillations) is lower than for higher voltages due to the less efficient L-valley electron injection.

3.2. Influence of the recess-to-drain distance, L_D

In figure 3(a) f_G is plotted vs. L_D when the bias is fixed to 1 V. For high values of L_D (L_D>550 nm) f_G perfectly scales as $1/L_D$, while for shorter devices the increase of f_G is not as high as expected. This deviation from the simple transit time criterion for L_D<550 nm is a consequence of the increase of L-valley population at the drain side of the recess (due to a sharper voltage drop at that point), which decreases the velocity of the depletion/filling mechanism (with respect to that exhibited by Γ electrons) at the origin of the observed Gunn-like oscillations, figure 3(b).

3.3. Influence of the recess length, L_R

Ultrafast quasiballistic Γ electrons, at the origin of the ultra fast dynamics of the observed oscillations, appear in the channel of slot diodes thanks to (i) the presence of the recess that focuses the electric field and (ii) the effect of degeneracy, which significantly reduces the rate of scattering mechanisms and much increases the electron mean free path.

The inset of figure 4 presents the dependence of f_G with the length of the recess L_R for V_{DS}=1 V, and L_D=550 nm. f_G decreases for longer L_R due

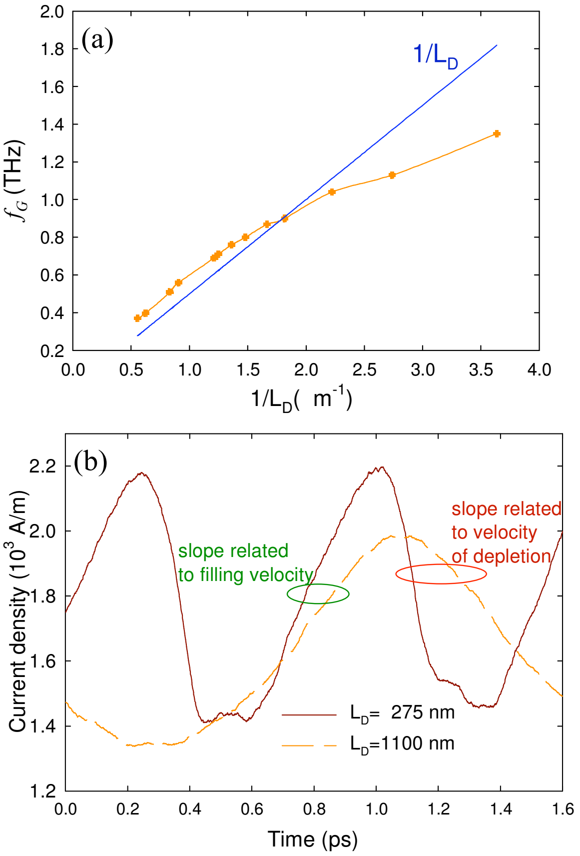

Figure 3. (a) f_G as a function of the inverse of the recess-drain distance (L_D) and (b) time-varying current for L_D=275 and 1100 nm. V_{DS}=1.0 V.

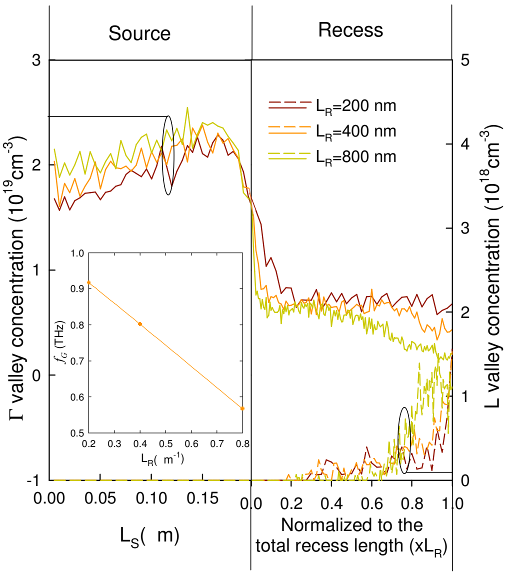

Figure 4. Instantaneous profile of Γ and L valley electron concentration inside the device for L_R=200, 400, 800 nm. V_{DS}=1V. The inset shows f_G as a function of L_R.

to the attenuation of the "electron-launching effect" of fast Γ electrons into the drain region. The injection velocity decreases for longer L_R due to a less efficient focusing of the electric field by the recess. The reduction of f_G comes along with a degradation of the amplitude of the oscillations due to the smaller presence of Γ-valley electrons under the recess, as shown in figure 4. This happens because part of the electrons can jump to the L valley before reaching the drain side of the recess, thus degrading the modulation of the current associated to the injection of Γ-valley electrons.

3.4. Influence of the δ-doping

Another necessary condition for Gunn-like oscillations to appear is the presence of a large enough amount of carriers in the channel below the recess. Therefore, a minimum value of the the δ-doping ($\delta=6\mathrm{x}10^{12}$ cm^{-2} in our device) is required for observing current oscillations, figure 5(a). However, if the δ-doping is further increased, the oscillation frequency is degraded because the electron concentration in the channel becomes more homogeneous and the recess is not able to correctly concentrate the electric field, figure 5(b).

4. Conclusion

We have performed a thorough study of the influence of different topological parameters on the THz Gunn-like oscillations found in heterojunction slot diodes. High oscillation frequencies can be achieved by correctly choosing values of the δ-doping level and applied voltage, ensuring an enough carrier concentration under the recess and allowing for the onset of the oscillations, respectively. Additionally, both L_D and L_R must be as short as possible, the first for decreasing the length of transit of the depletion/filling region, and the second for enhancing the electric field concentration under the recess, thus improving the velocity of the Γ-valley electrons that determine the speed of the mechanism.

Acknowledgements

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5. References

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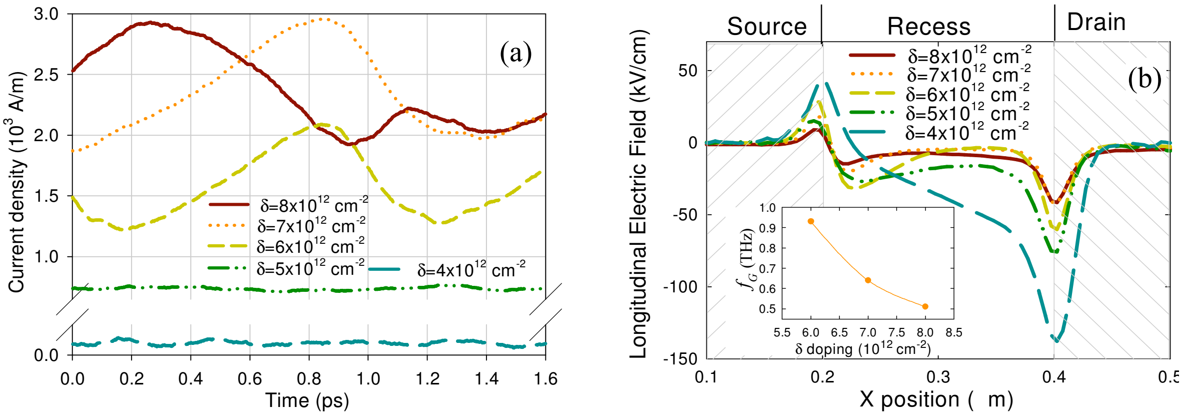

Figure 5. (a) Time-varying current and (b) profile of electric field along the channel for δ from 4 to $8\mathrm{x}10^{12}$ cm^{-2}. The inset shows the variation of f_G as a function of the δ-doping. V_{DS}=1.0 V.