phys. stat. sol. (c) 5, No. 1, 146–149 (2008) / DOI 10.1002/pssc.200776561

physica status solidi c
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current topics in solid state physics

Excitation of millimeter-wave oscillations in InAlAs/InGaAs heterostructures

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Received 9 July 2007, revised 18 August 2007, accepted 25 August 2007
Published online 23 October 2007

PACS 02.70.Uu, 05.10.Ln, 72.30.+q, 73.61.Ey, 85.30.Tv

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We study the origin of strong Terahertz (THz) oscillations taking place in InAlAs/InGaAs slot diodes - base of High Electron Mobility Transistor (HEMT) devices - when bias surpasses 0.5 V. To this end we perform a microscopic analysis of current fluctuations, calculated by means of an ensemble Monte Carlo (MC) simulator. The millimeter and submillimeter waves are caused by the presence of Gunn-like oscillations whose dynamics is controlled by ballistic Γ valley electrons in the channel. These carriers are capable to reach extremely high velocities due to the influence of degeneracy effects (preventing scattering mechanisms) and the presence of a recessed geometry. The dependence of this process on the recess and recess-drain lengths is analyzed in order to improve the frequency and magnitude of the oscillations.

1 Introduction A wide variety of new physical and biological applications are continuously being envisaged in the millimetre and submillimeter frequency range. These potential applications of THz radiation are related to so diverse fields as engineering, defence, pharmacy or medicine. For the development of all of these applications the critical point is the scarce availability of terahertz sources. Nowadays it does not exist a compact, room-temperature, high-power, source that is well controlled, ideally tunable and suitable for the terahertz frequency range. Powerful sources are difficult to fabricate mainly because THz radiation lies above the frequency range of traditional electronics, but below the range of optical and infrared generators. However this gap is tried to be filled by a wide range of new scientific concepts and technologies.

In this context recent experiments in nanometer gate length InAlAs/InGaAs HEMTs, demonstrating the emission of radiation at THz frequencies [1, 2], are of special interest. Initially, these results have been interpreted as emission caused by current driven plasma wave excitation in the channel of the HEMT as a result of Dyakonov–Shur instabilities [3]. However the threshold-like behaviour of THz emission (when increasing the drain bias) and the associated kinks appearing in the I-V curves indicate that a hot carrier mechanism such as Gunn effect could also be responsible for those high frequency oscillations [4].

In this work, by means of MC simulations, we study the presence of current oscillations in the heterostructures on which these HEMTs are based. The analysis of the current noise spectra can provide precise indications on the onset of collective phenomena such as plasma or Gunn oscillations. Ungated HEMT-like (slot) diodes are chosen because the gate terminal seems not to be essential to originate these oscillations on condition that the electric field is focused properly on the region of interest, effect obtained by means of a recessed geometry.

2 Device structure and Monte Carlo approach The active layer structure of the slot diodes (Fig. 1) consists of a 200 nm $In_{0.52}Al_{0.48}As$ buffer, a 15 nm $In_{0.70}Ga_{0.3}As$ channel, a 3-nm-thick undoped $In_{0.52}Al_{0.48}As$ spacer, a δ-doping layer of $6x10^{12}$ cm^{-2}, a 10-nm-thick $In_{0.52}Al_{0.48}As$ barrier layer, and, finally, a 10-nm $In_{0.53}Ga_{0.47}As$ cap layer (N_D=6x10^{18} cm^{-3}). The source-recess distance L_S is 200 nm, the recess length L_R is 200 nm, and the recess-drain separation L_D is 550 nm. An InP-based heteroestructure was chosen for its high InGaAs channel mobility and high sheet carrier density. Moreover, this layer structure is the base for the realization of real δ-doped HEMTs [5, 6], similar to those where THz radiation was measured [1, 2]. For the calculations we have

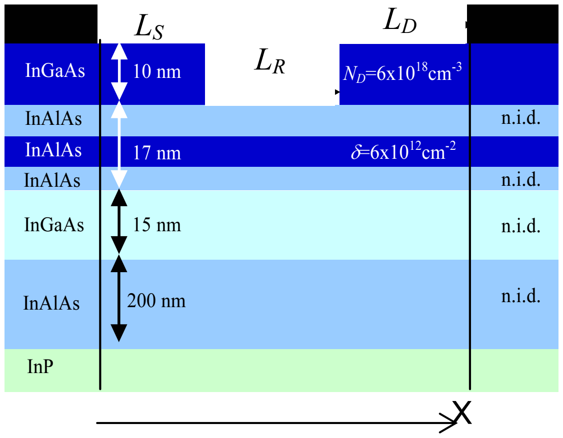

Figure 1 Geometry of the simulated InAlAs/InGaAs slot diode (Note that X axis is used in Figs. 4 and 5).

used an ensemble MC simulator at room temperature self-consistently coupled with a 2D Poisson solver. The material parameters and microscopic models used are reported in [5]. The devices are divided into meshes 50 Å long and 10 to 100 Å wide depending on the doping and the required resolution of the potential along the structure. Ohmic boundary conditions are considered in the source and drain contacts, which are placed vertically 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 [5].

The effect of degeneracy has been introduced by using locally the classical rejection technique, where the electron heating and nonequilibrium screening effects are accounting for by means of the local electron temperature. No other quantum effects are considered in the simulation in order to have reasonable computer simulation times. The validity of this approximation (mainly under high field conditions) and that of the whole MC model has been confirmed in a previous work [5].

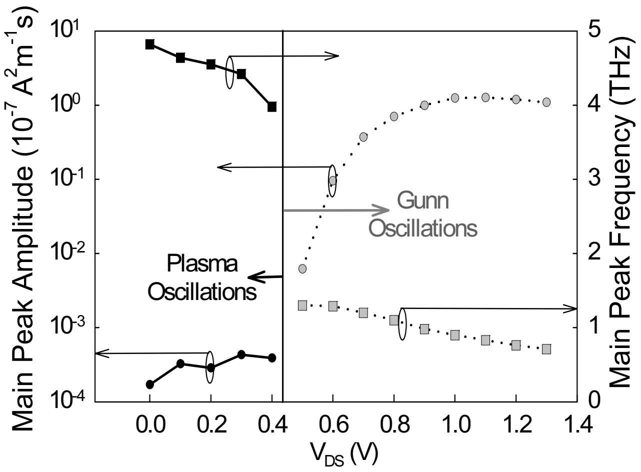

Figure 3 Amplitude (circles, left axes) and frequency (squares, right axes) of the main peak in the spectral density of current fluctuation as a function of V_{DS}. Dotted lines indicate the V_{DS} regime where Gunn oscillations take place.

In order to detect and emphasize the presence of plasma or Gunn oscillations, special attention is devoted to the calculation of noise spectra due to their extreme sensitivity to microscopic features of carrier dynamics and the possibility to perform a spatial and frequency analysis of electrical fluctuations.

3 Results and discussion The static current-voltage characteristic of the slot diode is shown in Fig. 2. It can be observed that a kink appears just when intervalley transfer starts to be important (for V_{DS} above 0.5 V). For such high voltages, current oscillations (that we attribute to a Gunn-like effect) clearly appear (right inset). It is important to remark that plasma oscillations also provide a peak in the current noise spectrum, however it is easily distinguished from that provided by Gunn-like oscillations, first

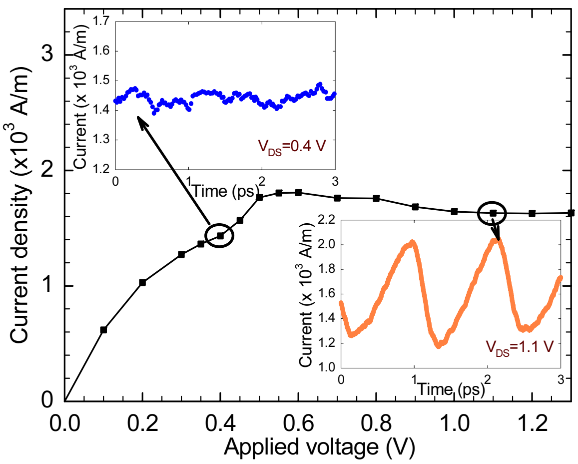

Figure 2 Static I-V characteristic. The insets show the time-varying current for the applied voltages V_{DS} = 0.4 V and V_{DS} = 1.1 V.

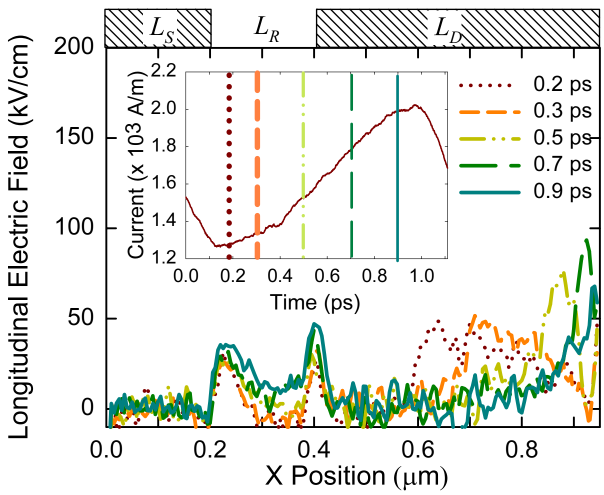

Figure 4 Profile of the longitudinal electric field in the channel of the heterostructure at different time moments within one period of the oscillation for a bias V_{DS} = 1.1 V.

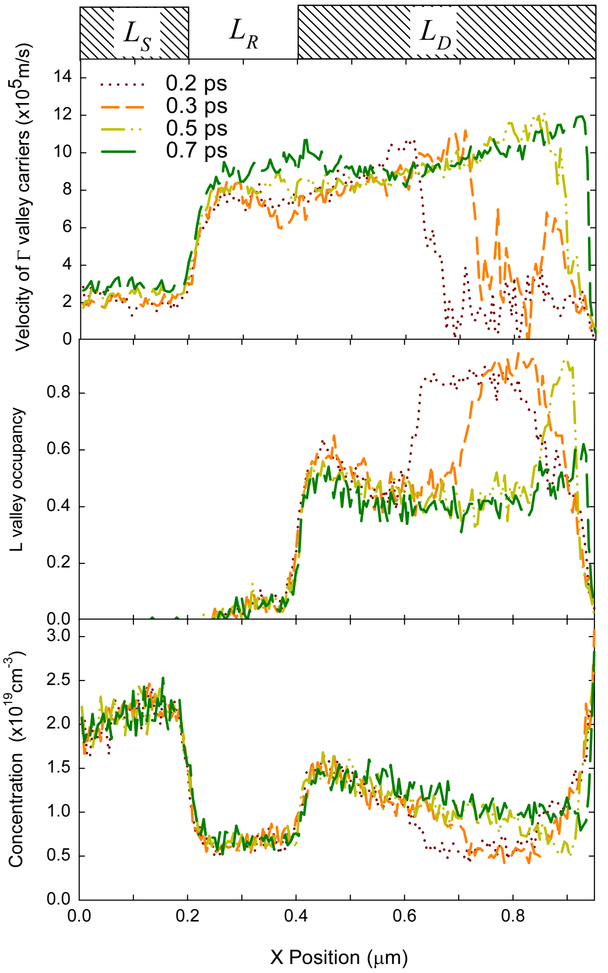

Figure 5 Profile of the Γ-valley electron velocity (upper panel), L valley occupancy (central panel) and carrier concentration (lower panel) in the channel of the heterostructure at different time moments within one period of the oscillation for a bias V_{DS} = 1.1 V.

because the position peak lays at much higher frequencies, and second, because its amplitude is much lower. Theses differences are clearly observed in Fig. 3, where the frequency and amplitude of the main peak found in the current noise spectrum are plotted as a function of the applied bias. High amplitude Gunn oscillations, with a frequency around 1 THz, appear for V_{DS} > 0.5 V, while for lower voltages there are only low-amplitude high-frequency plasma oscillations (around 4.5 THz). The frequency of these ultra-fast Gunn oscillations (entering the THz range) decreases with increasing bias, while the amplitude increases and then saturates (and even decreases).

Figure 4 shows the profiles of electric field in the channel of the heterostructure at different time moments within one period of the oscillation, for V_{DS} = 1.1 V. The presence of a peak in the electric field distribution that moves along the recess-drain region at extremely high velocity is observed. This increase of the electric field is linked spatially to an anomalously high occupancy of the L valley, as can be observed in Fig. 5 (central panel). Therefore, the oscillatory behavior of the current is due to intervalley mechanisms that push carriers into the upper satellite valley (from Γ to L valley). This fact is analogous to what happens in the typical Gunn diode oscillations. However the creation and annihilation of space-charge domains in heterostructure slot diodes exhibit important differences with respect to the behavior of classical devices. Firstly, the active region for the formation and displacement of the field inhomogeneity is not the total cathode-to-anode distance but only the recess-to-drain region, because the peak in the electric field at the drain edge of the recess is responsible for the onset of the oscillations if its value is high enough. This peak makes electrons gain energy and accelerate very fast, extremely shortening the distance necessary to reach the L valley (and thus reducing the length of the well known called "dead space" in classical Gunn diodes).

Secondly, the electric field domain travels at about 10×10^5 m/s, much faster than the mean velocity of electrons in the channel, around 5×10^5 m/s. To explain the difference between the values of these velocities it is necessary to note that electrons in the channel occupy Γ and L valleys. Electrons in the bottom valley move very fast (as can be seen in Fig. 5, upper panel), but electrons in the L valley are very slow. The process that makes the front edge of the domain move forward is the arrival of very fast Γ-valley electrons that jump to the L valley once they have surpassed the domain. The high velocity of these quasi-ballistic Γ electrons, reached as a consequence of the high electric field (focused by the recessed geometry) and the degeneracy of the electron accumulation in the channel (which much reduces the emission of optical phonons), leads to a fast advance of the domain. This ultra-high frequency non-stationary phenomenon is rather different to the classical Gunn effect, which is based on the propagation of a dipolar domain always travelling with the electron saturation velocity, v_{sat}.

As observed in Fig. 5, the increase of L valley occupancy leads to a decrease of carrier concentration in the channel (lower panel), and not to an accumulation domain like in classical Gunn effect. Such a decrease of carrier concentration in the channel is attributed to real space transfer processes in the L valleys, quite probable due to the low energy separation between L valleys in InGaAs and InAlAs. In the barrier material electrons drop to the Γ valley after a very short time, and return back to the channel.

In order to understand the bias dependence of the oscillation frequency one must consider that the velocity of Γ electrons increases with the bias, and therefore the drift of the domain is faster. But when arriving near the drain contact, the domain moves much slower, since both Γ and L carriers must leave the structure. When increasing the bias, a higher number of carriers reaches the L valley, leading to a longer exit time of the domain, since more L electrons must be removed from the structure. The longer time taken

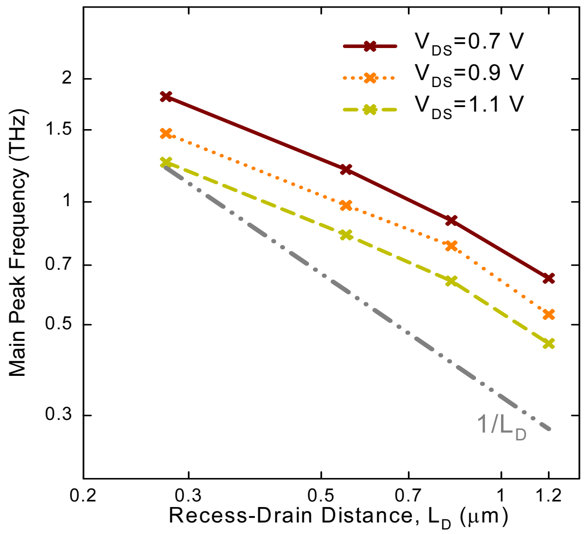

Figure 6 Main peak frequency as a function of recess-drain distance (L_D) for bias from V_{DS} = 0.7 V to V_{DS} = 1.1 V. L_R = 200 nm, L_S = 200 nm.

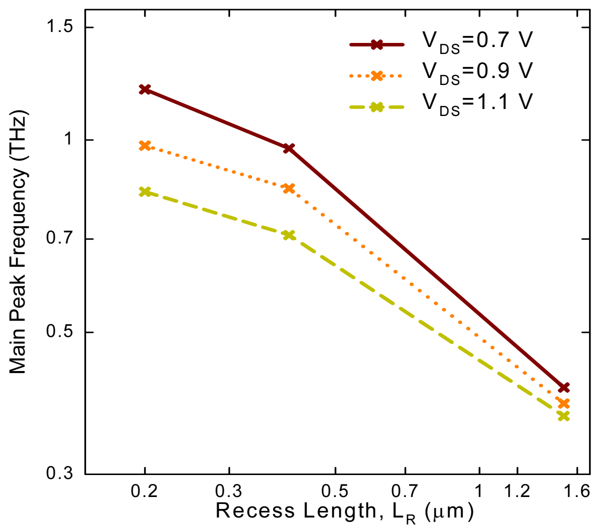

Figure 7 Main peak frequency as a function of the recess length (L_R) for bias from V_{DS} = 0.7 V to V_{DS} = 1.1 V. L_R = 200 nm, L_S = 200 nm.

by the domain to leave the device is not compensated by the shorter drift time, thus providing lower oscillation frequencies for higher bias, as observed in Fig. 3.

Fig. 6 shows the frequency of the main peak of the current noise oscillations as a function of the recess to drain distance for biases V_{DS} = 0.7 V, 0.9 V and 1.1 V, when L_S =L_R=200 nm are kept constant. By reducing the length of the recess-drain region, L_D, the oscillation frequency increases because the transit time of the high field domain is shortened. But such a frequency increase is not as pronounced as expected (proportional to $1/L_D$) due to the compensation of the faster drift with a slower exit process (due to an enhanced L valley population associated with higher electric fields under the recess). This effect is particularly important for the shortest devices. For long devices the drift velocity dominates the dynamics of the domain, and the oscillation frequency is essentially proportional to the inverse of L_D.

When the recess length increases (Fig. 7), while L_S= 200 nm and L_D = 550 nm are kept constant, the electric field is not well focused under the recess, the electron launching effect into the drain region is not so strong and, as a consequence, the velocity of Γ carriers decreases. The velocity of Γ electrons in the recess-drain region is reduced also because of the higher potential drop taking place in a longer recess, making the electric field in the recess-drain region decrease. As a result of both effects, the oscillation frequency is lowered for longer L_R.

4 Conclusion We propose a simple THz source based on ultra-fast Gunn-like oscillations in heterojunction slot diodes able to provide a frequency tuning by means of the applied voltage. However, in order to obtain a practical voltage controlled oscillator at THz frequencies with enough output power at a given frequency, a careful design of its geometry must be performed (together with the use of an adequate antenna).

Acknowledgements This work has been partially supported by the Dirección General de Investigación del Ministerio de Educación y Ciencia and FEDER through the project TEC2004-05231/MIC, by the Consejería de Educación de la Junta de Castilla y León through the project SA044A05, and by the Fundación Samuel Solórzano through the project FS/16-2005.

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