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Monte Carlo Simulation of Noise and THz Generation in InP FET at Excess of Electrons in Channel

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Electron transport and drain current noise in field effect transistor with n^+nn^+ InP channel have been studied by Monte Carlo particle simulation which simultaneously solves the Boltzmann transport and pseudo-2D Poisson equations. It is shown that at gate voltages giving excess electron concentration in n-region of channel the drain current self-oscillations in THz frequency range are possible. The self-oscillations are driven by electron plasma instability.

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1. Introduction

In recent years the THz technology gained great interest due to its potential application in radio astronomy, remote sensing, commercial imaging, biomedicine and other. The most important element in modern THz technology is a generator of coherent THz radiation. Semiconductor sources are of great interest due to compact sizes and possibility to be integrated into a single chip. At the moment one of the most perspective trends of THz source development is related with plasma phenomena in field effect transistors (FET) channels. There are proposed several instabilities (Dyakonov–Shur [1], Gunn, etc.) which can be used to create a THz generation source. Unfortunately, up to now, direct confirmation of these effects realization is absent, even if some results show such a possibility. In part, such a lack of information is due to practical absence of theoretical investigation of high frequency noise in transistors which can facilitate analysis of the generation conditions. The theoretical investigation of noise in FET's is complicated due to impossibility of direct usage of methods widely developed for two-terminal devices (diodes). We have developed original noise calculation procedures which allows to follow and identify a generation process from its onset up to transformation into stable periodic oscillations of current.

The aim of this article is to investigate the possibility of realization of plasma instabilities proposed for diodes [2]. In diode structures these instabilities are often damped by impurity scattering [3]. To diminish the impurity scattering in the FET channel is possible by remote doping with delta layers over the channel as it is used in high electron mobility transistors (HEMTs). Another possibility is to pump the excess electrons to low doped FET channel by the voltage applied to the gate. These electrons come from highly doped regions close to source and drain contacts. The latter situation is simulated by Monte Carlo particle (MCP) technique coupled to a pseudo-2D Poisson solver [4]. Main attention is paid for optimum conditions to achieve the current self-oscillations in THz frequency range by varying the FET geometry and design. The instability mechanism responsible for current oscillations is discussed.

2. Model

Below we shall present the calculations of electron transport and noise in FET structure based on 50–400–50 nm n^+nn^+ InP channel with the width 200 nm. 300 nm gate is centered in n-region at a distance 50 nm from the channel. The doping is $n = 10^{15}$ cm^{-3}, $n^+ = 5\times10^{17}$ cm^{-3}. The calculations were performed by simultaneous solution of coupled Boltzmann and pseudo-2D Poisson equations by MCP technique. The InP band and material parameters of a spherically symmetric nonparabolic conduction band were taken from Ref. [5]. Electron scatterings by polar optical and accoustic deformation phonons, and ionized impurities were included. Due to relatively high electron heating up to energies of 20–50 meV the accoustic scattering was considered as elastics. The common source configuration was considered. The applied voltage to the drain in all cases was $U_\mathrm{d} = 70$ mV. This voltage was found to be optimal for instability realization. All the calculations are made for lattice temperature 10 K (if not indicated additionally). The number of simulated particles depending on the case was varied from 10^5 to 5×10^5. The time step in all cases was 1 fs.

3. Numerical results

As a first step the long (up to 10 ns) drain current trajectories at different positive gate voltages were calculated.

In Fig. 1 the parts of these trajectories at different gate biases U_g are presented. To avoid the superimposing the upper trajectories are shifted by constant current value.

One can see that at U_g up to 100 mV the current trajectories are rather noisy while at higher values of U_g the current self-oscillations appear.

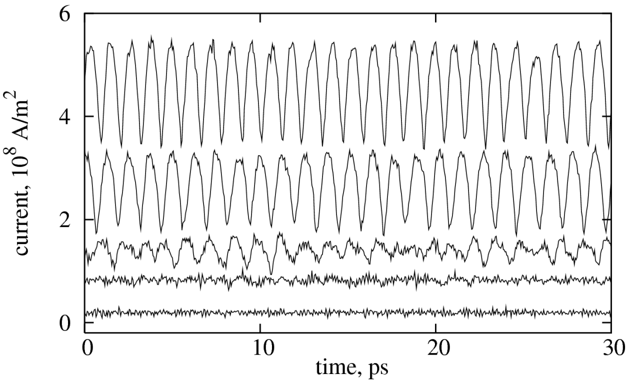

Fig. 1. Drain current time dependences at different gate voltages. From bottom to top: $U_g = 0$, 50, 100, 150 and 200 mV, respectively. To avoid the curve overlap the curves from bottom to top were shifted by 0, 0, 0, 0.9, 2.5×10^8 A/m^2, respectively. $U_d = 70$ mV, $T = 10$ K.

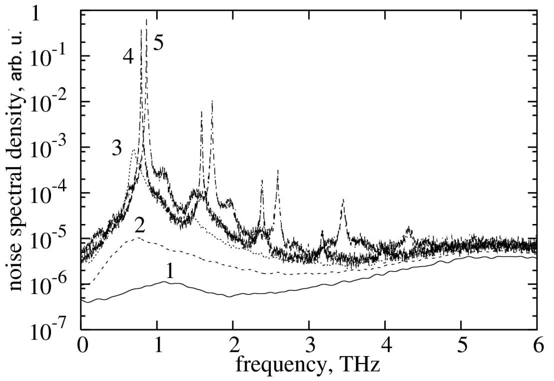

Fig. 2. Drain current noise spectral densities at different gate voltages U_g: 1 — 0, 2 — 50, 3 — 100, 4 — 150, 5 — 200 mV. $U_d = 70$ mV, $T = 10$ K.

The calculated current noise spectral densities of each trajectory of Fig. 1 are presented in Fig. 2. As expected we can see the growing noise spectra background at U_g increased due to the electron concentration growth in n-region. At low U_g values one can see the noise maxima in possible generation range (curves from 1 to 3). While at current self-oscillation regime (curves 4 and 5) the sharp peaks on the oscillation frequency and upper harmonics appear on the noise spectra. The fundamental harmonic frequencies are 0.79 and 0.86 THz in spectra 4 and 5, respectively. To identify the possible THz generation mechanism the averaged in time (over 200 ps long trajectory) electron concentration, electric field, velocity and local optical phonon emission rate profiles along the simulated FET channel were calculated at various U_g values.

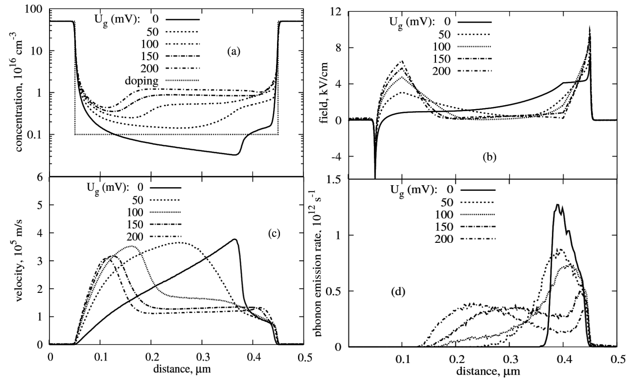

Fig. 3. The profiles of electron concentration (a), electric field (b), velocity (c) and local optical phonon emission rate (d) along InP FET channel at different gate voltages U_g. $U_d = 70$ mV, $T = 10$ K.

The calculation results are shown in Fig. 3. The electron concentration under the gate grows with the U_g increased (see Fig. 3a). At $U_g = 200$ mV the concentration more than 10 times exceeds n-region doping level. Due to growing electron concentration the considerable changes of electric field and velocity profiles are observed (Figs. 3b and c, respectively). At $U_g = 150$ and 200 mV the concentration, field and velocity profiles are similar to profiles of diodes at ballistic transport conditions when plasma instabilities are possible [2]. The presence of plasma instability is clearly shown in Fig. 3d where the local phonon emission rate is presented. In the stable case ($U_g = 0$) all the emissions are concentrated in the high field region near the drain, while at $U_g = 200$ mV the emissions are extended between source and drain instead to be localized in the high field region near the source if the case would be stable.

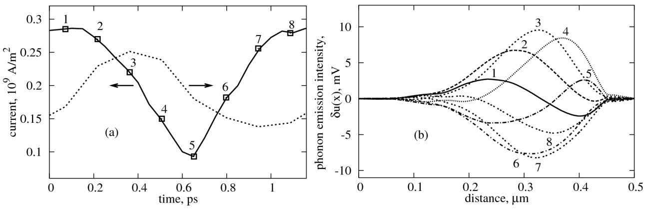

Fig. 4. (a) One period of drain current and optical phonon emission intensity oscillations. The numbered points from 1 to 8 indicate the time moments at which the potential deviation $\delta u(x)$ from average $u(x)$ profiles along InP FET channel are calculated. The time distance between points is of 0.145 ps. (b) Potential deviation $\delta u(x)$ profile evolution. Curve numbers correspond to time points in (a). $U_d = 70$ mV, $T = 10$ K.

The instability dynamics is shown in Fig. 4 where the one period of current and optical phonon emission intensity (Fig. 4a) and evolution of potential profile deviation from average value $\delta u(x)$ (Fig. 4b) are demonstrated. Figure 4b shows the space charge wave travelling with the speed 3×10^5 m/s. This wave modulates the optical phonon emission intensity which causes the current oscillations (Fig. 4a). It is well known that plasma instabilities are sensitive to the ambient temperature.

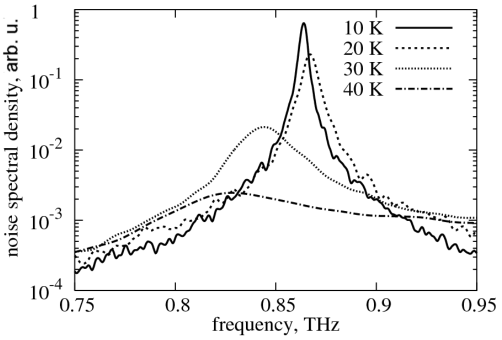

Fig. 5. The fundamental drain current noise spectral density peak at different temperatures. $U_{\mathrm{g}} = 200$ mV, $U_{\mathrm{d}} = 70$ mV.

In Fig. 5 the fundamental noise spectral density peak is shown at different temperatures and $U_{\mathrm{g}} = 200$ mV. One can see that at 40 K the peak practically disappears. This behavior can be considered as an additional argument for electron plasma instability mechanism.

Finally, we have investigated the electron transport and noise in InP FET with excess electron concentration in n-region of n^+nn^+ channel. It is shown that at these conditions drain current self-oscillations driven by electron plasma instability easily arise. Theoretically this instability was predicted about 30 years ago for diode with the ballistic or quasiballistic transport [2]. Unfortunately, the effect is strongly damped by impurity scattering the rate of which in diodes is close to the expected plasma instability frequency. In the case of FET we can increase the electron concentration and simultaneously the plasma instability frequency by the gate voltage. The impurity scattering rate in this case remains unchanged. This circumstance makes FET atractive as THz generation source at low temperatures.

Acknowledgments

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