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Plasma Instability Noise in InP n^+nn^+ Structures: Monte Carlo Simulation

V. Gružinskis, P. Shiktorov and E. Starikov

Semiconductor Physics Institute
Goštauto 11, LT-01108, Vilnius, Lithuania

The current noise in n^+nn^+ InP structures at dominating low temperature (T = 10 K) optical phonon emission is simulated by Monte Carlo particle technique. The n-region length of simulated structures is varied from 1 to 100 μm. The peaks related to the near collisionless and optical phonon emission dominated plasma instabilities are recognized in current noise spectral density spectra.

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1. Introduction

The plasma instabilities (PI) are promising mechanisms for high frequency microwave generation in semiconductor n^+nn^+ structures. The two types of PI at near collisionless (NCL) and optical phonon emission dominated (OPED) electron transport conditions in the n^+nn^+ structures are considered by Ryzhij et al. [1]. They found that both types of PI's can lead to current self-oscillations up to the plasma frequency, which depends on the carrier concentration in the n-region of the n^+nn^+ structure (see Ref. [1] and references therein). The regularity of self-oscillations is sensitive to the spatial resonance conditions for space charge waves periodically growing and decaying due to the PI, i.e. there exists the optimum length of n-region at the given doping of this region.

In real n^+nn^+ structures the OPED and especially NCL plasma instabilities are suppressed by the lattice (mainly due to accoustic phonons) and impurity scatterings. However, the progress in manufacturing structures with remote doped conducting channels recently gave the second breath to PI investigations. Also the recent achievements in THz frequency noise measurements have opened new directions in PI investigation. It is well known that the noise spectrum contains integrated information about physical processes such as carrier scattering, various instabilities, including PI, etc. Therefore, the identification of noise spectrum pecularities such as the peaks in the noise spectra related to the certain process is important.

This article presents the results of simulation of current noise in InP n^+nn^+ structures of different length L at constant bias U and lattice temperature 10 K.

2. Model

The calculations of electron transport in n^+nn^+ InP structures were performed by simultaneous solution of coupled Boltzmann and Poisson equations by Monte Carlo particle (MCP) technique [2]. The InP band and material parameters of a spherically symmetric nonparabolic conduction band were taken from Ref. [3]. Electron scatterings by polar optical and acoustic deformation phonons, and ionized impurities were included. Due to relatively high electron heating up to energies of 20–50 meV the acoustic scattering was considered as elastic. The doping of simulated 0.03–L–0.03 μm n^+nn^+ InP structure was $n = 10^{15}$ cm^{-3} and $n^+ = 10^{17}$ cm^{-3}. The InP structure n-region length L was varied between 1 and 100 μm. The number of simulated particles, depending on the L, was varied from 6×10^4 up to 10^6. The time step in all cases was 5 fs.

3. Numerical results

The current noise at the constant biases is simulated using correlation function method described in Ref. [4]. For each structure a different bias is chosen to keep the same averaged in time current density $\langle j_0 \rangle = 2.7 \times 10^7$ A/m^2. The noise spectral densities at different lengths L are shown in Fig. 1. The noise spectra for short, $L = 1-1.6$ μm, structures, when applied bias U is too low to accelerate electrons up to the optical phonon energy $\hbar\omega_0 = 0.043$ eV (i.e. $U < u_0 = \hbar\omega_0/e$), are demonstrated in Fig. 1a. The noise spectra peaks denoted by arrows can be assigned to strongly suppressed NCL PI [1], because the peak amplitude is growing and the frequency f_{p} is decreasing as L increases. In Fig. 1b the spectra for long structures, when $U > u_0$, are presented. Comparing the noise spectra in short and long structures one can see the strongly enhanced high frequency noise in long structures. The giant peaks in the spectra of the shortest long structures are related to the current oscillations (see Fig. 2a) due to OPED PI [1]. The onset of OPED PI gives the discontinuities in $f_{\mathrm{p}}(L)$ and $U(L)$ dependences, Fig. 2b, when L is increased from 1.6 to 1.7 μm.

The onset of the OPED PI divides the $f_{\mathrm{p}}(L)$ dependence into two branches corresponding to NCL and OPED PI. In Fig. 1b one can also see that very small peak related to OPED PI still is present in the structure even at length $L =$ 100 μm. To explain this phenomenon in Fig. 3 the averaged in time field, Fig. 3a, and velocity, Fig. 3 b, profiles along 1.5 and 50 μm InP structures are shown. As expected the field and velocity profiles near the cathode contact are similar at a given average current $\langle j_0 \rangle$. Thus the injected electrons undergo nearly the same physical processes in the region adjacent to the cathode (CR), independent of the structure length. The rest of the structure outside CR works as series resistance, which suppresses the noise in the CR.

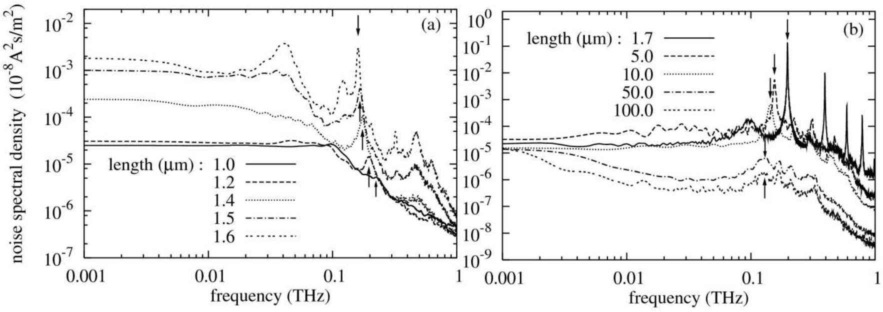

Fig. 1. The noise spectral density in short (a) and long (b) InP n^+nn^+n structures. Arrows indicate the peaks related to plasma instabilities.

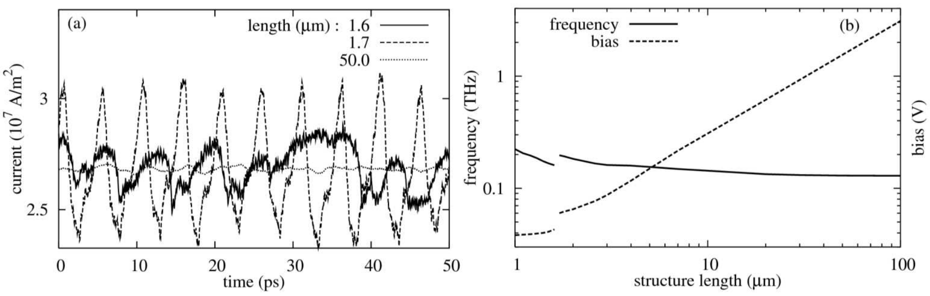

Fig. 2. (a) The simulated stationary time dependent currents in three InP structures of different length at a constant bias. (b) The noise peak frequency $f_{\rm P}$ and applied bias U dependence on length L of the InP n^+nn^+ stucture.

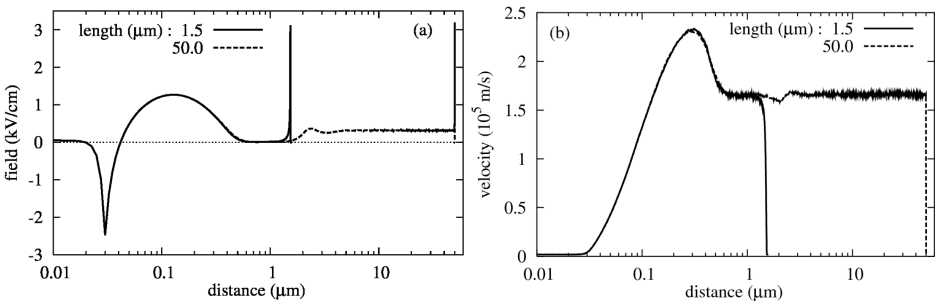

Fig. 3. The simulated field (a) and velocity (b) profiles in 1.5 and 50 μm long InP n^+nn^+ structures.

The effect of OPED PI on the current noise spectrum is much more stronger as compared to the NCL PI effect. The NCL PI in the InP n^+nn^+ structures is suppressed mainly by the impurity scattering. Figure 4a presents the simulated current noise spectrum in 1.4 μm InP structure with conventional impurity

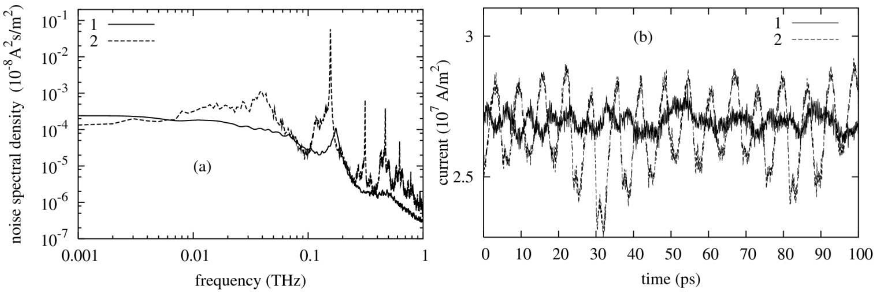

Fig. 4. The current noise spectra (a) and stationary time dependent currents (b) in 1.4 μm long InP n^+nn^+ structure at conventional (1) and reduced by factor of 3 impurity scattering rate (2).

scattering (curve 1) and when the ionized impurity scattering rate is artificially reduced by factor 3 (curve 2).

As one can see, the giant peak and its harmonics arise in the current noise spectrum at the reduced impurity scattering rate (Fig. 4a, curve 2). This peak corresponds to the current oscillations in the InP structure (see Fig. 4b, curve 2). Therefore, the NCL PI can play the significant role in modern structures with remote doping, where the electron concentration in the conducting channel exceeds the impurity concentration.

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