Simulation of Electron Plasma
Instability in n+nn+ GaAs Structure

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Abstract. High frequency microwave generation is feasible in n+nn+ structures because of the electron plasma instability in the device. The time and frequency behaviour of the current instability in the electron plasma of n+nn+ GaAs structure is simulated by Monte Carlo method. The simulation technique involves the particle-in-cell formalism. In the model for simulation, the energy dispersion band is taken to be parabolic and spherical. The other parameters like the effective mass, band gap etc. are taken from the standard literatures. The temperature is taken to be 25°C. Polar optical, acoustic phonon and impurity scatterings are taken into consideration. It is observed that the oscillation frequency in the THz region is affected by the structure length. The optical phonon dominated current instabilities show high peaks alternating with extremely high frequencies in the time scale of pico-seconds. For longer structures, the instability is found to be dominated strongly by the optic phonon scatterings while for short ones it is mainly by the ballistic mode. Smaller is the structure length higher is the instability frequency. It may also be remarked here that the structure length does not affect the carrier behavior very close to the cathode of the structure.

1. Introduction

High frequency oscillations in the millimeter (30-300GHz.) and sub-millimeter waves (300-3000GHz.) find potential applications in radar and communication systems. Instabilities in electron plasma in a semiconductor structure n+ n n+ is a promising mechanism responsible to generate such high frequency oscillations. Usually these instabilities in the plasma wave originate due to the bulk negative differential resistance (NDR) developed in consequence of the electron transfer from the conduction electrons to a high mobility energy valley to a low mobility satellite valley.

For plasma in short structures, the steady state NDR region is not so much feasible as that observed for plasma in bulk materials and therefore the short samples appear to lose their practical utility to generate the high and ultra-high microwave frequencies. Nevertheless, it is not really impossible to generate the high frequency microwaves in such short samples also. In fact, completely a different mode of operation sets in such small structures to develop effectively the NDR. Situation is created to occur the velocity over-shoot of the carriers by incorporating heating and transit time delay of the hot carriers in the plasma. In the subsequent process of relaxation to the equilibrium condition the temporal and spatial decrease of the velocity induces a spatial increase of the carrier concentration and hence an increase in the local electric field. An effective NDR region is thus developed.

In the long-time behavior of the conduction electrons in the plasma, the time evolution of the carrier density fluctuation for any reason, what so ever, leads to the formation of accumulation layer (excess electrons). The
3. Results and Discussion

The one-particle Monte Carlo (OPMC) technique [2,3] is a reliable tool to study the statistical behavior of a microscopic system as it does not suffer from any disadvantages of averaging procedures inherent in other methods. The simulator is supported by the theory of correlation functions of the physical parameters over a steady state trajectory of the particles [4]. We have used the OPMC to study the hot electron behavior of the plasma in n+n structure. Consideration of proper number of particles in the simulation is very important to cater the demand to exhibit the collective phenomena such as the formation of accumulation layers in short structures or high field domains in long ones. Abrupt homojunctions are assumed for simplicity. The simulation domain is discretized by taking uniform rectangular grid. The mesh spacing is taken sufficiently small (smaller than the characteristic Debye length of the system). To investigate the plasma instability noise we first calculate the correlation function of the current and then its Fourier spectrum is extracted.

In this article, we present results of simulation of electron plasma instability in n+ n n+ structure of GaAs. The simulation technique involves the particle-in-cell formalism.

2. Simulation Method

The one-particle Monte Carlo (OPMC) technique [2,3] is a reliable tool to study the statistical behavior of a microscopic system as it does not suffer from any disadvantages of averaging procedures inherent in other methods. The simulator is supported by the theory of correlation functions of the physical parameters over a steady state trajectory of the particles [4]. We have used the OPMC to study the hot electron behavior of the plasma in n+n structure. Consideration of proper number of particles in the simulation is very important to cater the demand to exhibit the collective phenomena such as the formation of accumulation layers in short structures or high field domains in long ones. Abrupt homojunctions are assumed for simplicity. The simulation domain is discretized by taking uniform rectangular grid. The mesh spacing is taken sufficiently small (smaller than the characteristic Debye length of the system). To investigate the plasma instability noise we first calculate the correlation function of the current and then its Fourier spectrum is extracted.

The electric field distribution is determined directly through the solution of the equation

\[ E(x) = E(0) + \frac{e}{\varepsilon_0} \int [ n(x) - N_D(x) ] \, dx \]

where \( n \) and \( N_D \) denote the free carrier concentration and the donor concentration at a given position in the active region. The energy band is taken to be spherical and parabolic. Electron-phonon scattering dominated by optical phonons and electron-ionized impurity scattering are included in the simulation method. The anode and the cathode are modelled as ideal ohmic contacts by maintaining all the time the charge-neutrality condition in the vicinity of the contacts by proper injection of the carriers at the appropriate boundary electrode. The charge assignment algorithm follows the particle-in-cell formalism. In our simulation, the following parameters are chosen for n+n GaAs: the doping levels in the active region are taken to be \( n = 1 \times 10^{23}, 3 \times 10^{23} \) and \( 5 \times 10^{23} \, \text{m}^{-3} \) while in all the cases the contact doping is \( n = 1 \times 10^{23} \, \text{m}^{-3} \); the three different lengths 1.2, 1.4 and 1.6 \( \mu \text{m} \) of the active region are considered. The number of simulated particles are \( 5 \times 10^6 \). The time step in all cases including also the self consistent calculation of Poisson potential is taken to be of 10 fs.

3. Results and Discussion

The plasma oscillation is initiated by the random velocity fluctuation of the carriers and hence by the fluctuation of the space charge at the n+n homojunction. This causes, in turn, fluctuation of the internal electric field in the structure. The dc bias is adjusted to get the same average current density of \( 1.5 \times 10^9 \, \text{A/m}^2 \) for all the structures. The spectral density of the instability noise is plotted in figure 1. The instabilities are considered to be optic phonon dominated if the structure is long enough where the applied bias is such as to excite the optic phonons by collision process as reported in [1]. These are clearly reflected by the presence of the tall and sharp peaks as we scan the figure up from lowest to the longest length of the n-region. It is also observed that the oscillation frequency is in the terahertz region which is the order of the plasma frequency of the electron plasma in the simulated structure. For the short structures, on the other hand, the instability occurs under the environment of ballistic mode [1]. Here the bias is too weak to excite the optic phonons and the plasma is of almost a collisionless plasma so far as the noise is concerned. For the short structures, it is thus seen that the peaks are too
low. In figure 2 we have shown the variation of the current with time for the same n+nn+ structure with three different active lengths. Macroscopically, the current oscillation and hence the internal field variations are the same at all parts of the structure; but microscopically, these fluctuations are different in different parts of the active region.

![Figure 1: Spectral density (S) of instability noise in n+nn+ GaAs structure: (1) S_1 for l = 1.2 µm (2) S_2 for l = 1.4 µm (3) S_3 for l = 1.6 µm. Frequency f in THz and S(x10^{-8}) in A^2s/m².](image)

![Figure 2: Variation of current (c) with time for three different lengths of the active region: (1) c_1 for l = 1.2µm (2) c_2 for l = 1.4µm (3) c_3 for l = 1.6 µm. Time t in pico-seconds and c(x10^7) in A/m².](image)

![Figure 3: Normalized correlation (corr 1) versus correlation time in pico-seconds corresponding to the doping level n = 1x10^{23} m^{-3}.](image)

![Figure 4: Normalised correlation (corr 2) versus correlation time in pico-seconds corresponding to the doping level n = 3x10^{23} m^{-3}.](image)

The growth and decay of the electron plasma current for different doping levels in the active region is reflected by the damped oscillation of the current correlation function as shown in figures 3 and 4. The correlation function in the plot is normalized to that at zero correlation time. The short time behavior of the current correlator is manifested by the sharp peaks in the plot. It is to be remarked here that in the submicron structure the resonant peak associated with the transit time corresponds to the condition nl > 10^{12}cm^{-2} where l is the length of the active region. Pronounced oscillation of the correlation function in the tail region of figure 4, as compared to the tail region oscillation depicted in figure 3, replicates the long time behavior of the electrons in the plasma. The spatial distribution of the electric field and the velocity of the electrons are shown in figures 5 and 6 respectively. It is observed from figure 5 that the field is highly negative near the cathode region and rises up to
positive peaks at different positions in the region. This is due to the accumulation layer formation at these points with much higher concentration. These points are determined by the transit time as well as the length of the active region. The sharp peak occurs at almost near to the anode. The spatial variation in the electron velocity conforms to the spatial variation of the electric field as is observed in figure 6.

Figure 5. Spatial field profile in n+n+ GaAs structure taking the active region length 1.2 μm.

Figure 6. Spatial velocity profile in n+n+ GaAs Structure taking the active region length 1.2 μm.

4. Conclusions
We have used the Monte Carlo simulator to simulate the plasma instability noise in n+n+ GaAs structure under different conditions of doping and length of the active region. It is noticed that the plasma instability is dominated mainly by the optic phonons for relatively longer structures. Smaller is the active region higher is the frequency of oscillation. For such smaller plasma region the instability is guided mainly by the ballistic mode. Further, the optic phonon dominated instability is affected more stronger compared to the ballistic mode of instability.

5. References
[1] Ryzhij V I, Bannov N A and Fedirko V A 1984 Fiz.Tekhn.Poluprovod. 18, 769
[2] Fawcett W, Boardman A D and Swain S 1970 J.Chem.Solids, 31, 1963
[3] Ghosh A and Ghosh K K 2008 Opt. Quant. Electron.(Springer) 40, 439
[4] Martin-Martinez M J, Perez S, Pardo D and Gonzalez T 2001 Jour.App.Phys. 90, 1582