Edited by H. Ryssel, P. Pichler - September 1995

Monte-Carlo simulation of inverted hot carrier distribution under strong carrier-optical phonon scattering

I. Nefedov, A. Andronov

Institute for Physics of Microstructures,
Russian Academy of Science,
46 Ulyanov str., Nyzhny Novgorod,
603600, RUSSIA

Abstract

Results of Monte-Carlo simulation of hot carrier transport in semiconductors with strong carrier-optical phonon interactions under electric and magnetic fields are presented. It is shown that inverted carrier distributions and negative differential conductivity in Teraherts range can be observed in $p-Ge$ under crossed fields, in low valley of $n-GaAs$ under crossed fields and small parallel electric field and in $n-GaAs$ with weak periodic superlattice potential and narrow minigaps under strong electric field.

1. Introduction

Search for new mechanisms of inverted carrier distribution and negative differential conductivity (NDC) in semiconductors is important for development of active semiconductor devices in submillimeter range and beyond. In this report results of Monte-Carlo (MC) simulation of hot carriers transport in low doped semiconductors at low temperature concerning such mechanisms are presented. Three situations are considered: 1) the inverted population of direct optical transitions between subbands of light and heavy holes in $p-Ge$ under crossed electric and magnetic fields; 2) inversion of electron distribution over energy of cyclotron rotation in low valley of $n-GaAs$ under crossed fields with small parallel electric field; 3) rod-like carrier distribution and NDC in $n-GaAs$ with weak periodic superlattice potential and narrow minigaps under strong electric field. In all these cases highly non-equilibrium carrier distribution take place and systems can demonstrate NDC in Teraherts range.

In all these situations emission of optical phonons plays dominating role for formation of carrier distribution. In "passive" region of the momentum space (energy below an optical phonon energy $\hbar\omega_0$) scattering rate of carriers is mainly due to carrier interactions with acoustic phonons and ionized impurities and is much less than the rate in "active" region (energy above $\hbar\omega_0$) where optical phonon emission is involved. For the electric field studied carriers "flight" through the passive region almost without scattering and quickly come back after emission of optical phonon. In crossed fields carriers move along closed trajectoris with rotation centre p_c. If p_c is less than p_0 (the momentum corresponding to $\hbar\omega_0$) there are trajectories entirely lying in the passive region. So, the carriers moving along such trajectories can be accumulated. In the case of $p_c > p_0$ the motion of carriers is similar to their motion in just electric field.

The simulations presented are based on standart one-particle MC algorithm and its modifications necessary for specific problems. The modified self-scattering procedure was included for describing acoustic phonon scattering in $p - Ge$. This procedure contains additional randomization of MC algorithm and is useful when explicit form of scattering probability is absent [1]. The direct transitions for $p - Ge$ and Bragg scattering and tunneling for the superlattices were also included in MC algorithm. Every time a carrier during free flight crosses the energy corresponding to the energy involved in intersubband transition or Brillouin zone boundary a random number is chosen to find which process takes place [2, 3].

2. Laser on hot holes of $p - Ge$

In $p - Ge$ one can choose such values of crossed fields that rotation centre in light hole subband p_c lies below optical phonon while for heavy holes $p_c > p_0$. This is possible due to difference between masses of light and heavy holes. So, light holes are accumulated on the closed trajectories in the passive region and over-population of light hole subband and inversion on direct intersubband transitions may take place (see for review [4]). Detailed MC simulations of hot holes in $p - Ge$ in crossed fields at low temperature have shown that this system demonstrates negative conductivity at the frequencies above 3 Teraherts and stimulated emission at these frequencies can be observed. Influence of the stimulated emission on distribution functions of holes and optimum orientation of the fields relative to crystal axis are also estimated by MC simulation [5, 2].

3. Cyclotron rotation inversion in $n - GaAs$

Carriers get into neighbourhood of point $p = 0$ after emission of optical phonon. So, in crossed fields carriers are accumulated around "main" trajectory crossing the point $p = 0$. If $p_c \leq p_0/2$ the main trajectory is closed and corresponds to large energy of cyclotron rotation (high Landau levels) and inversion over cyclotron rotation energy can take place. MC simulation of electron transport in low valley of $n - GaAs$ has shown that in crossed fields this inversion doesn't occur. Nevertheless adding a small electric field parallel to the magnetic results in higher population of main trajectory as compared with trajectories with small cyclotron energy. MC calculations have shown that in this case the inversion over energy of cyclorton rotation is observed. However, this inversion strongly depends on system parameters and so it will be difficult to obtain this inversion in real samples.

4. Rod-like electron distribution and NDC in superlattices with weak periodic potential and narrow minibands

In superlattices with narrow minigaps at low temperature we consider the situation when top of the first miniband is just below $\hbar\omega_0$. In the electric field a carrier performs Bloch oscillations before it is scattered in the passive region or reaches the active region due to interminiband tunneling. Under these conditions narrow stretched along the field almost symmetric relative to $p = 0$ carrier distribution ("roding") and dynamic NDC at the frequencies higher than Bloch frequency occur. The NDC is a result of carrier bunching in Brillouin zone in the lowest miniband produced by interminiband tunneling [3]. The results of MC simulation demonstrate the roding in carrier distribution and dynamic NDC in Teraherts range.

References

[1] V. A. Kozlov, I. M. Nefedov, Phys. Stat. Sol. (B), vol. 109, p. 393, 1982.

[2] A. V. Muravjev, I. M. Nefedov, S. G. Pavlov, V. N. Shastin, Kvantovaia Elektronika, vol. 20, p. 142, 1993 (russian).

[3] A. A. Andronov, I. M. Nefedov, Abstract 7th Int. Conf. on Superlattices Microstructures and Microdevices, Banff, Alberia, Canada, p. 2.85, 1994.

[4] A. A. Andronov, in Spectroscopy of Nonequilibrium Electrons and Phonos (C. V. Shank and B. P. Zacharchenya eds), Elsevier Science Publishers B. V., p. 169, 1993.

[5] A. V. Muravjev, I. M. Nefedov, Yu. N. Nozdrin, V. N. Shastin, Fizika i Technika Poluprovodnikov, vol. 23, p. 1739, 1989 (russian).