Negative absolute conductivity in quantum wires

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The effect of negative absolute conductivity in quasi-one-dimensional quantum wire structures is obtained by the Monte Carlo simulation. This negative conductivity is associated with inelastic optical phonon scattering leading to an asymmetric electron distribution function established under conditions of intensive electron photoinjection. Simulation results suggest that quantum wires are ideal for the experimental observation of negative absolute conductivity. The oscillations of photoconductivity as a function of injection energy can reveal the spectrum of optical phonons in quantum wires which differs considerably from that in bulk materials.

The effect of negative absolute photoconductivity (NAC) has been predicted independently by Elesin and Manykin[1] and Stocker.[2] If electrons are injected close to the optical phonon energy the electron distribution forms a spherical shell in **k** space. In an external electric field, electrons with positive longitudinal components of wave-vector **k** (against the electric field) will gain energy and enter (or stay in) the active region above optical phonon energy. These electrons will be scattered down to the conduction band bottom by the emission of optical phonons. The electrons with negative longitudinal components of **k** vector will be shifted down to lower energies, will enter (or stay in) the passive region below optical phonon energy, and cannot undergo optical phonon emission. As a result, electrons with negative velocity prevail over those with positive velocity and, accordingly, the drift velocity becomes negative. Recombination is required to eliminate electrons accumulated at the band bottom.

However, it is almost impossible to realize this type of NAC in bulk materials, because of the rapid randomization of the three-dimensional electron momentum due to electron–electron, acoustic phonon, and ionized impurity scattering as well as electron penetration deep into the active region. That is why NAC has never been observed experimentally although several experiments efforts have been reported.[3–6]

The situation has changed substantially with the invention of quasi-one-dimensional (1D) quantum wire (QWI) structures. In the present work, we demonstrate the possibility of realizing the effect of the NAC in a QWI. Numerical results are obtained by the Monte Carlo technique.

We have examined a rectangular 150×250 Å^2 GaAs QWI embedded in AlAs. The model of the QWI includes multisubband structure (all populated subbands up to 12 are taken into account). Usually in the range of temperatures and electric fields considered in the present work the first four subbands are partially populated but only the first subband affect transport since it contains over 90% of all electrons. We have considered electron intra- and intersubband scattering by confined longitudinal-optical (LO) and surface-optical (SO) phonons.[7,8] (It should be pointed out that electron intrasubband scattering is of major importance. Electron intersubband scattering is less important at $T=30$ K since electron must be heated far above optical phonon energy to be scattered to the second subband. In the range of electric fields considered in the present work it happens very rarely.) Two SO phonon modes: GaAs-like and AlAs-like, are taken into consideration. Existence of SO phonons with energies different than LO phonon energy is an important point of our models because it considerably affects the appearance of NAC. The role of SO phonons will be revealed by eliminating SO phonon scattering in a simplified model.

Electrons are permanently injected close to the optical phonon energy and their recombination is taken into account. To the best of our knowledge, so far there exist no data on hot electron recombination in QWIs. This is why we have used simplified recombination model with a step-like energy dependence of recombination rate—equal to a constant value R below some cutoff energy ϵ_1, and equal to zero above ϵ_1. We have chosen several values of ϵ_1 ranging from 0.01 to 0.03 eV in our simulations. The simulation results are not much sensitive to the value of ϵ_1 if it is chosen below optical phonon energy (otherwise the model is similar to the model of constant recombination rate) so that we present results obtained with an optimum value $\epsilon_1=0.022$ eV only.

A QWI presents very favorable conditions for NAC due to several reasons: (i) electrons in QWIs have no transverse components of velocity obstructing the observation of NAC, (ii) the optical phonon emission rate is very high at the active region threshold[7,8] so that electrons are prevented from penetrating into the active region, (iii) the rates of electrons scattering in the passive region decrease dramatically as the electron energy increases. Moreover, electron–electron scattering in single-subband 1D structures involves merely an exchange of momentum between two indistinguishable electrons and neither leads to the relaxation of electron momentum nor influences the electron transport at all.[9] Hence, the electron momentum randomization at the threshold of the active region is slow and does not prevent, accordingly, the realization of NAC.

The effect of NAC may take place not only when electrons are injected close to the optical phonon energy but also if they are injected close to an energy which is multiple of the phonon energy.

Figure 1 shows the steady-state drift velocity as a function of recombination rate at $T=10$ K. One can see from Fig. 1 that NAC occurs at recombination rates as low as 10^9 s^{-1}. The point is that electron scattering in the passive region is so weak that it does not lead to momentum randomization of electrons contributing to conductivity. The only obstacle is electron heating by an electrical field in the passive region. Roughly speaking the heating rate must be lower than the recombination rate in order to observe NAC. Consequently, the electric field defines the critical recombination rate required to get NAC. It is evident from Fig. 1 that the lower the electric field, the lower the recombination rate required to observe NAC. The strict criterion can be derived from electron balance equations. At very low temperatures when acoustic phonon scattering is weak and at low electric fields ($eE \ll Rp_i$) when electrons are injected below the optical phonon energy this criterion is given by

$$p_o e^{-R(p_o-p_i)/eE} + \frac{eE}{R} e^{-Rp_i/eE} > \frac{2eE}{R}, \qquad (1)$$

where p_i and p_o are magnitudes of the momenta corresponding to the electron injection energy and the optical phonon energy, respectively, E is electric field, and R is the recombination rate. The coincidence of curves 1 and 5 obtained within different models clearly demonstrates that NAC is defined by the electrons in the first subband only and that it does not depend on type and energy of the lowest optical phonon (LO) or (SO) if electrons are injected close to that lowest phonon. The difference between curves 3 and 5 obtained within the same realistic model but for different injection energies is essential. The point is that in one case (curve 5) electrons are injected at lowest phonon energy (SO) and in another case (curve 3) they are injected at higher phonon energy (LO), i.e., above lowest phonon energy where they are subjected to strong "background" scattering by SO phonons even if they shift below LO phonon energy. The "background" scattering randomizes electron momentum and reduces the magnitude of NAC or in some cases may even lead to a complete disappearance of NAC.

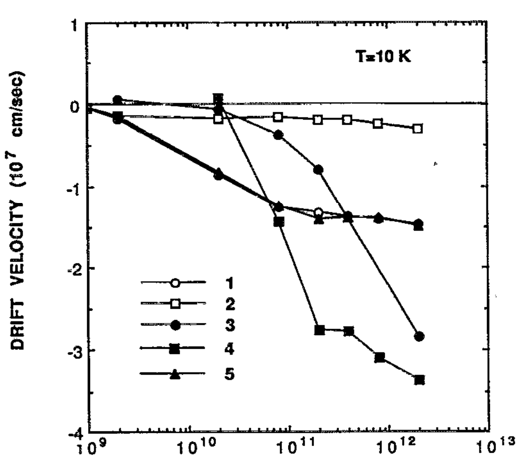

FIG. 1. The steady-state electron drift velocity as a function of recombination rate. Curve 1 represents simplified single-subband model of QWI when only LO phonon are taken into account, with electron injection at the LO phonon energy, $E=3$ V/cm; curves 2 and 4 are for the same simplified model but for $E=0.3$ V/cm and $E=30$ V/cm, respectively, curve 3 is for the realistic multisubband QWI model and account for both LO and SO phonons and electron injection at the LO phonon energy, $E=3$ V/cm; curve 5 is the same as curve 3 but injection is at the SO phonon energy.

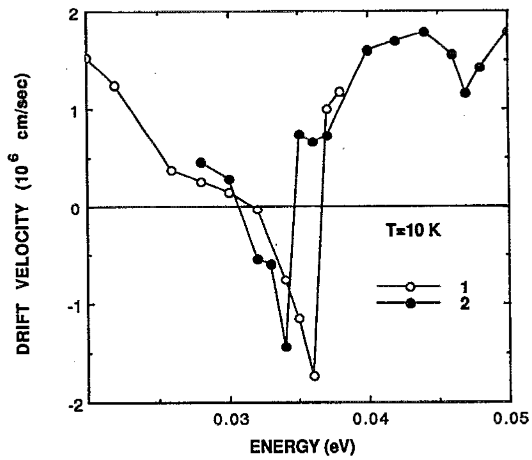

FIG. 2. Electron drift velocity as a function of injection energy. Curve 1 is for single-subband model which account for only LO phonons, and curve 2 is for multisubband model with both SO and LO phonons included; for both curves $R=2\times10^9$ s^{-1}, $E=3$ V/cm.

Figure 2 demonstrates the drift velocity as a function of injection energy for different QWI models. There exists just one minimum in the case of the simplified QWI model corresponding to the energy of the LO phonon. In the case of a real QWI, three minima appear on the dependence reflecting different phonon modes: SO modes at 0.034 and 0.044 eV as well as LO mode at 0.036 eV, but only the first one leads to NAC (curve 2). This is due to the fact that there exist strong "background" scattering by lower energy phonons at higher phonon energies. The different depths of the minima reflect the different electron scattering rates by various phonon modes as well as the different scattering rates in the regions *below* corresponding phonon energies.

The oscillatory dependence of photoconductivity on the injection energy contains all the information on electron scattering by confined and localized phonons in QWIs which could be deduced from the analysis of experimental dependence if they were available. This may be an indirect experimental technique for studying the peculiarities of optical phonon spectrum in low-dimensional structures.

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