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Electron mobility and terahertz absorption due to interactions with confined acoustic phonons in a free-standing quantum well

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Abstract

Electron transport and optical parameters of a free-standing quantum well are studied theoretically. Electron interactions with photons and confined acoustic phonons through the deformation potential are treated rigorously. The quantum kinetic equation for the electron distribution function is solved numerically for nondegenerate as well as degenerate electron gases and the electron momentum relaxation time, the electron mobility and the absorption coefficient in terahertz range are obtained. Both the electron transport and optical parameters exhibit peculiarities, related to the confined acoustic phonon spectrum. They are displayed as peaks at the electron momentum relaxation time dependence on energy and at the second derivative of the absorption coefficient over photon energy. The positions of the peaks is associated with the energies of confined acoustic phonons.

1. Introduction

At present, there is a considerable interest toward new type of nanostructures: free-standing quantum wells (FSQWs) and free-standing quantum wires (FSQWIs). A very important peculiarity of free-standing structures is the quantization of acoustic phonons. The acoustic phonon quantization has been observed both in optical and electrical experiments [1, 2]. The acoustic phonon modes in free-standing structures and their interaction with electrons have been studied in a number of papers (see e.g. Refs. [3–5] and references therein).

In this report, we present results of our investigation of the steady-state electron transport in FSQWs and of the terahertz radiation absorption by electron gas allowing for the exact form of the confined acoustic modes and their spectra. We have solved the kinetic equation for electrons in the low electric field limit. We have obtained the electron distribution function, the momentum relaxation time, and the electron mobility, and have analyzed their temperature dependences. We have also solved the quantum kinetic equation for electrons in the field of terahertz radiation and obtained the absorption coefficient, which has peculiarities at frequencies, corresponding to energies of confined acoustic phonons.

2. Basic approach

There are three different types of acoustic modes in FSQWs: shear waves, dilatational waves and the flexural waves (see e.g. Refs. [5] and references therein). They differ by their specific symmetry and their interaction with electrons depends on electron wave function symmetry. We restrict our consideration by the extreme quantum limit where only the first electron subband is occupied and we assume that electron potential energy is a symmetric function with respect to the mid-plane. Under these conditions, only the dilatational acoustic phonons contribute to the electron scattering through the deformation potential, and therefore, we will take into account only these modes. We will denote the frequencies of dilatational modes as $\omega_{m,q}$, where $m = 0, 1, 2, \ldots$, and q is the phonon in-plane wave vector.

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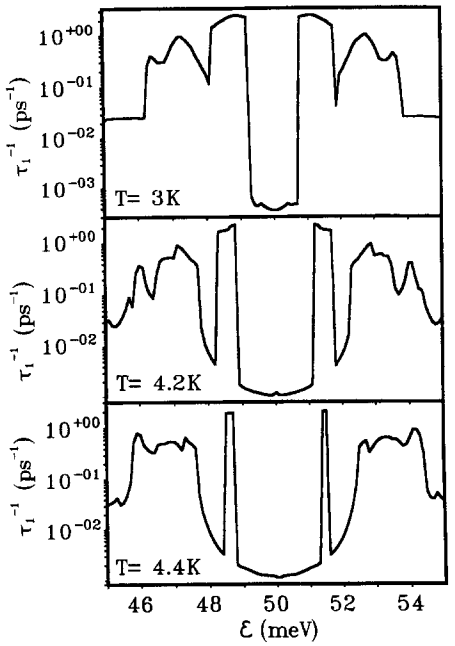

Fig. 1. The inverse momentum relaxation time τ_1^{-1} as a function of the electron energy ε for lattice temperatures $T = 3$, 4.2 and 4.4 K. Width of GaAs FSQW = 100 Å and $\varepsilon_F = 50$ meV.

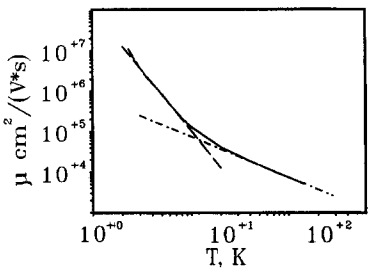

Fig. 2. The electron mobility μ (solid line) as a function of the lattice temperature. The dotted line corresponds to the $1/T$ dependence and the dashed line to the $1/T^3$ dependence. Transition to the Bloch–Grüneisen regime occurs in the temperature range 40–8 K. Width of GaAs FSQW = 100 Å and $\varepsilon_F = 50$ meV.

The electron subsystem may be described by the diagonal term of electron density matrix f_p where $\boldsymbol{p}$ is the electron in-plane momentum, which is governed by the kinetic equation

$$\frac{\partial f_p}{\partial t} + e\boldsymbol{E}_0 \frac{\partial f_p}{\partial \boldsymbol{p}} = J(f_p, \boldsymbol{E}_1, t)\,. \tag{1}$$

Eq. (1) takes into account both the constant electric field $\boldsymbol{E}_0$, and the high-frequency electric field $\boldsymbol{E}_1 \sin \Omega t$ (both are in-plane of FSQW), however, the time-dependent part of the electric field is included into collision integral of electrons with dilatational phonons, J. This equation may be obtained from the Liouville equation by a regular contraction procedure over phonon and electron variables. We have solved Eq. (1) for two particular cases: $E_0 \neq 0, E_1 = 0$ (stationary electron transport) and $E_0 = 0$, $E_1 \neq 0$ (terahertz absorption).

3. Stationary electron transport

In the low electric field limit, we may use the following expansion for electron distribution function $f_p = f_p^0 + \boldsymbol{f}_{1p} \cdot \boldsymbol{p}/p$ where f_p^0 is the equilibrium Fermi–Dirac distribution. $\boldsymbol{f}_{1p}$ may be expressed through the momentum relaxation time $\tau_1(p)$, which satisfies the integral equation

$$\tau_1(p)^{-1} = \sum_{p',m} W^m_{p\to p'} \left[1 - \frac{p'\cos\varphi}{p}\frac{\tau_1(p')}{\tau_1(p)}\right] \frac{1 - f^0_{p'}}{1 - f^0_p}, \tag{2}$$

where φ is an angle between $\boldsymbol{p}'$ and $\boldsymbol{p}$, $W^m_{p\to p'}$ is the rate of electron scattering by dilatational mode m.

We have solved Eq. (2) numerically and determined the electron transport parameters. Fig. 1 demonstrates the $\tau_1(p)^{-1}$ dependence on the electron energy for GaAs FSQW of width 100 Å with Fermi energy $\varepsilon_F = 50$ meV at three lattice temperatures. Fig. 2 displays the temperature dependence of electron mobility, μ. The peaks in $\tau_1(p)^{-1}$ occurs only at low lattice temperatures and related to the electron scattering by the lowest dilatational phonon modes. The low field electron mobility has a temperature dependence similar to the Bloch–Grüneisen formula: it has the T^{-1} dependence in the high-temperature region and the T^{-3} dependence (instead of T^{-5} in the Bloch–Grüneisen formula) in the low-temperature region.

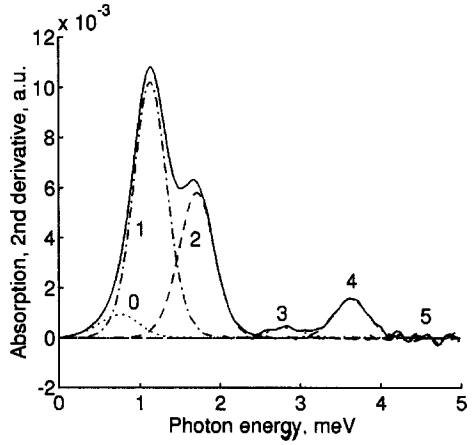

Fig. 3. The second derivative of the absorption coefficient over frequency as a function of photon energy (solid curve). Numbered curves display contributions by the corresponding phonon modes. Width of GaAs FSQW = 100 Å and $\varepsilon_F = 10$ meV and $T = 1$ K.

4. Terahertz absorption

We have solved the kinetic equation for one-particle density matrix (1) in the second order of the perturbation theory. Then, we have calculated the absorption coefficient of electromagnetic wave by free electrons in FSQW in the terahertz frequency range. We took into account a time-dependent electric field, an exact form of acoustic phonon spectrum and eigenmodes, and electron interactions with dilatational phonons through the deformation potential. The numerical results have been obtained for GaAs FSQW of width 100 Å at low lattice temperatures in the frequency range 0.1–1 THz. Fig. 3 displays the second derivative of the absorption coefficient over the frequency for $T = 1$ K for the six lowest acoustic phonon modes (numbers near the curves from 0 to 5 mark the phonon modes) and the total absorption coefficient.The absorption coefficient exhibits several maxima at frequencies corresponding to the lowest acoustic phonon modes. These maxima occur due to the absorption of photons by electrons which is accompanied by the emission of corresponding acoustic phonons.

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