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Energy losses of 2D electron gas due to near-surface acoustic phonon scattering

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We have shown that for quantum wells placed close to the stress-free surface of the semiconductor heterostructure, the energy relaxation rate of two-dimensional electrons interacting with acoustic phonons at low temperatures (Bloch–Grüneisen regime) is changed considerably in comparison with that of a two-dimensional electron gas placed in a bulk of semiconductor. The relaxation rate is enhanced in the case of a semiconductor–vacuum system and is suppressed in the case of the surface covered by a thin metal film. The enhanced energy loss is caused by additional scattering at localized and reflected acoustic waves, and the decrease appears due to suppression of piezoelectric scattering in the vicinity of the metal.

Key words: Bloch–Grüneisen regime, energy relaxation rate, electron–phonon scattering, piezoelectric, deformation potentials.

1. Introduction

At low temperatures scattering with acoustic phonons is a principal process leading to energy losses of electrons in semiconductor heterostructures [1]. In recent years, the influence of modification of the acoustic phonon modes in bounded semiconductor heterostructure on the electron relaxation process has attracted substantial interest; see, e.g. [2] and references therein. It was shown that proximity of a two-dimensional electron gas (2DEG) to the surface of semi-infinite semiconductor [2–4] or slab [5] may substantially change the relaxation processes compared with that for 2DEG placed in the bulk of semiconductor. A large change in energy loss occurs at low temperatures when the phonon scattering processes are inelastic (Bloch–Grüneisen regime). This regime corresponds to temperatures T which are less than or comparable to the characteristic temperature $T_0 = 2sp_F/k_B$ where s is sound velocity, p_F the electron Fermi momentum, and k_B Boltzmann's constant. The results [2, 3, 5] were obtained for electron–acoustic phonon interaction via the deformation potential (DP). For GaAs-based heterostructures, piezoacoustic (PA) scattering dominates over that of the DP interaction [1] at low temperatures and the transition from DP-coupled to PA-coupled phonon

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scattering takes place for temperatures close to the transition temperature T_0. Thus, to study the influence of the surface on the electron kinetics in real semiconductor materials, one also has to take into account the PA scattering. To the best of our knowledge, the energy relaxation of 2DEG interacting via DP and PA potentials with the full set of phonon modes in semi-bounded systems has not been carried out to date, and that is a subject of this paper. We consider a semi-bounded heterostructure with a stress-free surface and use two types of electrical boundary conditions; one corresponds to the semiconductor-vacuum system and the other to a semiconductor covered by a thin metal film.

2. Model and basic equations

We shall consider a semiconductor heterostructure which occupies the half space $z > 0$ with a stress-free plane boundary at $z = 0$. At the distance z_0 from the surface, there is a 2D electron channel formed by the electrons in a rectangular quantum well (QW) of width d. For the sake of simplicity, we assume the same elastic and piezoelectric properties, densities, and dielectric constants for all of the layers of the heterostructure. We assume that electrons occupy the lowest subband, and that the wavefunction for transverse movement is $\psi(z) = (2/d)^{1/2}\cos(\pi(z - z_0)/d)$ for $|z - z_0| \leq d/2$ and $\psi(z) = 0$ outside the QW.

The electron system is described by the Fermi distribution function with electron temperature, T_e. The energy relaxation rate, ν_e, is introduced through the balance equation

$$\frac{2}{n_s L^2}\sum_{\boldsymbol{p}} \varepsilon_p J_{e-ph}(\boldsymbol{p}) = -\nu_e(T_e - T). \tag{1}$$

Here n_s is the electron sheet density, L^2 is the normalization area in the xy-plane; $\boldsymbol{p} = (p_x, p_y)$, $\varepsilon_p = p^2/2m^*$ and m^* are the 2D momentum, the energy and the effective mass of electrons, $J_{e-ph}(\boldsymbol{p})$ is the integral of electron–phonon collisions. Electrons are assumed to be degenerate and the case of a small deviation from thermodynamic equilibrium is considered. The change of electron potential energy due to interaction with acoustic phonons is $V = D\ \mathrm{div}\boldsymbol{u} + e\phi$, where D is the deformation potential constant and ϕ is the sum of piezoelectric potential and potential induced by redistribution of the electron density. The displacement vectors, $\boldsymbol{u}$, are found from the elastic wave equation in the isotropic continuum approximation, the stress-free boundary conditions at the surface $z = 0$ are imposed. In our calculations, we exploit the full set of modes used in Refs [2, 4]. In this representation, phonons are characterized by the set of quantum numbers $\omega, \boldsymbol{q}$, and j, where ω is the angular frequency, $\boldsymbol{q} = (q_x, q_y)$ is the in-plane wavevector, and the label j specifies different types of the modes. The interaction Hamiltonian is

$$\hat{H} = \sum_{j,\boldsymbol{q}} \int \mathrm{d}\omega \left(\frac{\hbar}{2\rho\omega L^2}\right)^{1/2} \left[e\phi_{j\omega\boldsymbol{q}} + D\left(i\boldsymbol{q}\boldsymbol{u}_{j\omega\boldsymbol{q}} + \frac{\partial u_{zj\omega\boldsymbol{q}}}{\partial z}\right)\right] e^{i(\mathbf{qr}-\omega t)} b_{j\omega\boldsymbol{q}} + H.c., \tag{2}$$

where $b_{j\omega\boldsymbol{q}}$ is a phonon annihilation operator, ρ represents the density, and $j = l, th, tv, R$. The modes l, th and tv correspond to the following choice of incident waves: longitudinal incident wave (l-mode), transverse horizontal wave polarized in xy-plane (th-mode), and transverse vertical wave polarized in the plane of incidence (tv-mode); the R-mode denotes a Rayleigh wave which has velocity s_R and obeys the dispersion law $\omega = s_R q$. For each mode, the integration is over the range where the mode exists.

The potential $\phi_{j\omega\boldsymbol{q}}$ is determined from Poisson's equation. We assume that the z-axis is oriented along the (001) direction in a cubic crystal. We shall consider the two types of boundary conditions. For a semiconductor having an electrically free boundary with a vacuum, the electric potential vanishes in vacuum as the distance from the crystal increases, and the potential and normal components of dielectric displacement are continuous at the surface $z = 0$. The short-circuit condition, $\phi_{j\omega\boldsymbol{q}}(z = 0) = 0$, is applied for a piezoelectric sample covered with a metal film.

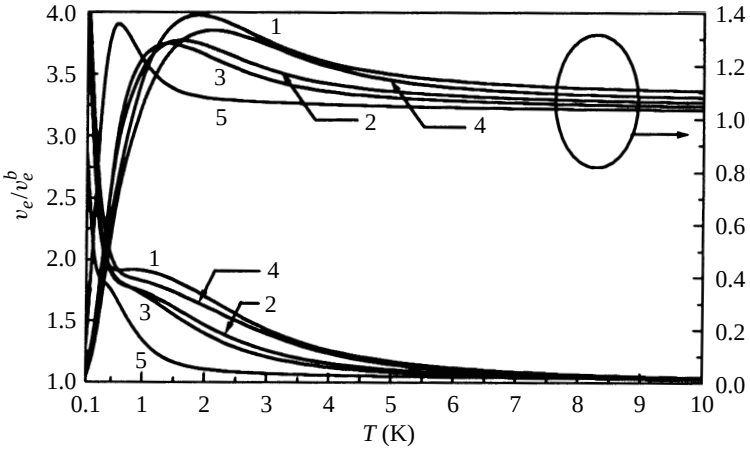

Fig. 1. Ratio of energy relaxation rates to bulk values vs. temperature for a semiconductor bounded by a vacuum (a metal film). The distance z_0 from the crystal surface to the center of a QW equals $3d/2$, where d is the width of the well. Sheet electron concentrations n_s are: 1–10^{11} cm^{-2}; 2, 4, 5–2.2×10^{11} cm^{-2}; 3–3×10^{11} cm^{-2}; well widths, d: 1, 2, 3–50 Å, 4–40 Å, 5–100 Å. The curves marked by a circle in the upper part of the figure correspond to a semiconductor in contact with a metal film.

The transition probability due to the interaction with phonons is calculated within the fermi golden rule approximation. Further derivation of the total relaxation rate may be carried out in analogy to that for DP scattering [3]; the procedure yields the following final form

$$\nu_e = \frac{m^{*2}}{4\pi\hbar\rho k_F^3 (k_B T)^2} \sum_j \int_0^\infty \mathrm{d}\omega \int_0^{2k_F} \mathrm{d}q \, \frac{\omega^2 |M_j(\omega, q)|^2}{|\epsilon_e|^2 \ (1 - (q/2k_F)^2)^{1/2} \sinh^2(\hbar\omega/2k_B T)}. \tag{3}$$

Hereafter, ω and q are expressed through the energy and momentum transfer of the electrons: $\hbar\omega = |\varepsilon - \varepsilon'|$, $\hbar q = |\boldsymbol{p} - \boldsymbol{p}'|$ in accordance with the energy and momentum conservation laws. M_j is the scattering matrix element, ϵ_e is the dielectric permittivity of 2DEG, and $k_F = p_F/\hbar$. The l, tv, and R-modes contribute to both the DP and the PA interactions, and the th-mode contributes to only the PA interaction. In the case of interest, when the surface of cubic crystal is spanned by two lattice axes, the scattering is isotropic (in xy-plane), and thus, the DP and PA mechanisms contribute to the transition rate additively: $|M_j|^2 = |M_j^{PA}|^2 + |M_j^{DP}|^2$. The dielectric permittivity ϵ_e of 2DEG depends on a QW position z_0 and is given by

$$\epsilon_e(z_0, q) = 1 + \frac{2}{a_B q} \int_0^\infty \mathrm{d}z \psi^2(z) \int_0^\infty \mathrm{d}z' \psi^2(z') [e^{-q|z-z'|} + g(\epsilon_0) e^{-q(z+z')}], \tag{4}$$

where $a_B = \epsilon_0 \hbar^2/m^* e^2$ is effective Bohr radius, ϵ_0 is the lattice dielectric permittivity, $g = (\epsilon_0 - 1)/(\epsilon_0 + 1)$ for contact with vacuum and $g = -1$ for contact with metal. The screening is taken into account within the Thomas–Fermi approximation which is a satisfactory one at low temperatures [2].

3. Results and discussion

Let us first discuss the temperature behaviour of the energy relaxation rates for the different types of electrical boundary conditions. For a narrow QW placed close to the surface and for the temperature T, small compared with the transition temperature T_0, the tangential and normal components of phonon wavevector, q and $q_j = (\omega^2/s_j^2 - q^2)^{1/2}$ respectively, are much smaller than the width of the well, d, and the distance z_0. The first nonzero term in the expansion of M_j^{PA} over $kz_0 \ll 1$, where $k = q_l, q_t, q$ is $(kz_0)^0$ in the case of

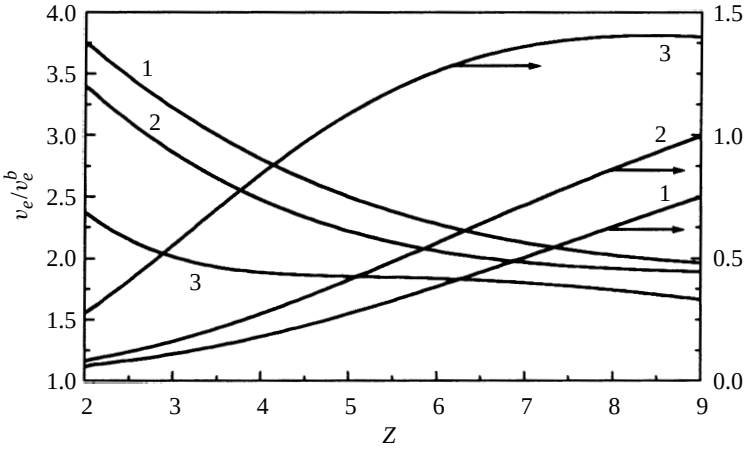

Fig. 2. Ratio of energy relaxation rates to bulk values as a function of distance from the crystal surface to the center of QW, $Z = 2z_0/d$, for a semiconductor in contact with a vacuum (a metal film) at temperature $T = 0.2$ K. The electron sheet concentrations $n_s = 10^{11}$ cm^{-2}; well widths d: 1–40 Å, 2–50 Å, 3–100 Å. The right y-axis refers to a semiconductor in contact with a metal film.

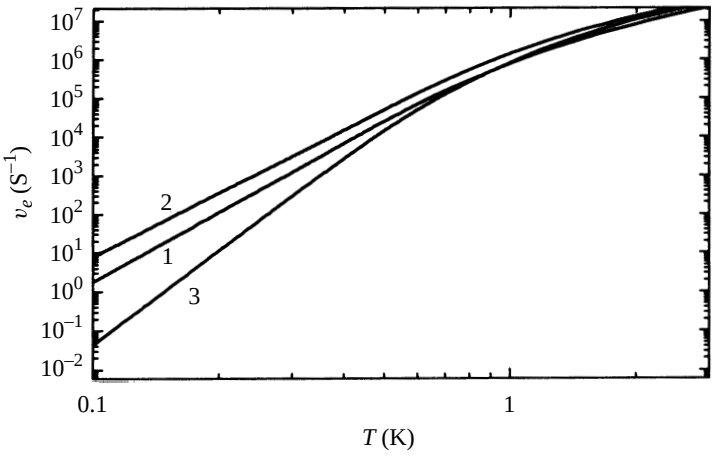

Fig. 3. Energy relaxation rates as a function of temperature for a semiconductor in contact with: 2: a vacuum, 3: metal film. Curve 1 corresponds to a bulk rate. Sheet electron concentration $n_s = 2.2 \times 10^{11}$ cm^{-2}, well width of 40 Å.

boundary with vacuum and is $(kz_0)^1$ for a surface covered by metal film. The corresponding expansion of M_j^{DP} begins with $(kz_0)^0$ regardless of a type of surface. In the limit of small q, ϵ_e increases as q^{-1} (contact with vacuum) or appears to be independent to q (metallized surface).

In the case of a semiconductor–vacuum system, from eqn (3) we get the following dependences: $\nu_e^{DP} \sim T^6$ for screened and $\sim T^4$ for unscreened interaction; $\nu_e^{PA} \sim T^4$ and $\nu_e^{PA} \sim T^2$, respectively. These power laws agree with known result for a 2DEG in the bulk [1]. For a semiconductor covered with a thin metal film, we find $\nu_e^{DP} \sim T^4$ and $\nu_e^{PA} \sim T^4$ for both the cases of screened and unscreened interactions. In a vicinity of metallic surface the bare PA interaction is suppressed but simultaneously the screening is decreased, so the power laws for the screened PA interaction remain the same for both types of surfaces. It should be noted that eqn (4) does not contain a small parameter which justifies the neglect the screening.

Numerical calculations were carried out for the following parameters of GaAs: $s_l = 5.2 \times 10^5$ cm s^{-1},

$s_t = 3.0 \times 10^5$ cm s^{-1}, $s_R = 2.77 \times 10^5$ cm s^{-1}, $\rho = 5.3$ g cm^{-3}, $\epsilon_0 = 12.5$, $m^* = 0.067\, m_0$, $D = 8$ eV, and the component of the piezoelectric tensor $e_{14} = 0.16$ C m^{-2}. The temperature dependences of the normalized energy relaxation rates of a 2DEG placed close to the surface of a semiconductor with vacuum and metal boundaries are shown in Fig. 1. The normalization function, ν_e^b, is the bulk value (ν_e ($z_0 \to \infty$)). Figure 1 shows that the proximity of the semiconductor–vacuum interface results in an enhancement of the electron–acoustic phonon scattering. The effect is more pronounced for thin QWs with low electron densities. As seen from Fig. 1, the temperature dependence of ν_e/ν_e^b in a semiconductor-metal system differs radically from that of a semiconductor bounding a vacuum. The most significant result illustrated in Fig. 1 is a decrease in the near-surface scattering. The rapid increase at the lowest temperatures in Fig. 1 illustrates the important role of PA scattering for a semiconductor bounded by a vacuum. At the same time, the rapid drop of the rates shown in Fig. 1 demonstrates that PA-coupled scattering near a metallized surface is suppressed. The right part of Fig. 1 shows that with the increase of temperature the relaxation rates approach to the bulk value, ν_e^b. The temperature dependences in this range are similar for the both types of boundary conditions. The enhancement of the energy loss is mainly due to additional scattering by surface-reflected and localized phonon modes. The dependences of the normalized energy relaxation rates on the QW position are shown in Fig. 2. We see that the influence of a crystal surface has a long-distance character and the corresponding scale is larger for thin electron channels. Figure 3 shows the temperature dependence of the energy relaxation rate for QW placed in the bulk of semiconductor and near the boundary with vacuum and metal film.

In conclusion, the peculiarities of the near-surface scattering originate from modification of the acoustic-phonon modes caused by the stress-free crystal surface, dependence of the phonon-induced piezoelectric potential and a dielectric permittivity of 2DEG on the dielectric properties of a medium in contact with the semiconductor.

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