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Energy Relaxation of 2D-Electrons Due to Near-Surface Acoustic Phonon Scattering

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The calculations of free and rigid surface effects on the energy losses for 2D-electrons in a semi-infinite heterostructure are carried out for the deformation electron−acoustic phonon interaction. It is shown that the efficiency of relaxation is changed substantially (up to two times) depending non-monotonically on the distance of the 2D-layer to the surface and on the electron temperature.

The energy losses of 2D-electrons are determined by collisions with near surface acoustic phonon modes if the width of a top clouding layer is compared to the characteristic wavelength transmitting under scattering. The efficiency of electron−phonon interaction, $D\,\mathrm{div}\,\mathbf{u}_\mathbf{r}$, ($D$ is the deformation potential, $\mathbf{u}_\mathbf{r}$ is a vector of displacement) depends on the near surface modification of the acoustic displacement field (the cases of the free and rigid surfaces are under consideration). Below we present calculated results for 2D-electron energy losses, Q, versus the distance to the 2D-layer, z_0, electron and phonon temperatures (T_e and T). The results are essentially different for the free and rigid boundary conditions and for the three temperature ranges determined by the characteristic energies [1],

$$\varepsilon_1 = 2s_\mathrm{l}p_\mathrm{F}\,, \qquad \varepsilon_2 = 2s_\mathrm{l}\hbar/d\,, \tag{1}$$

where s_l is the longitudinal sound velocity, p_F is the Fermi momentum, d is the width of the 2D-layer. While for the high-temperature range (T_e, $T > \varepsilon_2$) the surface effect is vanished, for the intermediate range (T_e, T between ε_1, ε_2) the dependencies $Q(T_\mathrm{e}, T)$ and $Q(z_0)$ are nonmonotonic; in the low-temperature case (T_e, $T \ll \varepsilon_1$) the surface effect is large, but the piezoelectric contributions are essential here, and this range will be considered separately.

The transition probability from the electron state $\psi_\mathbf{p}(\mathbf{r})$ to the state $\psi_{\mathbf{p}'}(\mathbf{r})$ ($\mathbf{p}$ and $\mathbf{p}'$ are 2D-momenta in the ground subband) is given by

$$W(\mathbf{p},\,\mathbf{p}') = \left(\frac{D}{\hbar}\right)^2 \int \mathrm{d}\mathbf{r} \int \mathrm{d}\mathbf{r}'\; \psi_{\mathbf{p}'}(\mathbf{r})^*\, \psi_{\mathbf{p}'}(\mathbf{r}')\, \psi_\mathbf{p}(\mathbf{r})\, \psi_\mathbf{p}(\mathbf{r}')^*\, \langle (\nabla\cdot\hat{\mathbf{u}}_\mathbf{r})\,(\nabla'\cdot\hat{\mathbf{u}}_{\mathbf{r}'})\rangle\,, \tag{2}$$

where $\langle\ldots\rangle$ means the statistic average over an equilibrium phonon distribution. The correlator $\langle \hat{u}^\alpha_\mathbf{r}\hat{u}^\beta_{\mathbf{r}'}\rangle$ can be expressed in terms of the elasticity theory Green function $G^{\alpha\beta}_\omega(\mathbf{r},\,\mathbf{r}')$ in the following form:

$$\langle \hat{u}^\alpha_\mathbf{r}\hat{u}^\beta_{\mathbf{r}'}\rangle = -2\hbar\;\mathrm{Im}\;G^{\alpha\beta}_{\omega+i0}(\mathbf{r},\,\mathbf{r}')\,(N_{\hbar\omega/T} + 1/2 \pm 1/2)\,. \tag{3}$$

Here $N_{\hbar\omega/T}$ is Planck distribution function for the phonons with the energy $\hbar\omega = |\varepsilon - \varepsilon'|$, where ε and ε' are initial and final electron energies. Using the familiar equations for $G_{\omega}^{\alpha\beta}(\mathbf{r}, \mathbf{r}')$ with boundary conditions on a free and clamped surfaces (see [2]) and excluding longitudinal electron motion from (2) we derive the transition probabilities for absorption and emission phonon processes (upper and lower occupation factors) in the form

$$W(\mathbf{p}, \mathbf{p}') = \frac{2D^2}{\hbar L^2} \int \mathrm{d}z\, \varphi_z^2 \int \mathrm{d}z'\, \varphi_{z'}^2 K_{\omega,q}(z, z') \begin{cases} (N_{\hbar\omega/T} + 1); & \varepsilon > \varepsilon', \\ N_{\hbar\omega/T}; & \varepsilon < \varepsilon'. \end{cases} \tag{4}$$

Here φ_z is the wave function of an electron at the ground subband, L^2 is the normalized area and the kernel $K_{\omega,q}(z, z')$ is given by

$$K_{\omega,q}(z, z') = \mathrm{Re}\, \frac{\omega^2}{2\varrho s_{\mathrm{l}}^4 k_{\mathrm{l}}} \left[\mathrm{e}^{ik_{\mathrm{l}}|z-z'|} + R(\omega, q)\, \mathrm{e}^{ik_{\mathrm{l}}(z+z')}\right], \tag{5}$$

ϱ is the density of the material, $R(\omega, q)$ is a reflectance coefficient from the surface [3] and k_j (with $j = l, t$) are determined as

$$\begin{aligned} k_j &= [(\omega/s_j)^2 - q^2]^{1/2}; \qquad q < \omega/s_j, \\ k_j &= i[q^2 - (\omega/s_j)^2]^{1/2}; \qquad q > \omega/s_j. \end{aligned} \tag{6}$$

The energy losses, $Q = (2/nL^2) \sum\limits_{\mathbf{p}} \varepsilon_p J_{\mathrm{e-ph}}(\mathbf{p})$, are expressed through the electron–phonon collision integral, $J_{\mathrm{e-ph}}(\mathbf{p})$, which is related to the transition probability by the usual way. Using the quasi-equilibrium Fermi distribution, $\tilde{f}_\varepsilon = \{\exp[(\varepsilon - \mu)/T_{\mathrm{e}}] + 1\}^{-1}$, we get

$$Q = \frac{1}{nL^2} \sum_{\mathbf{pp}'} (\varepsilon - \varepsilon')\, W(\mathbf{p}, \mathbf{p}') \left\{\exp\left(\frac{\varepsilon' - \varepsilon}{T}\right) \tilde{f}_{\varepsilon'}(1 - \tilde{f}_\varepsilon) - \tilde{f}_\varepsilon(1 - \tilde{f}_{\varepsilon'})\right\}. \tag{7}$$

The dependencies $Q(T, T_{\mathrm{e}})$ and $Q(z_0)$ may be obtained after the integration (4) and (7).

In order to demonstrate the surface effect on energy loss processes we calculated numerically the ratio Q/Q^{b}, where $Q^{\mathrm{b}} = Q(z_0 \to \infty)$. This value depends on the temperature ratio T_{e}/T, the dimensionless QWs position $2z_0/d$, and electron concentration n, which is involved in the ratio ε_1/T, while the main dependence on the material parameters amounts to the sound velocity ratio $s_{\mathrm{l}}/s_{\mathrm{t}}$. In the calculations below we used $s_{\mathrm{l}}/s_{\mathrm{t}} = 1.78$ which is closed to the GaAs- and InAs-based QW parameters. The dependencies of Q/Q^{b} versus T_{e}/T and $2z_0/d$ are presented in Figs. 1 and 2, respectively (the labels f and r denote the cases of free and rigid surfaces). Fig. 1 displays the nonmonotonic energy losses of electrons in narrow QWs with a thin top layer ($z_0 = d = 3$ nm) for different n and T. If T becomes higher, the surface effect on Q/Q^{b} is vanished rapidly with increasing of T_{e}/T. Fig. 2 demonstrates the distance dependencies of Q/Q^{b} and the surface effect is decreased with increasing T_{e}/T; more detailed results for the energy relaxation rate ($T_{\mathrm{e}}/T \to 1$) are presented in [4]. The modification of energy losses due to changing of the boundary conditions is demonstrated by the ratio of the energy losses $Q^{\mathrm{f}}/Q^{\mathrm{r}}$ in Fig. 3. Though the energy losses are increased (decreased) near the free (rigid) surface mainly (see Figs. 1, 2) the dependencies of $Q^{\mathrm{f}}/Q^{\mathrm{r}}$ show a more complicated behavior, moreover, the contributions of Rayleigh wave, existing near a free surface, and t $\to$ l-mode conversation (the case when k_{t} is real and k_{l} is imaginal in (6)) appear to be essential.

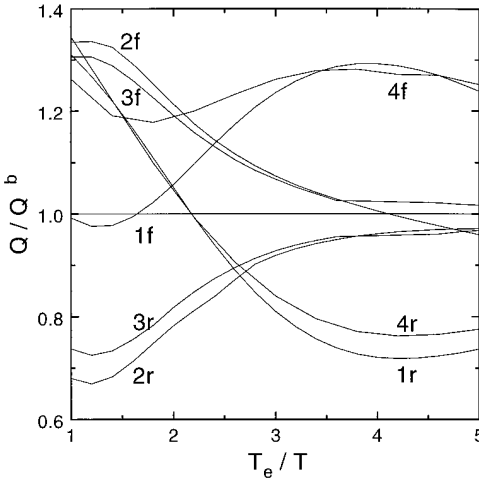

Fig. 1

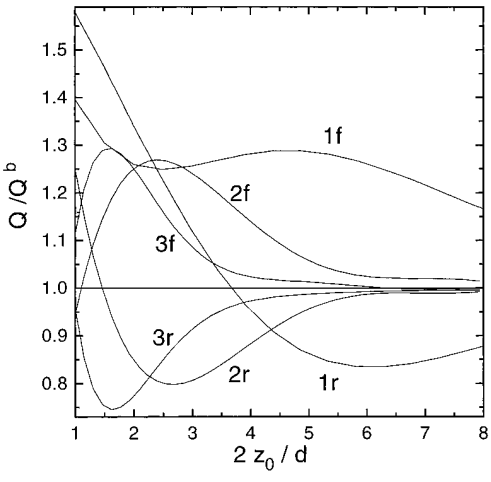

Fig. 2

Fig. 1. Energy losses normalized to the bulk value Q^{b} vs. the electron temperature calculated for: (1) $n = 10^{15}\,\mathrm{m}^{-2}$, $T = 1\,\mathrm{K}$; (2) $n = 10^{15}\,\mathrm{m}^{-2}$, $T = 3\,\mathrm{K}$; (3) $n = 3 \times 10^{15}\,\mathrm{m}^{-2}$, $T = 3\,\mathrm{K}$; (4) $n = 3 \times 10^{15}\,\mathrm{m}^{-2}$, $T = 1\,\mathrm{K}$

Fig. 2. Energy losses normalized to the bulk value vs. the distance calculated for: $d = 3\,\mathrm{nm}$, $n = 3 \times 10^{15}\,\mathrm{m}^{-2}$, and $T_{\mathrm{e}}/T = 1$; 3; 5 for curves 1, 2, 3, respectively

The surface effect is noticeable even the heating is large ($T_{\mathrm{e}}/T \gg 1$) and for large distance ($2z_0/d \gg 1$), and these modifications have to be taken into account in the interpretation of the experimental results [5]. Large surface effects may be revealed in the structures with extremely thin clouding layer that has been used for optical investigations recently [6]. Thus, the presented data demonstrate that due to near-surface modifications of phonons and electron–phonon interaction (so called *phonon engineering*) the energy relaxation processes are changing sufficiently.

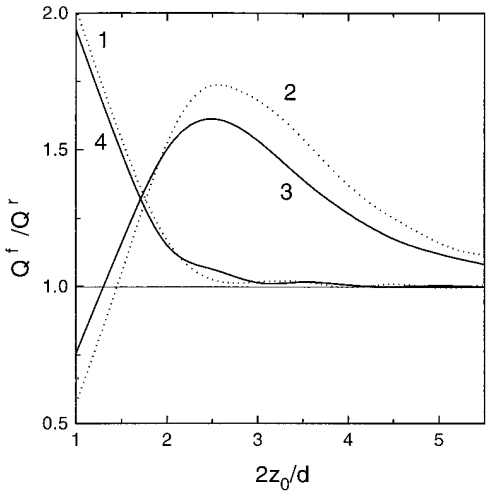

Fig. 3. Ratio of the energy losses for free and rigid surfaces vs. the distance to QW, calculated for: (1) $n = 10^{15}\,\mathrm{m}^{-2}$, $T = 1\,\mathrm{K}$; (2) $n = 10^{15}\,\mathrm{m}^{-2}$, $T = 3\,\mathrm{K}$; (3) $n = 3 \times 10^{15}\,\mathrm{m}^{-2}$, $T = 1\,\mathrm{K}$; (4) $n = 3 \times 10^{15}\ \mathrm{m}^{-2}$, $T = 3$ K for $T_{\mathrm{e}}/T = 3$ and $d = 3\,\mathrm{nm}$

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