Phonon-induced magnetoresistance oscillations in a high-mobility quantum well*

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Abstract: We examine the temperature dependence of acoustic-phonon-induced magnetoresistance oscillations in a high-mobility GaAs-based quantum well with conventional transverse and longitudinal phonon modes, using a model in which the temperature increase of the Landau level broadening or the single-particle scattering rate $1/\tau_s$ is attributed to the enhancement of electron-phonon scattering with rising temperature. The non-monotonic temperature behavior, showing an optimal temperature at which a given order of oscillation amplitude exhibits a maximum and the shift of the main resistance peak to higher magnetic field with rising temperature, is produced, in agreement with recent experimental findings.

Key words: two-dimensional electron gas; phonon-induced magnetoresistance oscillations; linear mobility; optimal temperature

DOI: 10.1088/1674-4926/31/9/092001 **PACC:** 7210D

1. Introduction

In addition to the well-known Shubnikov–de Haas oscillations (SdHOs) showing up at low temperature in the linear magnetoresistance of a two-dimensional (2D) electron gas (ES), other types of magnetoresistance oscillations in high-mobility 2D semiconductors, induced by microwave radiation and/or by a direct current, have been observed over the past decade. The discoveries of microwave-induced magnetoresistance oscillations (MIMOs)[1−8] and current-induced magnetoresistance oscillations (CIMOs)[9−12] stimulated intense theoretical studies on linear and nonlinear magnetotransport in 2D electron systems[13−23]. They stem mainly from impurity or disorder scatterings and the direct phonon contributions to the resistivity are believed to be relatively small in these systems at such low temperatures.

However, the magnetophonon resonance in semiconductors, previously known to result from electron coupling with optic phonons and to be observed only at high temperatures and high magnetic fields, has been demonstrated to occur at temperatures as low as $T \approx 2$ K and lower magnetic fields in GaAs-based high-mobility systems by acoustic phonon scatterings[24−26]. These phonon-induced magnetoresistance oscillations (PIMOs) are periodic in inverse magnetic field $1/B$ with the resistance peak located around integer values of $2k_F v_{s\lambda}/\omega_c$, where ω_c is the cyclotron frequency, k_F is the Fermi wavevector of electrons and $v_{s\lambda}$ is the velocity of the relevant acoustic phonon. When a finite current flows through the 2D system the behavior of PIMO changes drastically[27]. Theoretical studies have already appeared to explain these experimental observations[28,29].

Further careful measurement by Hatke *et al.*[30] on the temperature variation of these PIMOs disclosed that with rising temperature the oscillation amplitude increases first, and then decreases after reaching a maximum. Resonance peaks of different orders exhibit different optimal temperatures for the maximum amplitude, and higher order oscillations are best developed at lower temperatures. This behavior has been confirmed by a recent measurement of another group[31], and a shift of the peak position of the magnetophonon resistance oscillations to higher magnetic fields with increasing temperature was also observed. The temperature dependence was attributed to the electron-electron interaction modifying the single-particle lifetime[30,31].

In this letter we examine these PIMOs in a GaAs–AlGaAs quantum well using a balance-equation scheme, in which the temperature dependence of Landau level broadening or the single particle lifetime τ_s results from the enhancement of electron–phonon scattering with rising temperature. The non-monotonic temperature behavior, showing an optimal temperature at which a given order of the resistance oscillation amplitude exhibits a maximum and a peak position shift with rising temperature, is reproduced. The optimal temperature corresponding to the largest oscillation amplitude is found to scale approximately with $B^{1/2}$, in agreement with experimental findings.

2. Theory

We consider a quasi-2DES consisting of N_e electrons in a unit area of an x–y plane. These electrons are confined within a GaAs-based quantum well of width a, subjected to a uniform magnetic field $B = (0, 0, B)$ in the z direction and scattered by random impurities and by phonons in the lattice. The linear longitudinal resistivity consists of impurity and phonon con-

* Project supported by the National Basic Research Program of China (No. 2007CB310402), the National Natural Science Foundation of China (No. 60721004), and the Major Projects (Nos. KGCX1-YW-24 , KGCX2-YW-231) and the Hundred Scholar Plan of the Chinese Academy of Sciences.

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Received 23 March 2010

tributions, $R_{xx} = R_i + R_p$, which can be expressed, in the balance-equation transport theory[28], as

$$R_i = -\frac{1}{N_e^2 e^2} \sum_{q_\parallel} q_x^2 \left|U(\boldsymbol{q}_\parallel)\right|^2 \frac{\partial}{\partial \Omega} \Pi_2(\boldsymbol{q}_\parallel, \Omega)\big|_{\Omega=0}, \quad (1)$$

$$R_p = -\frac{1}{N_e^2 e^2} \sum_{q,\lambda} q_x^2 \left|M(\boldsymbol{q}, \lambda)\right|^2 \frac{\partial}{\partial \Omega} \Lambda_2(\boldsymbol{q}, \lambda, \Omega)\big|_{\Omega=\Omega_{q\lambda}}. \quad (2)$$

In this, $U(\boldsymbol{q}_\parallel)$ is the effective impurity potential, $M(\boldsymbol{q}, \lambda)$ is the effective coupling matrix element between a λ-branch 3D phonon having wave-vector $\boldsymbol{q}$ and energy $\Omega_{q\lambda}$ and a quasi-2D electron, $\Pi_2(\boldsymbol{q}_\parallel, \Omega)$ and $\Lambda_2(\boldsymbol{q}, \lambda, \Omega) \equiv 2\Pi_2(\boldsymbol{q}_\parallel, \Omega)\left[n\left(\Omega_{q\lambda}/T\right) - n\left(\Omega/T\right)\right]$ are the imaginary parts of the electron density correlation function and electron–phonon correlation function, and $n(x) \equiv 1/(e^x - 1)$ is the Bose function.

The $\Pi_2(\boldsymbol{q}_\parallel, \Omega)$ function of a 2D system in a magnetic field can be expressed in the Landau representation:

$$\Pi_2(\boldsymbol{q}_\parallel, \Omega) = \frac{1}{2\pi l_B^2} \sum_{n,n'} C_{n,n'}(l_B^2 q_\parallel^2/2) \Pi_2(n, n', \Omega), \quad (3)$$

$$\Pi_2(n, n', \Omega) = -\frac{2}{\pi} \int d\varepsilon \left[f(\varepsilon) - f(\varepsilon + \Omega)\right] \times \mathrm{Im}G_n(\varepsilon + \Omega)\, \mathrm{Im}G_{n'}(\varepsilon), \quad (4)$$

where $l_B = \sqrt{1/|eB|}$ is the magnetic length, $C_{n,n+l}(Y) \equiv n![(n+l)!]^{-1} Y^l e^{-Y} [L_n^l(Y)]^2$ with $L_n^l(Y)$ the associated Laguerre polynomial, $f(\varepsilon) = \{\exp[(\varepsilon - \mu)/T] + 1\}^{-1}$ is the Fermi function at lattice temperature T, and $\mathrm{Im}G_n(\varepsilon)$, the density-of-states of the broadened Landau level n (with energy centering at ε_n) is modeled with a Gaussian form[32]:

$$\mathrm{Im}G_n(\varepsilon) = -\left(\sqrt{2\pi}/\Gamma\right) \exp\left[-2(\varepsilon - \varepsilon_n)^2/\Gamma^2\right]. \quad (5)$$

The half-width of the Landau level $\Gamma = (2\omega_c/\pi\tau_s)^{1/2}$ ($\omega_c = eB/m$ is the cyclotron frequency) or the single-particle lifetime τ_s depends on electron-impurity, electron-phonon and electron–electron scatterings, and is temperature–dependent. In this paper, we assume that the single-particle lifetime τ_s is related to the transport scattering time τ_{tr}, which depends on electron–impurity and electron-phonon scatterings, by an empirical parameter α, such that Γ can be expressed in terms of the linear mobility μ_0 at lattice temperature T in the absence of the magnetic field[28, 33]:

$$\Gamma = (8e\omega_c\alpha/\pi m\mu_0)^{1/2}. \quad (6)$$

Here α serves as the only adjustable parameter in the present investigation.

3. Calculation result and discussion

In the numerical calculation we deal with a GaAs-based quantum well with $a = 30$ nm, $N_e = 3.75 \times 10^{15}$ m^{-2}, and low-temperature linear mobility $\mu_0(0) = 1200$ m^2/(V·s) in the absence of magnetic field, considering electron scatterings from bulk longitudinal acoustic phonons (one branch, via the deformation potential and piezoelectric couplings with electrons) and transverse acoustic phonons (two branches, via the piezoelectric coupling with electrons), as well as from impurities. The relevant matrix elements and material and coupling parameters are taken as typical values of GaAs[34]: electron effective mass $m = 0.068m_e$ (m_e is the free electron mass), acoustic deformation potential $\Xi = 8.5$ eV, piezoelectric constant $e_{14} = 1.41 \times 10^9$ V/m, transverse sound speed $v_{st} = 2.48 \times 10^3$ m/s, longitudinal sound speed $v_{sl} = 5.29 \times 10^3$ m/s, and material mass density $d = 5.31$ g/cm^3.

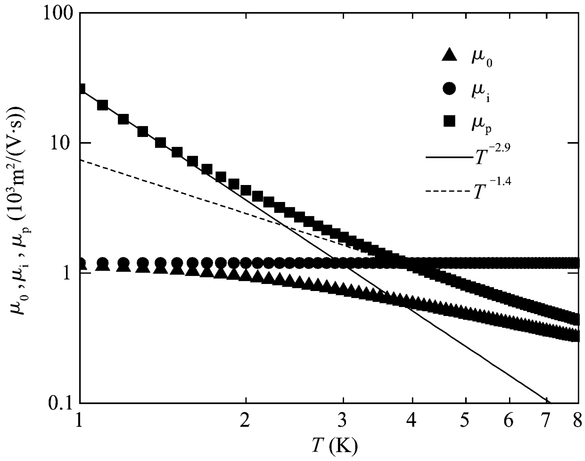

Fig. 1. Total mobility μ_0, impurity-limited mobility μ_i and acoustic-phonon limited mobility μ_p are plotted versus temperature T for a GaAs-based quantum well with $a = 30$ nm, $N_e = 3.75 \times 10^{15}$ m^{-2} and $\mu_0(0) = 1200$ m^2/(V·s).

The calculated linear mobility μ_0 is presented in Fig. 1 as a function of temperature, together with its impurity- and phonon-limited parts μ_i and μ_p respectively: $1/\mu_0 = 1/\mu_i + 1/\mu_p$. We can see that μ_i is almost constant and μ_p decreases rapidly with rising temperature from $\mu_p \propto T^{-2.9}$ around $T = 1$ K to $\mu_p \propto T^{-1.4}$ around $T = 8$ K, resulting in the diminishing of total mobility $\mu_0(T)$ with growing T. These features agree with the experiment observation[30].

Using these values of $\mu_0(T)$ in Eq. (6) we calculated the linear longitudinal resistivities R_i due to impurities, R_{st} due to transverse acoustic phonons, and R_{sl} due to longitudinal acoustic phonons. Figure 2 shows the calculated R_{st} and R_{sl} versus magnetic field at $T = 3.5$ K obtained with a parameter $\alpha = 6.2$. Magnetophonon resistance oscillation peaks showing up at magnetic fields around $2k_F v_{s\lambda}/\omega_c \approx j$ ($\lambda = $ t, l), the first three peaks ($j = 1, 2, 3$) in R_{st} are denoted in the figure.

Figure 3 demonstrates the temperature evolution of the total longitudinal resistivity $R_{xx} = R_i + R_{st} + R_{sl}$ from 2 K to 6 K in 0.25 K increments and from 6 K to 14 K in 1 K increments, obtained with $\alpha = 6.2$. PIMOs and SdHOs coexist at lower T. With increasing temperature, SdHOs decay uniformly, while PIMOs exhibit interesting features. When T ascends, the amplitude of a given order magnetophonon oscillation initially grows, then reaches a maximum at an optimal temperature T_0 before eventually weakening at higher temperature. Figure 4(a) shows the amplitudes of the three peaks of R_{xx}, $j = 1, 2, 3$, as functions of T, at $\alpha = 6.2$. The square of

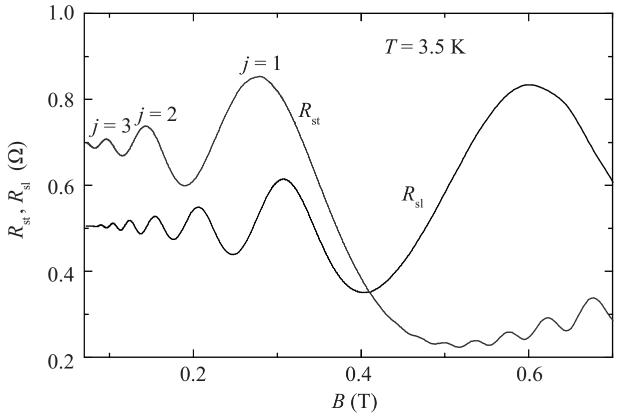

Fig. 2. Linear longitudinal resistivities R_{st} due to transverse acoustic phonons and R_{sl} due to longitudinal acoustic phonons at temperature $T = 3.5$ K in a GaAs-base quantum well as described in Fig. 1.

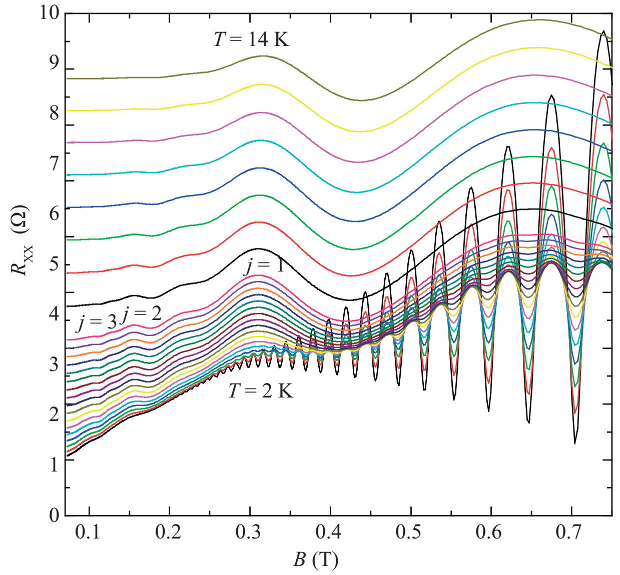

Fig. 3. The linear magnetoresistivity R_{xx} for the system described in Fig. 1 at temperatures from 2 K to 6 K in 0.25 K increments and from 6 K to 14 K in 1 K increments.

the optimal temperature T_0^2 is roughly proportional to the magnetic field strength B as shown in Fig. 4 (b), in agreement with the experimental results[30], which are shown as crosses in the figure. Note that at a given order of oscillation T_0^2 increases and the slope of the whole T_0^2-versus-B curve becomes larger when the parameter α decreases. A value of $\alpha = 6.2$ yields a reasonably good agreement with the slope of the experimental square of the optimal temperature to the magnetic field in Ref. [30]. This α value seems to be a quite reasonable one for the ratio of transport scattering time τ_{tr} to the single-particle life time τ_s in a high-mobility 2D semiconductor as related to the impurity and phonon scatterings.

Another interesting feature which can be clearly seen from Fig. 2 is that the $j = 1$ peak of magnetophonon resistance oscillations shifts slightly to higher magnetic field when temperature rises, as observed by a recent experiment[31].

The above discussion focuses mainly on the resonance peak series related to the transverse acoustic phonon scattering.

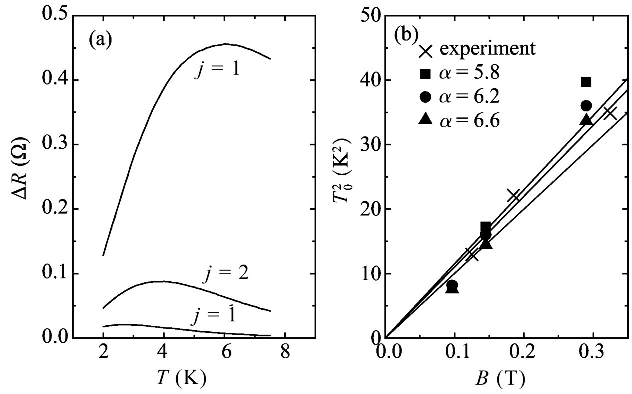

Fig. 4. (a) PIMO amplitude ΔR versus temperature T at $j = 1, 2$, and 3 peaks for the system described in Fig. 1 obtained with $\alpha = 6.2$. (b) Optimal temperature T_0^2 versus B, at $\alpha = 5.8, 6.2$ and 6.6. The crosses are the experiment results of Ref. [30].

When the temperature rises an additional distinct peak emerges around $B = 0.65$ T ($2k_F v_{sl} = \omega_c$) due to longitudinal phonon scattering as shown in Fig. 3, which should correspond to the $\downarrow$ peak in Fig. 2 of Ref. [30].

4. Conclusion

In summary, we have examined the temperature dependence of acoustic-phonon-induced magnetoresistance oscillations using a model in which the temperature increase of the Landau level broadening or the single-particle scattering rate $1/\tau_s$ results from the enhancement of electron–phonon scattering with rising temperature. The non-monotonic temperature behavior, showing an optimal temperature at which a given order of the resistance oscillation amplitude exhibits a maximum and a shift of the main resistance peak to higher magnetic field with rising temperature, is produced, in agreement with recent experimental findings. In Refs. [30] and [31] this temperature behavior of PIMOs was attributed entirely to the electron–electron interaction modifying the single-particle lifetime, while the effects of electron–phonon interactions are neglected. The present investigation, though not excluding the effect of electron-electron scattering on the single-particle lifetime, provides an alternative possible mechanism for the issue.

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