

Effect of electron-electron scattering on magnetointersubband resistance oscillations of two-dimensional electrons in GaAs quantum wells

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The low-temperature ($4.2 < T < 12.5$ K) magnetotransport ($B < 2$ T) of two-dimensional electrons occupying two subbands (with energy E_1 and E_2) is investigated in GaAs single quantum well with AlAs/GaAs superlattice barriers. Two series of Shubnikov-de Haas oscillations are found to be accompanied by magnetointersubband (MIS) oscillations, periodic in the inverse magnetic field. The period of the MIS oscillations obeys condition $\Delta_{12} = (E_2 - E_1) = k \cdot \hbar \omega_c$, where Δ_{12} is the subband energy separation, ω_c is the cyclotron frequency, and k is the positive integer. At $T = 4.2$ K the oscillations manifest themselves up to $k = 100$. Strong temperature suppression of the magnetointersubband oscillations is observed. We show that the suppression is a result of electron-electron scattering. Our results are in good agreement with recent experiments, indicating that the sensitivity to electron-electron interaction is the fundamental property of magnetoresistance oscillations, originating from the second-order Dingle factor.

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The Landau quantization in quasi-two-dimensional (2D) electron systems (with two or more occupied subbands) manifests itself in two or more sets of Landau levels. Resonance transitions of electrons between Landau levels corresponding to different two-dimensional subbands^{1,2} causes the so-called magnetointersubband (MIS) oscillations of the resistance ρ_{xx} .³⁻⁵ The interaction between two subbands can be also significant for other phenomena such as cyclotron resonance.⁶ The position of the maxima of the MIS oscillations obeys the condition $\Delta_{12} = E_2 - E_1 = k \cdot \hbar \omega_c$, where Δ_{12} is the intersubband energy gap, E_i is the energy of the bottom of i th subband, ω_c is the cyclotron frequency, and index k is the positive integer. The oscillations, similar to well-known Shubnikov-de Haas (SdH) oscillations, are periodic in the inverse magnetic field and appear in classically strong magnetic fields. The amplitude of SdH oscillations is limited by the broadening of Landau levels due to scattering and by thermal broadening of the Fermi distribution. With increasing temperature the thermal broadening of the Fermi distribution becomes the dominant factor, limiting the amplitude of SdH oscillations. MIS oscillations are significantly less sensitive to the electron distribution and their amplitude is predominantly determined by a quantum relaxation time τ_q .^{4,5}

MIS oscillations were recently observed in GaAs double quantum wells with AlAs/GaAs superlattice barriers with roughly equal electron densities in subbands ($n_1 \approx n_2$).⁷⁻¹⁰ The quantum lifetimes of the electrons in subbands was also approximately equal ($\tau_{q1} \approx \tau_{q2}$).¹¹ In the general case of two populated subbands the amplitude of the MIS oscillations of the resistance $\Delta\rho_{\text{MISO}}$ depends on the sum of the quantum scattering rates in each subband^{4,5}

$$\Delta\rho_{\text{MISO}} = \frac{2m}{e^2(n_1 + n_2)} \cdot \nu_{12} \cdot \exp[-(\pi/\omega_c)(1/\tau_{q1} + 1/\tau_{q2})] \cdot \cos\left(\frac{2\pi\Delta_{12}}{\hbar\omega_c}\right), \quad (1)$$

where $1/\tau_{qi}$ and n_i are the quantum scattering rate and electron density in i th subband, and m is electron band mass. Parameter ν_{12} is an effective intersubband scattering rate.⁵

In this Brief Report we investigate MIS oscillations in GaAs single quantum well with AlAs/GaAs superlattice barriers, when two subbands are occupied with substantially different densities. In the temperature range of $T = 4.2 - 12.5$ K a strong decrease in the amplitude of the MIS oscillations with the temperature is observed. We consider the suppression of the MIS oscillations as a result of a temperature dependence on quantum scattering times τ_{qi} . We have found that the temperature variation in the sum of quantum scattering rates ($1/\tau_{q1} + 1/\tau_{q2}$) is proportional to T^2 , indicating dominant contribution of the electron-electron scattering to the suppression of the MIS oscillations.

Heterostructures under the study were symmetrically doped GaAs single quantum wells with a width of 26 nm and AlAs/GaAs superlattice barriers.^{12,13} The diagram of the quantum well with two occupied subbands E_1 and E_2 is presented in the inset of Fig. 1. The structures were grown on GaAs substrates, whose deviation from the (100) plane did not exceed 0.02° . The measurements were carried out in the temperature range of $T = 4.2 - 12.5$ K in the magnetic field $B < 2$ T on 450×50 μm Hall bars, fabricated using optical lithography and liquid etching. Magnetoresistance $\rho_{xx}(B)$ and

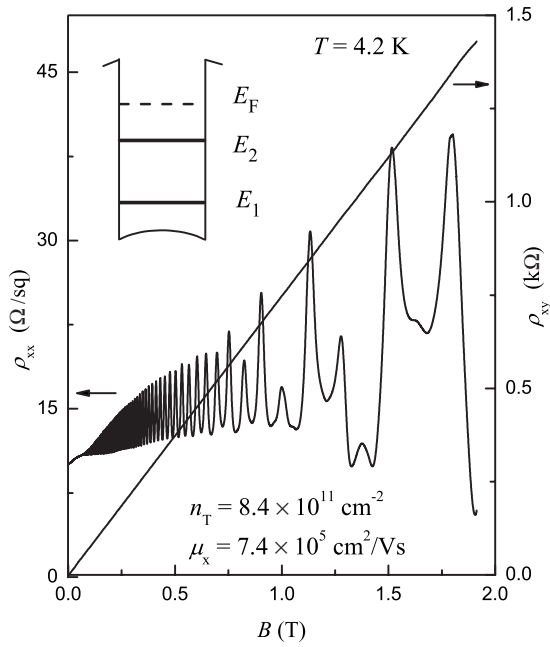


FIG. 1. Resistance $\rho_{xy}(B)$ and $\rho_{xx}(B)$ in GaAs quantum well with AlAs/GaAs superlattice barriers at $T=4.2$ K. The inset shows the diagram of the quantum well with two occupied subbands with energies at the bottom of the subbands E_1 and E_2 .

$\rho_{xy}(B)$ was measured using ac current $I_{ac} < 1 \mu A$ in the frequency range of 0.01–1 kHz. The total electron density, $n_T = 8.4 \cdot 10^{11} \text{ cm}^{-2}$, was calculated from the Hall resistance ρ_{xy} in magnetic field $B=0.5$ T. The electron mobility $\mu_x = 7.4 \cdot 10^5 \text{ cm}^2/\text{V s}$ was obtained from n_T and zero-field resistance $\rho_{xx}(B=0) = \rho_0$ at liquid-helium temperature.

Figure 1 presents typical experimental curves of resistance $\rho_{xy}(B)$ and $\rho_{xx}(B)$ in studied samples. In magnetic field $B < 1$ T the Hall resistance $\rho_{xy}(B)$ follows a straight line, indicating negligible contributions of the Landau quantization to the response. The slope of $\rho_{xy}(B)$ depends on the total electron density n_T . At $T=4.2$ K the longitudinal resistance ρ_{xx} oscillates with magnetic fields at $B > 0.07$ T. For the quantum well with two occupied subbands the oscillatory part of $\rho_{xx}(B)$ contains two series of SdH oscillations and the magnetointersubband oscillations,^{1–5} dominating at low magnetic fields $B < 0.5$ T.

Figure 2 presents $\rho_{xx}(1/B)$ dependence, demonstrating, that ρ_{xx} oscillations have only one period at the low magnetic fields ($1/B > 2 \text{ T}^{-1}$). The Fourier transform of the oscillatory part of $\rho_{xx}(1/B)$ is shown in the inset of Fig. 2. Three frequencies, associated with the peaks and marked as f_1 , f_2 , and f_3 , are identified as follows. The frequency f_3 corresponds to magnetointersubband oscillations, while $f_1 = 13 \text{ T}^{-1}$ and $f_2 = 4 \text{ T}^{-1}$ correspond to two series of SdH oscillations from the two subbands with electron densities $n_1 = 2ef_1/h = 6.3 \cdot 10^{11} \text{ cm}^{-2}$ and $n_2 = 2ef_2/h = 1.9 \cdot 10^{11} \text{ cm}^{-2}$. The frequency of the highest peak $f_3 = 9.1 \text{ T}^{-1}$ equals (with an accuracy of 1%) to the difference between the other two frequencies $f_1 - f_2$.

The sum of the two densities ($n_1 + n_2 = 8.2 \cdot 10^{11} \text{ cm}^{-2}$) is, to a high degree of accuracy (2%), equal to the total density n_T , calculated from the Hall resistance. The intersubband en-

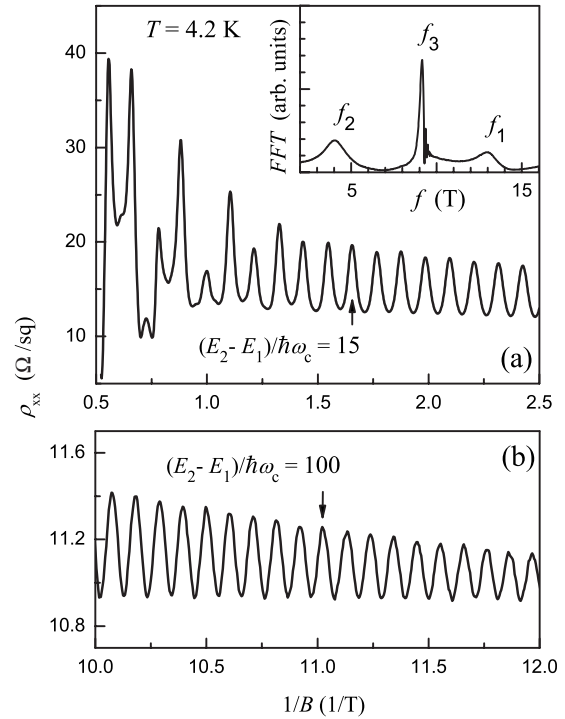


FIG. 2. Resistance ρ_{xx} vs inverse magnetic field $1/B$ in GaAs quantum well with two occupied subbands E_1 and E_2 at $T=4.2$ K. Arrows mark the positions of the maxima corresponding to $k = \Delta_{12}/\hbar\omega_c = 15$ and 100. The inset shows the Fourier transform of the oscillatory part of the resistance $\rho_{xx}(1/B)$.

ergy gap $\Delta_{12} = 15.8 \text{ meV}$, calculated from the frequency f_3 , is in a good agreement with band-structure calculations of the studied GaAs quantum well. Thus, the experimental data indicate that the magnetoresistance oscillations ρ_{xx} with frequency f_3 are the magnetointersubband oscillations and the position of the oscillation maxima obeys the relation $\Delta_{12} = k \cdot \hbar\omega_c$, where $\Delta_{12} = 15.8 \text{ meV}$ and k is the positive integer. It is worth mentioning, that at helium temperatures our samples show the MIS oscillations with the index k up to 100, indicating a very high quality of our samples. It has provided the study of the oscillations in a very broad range of the inverse magnetic fields.

Figure 3(a) presents the experimental dependences of $\rho_{xx}/\rho_0(1/B)$ at temperatures of 4.2 and 12.5 K. One can see a substantial suppression of MIS oscillations with the increase of the temperature. Figure 3(b) shows the amplitudes of the magnetointersubband oscillations plotted against $1/B$ on a semilogarithmic scale. In a wide range of magnetic fields the amplitude of the oscillations are well approximated by the expression [Eq. (1)] with a constant (B -independent) intersubband scattering rate ν_{12} and the B -independent broadening of Landau levels ($\sim 1/\tau_{qi}$). At $T=4.2$ K and in very small magnetic fields $B < 0.1$ T the approximation fails. Reasons of the discrepancy are not clear at the moment. A failure of the linear approximation is also observable at $T=12.5$ K at high magnetic fields. We attribute this discrepancy to the influence of magnetophonon resonance seen in high-mobility semiconductor structures at large filling factors.^{14,15}

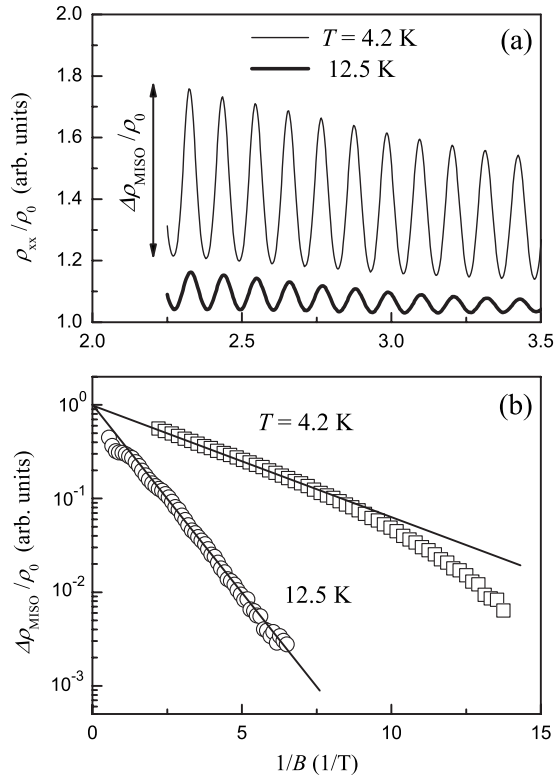


FIG. 3. (a) Normalized ρ_{xx}/ρ_0 vs $1/B$ in GaAs quantum well with two occupied subbands at temperatures 4.2 and 12.5 K. (b) $\Delta\rho_{\text{MISO}}/\rho_0$ vs $1/B$ at $T=4.2$ and 12.5 K. Straight lines correspond to Eq. (1) $\Delta\rho_{\text{MISO}}/\rho_0 = \exp[-(\pi/\omega_c) \cdot (1/\tau_{q1} + 1/\tau_{q2})]$.

Shown in Fig. 3(a), the strong temperature dependence of MIS oscillations indicates a significant variation in the quantum lifetime of electrons τ_q with the temperature. Figure 4 presents the temperature dependence of the sum of quantum scattering rates $1/\tau_{q1} + 1/\tau_{q2}$. In the plot each point is extracted from the slope of the dependence of the logarithm of the amplitude of MIS oscillations on the inverse magnetic field, measured at different temperatures [see Fig. 3(b)]. In accordance with Eq. (1), the slope is proportional to the sum $1/\tau_{q1} + 1/\tau_{q2}$. We have found that the temperature variation in the sum of the quantum scattering rates is well approximated by the square of the temperature. Figure 4 presents the data plotted versus T^2 . A linear plot $1/\tau_{q1} + 1/\tau_{q2} = A + B \cdot T^2$ provides a reasonable fit with $A=0.142$ (1/ps) and $B=0.00415$ [1/(ps K²)].

Figure 4 shows that the temperature-dependent terms of the inelastic-scattering rates are proportional to T^2 , indicating the dominant contribution of the electron-electron interaction to the broadening of the Landau levels. In accordance with the theory,^{16,17} the contribution of the electron-electron interaction into the electron lifetime is proportional to T^2 and inversely proportional to the electron Fermi energy E_F . For a two-band system, we have used the following approximation for the e - e scattering rate: $1/\tau_{ee} = \lambda_{eff}(1/E_{F1} + 1/E_{F2}) \cdot T^2$, where $E_{Fi} = E_F - E_i$ is the Fermi energy counted from the bottom of the i th band. A comparison between the expression and the experiment yields $\lambda_{eff} \approx 2$, which is close to theoretical estimations.

Elastic impurity scattering controls the temperature-

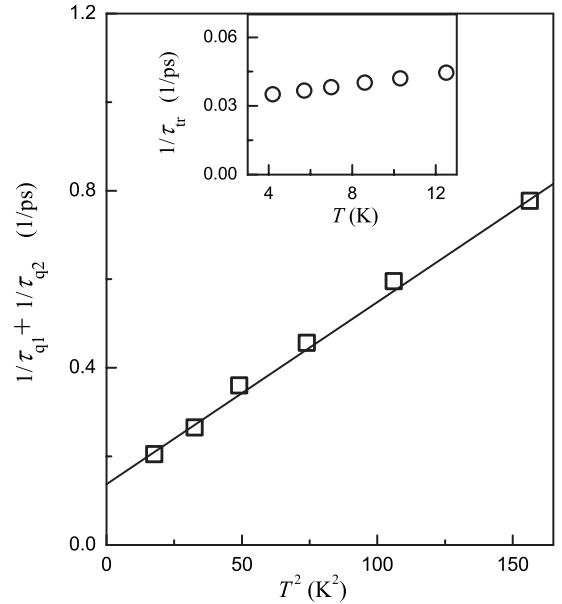


FIG. 4. Sum of the scattering rates $\Sigma_q = 1/\tau_{q1} + 1/\tau_{q2}$ vs T^2 in GaAs quantum well with two occupied subbands. Straight line corresponds to $\Sigma_q = A + B \cdot T^2$ with $A=0.142$ and $B=0.00415$.

independent term A of the Dingle factor. The obtained value of the sum of the impurity scattering rates $A = 1/\tau_{q1}^{im} + 1/\tau_{q2}^{im} = 0.142$ (1/ps) indicates the impurity scattering time $\tau_q^{im} > 14$ (ps) in one or both subbands, demonstrating again the high quality of the measured structures. The inset in Fig. 4 shows temperature dependence of the transport scattering rate $1/\tau_{tr}$, obtained from the resistance at zero magnetic field. The transport scattering rate depends weakly on the temperature. We note also, that in the studied range of temperatures, the value of the quantum scattering time τ_q is found to be considerably less than the transport scattering time τ_{tr} . The high value of the ratio $\tau_{tr}/\tau_q \gg 1$ is typical for GaAs quantum wells with AlAs/GaAs superlattice barriers.¹²

In summary, we have experimentally studied the magnetoresistance of GaAs quantum well with AlAs/GaAs superlattice barriers with two subbands occupied. Magnetointersubband oscillations of the resistance are found with the period, determined by relation $\Delta_{12} = k \cdot \hbar \omega_c$, where the index k is up to 100 at $T=4.2$ K. The high value of the index k provides measurements of the period with high accuracy, which can be useful for accurate calibration of the magnetic fields. The magnitude of the oscillations depends considerably on temperature, pointing to a large temperature variation in the quantum scattering time of electrons τ_q . The change in the quantum time is found to be proportional to the square of the temperature. It reveals the electron-electron interaction as the main agent, affecting the electron lifetime τ_q . Our results are in good agreement with the recent experimental observations,^{11,18–20} indicating that the sensitivity to electron-electron scattering is the fundamental property of magnetoresistance oscillations originating from the second-order Dingle factor.

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