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Anomalous dephasing of two-dimensional electrons in an AlGaAs/GaAs parabolic quantum well structure

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ABSTRACT

Magnetoconductivity measurements are performed on a parabolic quantum well structure. The weak localization effect is observed at a low magnetic field for both single-subband and double-subband occupation regimes. Applying weak-localization theory, we have extracted the dephasing rate. The extracted dephasing rate increases with increasing conductivity in the small-energy-transfer regime and shows a similar trend as the electron density is increased in the large-energy-transfer regime. This is in conflict with Fermi-liquid theory, and cannot be attributed to electron–phonon scattering.

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1. Introduction

The weak localization (WL) effect in a two-dimensional system is caused by the constructive interference of two phase-coherent electronic waves propagating in opposite directions along a closed trajectory [1]. This effect gives rise to a suppression of the conductivity. When a magnetic field (B) is applied perpendicular to the plane of the system the constructive interference is broken. Hence the suppression of the conductivity is rapidly lifted with increasing B and consequently a positive magnetoconductivity (MC) appears usually within a small B window around 0 T. From the weak field MC, one can experimentally determine the electron dephasing time τ_ϕ [2,3].

The electron dephasing time is an important quantity for analyzing transport in semiconductor samples since it determines the nature of the transition between quantum and classical behavior. For two-dimensional quantum well samples at low temperature, the inelastic electron–electron interaction is the main mechanism for dephasing the electron wave function [1]. Following the standard Fermi-liquid (FL) model [1,4], the dephasing rate (τ_ϕ^{-1}) determined by electron–electron scattering should decrease

monotonically with increasing conductivity in the small-energy-transfer regime. However, Minkov et al. [5] reported a nonmonotonic conductivity dependence of τ_ϕ^{-1} , namely τ_ϕ^{-1} was seen to decrease first with increasing conductivity before increasing at higher conductivity. Subsequently, Pagnossin et al. [6] found that τ_ϕ^{-1} is proportional to the conductivity in a GaAs double quantum well, and there is a similar observation for an InGaAs/InAlAs single quantum well [7]. These experimental results contradicting the FL model indicate that the nature of the electron dephasing in two-dimensional systems is still an open question and deserves further study.

A parabolic quantum well (PQW) is an interesting structure because it is possible to form an approximate jellium of electrons which moves in a constant background of positive charge. Since the first experimental realization of an AlGaAs/GaAs PQW [8], the properties of PQW structures have been investigated in a number of works [9–11]. Here, we report on measurements of an AlGaAs/GaAs PQW structure for which the electron dephasing rate is extracted from the low-field MC. The density and conductivity dependences of τ_ϕ^{-1} are at odds with the FL model.

2. Experiment

The sample is grown by molecular-beam epitaxy and is a 100 nm wide $\text{Al}_x\text{Ga}_{1-x}\text{As}$ PQW with the Al content x varied parabolically between 0 and 0.29. The PQW is separated from Si-delta doping of $5.0 \times 10^{15} \text{ m}^{-2}$ on both sides by undoped $\text{Al}_{0.29}\text{Ga}_{0.71}\text{As}$ spacer layers 15 nm wide. Full details of the sample structure can be found in Ref. [12]. The sample is processed into a

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Fig. 1. (a) V_g dependence of the electron density. The arrow marks the gate voltage at which the second subband starts to populate. (b) Magnetoconductivity (open circles) for $V_g = 0.22$ V. Solid line is the fit according to Eq. (1).

standard Hall bar with a front gate. Measurements are performed at a temperature $T = 1.3$ K using standard ac lock-in techniques.

3. Results and discussions

The electron density n_H is firstly determined from a linear fit of the low-field Hall resistivity. As shown in Fig. 1(a), n_H (open squares) initially shows a linear increase as the gate voltage (V_g) is increased from 0.22 to 0.32 V. The values are consistent with those for the electron density n_1 (filled triangles) obtained by a fast Fourier transform (FFT) of the Shubnikov–de Haas oscillations in the longitudinal resistivity (ρ_{xx}). This suggests that only one subband is occupied when $V_g \leq 0.32$ V. On the other hand, when V_g is made more positive than 0.32 V, n_1 gradually diverges from n_H , indicating that the second subband starts to populate. Note that the value of the electron density at which the double-subband occupation starts is $3.01 \times 10^{15} \text{ m}^{-2}$ ($V_g = 0.34$ V), consistent with our previous report [12]. For $V_g \geq 0.52$ V, the FFT analysis of ρ_{xx} yields in addition to the first peak a second peak so we can extract directly n_2 , namely the electron density in the second subband (star symbols). By adding n_2 to n_1 , we obtain the total electron density n_3 when $V_g \geq 0.52$ V. As shown in Fig. 1(a), values of n_3 (open triangles) are consistent with those for n_H . This demonstrates that there is no parallel conduction in our sample.

The quantum corrections to the Drude conductivity generally include the WL effect and electron–electron interactions (EELs). In a magnetic field the MC can be written as

$$\sigma_{xx} = ne\mu / (1 + \mu^2 B^2) + \Delta\sigma + \Delta\sigma_{ee}, \quad (1)$$

where μ is the mobility, and $\Delta\sigma$ and $\Delta\sigma_{ee}$ are respectively the WL and EEL corrections. $\Delta\sigma$ is dominant at low field but its influence

decreases as B increases. In contrast, $\Delta\sigma_{ee}$ is independent of the field. Because $\Delta\sigma$ is the main correction only at very low field, we first fit the conductivity σ_{xx} over a wide magnetic field range using Eq. (1) by neglecting $\Delta\sigma$. As seen in Fig. 1(b), Eq. (1) describes well the experimental data for $V_g = 0.22$ V, which shows a parabolic trend. Note that a large deviation from this parabolic trend due to the WL effect occurs only over a small field range $|B| < 0.04$ T, i.e., the contribution of WL effect to the conductivity is dominant just in this small field range. Since the MC we focus on below is in this small field range, we expect that the EEL correction to the conductivity is negligible compared with the WL correction in the following analysis.

Within the WL framework where the diffusion approximation applies, i.e., $B < B_{tr} = \hbar/2el^2$ (l is the mean-free path), the B dependence of $\Delta\sigma = \sigma_{xx}(B) - \sigma_{xx}(0)$ is expressed by

$$\Delta\sigma = \alpha G_0 \left[\psi \left(\frac{1}{2} + \frac{\tau}{\tau_\phi} \frac{B}{B_{tr}} \right) - \psi \left(\frac{1}{2} + \frac{B}{B_{tr}} \right) - \ln \left(\frac{\tau}{\tau_\phi} \right) \right], \quad (2)$$

where $G_0 = e^2/(2\pi^2\hbar)$, τ is the momentum relaxation time, $\psi(x)$ is the digamma function, and α is equal to unity [3]. Although this equation was derived with the diffusion approximation in mind, it can be adapted to fit experimental data in a regime where the diffusion approximation no longer applies by setting α to be less than unity in order to estimate the value of τ_ϕ [5,13]. To determine τ_ϕ^{-1} we used Eq. (2) to fit our data when only one subband is populated. The experimental data and the fits are shown in Fig. 2(a). One can see that Eq. (2) clearly describes the experimental data well up to 16 mT. The conductivity dependence of τ_ϕ^{-1} extracted from these fits is shown in Fig. 3(a) (open triangles), and reveals a monotonic increase with conductivity.

For $V_g > 0.32$ V, the second subband starts to populate. WL in a two-dimensional system with two occupied subbands has been theoretically studied [14,15]. It was shown that if short-range scattering is dominant and intersubband scattering is strong, the subbands couple and the electrons behave as if they occupy a single subband characterized by an average kinetic parameter. In this case, Eq. (2) can be substituted [16,17] by

$$\Delta\sigma = \alpha G_0 \left[\psi \left(\frac{1}{2} + \frac{\hbar}{4eDB\tau_i} \right) - \psi \left(\frac{1}{2} + \frac{\hbar}{4eDB\tau_e} \right) - \ln \left(\frac{\tau_e}{\tau_i} \right) \right], \quad (3)$$

where τ_i and τ_e are the inelastic and elastic scattering times, which respectively correspond to the dephasing time and the momentum relaxation time in Eq. (2). D is the mean diffusion coefficient equal to $(1/n) \sum_{j=1,2} n_j (\hbar k_F^j / m^*)^2 \tau_j / 2$, where τ_j is the transport scattering time for the first or the second subband. Since the short-range scattering is dominant in our sample [12], we use Eq. (3) to fit the data in the V_g range of $0.32 \text{ V} < V_g \leq 0.56 \text{ V}$, but for $V_g > 0.56 \text{ V}$ the WL-induced MC becomes so weak that we cannot obtain a reliable fit. Since the transport scattering time in the second subband cannot be accurately determined when the electron density for this subband is very small, D is treated as a fitting parameter in the fitting procedure. Fig. 2(b) shows the result of this procedure for selected values of V_g and clearly the fitted curves follow closely the measured curves. The extracted values of D (filled squares) are shown in Fig. 2(c). The calculated values of D (open squares) for $V_g \leq 0.32 \text{ V}$ are also given for comparison. Evidently, the points marked by filled and open squares together form a smooth continuous curve near $V_g = 0.32 \text{ V}$ indicating the validity of our fits using Eq. (3). The slight divergence of the filled square points from the linear trend for $V_g > 0.4 \text{ V}$ may result from enhanced intersubband scattering [18].

The extracted values of τ_ϕ^{-1} are also given in Fig. 3(a) (filled triangles). As seen, τ_ϕ^{-1} shows an increase with conductivity,

Fig. 2. Magnetoconductivity $\Delta\sigma = \sigma_{xx}(B) - \sigma_{xx}(0)$ (open triangles) for various values of V_g fitted in (a) following Eq. (2) and in (b) following Eq. (3). The curves are vertically shifted for clarity. (c) Fitted (filled squares) and calculated (open squares) values of the mean diffusion coefficient D as a function of V_g .

similar to the data (open triangles) obtained from the fits with Eq. (2) at lower conductivity. However, τ_ϕ^{-1} extracted using Eqs. (2) and (3), when combined, shows a kink at $V_g = 0.36$ V (indicated by the arrow), marking the onset of suppressed dephasing rate for $V_g > 0.36$ V. To clarify the origin of this effect, we calculated the parameter $k_B T \tau / \hbar$ (k_B is the Boltzmann constant) over the whole range of V_g . In the calculation, τ is substituted by τ_e extracted from the earlier fits using Eq. (3) for $V_g > 0.32$ V. We find that the $k_B T \tau / \hbar$ increases from 0.18 at $V_g = 0.22$ V to 0.91 at $V_g = 0.36$ V and it shows a further increase from 1.28 at $V_g = 0.38$ V to 2.36 at $V_g = 0.56$ V. In other words, $k_B T \tau / \hbar < 1$ for $V_g \leq 0.36$ V and $k_B T \tau / \hbar > 1$ for $V_g > 0.36$ V. This indicates that small-energy-transfer scattering is dominant for $V_g \leq 0.36$ V but large-energy-transfer scattering becomes important for $V_g > 0.36$ V. We therefore attribute the kink at $V_g = 0.36$ V to the transition from the small- to the large-energy-transfer scattering regime.

According to the FL model [1,4,19], τ_ϕ^{-1} is given by

$$\tau_\phi^{-1} = \frac{\pi}{2} \frac{(k_B T)^2}{\hbar E_F} \ln \left(\frac{E_F}{k_B T} \right), \quad \text{for } k_B T \tau / \hbar > 1, \\ \frac{k_B T}{\hbar} \frac{\pi G_0}{\sigma} \ln \left(\frac{\sigma}{2\pi G_0} \right), \quad \text{for } k_B T \tau / \hbar < 1, \quad (4)$$

where E_F is the Fermi energy. We calculated τ_ϕ^{-1} as a function of electron density using this equation for $k_B T \tau / \hbar > 1$ (plotted in the inset of Fig. 3(a) as a solid line). Clearly, the calculated τ_ϕ^{-1} monotonically decreases with increasing electron density. However, for $V_g > 0.36$ V, when $k_B T \tau / \hbar > 1$, τ_ϕ^{-1} (filled triangles) extracted from the data (only selected data is shown in the inset of Fig. 3(a)) shows an increase with electron density, in conflict with the FL model. For $k_B T \tau / \hbar < 1$, the conductivity dependence of τ_ϕ^{-1} is also calculated (see Fig. 3(a)). Evidently, the calculated τ_ϕ^{-1} also monotonically decreases with increasing conductivity, which is again contrary to the experimental results. Therefore, we conclude that an anomalous dephasing of the electrons in a PQW structure is observed in both the small-energy-transfer and the large-energy-transfer regimes.

In order to further confirm this anomalous electron dephasing behavior, another method is employed to extract τ_ϕ^{-1} when just the first subband is occupied. One can fit the weak field MC data using the theory [20] developed by Golub. In this theory, the B dependence of $\Delta\sigma$ is expressed by

$$\Delta\sigma = \sigma_a(B) + \sigma_b(B), \quad (5)$$

where $\sigma_a(B)$ and $\sigma_b(B)$ are the respective contributions from the backscattering and nonbackscattering interference corrections to the conductivity. The detailed expressions for $\sigma_a(B)$ and $\sigma_b(B)$ can be found in Ref. [20]. There are two aspects of this theory to note: (1) it includes both backscattering and nonbackscattering contributions while the latter is not included in either Eq. (2) or Eq. (3), and (2) it is valid for both diffusive and ballistic regimes of WL, indicating that we can use it to describe the data over a large B range. In the fitting procedure, we neglected the spin-orbit interaction because no weak antilocalization effect is observed in our sample. Fig. 3(b) shows the experimental data and the fits. Golub's theory clearly describes the experiment data well up to 38 mT, equal to $\sim 5B_{tr}$, for $V_g = 0.22$ V. The extracted values of τ_ϕ^{-1} are also given in Fig. 3(a) (open circles). As shown, the plot of τ_ϕ^{-1} determined this way from Eq. (5) is a little above that determined from Eq. (2), which may originate from both the nonbackscattering contribution and the fit following Eq. (2) with $\alpha < 1$. Nonetheless, it is noteworthy that τ_ϕ^{-1} still shows the increase with conductivity similar to the data (open triangles) obtained from Eq. (2). This confirms that the observed anomalous dephasing of the electrons is an inherent feature of our sample, which contradicts with the FL model of electron-electron scattering.

In addition to electron-electron scattering, although usually considered negligible at $T = 1.3$ K, electron-phonon scattering could in principle affect the dephasing rate. According to calculations by Iordanski et al. [21] that just considers the electron-phonon interaction, $\tau_\phi^{-1} \propto T^2/l$ for $T \gg \hbar C_t/k_B l$ and $\tau_\phi^{-1} \propto T^4 l$ for $T \ll \hbar C_t/k_B l$, where C_t is the transverse velocity of sound. Using $C_t = 3 \times 10^3$ m/s [21], we determine the parameter $\hbar C_t/k_B l = 0.03 \sim 0.11$ over the whole V_g range applied. Following Ref. [21], we would then expect τ_ϕ^{-1} at $T = 1.3$ K

Fig. 3. (a) Conductivity dependence of the dephasing rate. Dashed lines provide a guide to the eye. The solid line is calculated from Eq. (4). The open (solid) triangles and open circles present the dephasing rate obtained from Eq. (2) [Eq. (3)] and Eq. (5). Inset shows the fitted dephasing rate as a function of the electron density for $V_g > 0.36 \text{ V}$. The solid line is calculated from Eq. (4). (b) Magnetoconductivity (open triangles) for various values of V_g . Solid lines are fits according to Eq. (5). The curves are vertically shifted for clarity.

to show a decrease with increasing conductivity because the condition $T \gg \hbar C_t/k_B l$ is valid. As clearly seen from Fig. 3(a), this is not the case. We therefore conclude that electron–phonon scattering cannot explain the anomalous conductivity dependence of τ_ϕ^{-1} . This anomalous behavior is therefore suggestive of the existence of another dephasing mechanism for electrons.

4. Conclusions

In conclusion, we measured the MC of an AlGaAs/GaAs parabolic quantum well structure. The WL effect at a low magnetic field is observed for both single-subband and double-subband occupation. By fitting the low-field MC, τ_ϕ^{-1} is extracted and found to increase with increasing conductivity in the small-energy-transfer regime, and it shows the same trend with increasing electron density in the large-energy-transfer regime. Neither of these observations is consistent with the FL theory.

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