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Effect of a dc electric field on the longitudinal resistance of two-dimensional electrons in a magnetic field

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The effect of a dc electric field on the longitudinal resistance of highly mobile two-dimensional (2D) electrons in heavily doped GaAs quantum wells is studied at different magnetic fields and temperatures. Strong suppression of the resistance by the electric field is observed in magnetic fields at which the Landau quantization of electron motion occurs. The phenomenon survives at high temperature where Shubnikov-de Haas oscillations are absent. The scale of the electric fields essential for the effect is found to be proportional to temperature in the low temperature limit. We suggest that the strong reduction of the longitudinal resistance is the result of a nontrivial change in the distribution function of 2D electrons induced by the dc electric field. Comparison of the data with recent theory yields the inelastic electron-electon scattering time τ_{in} and the quantum scattering time τ_q of the electrons at high temperatures, a regime where previous methods were not successful.

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The nonlinear properties of highly mobile two-dimensional (2D) electrons in AlGaAs/GaAs heterojunctions is a subject of considerable current interest. Strong oscillations of the longitudinal resistance induced by microwave radiation have been found at magnetic fields which satisfy the condition $\omega = n \times \omega_c$, where ω is the microwave frequency, ω_c is cyclotron frequency and $n = 1, 2 \ldots$.[1,2] At high levels of the microwave excitations the minima of the oscillations can reach values close to zero.[3–6] This so-called zero resistance state (ZRS) has stimulated extensive theoretical interest.[7–12] At higher magnetic field $\omega_c > \omega$, a considerable decrease of magnetoresistance with microwave power is found[2,5,6] which has been attributed to intra-Landau-level transitions.[13]

Another interesting nonlinear phenomenon has been observed in response to a dc electric field.[14,15] Oscillations of the longitudinal resistance, periodic in inverse magnetic field, have been found at dc biases satisfying the condition $n \times \hbar\omega_c = 2R_c E_H$, where R_c is the Larmor radius of electrons at the Fermi level and E_H is the Hall electric field induced by the dc bias in the magnetic field. The effect has been attributed to "horizontal" Landau-Zener tunneling between Landau levels, tilted by the Hall electric field E_H.[14]

In this paper we report a new phenomenon. We have observed a strong reduction of the 2D longitudinal resistance induced by dc electric field E_{dc} that is substantially smaller than that required for the "horizontal" electron transitions between Landau levels.[14,15] In contrast to the inter-Landau-level scattering, the observed effect depends strongly on temperature. We suggest that the phenomenon is due to a substantial and nontrivial deviation of the electron distribution function from equilibrium induced by the dc electric field E_{dc}. We find reasonable agreement between our results and a recent theory that considers such an effect in the high temperature limit $kT > \hbar\omega_c$.[12] It is interesting and important that the effect provides a significant contribution to the nonlinear transport at low temperatures where the strongly temperature dependent quantum oscillations of the longitudinal conductivity are well developed.

Our samples were cleaved from a wafer of a high-mobility GaAs quantum well grown by molecular beam epitaxy on semi-insulating (001) GaAs substrates. The width of the GaAs quantum well was 13 nm. AlAs/GaAs type-II superlattices served as barriers, making possible a high-mobility 2D electron gas with high electron density.[17] Two samples ($N1$ and $N2$) were studied with electron density $n_1 = 1.22 \times 10^{16}\ \text{m}^{-2}$, $n_2 = 0.84 \times 10^{16}\ \text{m}^{-2}$, and mobility $\mu_1 = 93\ \text{m}^2/\text{V s}$, $\mu_2 = 68\ \text{m}^2/\text{V s}$ at $T = 2.7$ K. Measurements were carried out between $T = 1.8$ K and $T = 77$ K in magnetic field up to 3.2 T on $d = 50\ \mu$m wide Hall bars with a distance of 250 μm between potential contacts. The longitudinal resistance was measured using a current of 0.5 μA at a frequency of 77 Hz in the linear regime. Direct electric current (bias) was applied simultaneously with ac excitation through the same current leads (see inset to Fig. 1). Although we have studied, strictly speaking, the differential resistance, for the sake of simplicity we will refer to it below as resistance.

Typical curves of the longitudinal resistance r_{xx} are shown as a function of the dc bias in Fig. 1 at two temperatures. At high dc bias the resistance exhibits maxima that satisfy the condition $n \times \hbar\omega_c = 2R_c E_H$, corresponding to "horizontal" transitions between Landau levels.[14,15] Another striking feature is the sharp peak at zero dc bias which broadens as the temperature is raised. This zero bias peak is the main topic of our paper.

The evolution of the magnetoresistance with dc bias and magnetic field is shown in Fig. 2. The zero bias peak appears at relatively high magnetic field $B \approx 0.2 - 0.3$ T [see Fig. 2(a)]. At these fields the Landau level width $\hbar/\tau_q$ extracted from the amplitude of Shubnikov de Haas (SdH) oscillations becomes comparable with $\hbar\omega_c$, and the SdH oscillations are

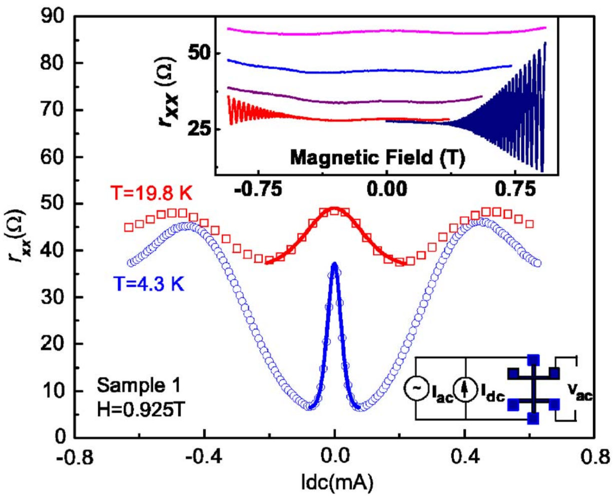

FIG. 1. (Color online) Dependence of the differential resistance r_{xx} on a dc bias at $B=0.925$ T. Circles correspond to $T=4.3$ K, squares correspond to $T=19.8$ K. The solid lines are theoretical curves obtained from Eq. (3). The fitting parameters are $I_0=0.055$ mA and $\delta=0.334$ for $T=4.3$ K and $I_0=0.1802$ mA and $\delta=0.177$ for $T=19.8$ K. The top inset shows quantum oscillations of the longitudinal resistance at different temperatures $T=1.9$ K (bottom curve, right), 4.2 K (bottom curve, left), 9.9, 19.8, and 35 K (remaining curves in ascending order); $I_{dc}=0$ A. The experimental setup is shown at bottom right.

visible at low temperatures (see curve at $T=1.9$ K in the top inset to Fig. 1). The strength of the peak increases gradually with magnetic field. Clear SdH oscillations are present in high magnetic field at zero bias. The magnitude of the SdH oscillations at $T=4.3$ K is substantially smaller than the amplitude of the zero bias peak. The peak is still present at temperatures above $T=30$ K where no SdH oscillations are detected. A better resolved snapshot of the peak evolution is shown in Fig. 2(b). The figure demonstrates the effect at low temperatures $T=1.9$ K, where the SdH oscillations are well developed.

The striking reduction of the resistance is observed at high temperatures where no SdH oscillations are present. This is quite different from what one expects for electron heating by the electric field. As shown in the inset to Fig. 1, the resistance increases for higher temperatures, in contrast with the observed decrease with applied electric field. It should also be noted that at low temperatures, the largest effect possible due to heating is to reduce the resistance from its value at a SdH maximum to the "average" baseline value (which is $\approx 26-28$ Ω in the inset to Fig. 1). The observed reduction in Fig. 2(b) is much greater than this, indicating this is a new phenomenon associated with the application of an electric field.[16]

From a theoretical perspective, nonlinear phenomena in high mobility 2D electron systems can be conveniently separated into (a) effects of electric field on the electron distribution function[12] and (b) effects of electric field on the kinematics of electron scattering.[8,11] It was recently realized that the first of these should provide the dominant contribution to the nonlinear response in 2D electron systems. Below we will compare our results with this approach.[12]

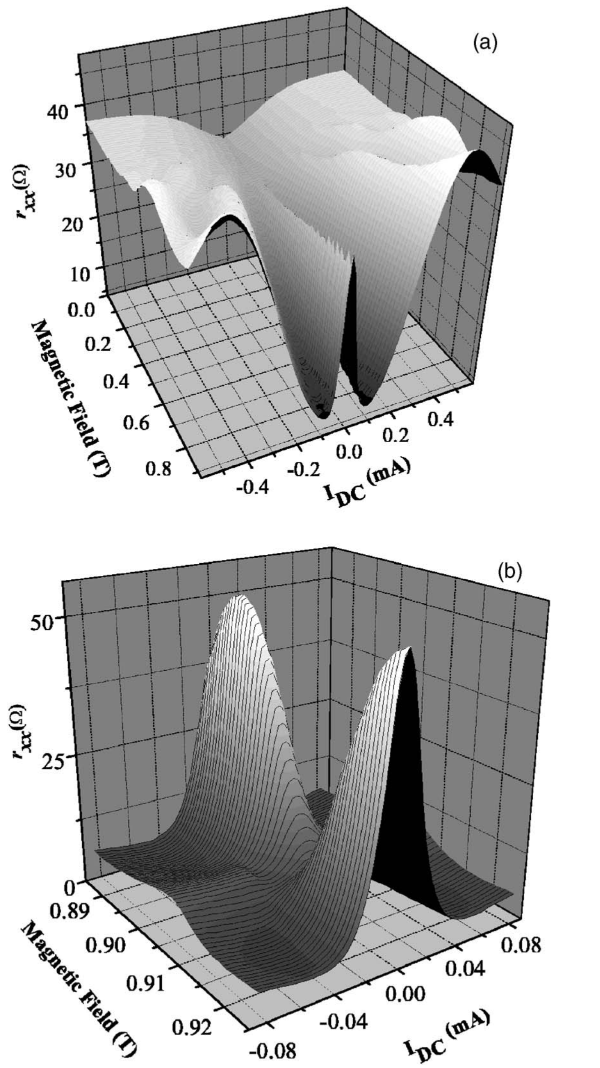

FIG. 2. (a) The differential resistance r_{xx} as a function of magnetic field and a dc bias at temperature $T=4.3$ K. (b) A similar plot at $T=1.9$ K over a narrower range of the experimental parameters, yielding better resolution.

The theory considers 2D electrons in classically strong magnetic field at finite electric field E_{dc} and at relatively high temperature $kT > \hbar\omega_c$. Due to conservation of total electron energy $(\epsilon + eE_{dc}x)$ in the dc electric field E_{dc}, the spatial electron diffusion translates into the diffusion of the electrons in energy space. The solution of the diffusion equation in ϵ-space yields nontrivial oscillations of the nonequilibrium electron distribution function with period $\hbar\omega_c$. The temporal growth of the oscillations due to the diffusion is limited by inelastic electron-electron scattering, which smear the nonequilibrium contribution. The inelastic scattering time τ_{in} is inversely proportional to the square of the temperature (see Sec. VII of Ref. 12) $\tau_{in} \sim 1/T^2$, making the stationary amplitude of the oscillations (and nonlinear conductivity) strongly temperature dependent. Relative to the Drude conductivity, σ_D, in magnetic field, the theory predicts a longitudinal conductivity,

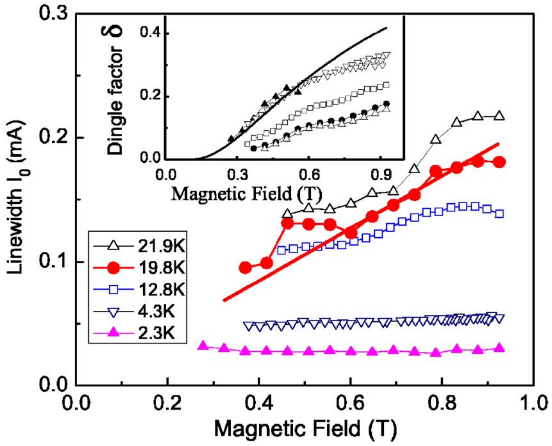

FIG. 3. (Color online) Dependence of the width of the peak I_0 on magnetic field at different temperatures, as labeled. The solid line represents the linear dependence expected from the theory in the high temperature limit [see Eq. (2)]. The inset shows the magnetic field dependence of the parameter δ obtained from the fit of the zero bias peak using Eq. (3). The solid line presents the theoretical dependence of the Dingle parameter δ on magnetic field, corresponding to a quantum scattering time $\tau_q = 1.5$ ps.

$$\Delta\sigma_{xx}/\sigma_D = 2\delta^2\left(1 - \frac{4Q_{\mathrm{dc}}}{1+Q_{\mathrm{dc}}}\right), \tag{1}$$

where $\delta = \exp(-\pi/\omega_c\tau_q)$ is the Dingle factor, τ_q is the quantum scattering time and the parameter Q_{dc} is

$$Q_{\mathrm{dc}} = \frac{2\tau_{\mathrm{in}}}{\tau_{\mathrm{tr}}}\left(\frac{eE_{\mathrm{dc}}v_F}{\omega_c}\right)^2\left(\frac{\pi}{\hbar\omega_c}\right)^2. \tag{2}$$

Here τ_{tr} is the transport scattering time and v_F is the Fermi velocity.

In order to compare with experiment, the differential conductivity at frequency ω, $\sigma_\omega = dJ/dE = d[\sigma(E)E]/dE$, is obtained using Eq. (1), and the variation of the differential resistance is found to be

$$\Delta r_{xx}/R_0 = 2\delta^2\left(\frac{1-10Q_{\mathrm{dc}}-3Q_{\mathrm{dc}}^2}{(1+Q_{\mathrm{dc}})^2}\right), \tag{3}$$

where R_0 is the resistance at zero magnetic field. In a classically strong magnetic field $\omega_c\tau_{tr} \gg 1$, the dc electric field is almost perpendicular to the electric current I_{dc}: $E_{\mathrm{dc}} = \rho_{xy}I_{\mathrm{dc}}/d$, where d is the sample width. Using Eq. (2), we rewrite the parameter Q_{dc} in the form $Q_{\mathrm{dc}} = (I_{\mathrm{dc}}/I_0)^2$, where the scale I_0 is a fitting parameter. In accordance with Eq. (3), the parameter I_0 is directly related to the width of the zero bias peak and the peak magnitude is proportional to δ^2. Below we refer to the parameter I_0 as the linewidth. Examples of theoretical fits to the data using Eq. (3) are shown by the solid lines in Fig. 1, using δ and I_0 as fitting parameters.[18]

The dependence of the width of the peak (I_0) on magnetic field is presented in Fig. 3 at different temperatures. At high temperature $kT > \hbar\omega_c$ ($\hbar\omega_c/k = 18$ K at $B = 0.925$ T), the peak width varies considerably with magnetic field. The approximately linear increase of the scale I_0 with magnetic field agrees with the theory predicting the linear dependence [see Eq. (2) and $I_{\mathrm{dc}} = E_{\mathrm{dc}}d/(\rho_{xy} \sim B)$]. The deviations from the linear dependence are beyond the scope of the theory. The oscillations could be related to magnetophonon resonances observed in these systems at high temperature.[19] At low temperatures, $kT < \hbar\omega_c$, the width of the zero bias peak depends weakly on magnetic field, in contradiction with a simple extension of the high temperature results [Eq. (1) and Eq. (2)] to the low temperatures.

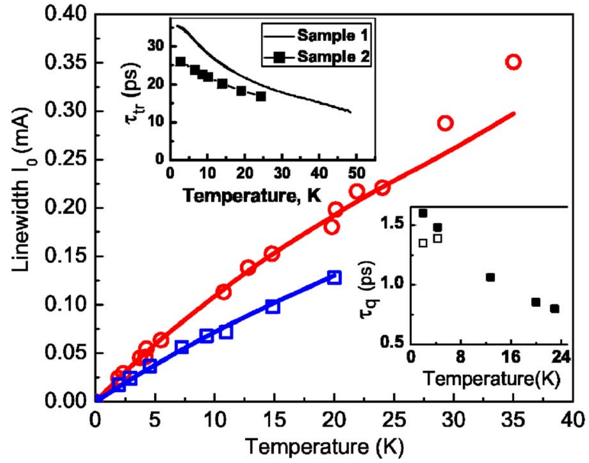

FIG. 4. (Color online) Dependence of the width of the zero bias peak I_0 on temperature for sample $N1$ (open cirles) and sample $N2$ (open squares) at $B = 0.925$ T. The solid lines are the theory using Eq. (2). The comparison gives an inelastic scattering time $\tau_{\mathrm{in}} = 10/T^2 (12/T^2)$ ns for sample $N1$ ($N2$). The top inset shows the transport time τ_{tr} vs temperature at zero magnetic field. The dependence of the quantum scattering time τ_q on temperature is shown in the bottom inset. Open squares correspond to τ_q determined from the amplitude of the SdH oscillations using Lifshits-Kosevich formulas (Ref. 20). Filled squares are the τ_q determined by comparison of the amplitude of the zero bias peak with Eq. (3).

For several different temperatures, the inset to Fig. 3 shows the magnetic field dependence of the Dingle parameter, δ, which is obtained from comparison of the magnitude of the zero bias peak with the theory [see Eq. (3)]. The parameter δ decreases with decreasing magnetic field, and disappears below $B = 0.2$ T. We have plotted the parameter $\delta = \exp(-\pi/\omega_c\tau_q)$, vs magnetic field using the quantum scattering time τ_q as a fitting parameter (see the solid line in the inset to the figure). The quantum time $\tau_q = 1.5$ ps obtained by the fitting is close to the quantum time extracted from the usual analysis of SdH oscillations at different temperature and/or magnetic field.[20] A comparison between these two results is shown in the bottom inset to Fig. 4. Using the new method, the quantum time τ_q is found for temperatures up to 24 K, where SdH oscillations are absent and previous methods fail to work. Thus the method extends considerably the temperature range in which the quantum scattering time can be studied.

The temperature dependence of the width of the peak is shown in Fig. 4.[21] At low temperatures the width of the peak is found to be proportional to the temperature T. At higher temperature a noticeable sublinear deviation is observed, followed by a superlinear temperature dependence of the linewidth at temperatures $T > 30$ K (not shown for sample $N2$).

The solid lines in the figure are theoretical curves plotted in accordance with Eq. (2) in which the temperature variations of the transport time τ_{tr} (shown in the top inset to the figure) are taken into account. The inelastic scattering time τ_{in} is approximated by the theoretical expression[12] $\tau_{in}=\alpha/T^2$ with the constant α used as the only fitting parameter. For the inelastic time we have found $\tau_{in}^{(1)}=10\times10^{-9}/T^2$ s and $\tau_{in}^{(2)}=12\times10^{-9}/T^2$ s for samples 1 and 2. The corresponding theoretical estimates[12] of the inelastic time give $\tau_{in,t}^{(1)}=4.8\times10^{-9}/T^2$ s and $\tau_{in,t}^{(2)}=3.2\times10^{-9}/T^2$ s. We consider this as satisfactory agreement, in light of several approximations used in the theory. The somewhat larger values of the inelastic time τ_{in} obtained in the experiment could also be due to additional electron screening of the 2D electrons by X electrons in AlAs/GaAs type-II superlattices.[17]

Although the theory works for $kT>\hbar\omega_c$, Fig. 4 shows there is good agreement between the experiment and the theory [Eq. (1) and Eq. (2)] at much lower temperatures ($kT\ll\hbar\omega_c$). Such correspondence does not appear for the magnetic field dependence of the width of the peak at the low temperatures discussed above (see curves at T=4.3 K and 2.3 K in Fig. 3). Thus, despite reasonable agreement between our experiments and the theory, additional investigations are required to understand the nonlinear response in the low temperature regime.

In summary, a strong reduction of the longitudinal resitivity of 2D electrons in classically strong magnetic fields is observed in response to dc electric field. The effect is not related to Joule heating even at temperatures down to 2 K, where strong quantum oscillations (SdH) are present that are highly sensitive to the temperature. At low temperature (2–10 K), the scale of the electric fields at which the effect occurs is proportional to the temperature. In the high temperature regime, $kT>\hbar\omega_c$, reasonable agreement is established with recent theory[12] that has predicted significant and nontrivial variations of the electron distribution function in response to a dc electric field. Comparison with the theory allowed us for the first time to obtain the inelastic electron-electron scattering time τ_{in} in magnetic field, and the quantum scattering time τ_q of the 2D electrons at high temperatures.

Recently, the reduction of the resistance by the Hall electric field was reported by another research group.[22]

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