# Shubnikov–de Haas effect in a two-dimensional electronic system under the conditions of the quantum Hall effect

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The experimental results on the Shubnikov–de Haas effect in a two-dimensional electronic system in moderate magnetic fields are at variance with existing theories when the Hall resistance is quantized.

The Shubnikov–de Haas effect (SdHE) is widely used for studying the properties of the two-dimensional electron gas (TEG).[1] From investigation of this effect in a weak magnetic field ($\omega_c \sim \Gamma$, where $\Gamma$ is the width of the Landau level), one can find the value of $\Gamma$, which is a measure of the degree of disorder of a two-dimensional system in a magnetic field. Interest in such studies has increased considerably in recent years in connection with the discovery of the quantum Hall effect.[2] For example, Paalanen *et al.*[3] used the value of $\Gamma$ to study the relationship between the disorder of the TEG and the fractional quantum Hall effect.[4] Here, however, there arises the question of the applicability of the theory of the SdHE to the description of the experiment under the conditions of the quantum Hall effect.

In this letter we report on a study of the SdHE in a two-dimensional electronic system in moderate magnetic fields which are nevertheless strong enough for observing the quantum Hall effect. We will also show that the theories usually used to describe the SdHE in TEG[5,6] do not agree with experiment.

The measurements were performed on the heterostructures GaAs–$Al_0$ and $_3Ga_0$, $_7As$ obtained by liquid-phase epitaxy.[7] The samples to be studied were selected with the stipulation that the equality $\rho_{xy} = h/ie^2$ for $i = 4$ be satisfied on the Hall-resistance plateau (the accuracy of the measurements is $\sim 1\%$). The samples had the shape of Hall bridges with four voltage probes, and the measurements were performed with direct current.

Figure 1 shows the dependence of the diagonal component $\rho_{xx}$ and the Hall component $\rho_{xy}$ of the resistance tensor on the magnetic field $H$ normal to the plane of

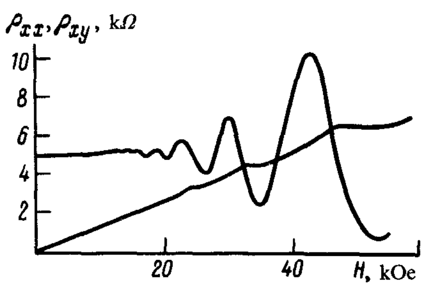


FIG. 1. Magnetic field dependence of the diagonal component $\rho_x$ and the Hall component $\rho_{xy}$ of the resistance tensor. $T = 4.12$ K.

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the TEG for one of the samples studied at $T = 4.12$ K. In the interval $10 < H < 35$ kOe, the Shubnikov–de Haas oscillations are essentially sinusoidal, and quantization of the Hall resistance is observed in the same range of fields: at $H \approx 24$ kOe ($i = 8$) and $\approx 34$ kOe ($i = 6$).

The use of the theory of Ref. 5 to interpret our results leads to a contradiction. The Dingle factor, which describes the damping of the oscillation amplitude due to collisional broadening of the levels, can, according to Ref. 5 be written as $\exp\{-(\pi/\omega_c \tau_p)\}$, where $\tau_e$ is the relaxation time in the absence of a magnetic field. On the other hand, the relaxation time determined experimentally from the field-dependence of the oscillation amplitude differs from $\tau_0$ by a factor of $\sim 10$. An analogous, but smaller in magnitude, disagreement between theory and experiment was observed previously in inversion layers on the silicon surface.[8,9] For this reason, we have used in our study the more recent theory of SdHE for a two-dimensional system,[6] in which an expression for the longitudinal conductivity $\sigma_{xx}$ is obtained at $\omega_c \sim \Gamma$, with allowance for the scattering by impurities and acoustic phonons, as well as the electron-electron interaction.

According to Ref. 6, we have

$$\sigma_{xx} = \frac{Ne^2 \tau}{m^*} \frac{1}{1+(\tau_0 \Gamma)^2} \left\{ 1 + \frac{2(\tau_0 \Gamma)^2}{1+(\tau_0 \Gamma)^2} \frac{2\pi^2 kT}{\hbar \tilde{\omega}_c} \times \operatorname{cosech}\left[\frac{2\pi^2 kT}{\hbar \tilde{\omega}_c}\right] \exp\left[-\frac{\pi \Gamma}{\tilde{\omega}_c}\right] \cos\left[\frac{2\pi^2 \hbar N}{m^* \omega_c} - \frac{\pi}{2}\right] \right\}. \quad (1)$$

Here $N$ is the surface density of electrons, $m^*$ is the single-particle effective mass, $\tilde{\omega}_c = eH/mc$, $m$ is the effective mass, renormalized by electron-phonon and electron-electron interactions, and $\tau = \tau_0(\Gamma/\omega_c)$.

It follows from (1) that the damping of the Shubnikov–de Haas oscillations with temperature and due to scattering depends on the value of $m$. For this reason, the value of $m$ was obtained from the temperature dependence of the oscillation amplitude (Fig. 2). It is evident that as in the TEG on the silicon surface,[8] $m$ differs from $m^*$ and

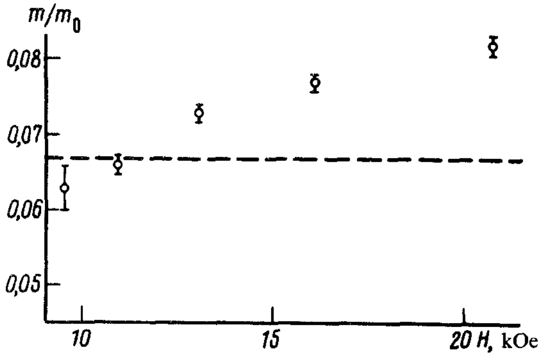


FIG. 2. Magnetic field dependence of the effective mass $m$. The broken line shows the value $m^* = 0.067\ m_0$.

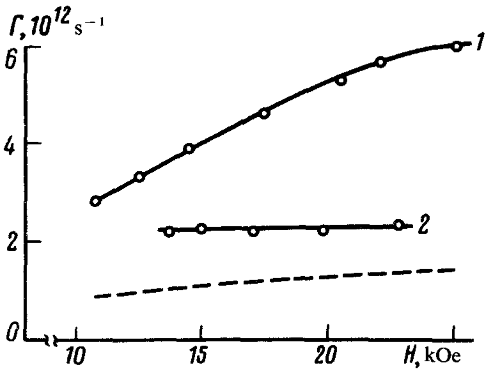


FIG. 3. Magnetic field dependence of the width of the Landau level $\Gamma$.

depends on $H$. This indicates that the magnetic field affects the interactions, which determine the renormalization of the effective mass.

Figure 3 shows the magnetic-field dependence of the width of the Landau level $\Gamma$. Curve 1 was obtained by calculating $\Gamma$ from the monotonic field dependence of $\sigma_{xx}$ with the help of (1). The value of $\tau_0$ in (1), which was determined from measurements of the mobility at $H=0$, is $2.2\times 10^{12}$ s; the value of $N$ is $3.36\times 10^{11}$ cm$^{-2}$. Curve 2 was obtained by calculating $\Gamma$ from the oscillation amplitude of $\sigma_{xx}$ with allowance for the experimental dependence $m(H)$. It is evident from the figure that the values of $\Gamma$, calculated from the monotonic and oscillating parts of $\sigma_{xx}$, differ by approximately a factor of two, which greatly exceeds the limits of the experimental error. Furthermore, there is a qualitative difference in the dependence $\Gamma(H)$, which were determined from the same expression (1) for $\sigma_{xx}(H)$.

The broken line in Fig. 3 shows the field dependence of $\Gamma$ calculated from the equation $\Gamma=\sqrt{(2/\pi)(\omega_c/\tau_0)}$ (Ref. 5 and 6), which describes the broadening of the Landau level due to the scattering by a short-range impurity potential.

The considerable differences among all three dependences $\Gamma(H)$ most likely indicates that scattering by large-scale fluctuations of the potential contributes significantly to the broadening of the Landau level in the comparatively weakly disordered TEG [the mobility is (5–6$\times 10^4$ cm$^2$/V·S]. Our results also suggest that the disagreement between experiment and existing theories[5,6] is attributable to the fact that in Ref. 5 and 6 the localization of electrons in the state-density tails at the Landau levels, which is responsible for the quantum Hall effect, is ignored in the calculations of $\sigma_{xx}$.

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