Quantized Hall effect in disordered GaAs layers with 3D spectrum in tilted magnetic fields

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The quantum Hall effect structure in the transverse magnetoresistance R_{xx} and the Hall resistance R_{xy} of heavily doped GaAs layers with a three-dimensional spectrum of the charge carriers is investigated for different field orientations. The characteristic structures (minima in R_{xx} and plateaus in R_{xy}) shift much more slowly to higher fields and are suppressed much more rapidly in comparison with the expected angular dependence for a two-dimensional system. The results are discussed in terms of the anisotropic change of the three-dimensional conductivity tensor with magnetic field rotation. © *1998 American Institute of Physics.* [S0021-3640(98)01116-5]

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It is well known that in two-dimensional (2D) electron systems the Hall resistance R_{xy} and the Hall conductance G_{xy} are quantized such that $G_{xy}=1/R_{xy}=ie^2/h$ (i is an integer) due to the discrete energy spectrum of the charge carriers in a quantizing magnetic field.[1] In 2D electron systems with a high mobility, electron–electron correlations even lead to a quantum Hall effect (QHE) with fractional i. Recently, a quantization of the Hall conductance has been observed in disordered layers consisting of epitaxial layers of heavily doped n-type GaAs.[2] In this case, the electronic system is supposed to have a three-dimensional (3D) single-particle energy spectrum like that for the bulk material. At $T=4.2$ K, the magnetoresistance of the samples shows the typical behavior of the bulk material, with weak Shubnikov–de Haas oscillations with increasing field and a strong monotone upturn in the extreme quantum limit (EQL), where only the lowest Landau level is occupied. The bulk electron densities n determined from the periodicity of the Shubnikov–de Haas oscillations in reciprocal field were close to the nominal values. Below 1 K, the magnetic-field dependence of the Hall conductance G_{xy} shows steps at quantized values ie^2/h ($i=2,4,6$) together with pronounced minima in the transverse conductance G_{xx} in the extreme quantum limit of the applied magnetic field, while the

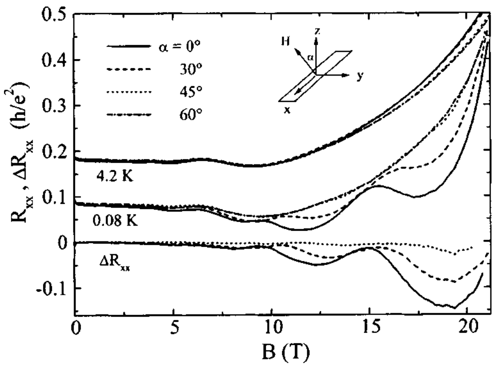

FIG. 1. Magnetic field dependence of the transverse resistance R_{xx} (per square) in magnetic fields at different angles α with respect to the normal of the GaAs layer at $T=4.2$ and 0.08 K. The curves for 4.2 K are shifted vertically by 0.1. ΔR_{xx} shows the difference $R_{xx}(\alpha)-R_{xx}(60°)$ at 0.08 K.

amplitude of the usual Shubnikov–de Haas oscillations does not depend on temperature below 4 K. The minima in G_{xx} and $|dG_{xy}/dH|$ appear in magnetic fields, where $G_{xy}=ie^2/h$ at $T=4$ K.

In this work we study this novel phenomenon of a quantized Hall effect in a disordered GaAs layer in a tilted magnetic field. This study allows for a comparison with the QHE in a 2D system, where the projection of the field perpendicular to the 2D electron system determines the effect in a tilted magnetic field (without taking spin-splitting effects into account). Our experiment reveals a strongly different dependence on the field orientation.

The investigated Si-doped GaAs layers sandwiched between undoped GaAs have been grown by molecular-beam epitaxy as described in Ref. 2. The quantized Hall effect structure has been observed for a perpendicular magnetic field in various samples with thicknesses about 100 nm and electron concentrations from 0.6 to 2.5×10^{17} cm^{-3} (Ref. 2). Here we will present experimental data for different field orientations measured at 4.2 and 0.08 K on a heavily doped GaAs layer (sample 2 in Ref. 2, which showed the most pronounced effect) with a nominal thickness $d=100$ nm, with a bulk electron density $n=1.5\times10^{17}$ cm^{-3} and mobility $\mu=2400$ cm^2/(V· s) at 4.2 K. The estimated mean free path $l=28$ nm and screening length $\lambda_D=7$ nm in zero magnetic field are smaller than the thickness of the layer. Sample 1, with a nominal thickness of 100 nm, a bulk density $n=0.6\times10^{17}$ cm^{-3} and mobility 1900 cm^2/(V· s) was measured only in parallel and perpendicular magnetic fields at $T=0.3$ and 4.2 K. The magnetoresistance R_{xx} and Hall resistance R_{xy} were measured in a Hall-bar geometry by a phase-sensitive detection method for several orientations α of the magnetic field with respect to the normal of the plane of the GaAs layer ($\alpha=0°$ corresponds to the perpendicular orientation). In our convention, the *xyz* coordinates refer to the frame of the layer. The applied current is along the *x* axis, the Hall contacts are along the *y* axis, and the *z* axis is perpendicular to the layer. The magnetic field is rotated perpendicular to the current direction (see the inset of Fig. 1). The measured resistance was converted to the resistance per square R_{xx} using the lateral dimensions of the Hall bar.

In Fig. 1 the transverse magnetoresistance R_{xx} of sample 2 is plotted for different

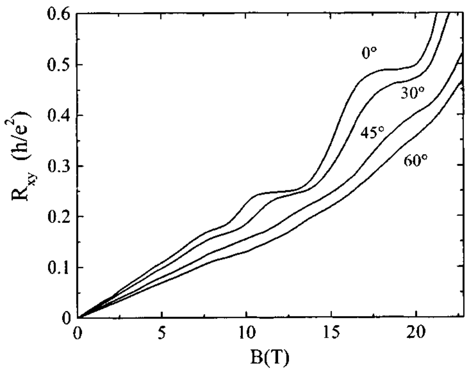

FIG. 2. Magnetic field dependence of the Hall resistance R_{xy} in a tilted magnetic field at different angles α at $T=0.08$ K.

angles α of the applied magnetic field with respect to the normal of the sample plane at temperatures $T=4.2$ K and 0.08 K. At 4.2 K, the characteristic Shubnikov–de Haas oscillations below 8 T and the strong increase in magnetoresistance in the EQL above 8 T are practically independent of the field direction. This is a strong indication of three-dimensionality of the electronic spectrum of the investigated system. At $\alpha=0°$ and $T=0.08$ K, the pronounced minima in R_{xx} coincide with the plateaus in R_{xy} shown in Fig. 2. These structures in the magnetoresistance tensor components resemble the QHE for a 2D electron system, although the plateaus in R_{xy} aren't completely flat nor do the minima in R_{xx} go to zero. As we have shown for samples with the same nominal thickness but different electron density,[2] the quantized structures occur at quantized values ie^2/h of the Hall conductance $G_{xy}=R_{xy}/(R_{xx}^2+R_{xy}^2)$ with $i=2,4,6$.

By rotating the magnetic field away from the perpendicular orientation both the plateaus in R_{xy} and the minima in R_{xx} are strongly suppressed simultaneously. In Fig. 3 we have plotted the field positions $B_{\min}(\alpha)/B_{\min}(0°)$ normalized by the 0° result as functions of the field orientation α. The field positions $B_{\min}(\alpha)$ were extracted from the

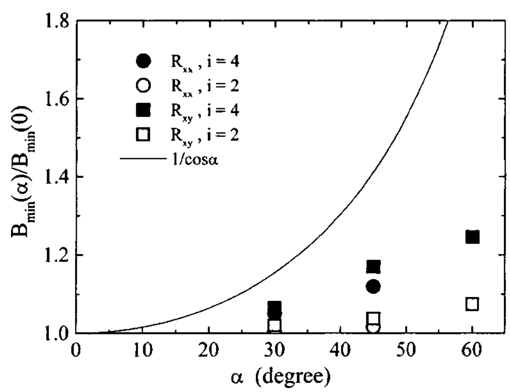

FIG. 3. Normalized magnetic field positions $B_{\min}(\alpha)/B_{\min}(0°)$ of the minima in ΔR_{xx} and dR_{xy}/dB as a function of the field inclination α. The solid curve shows the $1/\cos\alpha$ dependence.

minima in both $\Delta R_{xx}=R_{xx}(\alpha)-R_{xx}(60°)$ and dR_{xy}/dB. These field values are substantially smaller than the $1/\cos\alpha$ dependence expected for a 2D QHE. The discrepancy at higher magnetic fields is more pronounced for the structure at $i=2$ than for the $i=4$ structure. Because of the absence of a $1/\cos\alpha$ angular dependence of the quantized structures in the tensor components, we can exclude any trivial explanation of the observed phenomenon in terms of a hidden 2D electron system in our MBE grown structure.

For an explanation of the quantized phenomenon, we have suggested[2,3] the importance of diffusive corrections to the conductance due to electron–electron interaction.[4] These effects are strongly enhanced in the extreme quantum limit due to the decreasing diffusion perpendicular to the magnetic field and could possibly cause a correlation gap in the density of states at the Fermi level at the lowest temperatures. In the case that the corrections are small (at $T=4.2$ K in our case), the probability $P(t)$ of again finding two diffusing electrons within a distance of the order of the screening length in a time t is given for an anisotropic conductor by

$$P(t)\sim\frac{\lambda_D^3}{d(D_{xx}D_{yy})^{1/2}t}\propto(G_{xx}G_{yy})^{-1/2}, \tag{1}$$

where D_{xx} and D_{yy} are the diffusion coefficients. Within this description of electron–electron interactions in a disordered system, the effect in a rotated magnetic field would depend on the conductance average $\sqrt{G_{xx}(4.2)G_{yy}(4.2)}$. From our previous investigation of the phenomenon on different samples[2] in a perpendicular magnetic field, we concluded that the quantized structure is more pronounced the more closely the conductance $G_{xx}(4.2)=G_{yy}(4.2)$ at $T=4.2$ K comes down to the value e^2/h (Ref. 2). In a tilted field $G_{xx}(4.2)\neq G_{yy}(4.2)$, and one can expect that the strength of the quantized structure depends on the value of $\sqrt{G_{xx}(4.2)G_{yy}(4.2)}$. The suppression of the quantization phenomenon could be explained by the increase of G_{yy}. For a three-dimensional system the angular dependence of the conductivity σ_{yy} can be written as

$$\sigma_{yy}(\alpha)=\sigma_{yy}(0°)\cos^2\alpha+\sigma_{zz}(0°)\sin^2\alpha. \tag{2}$$

The other important (to us) components of the conductivity and resistivity tensor in the tilted field are equal to

$$\sigma_{xx}(\alpha)=\sigma_{xx}(0°),\quad \rho_{xx}(\alpha)=\rho_{xx}(0°),$$
$$\sigma_{xy}(\alpha)=\sigma_{xy}(0°)\cos\alpha,\quad \rho_{xy}(\alpha)=\rho_{xy}(0°)\cos\alpha. \tag{3}$$

$\sigma_{yy}(\alpha)=G_{yy}(\alpha)/d$ is larger than $\sigma_{yy}(0°)$ because of the larger value of $\sigma_{zz}(0°)$ along the magnetic field. We can get an estimate for this from measurements of the longitudinal magnetoresistance of a single crystal with practically the same electron density and mobility as for our layer.[5] At 4.2 K and in a field of 12 T, the value of $\sigma_{zz}(0°)\approx 55$ S/cm while $\sigma_{xx}(0°)=\sigma_{yy}(0°)=9$ S/cm only. For our sample this would lead to an increase in $G_{yy}=\sigma_{yy}d$ upon rotating the sample. The resulting increase of $(G_{xx}G_{yy})^{1/2}$, i.e., the increase of the diffusion in the plane of the layer, could therefore cause the suppression of the quantized Hall effect structures.

We note that Eq.(2) probably gives a not very precise description of the anisotropic transport in our samples because the scattering length l and the magnetic length l_H

($\approx$7 nm at $B=14$ T) are not much less than the layer thickness d. This would lead to an influence of the surface boundaries on the conductance tensor $\hat{G}$. In a tilted magnetic field, the motion of an electron at the top and surface boundaries is absolutely different from the motion inside the layer. The orbits become skipping (classically speaking) at a distance of the order of l_H from the surfaces, leading to a nonuniform current distribution along the thickness of the layer. Therefore, the $\hat{G}$ and, correspondingly, $\hat{R}$ tensor can be rather different from those obtained by the conventional transformation in a tilted field. Indications for this can be seen in the differences at 4.2 K between $R_{xx}(0°)$ and $R_{xx}(\alpha)$ (see Fig. 1) and also between $R_{xy}(\alpha)$ and $R_{xy}(0°)\cos\alpha$, which are rather pronounced at $\alpha=60°$. However, the anisotropic magnetoconductivity would still give $G_{yy}(\alpha) > G_{yy}(0°)$.

We have no explanation for the observed shift of the minima with rotation of the field, but our measurements show that the behavior of our disordered GaAs layer system is definitely different from the behavior of 2D systems.

In summary, the minima in R_{xx} and dR_{xy}/dB in the quantized Hall effect of a disordered heavily doped GaAs layer with a 3D single-particle spectrum have a much weaker shift to higher magnetic fields in a tilted magnetic field than the $1/\cos\alpha$ dependence for the quantum Hall effect measurements in the 2D case. The suppression of the quantized phenomenon in a rotated magnetic field could be related to the mixing of the conductivity tensor component $\sigma_{zz}(0°)$ into the component $\sigma_{yy}(\alpha)$, which would reduce electron–electron interaction effects in the diffusive transport of a disordered system.

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