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Transport properties of a quantum Hall ferromagnet in parabolic wells

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Abstract

We report on the observation of an anomalous resistance peak in a tilted magnetic field corresponding to the filling factors 2 and 4 in parabolic wells with different widths. This phenomenon is due to unpolarized ferromagnetic transitions in quantum Hall ferromagnets. We find that the effect is isotropic when an in-plane magnetic field is applied along and perpendicular to the current direction. Isotropic domain-wall transport is responsible for the magnetoresistance peak.

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Keywords: Quantum Hall ferromagnet; Parabolic quantum well

1. Introduction

Recently, a broad class of phenomena associated with the crossing of Landau levels with opposite spin orientation has received much attention. The interest has been motivated by the close analogy between two-dimensional (2D) states in the quantum Hall regime and conventional electron ferromagnets. It has been noted that a 2D electron gas at Landau filling factors $n = 2, 4, 6\ldots$ resembles a 2D ferromagnet because, when the electron exchange–correlation energy becomes larger than the cyclotron energy, unpolarized ferromagnetic transitions occur in the limit of vanishing effective Lande g factor [1,2]. The transport properties of such a quantum Hall ferromagnet (QHF) are not well understood. In an early work, it has been predicted that the exchange interaction for crossing Landau levels in a single well leads to non-zero energy gaps through this transition [3]. The measurements of the activation energy in a 2D hole gas in tilted fields supported this prediction [4]. However, another experiment demonstrated the disappearance of the $\nu = 4$ minimum in GaAs quantum wells [5], a sharp reduction of the activation energy at $\nu = 3, 4$ [6], or even hysteretic spikes in the resistance at filling factors $\nu = 3, 5, 7$ in AlAs wells [7] and spikes in magnetically doped semiconductors [8]. Such behaviors can be attributed to spatial random potentials which always exist in quantum wells. Disorder leads to a variation of the effective Zeeman field acting on the pseudospins. This is expected to produce domains with particular pseudospin orientations [9]. The transport in a QHF is attributed to the diffusion along the network formed by the domain walls in analogy with transport in integer quantum Hall effect. Recently, very large transport anisotropy for a QHF

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has been reported in Si/Ge heterostructures [10] and GaAs wide wells [11] in the presence of a strong in-plane magnetic field. Such an anisotropy has been explained by the formation of skyrmion stripe phases which can be stabilized by a parallel magnetic field [12]. Alternatively, the anisotropic domain-walls structure due to the sample surface roughness has been proposed to describe the observed transport anisotropy [13]. Therefore, in spite of the several unusual magnetotransport observations and theoretical models, additional experiments with new systems are desirable in order to examine a different possible explanation of the transport properties in a QHF. A promising system for studying the transport anomalies in a QHF is a wide parabolic quantum well (PQW) with several subbands, because the energy gap between Landau levels in a strong magnetic field is determined by the energy-level spacing in zero field, which is much smaller than the cyclotron energy. Therefore, it is expected that, in a PQW, the exchange–correlation energy should be larger than the energy level separation, and magnetic transitions may occur. The correlation energy can be tuned by tilting the magnetic field.

2. Experimental results

The samples were grown in a Mod. Gen II molecular-beam-epitaxy system on GaAs(0 0 1) semi-insulating substrates. The structure consisted of a 1000–3000 Å-wide parabolic $Al_xGa_{x-1}As$ well, with x varying quadratically between 0 and 0.29, surrounded by a 1000 Å-thick $Al_{0.29}Ga_{0.71}As$ barrier containing a silicon δ-doped layer on both sides of the PQW. The electrons mobility and density in our samples were $(70\text{–}100) \times 10^3\ \mathrm{cm}^2/\mathrm{Vs}$ and $(1\text{–}2) \times 10^{11}\ \mathrm{cm}^2$, respectively, indicating that the PQWs were only partially full with two or three subbands occupied. The test samples were Hall bars with a width and distance between the voltage probes of $d = 200\ \mu\mathrm{m}$ and $L = 500\ \mu\mathrm{m}$, respectively. Four-terminal resistance R_{xx} and Hall R_{xy} measurements were performed down to 50 mK in a magnetic field up to 15 T. The samples were immersed in the mixing chamber of a top-loading dilution refrigerator. The measurements were carried out with an AC current not exceeding 10^{-7} A. We measured the magnetoresistance at different angles Θ between the field and the normal to the parabolic-well plane, rotating our samples in situ.

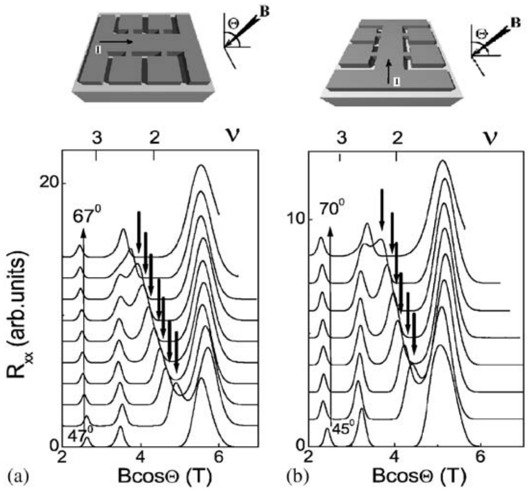

Fig. 1. Magnetoresistance of a 2000 Å-wide PQW as a function of the normal component of the magnetic field for different angles $45° < \Theta < 70°$ between the applied magnetic field and the plane of the substrate at $T = 50$ mK. The magnetic field is tilted (a) in the direction parallel to the current flow, (b) in the direction perpendicular to the current flow. The arrows indicate the anomalous resistance peak. Top—Schematic view of the sample and experiment geometry.

Fig. 1 shows the magnetoresistivity traces in a tilted magnetic field parallel and perpendicular to the current flow for angles $45° < \Theta < 70°$. At $\Theta < 45°$ we observed the typical quantum Hall effect behavior. It is worth noting that the minimum in R_{xx} at $B\cos\Theta = 4.3$ T corresponds to the gap between $n = 0$ and 1 (filling factor $\nu = 2$) spin resolved Landau levels. The magnetoresistance peaks in stronger magnetic fields are not shifted, and their position is determined by the normal component of the magnetic field $B\cos\Theta$. Surprisingly, this picture changes at larger tilt angles: in the interval $55° < \Theta < 68°$ and magnetic field corresponding to the filling factor $\nu = 2$, an additional anomalous peak can be observed between two magnetoresistance peak. It appears at $B_{\mathrm{total}} = 8.9$ T, shifts from the peak corresponding to $\nu = \frac{3}{2}$ to the peak related to $\nu = \frac{5}{2}$ with increasing tilt angles and, at $\Theta = 70°$, the conventional Hall effect is recovered. We did not find any anisotropy in its behavior: indeed, the magnetoresistance traces are identical when the magnetic field is tilted in the direction parallel (Fig. 1a) and perpendicular (Fig. 1b) to the current flow.

For a $W = 1000$ Å-wide PQW, we did not find any anomalous peak at $\nu = 2$ but, rather, we observed an additional peak at $\nu = 4$. Fig. 2 shows a gray-scale presentation of the magnetoresistivity traces as a function

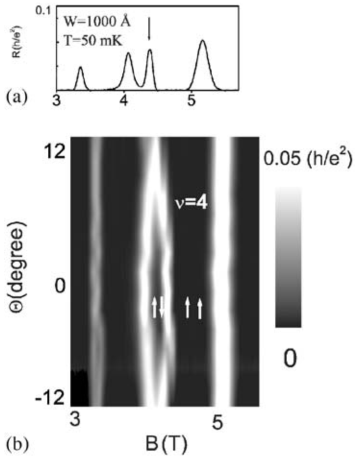

Fig. 2. (a) Magnetoresistance of a 1000 Å-wide PQW as a function of the normal component of the magnetic field for a tilt angle $\Theta = 8°$ at $T = 50$ mK near the filling factor $\nu = 4$. (b) Gray-scale presentation of the tilt-angle dependence of the magnetoresistance on the magnetic field.

of the total magnetic field B_{tot} for that sample. One can see that the anomalous peak appears near the peak corresponding to a filling factor $\nu = \frac{9}{2}$ in a perpendicular magnetic field, and then the quantum Hall effect is recovered at a tilt angle $\Theta = 12°$.

The anomalous peak is not accompanied by a step in the Hall resistance. Fig. 3 shows the transverse and Hall conductivities σ_{xx} and σ_{xy}, recalculated from the resistivities, as a function of the normal component of the magnetic field at $\Theta = 0°$ and in a tilted field, when the anomalous peak is situated exactly between the $\nu = \frac{3}{2}$ and $\frac{5}{2}$ peaks for two electron densities. We can observe that, for $n_s = 2.2 \times 10^{11}$, the plateau in σ_{xy} is only slightly distorted at the place where the anomalous peak appears. However, for a lower electron density, the distortion of the Hall plateau is stronger, as seen in Fig. 3b. The Position of the anomalous peak does not depend on the electron density: indeed, it always appears at a critical total magnetic field $B_c = 8.9$ T. Since it occurs at $\nu = 2$, we can obtain the value of the tilt angle, when the peak is observed in the center of the minima corresponding to $\nu = 2$, by $\Theta_c = \arccos(2eB^c_{total} n_s / hc)$. Therefore, when the density decreases, the parallel component of the magnetic field increases.

Fig. 4 shows the Hall and longitudinal conductivities for different tilt angles in the presence of a strong in-plane magnetic field and for a low electron density. We can see the evolution of the distortion in the

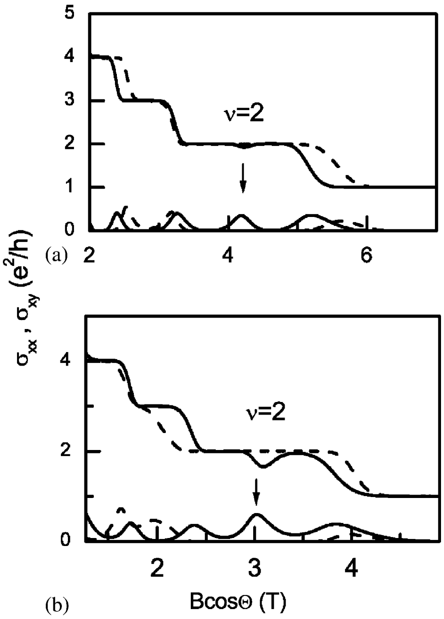

Fig. 3. Longitudinal σ_{xx} and transverse conductance σ_{xy} at $T = 50$ mK of a 2000 Å PQW as a function of the normal component of the magnetic field for an electron density (a) $n_s = 0.9 \times 10^{11}$ cm^{-2} and (b) $n_s = 2.2 \times 10^{11}$. The dashed traces show the magnetoconductance measured at $\Theta = 0°$, while the solid lines represent the magnetoconductance at $\Theta = 60°$ (a) and $\Theta = 72°$ (b).

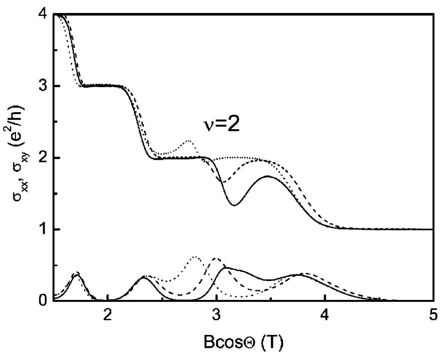

Fig. 4. Longitudinal σ_{xx} and transverse conductance σ_{xy} (b) of a 2000 Å-wide PQW as a function of the normal component of the magnetic field for different tilt angles $\Theta = 70.4°$ (solid), $\Theta = 71°$ (dashes), $\Theta = 72.5°$ (dots). In all the cases, $n_s = 0.9 \times 10^{11}$ and $T = 50$ mK.

Hall-conductivity plateaux when the anomalous peak shifts from the peak corresponding to $\nu = \frac{3}{2}$ to the peak at $\nu = \frac{5}{2}$.

3. Transport properties of a quantum Hall ferromagnet

We attribute the anomalous peak to an unpolarized-ferromagnetic transition in a quantum Hall ferromagnet. The electrons energy in a parabolic quantum well in a tilted magnetic field is given by [14]

$$E = \frac{h}{2\pi}\,\omega_1(n_1 + \tfrac{1}{2}) + \frac{h}{2\pi}\,\omega_2(n_2 + \tfrac{1}{2}) - g^* \mu_B B\,\frac{\sigma}{2}, \qquad (1)$$

where $\omega_{1,2}$ are characteristic frequencies of the PQW in the tilted magnetic field and $g^*\mu_B\sigma/2$ is the Zeeman splitting. In a perpendicular magnetic field, we have $\omega_1 \to \omega_c$ and $\omega_2 \to \omega_0$, where ω_c is cyclotron frequency and ω_0 is a harmonic frequency of the parabolic potential. Therefore, for the last two Landau levels $E_1(n_1=0, n_2=0)$ and $E_2(n_1=0, n_2=1)$, we obtain $\Delta E_{12} = (h/2\pi)\omega_0 < (h/2\pi)\omega_c$. The minimum in R_{xx} at filling factor $v = 2$ corresponds to the gap between the states $n_1 = 0,\ n_2 = 0,\ \sigma = -1$, and $n_1 = 0,\ n_2 = 1,\ \sigma = 1$. The position of the peak corresponds to the crossing of these levels, when the exchange energy is coincident with the energy level separation ΔE_{12}, since the Zeeman splitting in our system is very small. Such level crossing is tuned in the tilted-field experiments because the energy-level separation decreases more rapidly with the tilt angle than the exchange–correlation energy does. The peak in R_{xx} at filling factor $v = 4$ corresponds to the crossing of the states $n_1 = 1,\ n_2 = 0,\ \sigma = 1$ and $n_1 = 0,\ n_2 = 1,\ \sigma = -1$.

As has already been argued in Ref. [9], disorder arising from the density inhomogeneities produces a multidomain structure. Therefore, transport in a QHF is attributed to the diffusion along the network formed by the domain walls in analogy with transport in the integer quantum Hall effect. However, in contrast to the quantum Hall system, when transport is associated with electrons, in a QHF the current-carried states are quasiparticles denominated Skyrmions that carry a charge and can be observed in transport at $v = 1$. At $v = 2$, pseudo Skyrmions are formed due to the alignment of the pseudospin and therefore they are still the excitation states which form the main propagating modes along the domain walls in the QHF. The percolation nature of the anomalous peak in our QHF can be justified by the model considered in Ref. [13]. In that model, the Ising-like domain walls structure has been argued, which leads to the temperature-independent percolation of the two counter propagating sets of modes along the domains walls. We should mention that the model [13] describes also the transport anisotropy observed in Si/Ge heterostructures [10] and GaAs wide wells [11]. In those structures, the domain wall network should be strongly anisotropic as a consequence of the sample-surface roughness. We did not find such anisotropy in our PQWs and this is in agreement with the model considered in Ref. [13]. Since the QHF in Si/Ge heterostructures and GaAs wide wells has been observed at very large tilt angles ($\sim 80°$), any small variation of the sample surface corrugation leads to a variation of the local angle by 0.5° and, consequently, to a variation of the local effective magnetic field by 20%. In our PQWs, the QHF is observed at $\Theta = 60°$ and 70° (see Figs. 3 and 4), and the same variation of the local angle leads to a 0.8–3% fluctuation of the local effective magnetic field. Such a small variation is not enough to produce anisotropy in domain-wall transport. It is worth noting that we did not observe any hysteresis behavior in our samples. We believe that the domains are stabilized by the disorder.

Acknowledgements

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