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Fractional quantum Hall effect in CdTe

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The fractional quantum Hall (FQH) effect is reported in a high mobility CdTe quantum well at millikelvin temperatures. Fully developed FQH states are observed at filling factor 4/3 and 5/3 and are found to be both spin-polarized ground state for which the lowest energy excitation is not a spin flip. This can be accounted for by the relatively high intrinsic Zeeman energy in this single valley two-dimensional electron gas. FQH minima are also observed in the first excited ($N=1$) Landau level at filling factor 7/3 and 8/3 for intermediate temperatures. In contrast, the 5/2 FQH state remains absent down to $T \sim 10$ mK.

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Interacting carriers in certain fractional quantum Hall (FQH) ground states can have opposite spins provided the Zeeman energy is sufficiently small. This is typically observed in GaAs-based two-dimensional electron gases (2DEGs), where an increase in the Zeeman energy induces a change in the spin polarization of the ground state from unpolarized to fully spin polarized. This transition has been reported for the FQH states at filling factor $\nu=4/3$, $\nu=8/5$, $\nu=2/3$, or $\nu=2/5$,[1–4] as well as in a GaAs 2D hole gas.[5] Subsequently, this behavior was elegantly interpreted within the composite fermions (CFs) model[6] for the FQH effect by invoking Zeeman energy-induced crossings between spin-split composite fermion Landau levels (LLs), leading to possible changes in the spin configuration of the ground state.[7] More recently, the $\nu=4/3$ FQH state was investigated in a strained Si quantum well,[8] where the associated resistance minimum was found to maintain its strength with increasing Zeeman energy, which was interpreted as the consequence of a spin-polarized ground state. The latter work addresses the interesting question of how the FQH effect manifests itself in a 2D system with an intrinsically larger Zeeman energy than in GaAs. However, the influence of the valley degeneracy inherent in Si is another degree of freedom that may also interfere with the FQH physics.

In the present work, we study the evolution of FQH states under relatively high intrinsic Zeeman energy in a *single valley* electron system. This is made possible by investigating the FQH effect in a high-quality 2D electron gas in CdTe, a single valley, direct gap, semiconductor in which the bare electronic g factor is about four times larger than in GaAs. A fundamental asset of this system is the possibility to incorporate magnetic ions to form a so-called diluted magnetic semiconductor, which offers possible applications in the fields of spintronics and quantum computing. The transport measurements performed at millikelvin temperature reveal *fully developed* FQH states (i.e., zero longitudinal resistance and exact quantization of the Hall resistance) in the upper spin branch of the lowest ($N=0$) LL, which constitutes to our knowledge the first observation of the FQH effect in a II-VI semiconductor. Tilted magnetic fields experiments up to 28 T show no significant changes in the FQH gap both at filling factor 4/3 and 5/3, a behavior typical of spin-polarized ground states for which the lowest energy excitation is not a spin flip. This can be accounted for by the relatively high intrinsic Zeeman energy which wins over the Coulomb energy to force the spins to align with the magnetic field. This can also be seen as the consequence of energy-level crossings in the composite fermion approach for the FQH effect. Significantly, emerging FQH minima at filling factor 7/3 and 8/3 are also observed at intermediate temperatures in the first excited ($N=1$) LL, demonstrating the high quality of the 2DEG that it is now possible to achieve in this material. Intriguingly, there is no sign of the $\nu=5/2$ FQH effect down to $T \sim 10$ mK. Future studies of the $\nu=5/2$ FQH state in this high Zeeman energy system could be of great importance to shed further light on the long-standing question regarding the spin polarization of this state.

The sample studied here is a 20-nm-wide CdTe quantum well, modulation doped on one side with iodine, and embedded between $Cd_{1-x}Mg_xTe$ barriers ($x \simeq 0.26$). It was cooled down in a $^3He/^4He$ dilution fridge to millikelvin temperature in a number of different ways: under continuous illumination with a green laser or a green light-emitting diode (LED), under continuous illumination with a yellow LED, and, in the darkness. These types of cooldowns will be referred to as cooldown A, B, and C, respectively. The resulting electron density for cooldown A, B, and C, are $n_s=4.50 \times 10^{11}$ cm^{-2}, 4.53×10^{11} cm^{-2}, and 3.80×10^{11} cm^{-2}, respectively, and the electron mobility at $T \sim 600$ mK for cooldown A is around $\mu=260\,000$ cm^2/V s. Transport measurements were performed with a standard low-frequency lock-in technique for temperatures between 40 mK and 1.4 K under magnetic fields up to 28 T.

In Fig. 1, we plot the longitudinal resistance R_{xx} for cooldown A as a function of the perpendicular magnetic field for different temperatures. Pronounced FQH states are observed at low temperature at filling factor $\nu=4/3$, and $\nu=5/3$, with the resistance falling to zero, together with well-defined quantized Hall resistance. The role of illumination in improving the sample quality is critical, as the quantum life-

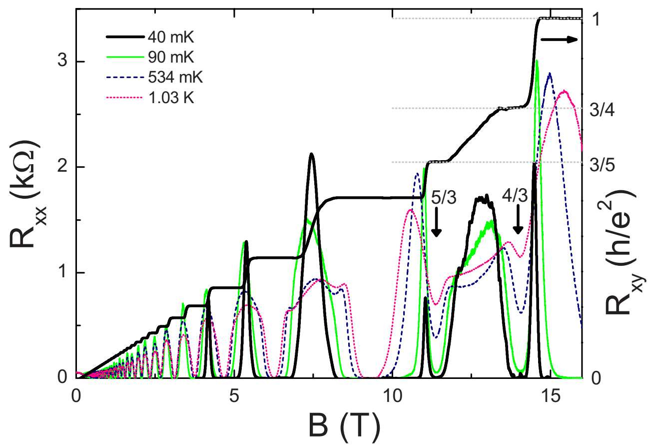

FIG. 1. (Color online) Hall resistance R_{xy} and longitudinal resistance R_{xx} versus perpendicular magnetic field for different temperatures.

time τ_q extracted from the low-field Shubnikov de Haas (SdH) oscillations is found to increase more than five times, from 0.6 ps in the dark to 3 ± 0.3 ps after illumination. This value of τ_q is comparable to the one which can be observed in GaAs samples with several million mobility, despite our moderate measured mobility of 260 000 $\mathrm{cm}^2/\mathrm{V\,s}$.[9]

Nevertheless, at low temperature, an important number of electronic states are localized, leading to wide zero resistance states in the integer quantum Hall effect which prevent the observation of any signs of the FQH effect in the first excited ($N=1$) LL. As the temperature is increased, the fraction of localized states is reduced and weak FQH minima become visible in the $N=1$ LL. These features persist up to relatively high temperature, demonstrating again the quality of the sample.

In Fig. 2 we focus on the FQH effect in the $N=0$ LL. Figure 2(a) shows the temperature dependence of the longitudinal resistance at $\nu=5/3$ and 4/3, for cooldown A and B as a function of the inverse temperature. The difference in sample quality between cooldowns appears clearly when comparing the low-temperature behavior of the initially similar resistance at filling factor 4/3. The so-called "activation plots" or Arrhenius plots are generally used to extract an activation gap or mobility gap, corresponding to the energy difference between the edge of the delocalized states of the ground and excited states. However, a simple extraction of this activation gap Δ requires the observation of an expanded linear region (typically at least one order of magnitude) where $R_{xx} \sim e^{-\Delta/2k_BT}$, whereas such a region is rather absent in our data. This nonthermally activated behavior is actually expected when a Gaussian or Lorentzian level shape is taken into account, for which one expects the linear behavior in an activation plot to deviate at low temperature in the presence of a broadening which reduces the mobility gap. This effect becomes important when the particles level broadening is non-negligible compared to the total (spectral) gap. To analyze our data, we therefore use the model proposed in Ref. 10 which includes a disorder-induced Gaussian broadening to calculate the temperature dependence of the resistance. The LL broadening is imposed by the one extracted for elec-

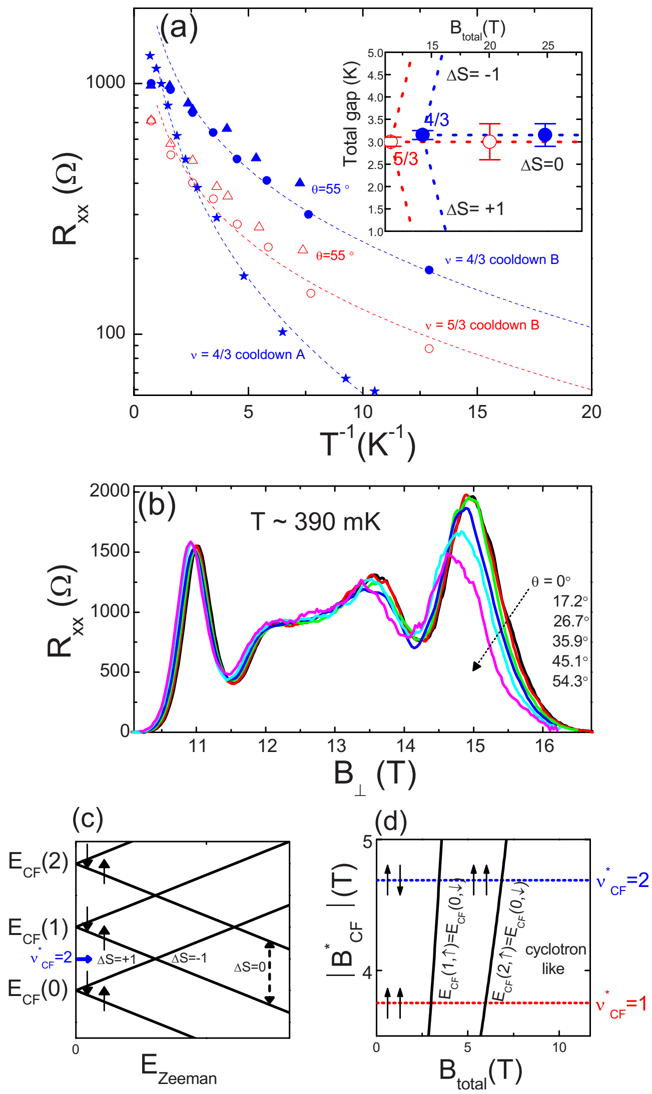

FIG. 2. (Color online) (a) Longitudinal resistance R_{xx} at $\nu=4/3$ as a function of inverse temperature for cooldown A (stars) and for cooldown B at $\theta=0°$ (circles) and $\theta=55.6°$ (triangles). Same data for cooldown B at $\nu=5/3$ (open symbols). Simulations of the thermally activated resistance (dashed lines) (see text). Inset: corresponding total FQH gaps at $\nu=4/3$ and $\nu=5/3$ as a function of the total field B_{total}. Expected evolution of the gaps for different ground states (dotted lines) (see text). (b) Angular dependence of magnetotransport in the upper spin branch of the $N=0$ LL at fixed temperature $T \sim 390$ mK. Increasing tilting angle θ indicated by the arrow. (c) Schematic representation of the CF fan diagram at fixed CF cyclotron energy as a function of the Zeeman energy (see text). $E_{\mathrm{CF}}(N)$ is the energy of the Nth CF level. The arrows depict the spin orientation of each subband. (d) Position of the CF level crossings in the $(|B^*_{\mathrm{CF}}|, B_{total})$ plane (see text). The arrows depict the spin polarization of the ground state in different region.

trons via SdH measurements. The results of these simulations are plotted as dotted lines in Fig. 2(a) and show a very good agreement with the experimental behavior. From this model we estimate the *total* FQH gap in cooldown B to be 3.15 K and 3.0 K for $\nu=4/3$ and $\nu=5/3$, respectively. In units of Coulomb energy, $e^2/4\pi\epsilon_0\epsilon_r l_B$, where $\epsilon_r=10$ is the relative dielectric constant in CdTe and $l_B=\sqrt{h/eB}$ the magnetic length, this corresponds to 0.013 and 0.014, respectively.

Activation data was also collected when tilting the 2DEG plane in the total magnetic field with an *in situ* rotation stage at an angle of $\theta=55°$. This data, also plotted in Fig. 2(a), is very similar to the $\theta=0°$ behavior for $\nu=4/3$ and $\nu=5/3$. The small difference can be well reproduced for both fractions either by introducing a small increase ($\sim 10\%$) in the level width, while the total gap remains constant, or by using a constant level width and a slightly reduced gap ($\sim 10\%$ also). The total gap extracted from our analysis at $\theta=0°$ and $\theta=55°$ are plotted in the inset of Fig. 2(a) as a function of the total field at fixed perpendicular field (filling factor), the vertical error bar representing the possible gap decrease at $\theta=55°$. Starting with the measured gap value for $\theta=0°$, we show how the gap should evolve as a function of total magnetic field (Zeeman energy) in three different configurations: a spin-polarized ground state with single-particle spin-reversed excitation ($\Delta S=-1$, where ΔS is the net spin change of the excitation), a spin-polarized ground state with no spin-reversed excitations ($\Delta S=0$), and a spin-unpolarized ground state ($\Delta S=+1$). The bare g factor $g^*=-1.6$ is taken from Raman-scattering measurements performed on the same sample.

The fact that the $\nu=5/3$ gap remains nearly constant at $\theta=55°$ suggests, as observed in GaAs, a spin-polarized ground state with a lowest energy excitation which is not a spin flip since no increase is observed despite of a significant variation (nearly a factor of 2) of the Zeeman energy. If the $\nu=4/3$ state was to be unpolarized, one would expect a sharp decrease in the gap as well as its disappearance, here around $B_{total}=16$ T, before reentrance at higher fields due to a change in the ground-state polarization. This transition has been observed in GaAs 2DEG at low electron density[1,7] and also for higher densities close to the one of our CdTe sample. In Refs. 1 and 11, the $\nu=4/3$ FQH gap for sample G71 with initial electron density $\sim 2.7\times 10^{11}$ cm^{-2} decreases as the density (total field) is increased and is close to vanishing for magnetic fields of about 12 T. Our observation of a quasiunchanged gap at $\theta=55°$ shows the $\nu=4/3$ FQH state is spin polarized in CdTe. The fact that this gap is *not increasing* further suggests that the lowest energy excitations in this state do not involve spin reversal.

The qualitative behavior of the gap at different tilt angles between $\theta=0°$ and $\theta=55°$ can be inferred from a detailed angular dependence of R_{xx} measured for a fixed intermediate temperature of $T\sim 390$ mK. At this temperature the gap variation can efficiently be probed as observed when comparing the resistance values at $\nu=4/3$ and $\nu=5/3$ for cooldown A and B [Fig. 2(a)]. This angular dependence plotted in Fig. 2(b) shows only a very weak variation in the resistance at $\nu=5/3$ and $\nu=4/3$ over the entire θ range studied ($0° < \theta < 55°$). This demonstrates that no significant changes in the $\nu=4/3$ and $\nu=5/3$ FQH gaps are observed upon tilting, as expected for a spin-polarized state with no spin-reversed excitation.

This behavior can actually be understood more quantitatively using the CF theory for FQH effect, where FQH for electron is mapped onto the integer quantum Hall effect for composite fermions. In the upper spin branch of the $N=0$ LL, around $\nu=3/2$, these CF see an effective magnetic field $B^*_{CF}=3(B_\perp - B_{\perp 3/2})$, where $B_{\perp 3/2}$ is the magnetic field corresponding to $\nu=3/2$.[7,12] In this case the $\nu=4/3(5/3)$ FQH effect for electrons is the $\nu^*_{CF}=2(1)$ integer quantum Hall effect for CF. The scale of the CF cyclotron gap between two CF levels is then given by $\hbar e|B^*_{CF}|/m^*_{CF}$, where m^*_{CF} is the CF effective mass. When the Zeeman energy is added to this simple picture, which is schematically depicted in Fig. 2(b), the lower spin branch of the $N=1$ CF level $[(1,\uparrow)]$ may have a lower energy than the upper spin branch of the $N=0$ CF level $[(0,\downarrow)]$. In this situation the ground state at $\nu^*_{CF}=2$, initially formed by $(0,\uparrow)$ and $(0,\downarrow)$ CF levels for small Zeeman energies, is now formed by the $(1,\uparrow)$ and $(0,\uparrow)$ CF levels and therefore spin polarized. This picture can be applied to our 2DEG in CdTe, with a g factor of $g^*=-1.6$ and the composite fermions effective mass experimentally determined in Ref. 13 as a function of B^*_{CF} ($m^*_{CF}=0.51+0.074|B^*_{CF}|$).[14] In Fig. 2(c), we plot in a ($|B^*_{CF}|$, B_{total}) plane the position of the crossing points of the $(0,\downarrow)$ CF level with the $(1,\uparrow)$ and $(2,\uparrow)$ levels. For $\nu=4/3(\nu^*_{CF}=2)$, these crossings occur for $B_{total}\sim 3.4$ T and $B_{total}\sim 6.8$ T, respectively, explaining why the $\nu=4/3$ FQH ground state is spin polarized with no spin-reversed excitations for the total magnetic field range investigated ($14 < B_{total} < 25$ T). The excitation gap in this domain corresponds to a CF cyclotron gap [referred to as "cyclotronlike" in Fig. 2(c)]. The same conclusions are drawn for the $\nu=5/3(\nu^*_{CF}=1)$ FQH state, provided $B_{total} > 3$ T. We note that the CF cyclotron gap used in these calculations is larger than the experimentally measured FQH gap discussed above, meaning that the transition to cyclotronlike excitations should occur at even smaller magnetic field.

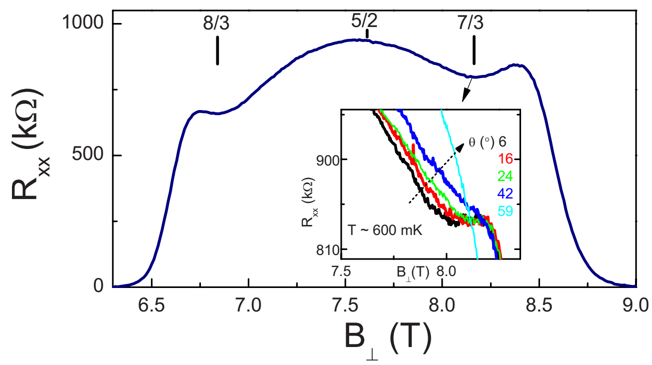

FIG. 3. (Color online) Magnetoresistance R_{xx} in the lower spin branch of the $N=1$ LL at $T=534$ mK. Corresponding filling factors are indicated on top. Inset: angular dependence of the $\nu=7/3$ minimum at $T=600$ mK.

Finally, we turn to the description of the emerging FQH effect in the $N=1$ LL which can be observed in our sample at intermediate temperatures. As can be seen in Fig. 1, weak minima are emerging at filling factors $\nu=7/3$ and $\nu=8/3$ for temperatures above 400–500 mK. At lower temperatures, the increasing number of localized states leads to the FQH effect being masked by the integer quantum Hall effect. The $T=534$ mK perpendicular field data of Fig. 1 are replotted for clarity in Fig. 3. In the inset of Fig. 3, we focus on the evolution of the local minimum at $\nu=7/3$ and $T=600$ mK for different tilt angles. The minimum maintains its strength at low angles before starting to weaken around $\theta=24°$ and finally disappearing for $\theta>42°$. The relative initial stability with respect to tilt angle is similar to the one observed in the $N=0$ LL, and suggest that, as for $\nu=5/3$ and $\nu=4/3$, the $\nu=7/3$ state is already in a regime where the ground state is spin polarized with a lowest energy excitation which is not a spin flip. However, the observation of a $\nu=7/3$ state at lower temperatures (not possible because of localization) would be necessary to validate this hypothesis. At higher angles however, the minimum clearly disappears and the resistance at the broad maximum in R_{xx} associated with the $N=1$ LL starts to increase. Depending on the orientation between the parallel magnetic field and the current flow, the transport was found to be anisotropic, somewhat reminiscent of the anisotropy observed at low temperature in high mobility GaAs-based 2DEG.[15,16]

At variance with $\nu=7/3$ and $\nu=8/3$, no minimum is observed at filling factor $\nu=5/2$. This remains true at ultralow temperature ($T\sim10$ mK), where we still have delocalized electrons around $\nu=5/2$. The absence of a $\nu=5/2$ FQH minimum could primarily be attributed to insufficient sample quality. However, it is also possible that the high Zeeman energy in CdTe plays a particular role in the formation of the 5/2 FQH state. The present extraordinary interest in the even-denominator $\nu=5/2$ FQH state is partly motivated by its possible description using the so-called Moore Read (MR) wave function[17] exhibiting exotic non-Abelian statistics (for a review, see Ref. 18). Despite of a great deal of theoretical evidence for the $\nu=5/2$ FQH state to be described by the MR wave function, there is still no direct experimental observation of the *full* spin polarization expected within this framework. Instead, recent optical measurements[19] point toward a spin-unpolarized state. In our experimental conditions at $\nu=5/2$ ($B=7.6$ T, $g^*=-1.6$), the Zeeman energy is about ~8 K, which is more than one order of magnitude larger than the very weak energy gap usually associated with the 5/2 FQH state (even in the highest mobility GaAs samples). Under such conditions, the stabilization of an unpolarized ground state is very unlikely. Whether this is the reason or not for the "missing" minimum at $\nu=5/2$ in our CdTe sample is a fundamental question which could only be decisively answered provided further significant improvement are made in terms of sample quality.

In conclusion, we have shown that the 2DEG in a CdTe quantum well can have a high quality, leading to the observation of pronounced FQH states in the upper spin branch of the $N=0$ LL, as well as emergent FQH minima in the $N=1$ LL. The physics of these FQH state is strongly influenced by the intrinsic Zeeman energy, resulting in the complete spin polarization of the FQH ground state, in agreement with a CF approach for FQH effect. The high quality of the 2D electron gas in CdTe offers a promising single valley "model system" to study delicate many-body effects (e.g., the $N=1$ LL FQH effect) in the presence of a relatively high Zeeman energy.

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