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 mK temperatures. Fully-developed FQH states are observed at filling factor 4/3 and 5/3 and are found to be both 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 in this single valley 2D 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.

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Interacting carriers in certain FQH ground states can have reversed spins provided the Zeeman energy is sufficiently small. This is typically observed in GaAs-based 2D 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 \( \nu = 4/3, 8/5, 2/3 \), 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 (CF) model [6] for the FQH effect by invoking Zeeman energy-induced crossings between spin-split composite fermion Landau levels, leading to possible changes of 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 mK 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) Landau level (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 Tesla show no significant changes of 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. This leaves open a possible future observation of the \( \nu = 5/2 \) FQH state in the presence of a relatively high intrinsic Zeeman energy.

The sample studied here is a 20 nm-wide CdTe quantum well, modulation doped on one side with iodine, and embedded between Cd₁₋ₓMgₓTe barriers (\( x \approx 0.26 \)). It was cooled down in a \(^3\)He/\(^4\)He dilution fridge to mK 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 \( n_x = 4.50, 4.53 \) and \( 3.80 \times 10^{11} \text{cm}^{-2} \) respectively, and the electron mobility at \( T \approx 600 \text{mK} \) for cooldown A is around \( \mu = 260000 \text{cm}^2/\text{Vs} \). Transport measurements were performed with a standard low frequency lock-in technique for temperatures between 40 mK and 1.4K under magnetic fields up to 28 T.
which prevent the observation of any signs of the FQH zero resistance states in the integer quantum Hall effect. Due to the fact that in such high mobility GaAs samples, the long-range scattering by remote donors is even more prominent and leads to a longer transport time $\tau_{tr}$, for a comparable $\tau_q$.

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 Landau level. Fig. 2a. shows the temperature dependence of the longitudinal resistance at $v=5/3$ 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 $\nu=5/3$ and 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 state.

In Fig. 1 we plot the longitudinal resistance $R_{xx}$ for cooldown A as a function of the perpendicular magnetic field for different temperatures, $T=40$K (thick solid line), $T=90$K (thin solid line), $T=534$mK (dashed line), and $T=1.03$K (dotted line). Cookdown A. Inset: Dingle plots. Semi-logarithmic plot of $\Delta R_{xx}/R_0=(R_{xx}-R_0)/R_0$ where $R_0$ is the zero-field resistance versus $1/B$ for cooldown A (open circles) and for a cooldown C (open squares).

![Figure 1](image1.png)

**FIG. 1:** (Color online) Hall resistance $R_{xy}$ and longitudinal resistance $R_{xx}$ versus perpendicular magnetic field for different temperatures, $T=40$mK (thick solid line), $T=90$mK (thin solid line), $T=534$mK (dashed line), and $T=1.03$K (dotted line). Cookdown A. Inset: Dingle plots. Semi-logarithmic plot of $\Delta R_{xx}/R_0=(R_{xx}-R_0)/R_0$ where $R_0$ is the zero-field resistance versus $1/B$ for cooldown A (open circles) and for a cooldown C (open squares).

![Figure 2](image2.png)

**FIG. 2:** (Color online) (a) Longitudinal resistance $R_{xx}$ at $v=4/3$ as a function of inverse temperature for cooldown A (stars) and for cooldown B at $\theta=0^\circ$ (circles) and $\theta=55.6^\circ$ (triangles). Same data for cooldown B at $v=5/3$ (open symbols). Simulations of the thermally activated resistance (dashed lines) (see text). Inset: Corresponding total FQH gaps at $v=4/3$ and $v=5/3$ as a function of the total field $B_{total}$. Expected evolution of the gaps for different ground states (dotted lines) (see text). (b) Schematic representation of the CF fan diagram at fixed CF cyclotron energy, as a function of the Zeeman energy (see text). $E_{CF}(N)$ is the energy of the $N^{th}$ CF level. The arrows depict the spin orientation of each sub-band. (c) Position of the CF level crossings in the ($B_{CF},B_{total}$) plane (see text). The arrows depict the spin polarization of the ground state in different region.
In the FQH regime, this activation gap has been shown to be in agreement with the calculated FQH mobility gap once disorder (and other corrections) are taken into account (see e.g. Refs. [11, 12]). However, a simple extraction of this activation gap $\Delta$ requires the observation of an expanded linear region (typically at least one order of magnitude) where $R_{xx} \sim e^{-\Delta/\kappa}$, whereas such a region is rather absent in our data. This none-thermally-activated behavior is actually expected when an accurate level shape is taken into account (i.e. Gaussian or Lorentzian broadening), for which one expects the linear behavior in an activation plot to deviate at low temperature in the presence of the 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. [13] which includes a disorder-induced Gaussian broadening to calculate the temperature dependence of the resistance. The results of these simulations (which details will be given elsewhere) are plotted as dotted-lines in Fig.2.a, and show a very good agreement with the experimental behavior.

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 $\theta = 55^\circ$. This data, also plotted in Fig.2.a, is very similar to the $\theta = 0^\circ$ 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 $\theta = 0^\circ$ and $\theta = 55^\circ$ 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 $\theta = 55^\circ$. We also plot here the expected evolution of the total gap 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 $\Delta S$ 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 $\theta = 55^\circ$ 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 un-polarised, one would expect a sharp decrease of the gap as well as its disappearance, here around $B_{\text{total}} = 16T$, 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, 13], 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 quasi-unchanged gap at $\theta = 55^\circ$ 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 $\theta = 0^\circ$ and $\theta = 55^\circ$ can be inferred from a detailed angular dependence of $R_{xx}$ measured for a fixed intermediate temperature of $T \sim 390\text{mK}$. 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 (not shown) shows only a very weak variation of the resistance at $\nu=5/3$ and $\nu=4/3$ over the entire $\theta$ range studied ($0 < \theta < 55^\circ$). This confirms 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 $B_{\text{CF}} = 3(B_{\perp} - B_{1,3/2})$, where $B_{1,3/2}$ is the magnetic field corresponding to $\nu=3/2$ [1, 13]. In this case the $\nu=4/3(5/3)$ FQH effect for electrons is the $\nu_{\text{CF}} = 2(1)$ integer quantum Hall effect for CF. The scale of the CF cyclotron gap between two CF levels is then given by $\hbar eB_{\text{CF}}/m_{\text{CF}}$, where $m_{\text{CF}}$ is the CF effective mass. When the Zeeman energy is added to this simple picture, which is schematically depicted in Fig.2b, 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 $\nu_{\text{CF}} = 2$, 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. [10] as a function of $B_{\text{CF}}^*$ ($m_{\text{CF}}^* = 0.51 + 0.074B_{\text{CF}}^*$). In Fig.2.c., we plot in a $(B_{\text{CF}}^*, B_{\text{total}})$ plane the position of the crossing points of the $(0, \downarrow)$ CF level with the $(1, \uparrow)$ and $(2, \uparrow)$ levels. For $\nu = 4/3(\nu_{\text{CF}} = 2)$, these crossings occur for $B_{\text{total}} \sim 3.4T$ and $B_{\text{total}} \sim 6.8T$ 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 ($14 < B_{\text{total}} < 25T$). The excitation gap in this domain corresponds to a CF cyclotron gap (referred to as “cyclotron-like” in Fig.2.c.). The same con-
conclusions are drawn for the $\nu = 5/3 (\nu_{C_F} = 1)$ FQH state, provided $B_{\text{total}} > 3T$. 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 “cyclotron-like” excitations should occur at even smaller magnetic field.

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 $T = \rho_{\Omega}$ perpendicular field data of Fig.1 are replotted for clarity in Fig.3. We note that no minimum is observed at filling factor $\nu = 5/2$, most likely due to insufficient sample quality. The behavior of the $N=1$ FQH effect under tilted magnetic field have recently been revisited [17–19] notably due to the extraordinary interest in the even-denominator $\nu = 5/2$ FQH state (for a review, see Ref. [20]). The tilted-field behavior of the $\nu = 7/3$ gap turns out to be non-trivial, increasing with tilt in the low field limit [18], decreasing in higher density samples [21], and eventually disappearing at high angles where an anisotropic phase settles [17, 18]. The tilted-field behavior of the magnetoresistance in the $N=1$ LL was examined at intermediate temperature in our CdTe 2DEG and is presented in Fig.3. In the inset, we focus on the evolution of the local minimum at $\nu = 7/3$ and $T = 600\,\text{mK}$ for different tilt angles. We observe that this minimum maintains its strength at low angles, before starting to weaken around $\theta = 24^\circ$ and finally disappearing for $\theta > 42^\circ$. 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 [17, 18]. Thus the $N=1$ LL physics of our CdTe 2DEG looks globally similar to the one observed in the well-known GaAs-based 2DEG, leaving open a possible observation of the $\nu = 5/2$ FQH state 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 in the presence of a relatively high Zeeman energy.

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