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Emergent fractional quantum Hall effect at even denominator $\nu=3/2$ in a triple quantum well in tilted magnetic fields

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Abstract. This work reports on the experimental observation of the even-denominator state $\nu=3/2$ in a trilayer electron system in tilted magnetic fields. The $\nu=3/2$ state demonstrates a strong minimum in longitudinal resistance and is accompanied by a plateau in Hall resistance in a narrow range of tilt angles.

1. Introduction

The observation of fractional quantum Hall (FQH) states at even denominators, in particular at filling factor $\nu=5/2$, has attracted much attention, motivated by implications of fault-tolerant quantum computation [1]. After its discovery [2], many theoretical works indicate that the $5/2$ FQH state, observed in a single quantum well, is an exotic non Abelian Pfaffian state. This state is a subject of ongoing discussions and recent experimental studies indicate implications for the Pfaffian State and can be of importance in clarifying Pfaffian versus anti-Pfaffian as the relevant ground state [3].

On the other hand, an even-denominator FQH state has been found in high mobility bilayer systems in the lowest Landau level (LL) at filling factor $\nu=1/2$ which has no counterpart in a single-layer 2D system [4, 5]. So far, it is assumed that the observed $\nu=1/2$ state in bilayer systems is most likely described by the Abelian so-called Halperin (331) state. A recent theoretical study on the $\nu=1/2$ FQH state as function of tunneling strength and layer separation discusses whether bilayers support both an Abelian Halperin (331) and a non-Abelian Pfaffian state [6]. This work also discusses if the transition between these two states might be observed experimentally in standard transport measurements of the FQH-effect [6].

A further advance in physics of FQH states with even denominators depends on experimental search for non-Abelian states, especially in systems which are distinct from bilayers. Multi-component quantum Hall (QH) systems, which consist of multiple quantum wells separated by thin barriers, exhibit new interesting FQH states due to many-body phenomena and might contribute to the understanding of FQH states [5]. In the present work we have carried
out magnetotransport measurements in a coupled trilayer electron system, formed by a triple quantum well (TQW) in magnetic fields up to $B=34$ T and at a temperature of $T=100$ mK. If we apply a parallel component of the magnetic field, we observe an even-denominator state at total filling factor $\nu=3/2$, which is to the best of our knowledge, the first experimental observation of an even-denominator state in a trilayer electron system. Note that the observed $\nu=3/2$ FQH state is a hole conjugate of the $\nu=1/2$ FQH state ($\nu=3/2=2-1/2$).

2. Trilayer electron system

Our samples are symmetrically doped GaAs TQWs, separated by Al$_x$Ga$_{1-x}$As barriers, with a high total electron sheet density of $n_s=6.9 \times 10^{11}$ cm$^{-2}$ and a mobility of $8 \times 10^5$ cm$^2$/V s. The central well width is about 220 Å and both side wells have equal widths of 100 Å. The barrier thickness is $d_b=20$ Å. In order to populate the central, we increased its width. Corresponding energy gaps $\Delta_{j'j}$ between populated subbands are $\Delta_{12}=1.34$ meV, $\Delta_{13}=3.65$ meV, $\Delta_{23}=2.31$ meV, extracted from a self-consistent Hartree-Fock calculation, and are in agreement with the periodicity of magneto-intersubband oscillations [7, 8]. The trilayer system with corresponding parameters is sketched in the inset of Figure 1. The energies in TQWs are described by the expression $\hbar\omega_c(N + 1/2) \pm \Delta_Z/2 + E_j$, where $\hbar\omega_c$ is the cyclotron energy, $\Delta_Z$ the Zeeman energy, and $E_j$ ($j = 1, 2, 3$) the energies of quantization in the TQW potential.

![Figure 1.](image-url) (Color online) Longitudinal resistance and quantum Hall effect in the trilayer electron system subjected to a perpendicular magnetic field at a temperature of 100 mK. Inset: Sketch of a TQW with corresponding subbands.

In contrast to previous studies in trilayer systems [9], the Landau fan diagram of this particular trilayer system investigated here deviates from the standard sequence of spin-split LLs separated by the subband gaps. Whereas in Ref. [9], we found FQH effect for the highest subband of each Landau level (FQH effect between, e.g. filling factors $\nu=2$ and $\nu=3$), we observe
now FQH effect between integer filling factors $\nu=1$ and $\nu=2$, see Figure 1. The variation of energy gaps $\Delta_{jj'}$ with the magnetic field might be ascribed to charge transfer from the central well to the lateral wells.

3. Observation of the even-denominator state $\nu=3/2$

Tilting the magnetic field leads to the observation of numerous minima in $R_{xx}$ accompanied by plateaus in the Hall resistance $R_{xy}$ at integer and fractional filling factors $\nu > 3$. For $\Theta > 37^\circ$, integer filling factor $\nu=2$ starts to collapse and a new FQH states are developed for $\nu < 2$. With increasing tilt angle, a new deep and broad minimum in $R_{xx}$ appears at fractional filling factor $\nu = 3/2$, see Figure 2(a). This minimum persists up to an angle of $\Theta=43.2^\circ$ and then collapses. In Hall resistance, we observe a plateau quantized at $R_{xy} = 2h/3e^2$, which is shown in Figure 2(c). The even-denominator state is very sensitive to the component of the parallel magnetic field which is pointed out in Hall resistance in Figures 2(b) and (d).

A further increase of the tilt angle leads to a symmetric order in FQH states around even-denominator state $\nu=3/2$ with denominators 5, 7, 9 etc. The best pronounced state is $\nu=7/3$ which occurs at $B_{\perp} \simeq 14$ T.

![Figure 2](image-url)

Figure 2. (Color online) (a) Longitudinal resistance $R_{xx}$ as a function of the perpendicular component of the magnetic field for several chosen tilt angles from $\Theta=37^\circ$ to $\Theta=49^\circ$. For $\Theta > 37^\circ$ a minimum at even-denominator $\nu=3/2$ is developed which persists until $\Theta=43.2^\circ$. (b)-(d) Corresponding Hall resistance exhibits a well developed plateau at $\nu=3/2$ for $\Theta=43.2^\circ$.

Using the derivative of $R_{xy}$, we demonstrate in Figure 3(a)-(c) the evolution of magnetoresistance with increasing tilt angle for $\Theta=41.3^\circ$, $\Theta=43.2^\circ$ and $\Theta=44.5^\circ$. Starting from the integer filling factor $\nu=3$, we observe for $\Theta=41.3^\circ$ a profound minima which first narrows for $\Theta=43.2^\circ$ and is almost vanished for $\Theta=44.5^\circ$. 


Figure 3. (Color online) (a)-(c) Evolution of magnetoresistance with increasing tilt angle. Derivative $dR_x/dB$ demonstrates a clear minimum for $\Theta=41.3^\circ$ and $\Theta=43.2^\circ$. For $\Theta=44.5^\circ$, the even-denominator state at $\nu=3/2$ disappears and we find several developed minima on the low- and high-field side with respect to $\nu=3/2$.

4. Discussion

Multicomponent FQH states can be obtained by a generalization of the Laughlin state. Such incompressible states have been predicted for trilayer systems in Ref. [10]. The state at total filling factor $\nu=5/7$ which is among the strongest states in a trilayer system, is a combination of filling factors $2/7$ in the side layers and $1/7$ in the central layer. This state has been found experimentally [11]. Recently, FQH states at even-denominator filling factors $\nu=1/2$ and $\nu=1/4$ in electron systems confined to a wide GaAs quantum well have been found with a significantly asymmetric charge distribution [12]. Those states disappear when the charge distribution is made symmetric and the subband splitting is lowered.

However, first we point out that the observation of the even-denominator state $\nu=3/2$ in our trilayer electron system cannot be ascribed to a generalization of the Laughlin state. Second, we observe $\nu=3/2$ in the presence of both perpendicular and parallel magnetic field and in a very narrow range $\Delta\Theta$. In general, the presence of an in-plane magnetic field adds an Aharonov-Bohm phase to the tunneling amplitude, which consequently leads to oscillations of the tunnel coupling between electronic states in the layers [13] and to a suppression of this coupling for low Landau levels. Oscillations in the tunnel coupling affect fractional quantized Hall phenomena in highly tilted samples as it has been demonstrated in Ref. [9].

Having a closer look to the sequence of fractional states around $\nu=3/2$, one might suggest that this state in our trilayer electron system is an analog of the two-component $\nu=1/2$ state in a wide quantum well [12]. We can further assume that the electron density is $1/3$ of the total density which implies that our $\nu=3/2$ is a $\nu=1/2+1$ state, i.e., a $\nu=1/2$ state with an
inert background of a fully occupied LL. However, comparing our results to Ref. [12], we notice that the induced asymmetry by gating the wide quantum well gives rise to the appearance of a deep minimum in resistivity. In our TQW, we might have the situation of a slight asymmetry at high magnetic fields as well under certain conditions (tilt angles) but it could also be likely that oscillations of the tunneling gap create a favourite condition (charge distribution) for the observation of the even-denominator state $\nu=3/2$.

5. Conclusion

In the present work we have found first experimental evidence of an even-denominator state at total fractional filling factor $\nu=3/2$. This state is sensitive with respect to the component of the parallel magnetic field and is developed around $\Theta \approx 42^\circ$. We assume that our experimental finding challenges theory in order to understand the origin of this emergent $\nu=3/2$ FQH state in a trilayer electron system in a tilted magnetic field.

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