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Emergent and reentrant fractional quantum Hall effect in trilayer systems in a tilted magnetic field

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Magnetotransport measurements in triple-layer electron systems with high carrier density reveal fractional quantum Hall effect at total filling factors $\nu > 2$. With an in-plane magnetic field we are able to control the suppression of interlayer tunneling which causes a collapse of the integer quantum Hall plateaus at $\nu = 2$ and $\nu = 4$, and an emergence of fractional quantum Hall states with increasing tilt angles. The $\nu = 4$ state is replaced by three fractional quantum Hall states with denominator 3. The state $\nu = 7/3$ demonstrates reentrant behavior and the emergent state at $\nu = 12/5$ has a nonmonotonic behavior with increasing in-plane field. We attribute the observed fractional quantum Hall plateaus to correlated states in a trilayer system.

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Fabrication of multiple two-dimensional (2D) layers in a close proximity to each other allows one to control interlayer electron-electron interaction and creates correlated states in strong magnetic fields. The correlated states characteristic for quantum Hall bilayers or double quantum wells (DQWs) can be divided into two classes: an interlayer coherent state and a two-component fractional quantum Hall (FQH) state which are described by the {111} (Ref. 1) and {331} (Refs. 1 and 2) Jastrow-type wave functions, respectively. The {111} state is responsible for a resistance minimum at filling factor $\nu = 1$ and is often interpreted in terms of a Bose-Einstein condensate of interlayer electron-hole pairs or an excitonic superfluid. The {331} state observed at total filling factor $\nu = 1/2$ (Ref. 3) is determined by interlayer many-body correlations. Both states can be considered as different paired states of composite fermions.[4] Similar as in DQWs, coherent FQH states in trilayer systems or triple quantum wells (TQWs) should exist in a certain interval of parameters determined by the ratio of interlayer separation d to the magnetic length.[5] Such correlated states appear at odd-denominator total filling factors and are different from coherent states in bilayers, though, in both cases, the multicomponent FQH states can be obtained by the generalization of the Laughlin state.[6] The tunnel coupling in multilayer systems adds new degrees of freedom and calls for novel theoretical approaches such as the parton construction.[7] It is shown that correlated states, which are distinct from a stacking of weakly coupled Laughlin states, can exist in the intermediate tunneling regime, when the Coulomb energy is of the same order as the interlayer tunnel coupling strength.[7]

A further advance of the physics of FQH effect in multiple layers depends on experimental search for new many-body ground states, especially in the systems different from bilayers. Previous magnetotransport measurements in TQWs[8,9] have revealed FQH states which, however, are unlikely to be multicomponent FQH states governed by interlayer correlations. The state at $\nu = 5/7$, indicated by a minimum in the longitudinal resistance in the absence of Hall plateau,[8] has not been confirmed in a later experiment.[9] Several even-numerator FQHE states observed in TQWs with low electron density[9] are interpreted as the states characteristic for a bilayer system without interlayer interaction, since the low-density TQW system transforms to a bilayer one with increasing magnetic field.

One of the ways to create more favorable conditions for many-body correlations is to increase localization of electrons by applying a magnetic field in the plane of 2D layers. The influence of this field on multilayer systems deserves a special attention. The in-plane field adds an Aharonov-Bohm phase to the tunneling amplitude, which causes oscillations of the tunnel coupling between electron states in the layers[10–12] and suppression of this coupling for low Landau levels. As a consequence, the many-body coherent states in bilayers are highly sensitive to the in-plane field.[13] The in-plane field can induce stripe phases[14,15] or a complex sequence of commensurate liquids, incommensurate liquids and stripe states[16] in bilayers. No experimental evidence of such states has been reported for TQWs.

In order to reveal possible many-body ground states, we have carried out magnetotransport studies of TQWs with a density much higher compared to previous experiments,[8,9] in magnetic fields up to $B = 34$ T. In a purely perpendicular field we observe numerous plateaus in the Hall resistance R_{xy} at integer ν and the FQH effect at filling factors $\nu = 17/3$, 16/3, 8/3, and 7/3 whereas no FQH states at $\nu > 2$ have been found in.[8,9] When the magnetic field is tilted to an angle $\Theta \sim 45°$, the plateaus at $\nu = 2$ and $\nu = 4$ are suppressed, and several new plateaus in R_{xy} appear at fractional filling factors. Moreover, for the FQH state $\nu = 7/3$ we observe the reentrance effect.

The samples are symmetrically doped GaAs triple quantum wells with equal widths $d_W = 100$ Å of the lateral wells and a wider (230 Å) central well, separated by $Al_xGa_{1-x}As$ barriers with thicknesses $d_b = 14$ Å (wafer A) and $d_b = 20$ Å

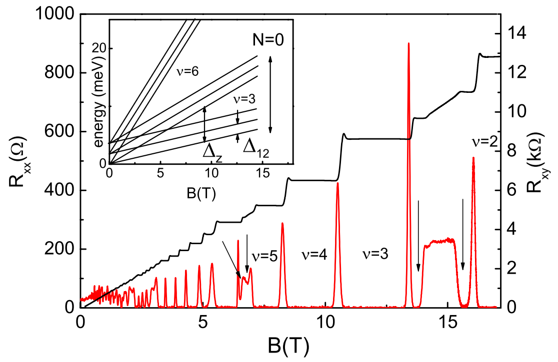

FIG. 1. (Color online) Longitudinal (red/gray) and Hall resistances as functions of the perpendicular magnetic field for a TQW with a barrier thickness d_b=20 Å. Filling factors determined from the Hall resistance are labeled. FQH states are marked with arrows. The inset shows the electron energy levels.

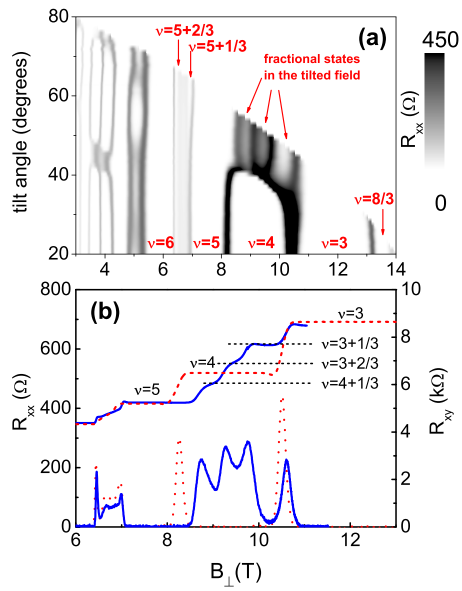

FIG. 2. (Color online) (a) Resistance in the tilt angle—magnetic field plane for a TQW with d_b=20 Å. The minimum at filling factor ν=4 is suppressed and three minima with denominator three are developed. (b) Longitudinal and Hall resistances as functions of the perpendicular magnetic field for two angles: 0 (red dashed) and 49° (blue/dark gray) at T=50 mK.

(wafer B). The samples have high total sheet electron density $n_s=9\times10^{11}$ cm^{-2} and mobilities of $\mu=4\times10^5$ cm^2/V s (wafer A) and 5×10^5 cm^2/V s (wafer B). Due to a combined action of electron repulsion and confinement, the electrons tend to concentrate mostly in the side wells. To make the central well populated, we increased its width. The estimated density in the central well is 35% smaller than in the side wells. The layers are shunted by ohmic contacts. We have measured magnetoresistance for different tilt angles using a conventional ac lock-in technique with a bias current of 0.01–0.1 μA. The measurements have been performed at T=50 mK in a dilution refrigerator with a superconducting magnet up to B=17 T and at $T\sim100$ mK in a resistive magnet up to B=34 T. Several specimens of both Hall bars and van der Pauw geometries from these two wafers have been studied.

Figure 1 shows the longitudinal and Hall resistances of a TQW measured at T=50 mK in van der Pauw geometry. The Landau-level (LL) fan diagram for the TQW consists of spin-split LLs separated by the subband gaps, see the inset to Fig. 1. These energies 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, Δ_Z the Zeeman energy, and E_j (j=1,2,3) the energies of quantization in the TQW potential. These energies, as well as the corresponding single-electron wave functions can be estimated within the tight-binding model.[5] For a symmetric structure,

$$E_{1,3}=(\varepsilon_c+\varepsilon_s)/2\mp\sqrt{(\varepsilon_c-\varepsilon_s)^2/4+2t^2},\quad E_2=\varepsilon_s, \qquad (1)$$

where ε_s and ε_c are the energies of electrons in the side and central wells in the absence of tunneling, and t is the tunneling amplitude. Since $\varepsilon_c>\varepsilon_s$ and $t\neq0$, one has a subband sequence $E_1<E_2<E_3$ and well-defined gaps for each spin-split LL. We identify the minima at ν=6 with the cyclotron gap, the minimum at ν=3 with the Zeeman gap and the minima at ν=1, ν=2, ν=4, and ν=5 with the subband gaps of the first LL (N=0).

In Fig. 1 one may see several minima in R_{xx} accompanied by plateaus in Hall resistance at fractional filling factors ν=17/3, 16/3, 8/3, and 7/3. This observation clearly indicates the difference of TQWs from single quantum wells where FQH effect is developed for all LLs with filling factors $\nu<3$. Moreover, the fractional states are observed only in the regions of transition from ν=2 to ν=3 and from ν=5 to ν=6 which correspond to filling of the upper subband for each spin sublevel of the first LL. Since the FQH effect requires high mobility, our observation may indicate that the mobilities are maximal for electrons in these upper subbands. Indeed, the electron wave function for an upper subband (j=3) is localized mostly in the central well, especially if t is small. Therefore, the electrons of the upper subband experience less scattering and have the highest mobility, sufficient to form fractional states. Figure 2(a) shows the plot of R_{xx} in the tilt angle—perpendicular magnetic field plane for a triple well with a barrier of d_b=20 Å. This diagram clearly demonstrates that resistance minima corresponding to filling of the second LL at ν=7, 9, and 10 vanish and re-establish with increasing tilt angle. The reentrance of the quantum Hall minima at these filling factors is a single-particle phenomenon known for DQWs and originating from oscillations of the tunneling amplitude due to the Aharonov-Bohm effect.[11,12] The period of these oscillations $\Delta B_\parallel\simeq\hbar/edl_\perp$ is determined by the magnetic flux through the area $dl_\perp$, where $l_\perp=\sqrt{\hbar/eB_\perp}$ is the magnetic length associated with the perpendicular component of the field, $B_\perp$. The resistance peaks (or minima) correspond to suppression (or enhancement) of the tunneling gap. For the lowest LL (N=0) the gap is suppressed according to $t\propto\exp[-(B_\parallel/B_\parallel^c)^2]$, where $B_\parallel^c=(2/d)\sqrt{B_\perp\hbar/e}$, and does not oscillate.

Figure 2 shows that the resistance minimum at ν=4 is completely suppressed at $\Theta\approx40°$ whereas the state at ν=5 remains robust against increasing Θ. The corresponding $B_\parallel$ for these conditions (at ν=4) is approximately equal to $B_\parallel^c$, so

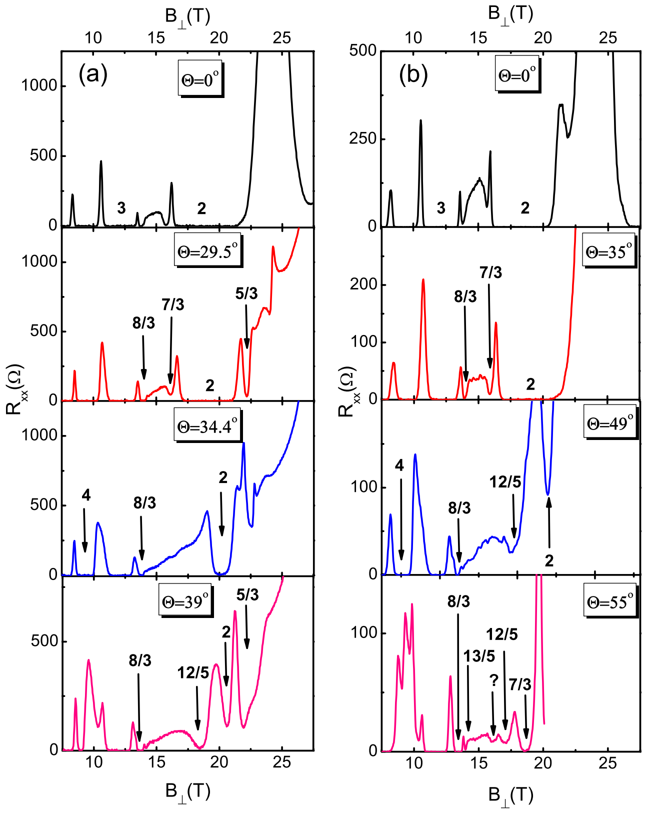

FIG. 3. (Color online) Longitudinal resistance as a function of the perpendicular magnetic field for TQWs with a barrier width of (a) 20 Å for different tilt angles $\Theta=0$ (black), 29.5 (red/gray), 34.4 (blue/dark gray), 39° (pink/light gray) and (b) 14 Å for $\Theta=0$ (black), 35 (red/gray), 49 (blue/dark gray), 55° (pink/light gray) at $T=100$ mK.

the exponential suppression of the tunneling is expected and electron motion is confined to single layers. Now correlation of electrons in nearby layers can lead to new FQH states. The different sensitivity to $B_\parallel$ at different ν takes place because a suppression of the tunneling amplitude ($t \rightarrow 0$) closes the gap between the two lowest subbands of each spin sublevel ($E_1 \rightarrow E_2 = \varepsilon_s$), while the gap between the upper and middle subbands decreases but does not vanish ($E_3 \rightarrow \varepsilon_c$). When the sample is tilted to an angle $\Theta > 45°$, three minima in R_{xx} are developed near $\nu=4$, while the Hall resistance R_{xy} shows precursors of the corresponding quantized plateaus. With increasing tilt angles these FQH states are improved, and one of the plateaus becomes fully developed together with vanishing R_{xx}, as shown in Fig. 2(b). Within the accuracy of 2%, this plateau corresponds to the filling factor $\nu=10/3$. The excitation gap $\simeq 0.7$ K at $\nu=10/3$ was estimated from temperature dependence of the corresponding resistance minimum. Similar behavior is observed around filling factor $\nu=2$. Figure 3 displays traces of R_{xx} and demonstrates the collapse of integer minima at $\nu=2$ and at $\nu=4$ with increasing in-plane magnetic field. The fractional state $\nu=7/3$ also collapses (but reappears at higher Θ) while the state $\nu=8/3$ remains robust and is even improved for higher tilt angles. A further increase in Θ leads to other developed fractional states on the low-field and on the high-field sides with respect to $\nu=5/2$. In both samples we observe minima which can be ascribed to $\nu=12/5$ and $\nu=13/5$. Some additional minima appear at $\Theta \simeq 29.5°$ [Fig. 3(a)] but they collapse with increasing tilt angles and are not accompanied by plateaus in R_{xy}. In the region $\nu<2$ we see (also in R_{xy}) indications of the states at $\nu=12/7$, 8/5, 11/5, and 7/5. Note that we also observe an additional feature [Fig. 3(b)] for $\Theta=55.0°$ at $B=16.1$ T. This state might be attributed to a higher odd-denominator FQH state.

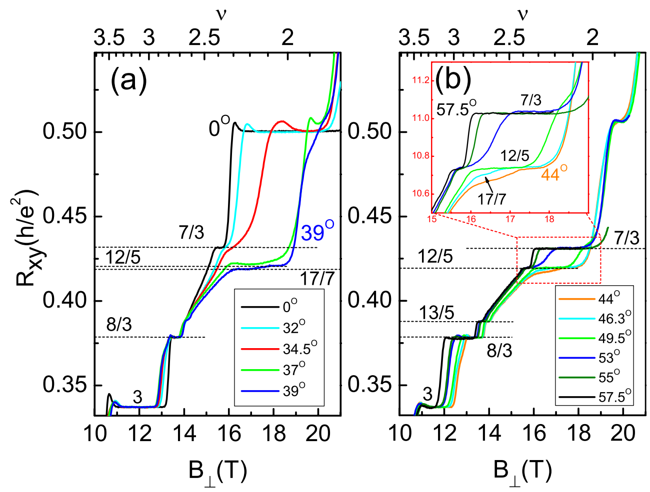

FIG. 4. (Color online) Hall resistance as a function of $B_\perp$ for different tilt angles of a TQW with $d_b=20$ Å at $T \simeq 100$ mK. As Θ increases, the plateau $R_{xy}=3h/7e^2$ disappears and is replaced by the plateau $R_{xy}=5h/12e^2$ (a), then the plateau $R_{xy}=3h/7e^2$ reappears and becomes wide while the width of the plateau $R_{xy}=5h/12e^2$ decreases (b).

An interesting behavior (Fig. 4) is observed in the region between filling factors 2 and 5/2, where a competition of the FQH plateaus corresponding to $\nu=7/3$ and $\nu=12/5$ takes place. As Θ increases, the plateau $R_{xy}=3h/7e^2$ disappears and the plateau $R_{xy}=5h/12e^2$ emerges. The collapse of the plateau $R_{xy}=3h/7e^2$ correlates with the suppression of the integer plateau at $\nu=2$. The plateau $R_{xy}=5h/12e^2$ develops very wide and its center is considerably shifted away from the corresponding fractional filling 12/5 toward higher $B_\perp$. With a further increase in Θ the plateau $R_{xy}=3h/7e^2$ reenters and becomes wide, while the plateau $R_{xy}=5h/12e^2$ narrows. Both plateaus coexist at $\Theta > 49.5°$. No such behavior is observed for the other, symmetric with respect to $\nu=5/2$, pair of plateaus at $\nu=8/3$ and $\nu=13/5$. These plateaus are continuously improved by the in-plane magnetic field. The suppression of the $R_{xy}=3h/7e^2$ and $R_{xy}=h/2e^2$ plateaus and the emergence of $R_{xy}=5h/12e^2$ plateau is clear. If tunnel coupling is present, the gaps between subbands always exist. An increase in $B_\perp$ leads to a consecutive depopulation of the subbands, and the Hall resistance in the interval between $\nu=3$ and $\nu=2$ shows plateaus corresponding to fractional filling of the upper (third) subband at partial filling factors $\nu_3=2/3$ and $\nu_3=1/3$. When tunnel coupling is cut off by the in-plane field (so $E_1=E_2=\varepsilon_s$ and $E_3=\varepsilon_c$), depopulation of the upper subband with increasing $B_\perp$ is accompanied, according to electrostatics, with a decrease of the separation $(\varepsilon_c-\varepsilon_s)$ between the upper subband and lower subbands.

This gap decreases proportional to $-B_\perp$ until the subbands start to overlap. Then both the partial filling of the upper subband, ν_3, and subband separation decrease much slowly with increasing $B_\perp$ since they are accompanied with depopulation of the lower subbands. According to our estimates, the overlap regime becomes essential at $\nu<5/2$, thus the state at $\nu=8/3$ and the emergent state at $\nu=13/5$ are not affected. On the other side, the depletion of the upper subband to $\nu_3=1/3$ corresponds to a strong overlap, while the depletion to $\nu_3=2/5$ is characterized by a weak overlap. Therefore, the plateau $R_{xy}=3h/7e^2$ is suppressed and replaced by the plateau $R_{xy}=5h/12e^2$, the latter still can be explained as the conventional FQH effect associated with filling of the upper subband at $\nu_3=2/5$. Since partial filling of this subband slowly changes with $B_\perp$, the plateau is wide.

The origin of $B_\parallel$-induced reentrance of FQH effect at $\nu=7/3$ differs from that in a single 2D layer, where the reentrance of FQH states[17] is explained in terms of energy-level crossing for composite fermions with spin. First, such a crossing cannot occur for the FQH states with lowest-order denominator 3. Second, we do not observe similar reentrance effects on the other side of even-denominator filling ($\nu>5/2$). While the suppression and disappearance of the plateau at $\nu=7/3$ is explained above in terms of influence of interlayer charge transfer on the conventional FQH state in the upper subband, the emergence of the plateau at the same filling factor under condition of *three partially occupied subbands* most probably signifies a correlated state. Since this emergent plateau is sensitive to the in-plane field, we believe that interlayer correlations are essential. The emergent FQH effect around $\nu=4$ (Fig. 2) occurs under condition of two partially occupied subbands, so the plateaus at $\nu=10/3$, 11/3, and 13/3 also can be attributed to correlated states. Finally, we do not exclude a possibility that interaction effects in TQWs can lead to inhomogeneous correlated states which are similar to those discussed for bilayer quantum Hall systems.[14,16]

In summary, we report on the observation of the collapse of $\nu=4$ and $\nu=2$ states, and the emergence of additional states at fractional filling factors in tilted magnetic fields for trilayer systems. These states are developed as the in-plane magnetic field suppresses the tunneling, and some of them can be ascribed to multilayer many-body correlations. The states $\nu=7/3$ and $\nu=12/5$ show unusually wide plateaus in Hall resistance and demonstrate reentrant or nonmonotonic behavior with increasing in-plane field. More theoretical and experimental work is desirable in order to understand the origin of these emergence and reentrance phenomena.

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[1] B. I. Halperin, Helv. Phys. Acta **56**, 75 (1983).
[2] *Perspectives in Quantum Hall Effects*, edited by S. Das Sarma and A. Pinczuk (Jonh Wiley and Sons, New York, 1997).
[3] J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer, K. W. West, and Song He, Phys. Rev. Lett. **68**, 1383 (1992); Y. W. Suen, L. W. Engel, M. B. Santos, M. Shayegan, and D. C. Tsui, *ibid.* **68**, 1379 (1992).
[4] *Composite Fermions: A Unified View of the Quantum Hall Regime*, edited by O. Heinonen (World Scientific, Singapore, 1998).
[5] C. B. Hanna and A. H. MacDonald, Phys. Rev. B **53**, 15981 (1996).
[6] A. H. MacDonald, Surf. Sci. **229**, 1 (1990).
[7] M. Levin and M. P. A. Fisher, Phys. Rev. B **79**, 235315 (2009).
[8] J. Jo, Y. W. Suen, L. W. Engel, M. B. Santos, and M. Shayegan, Phys. Rev. B **46**, 9776 (1992).
[9] S. P. Shukla, Y. W. Suen, and M. Shayegan, Phys. Rev. Lett. **81**, 693 (1998).
[10] J. Hu and A. H. MacDonald, Phys. Rev. B **46**, 12554 (1992).
[11] V. M. Yakovenko and B. K. Cooper, Physica E **34**, 128 (2006).
[12] G. M. Gusev, C. A. Duarte, T. E. Lamas, A. K. Bakarov, and J.-C. Portal, Phys. Rev. B **78**, 155320 (2008).
[13] S. Q. Murphy, J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **72**, 728 (1994).
[14] D.-W. Wang, E. Demler, and S. Das Sarma, Phys. Rev. B **68**, 165303 (2003).
[15] G. M. Gusev, A. K. Bakarov, T. E. Lamas, and J.-C. Portal, Phys. Rev. Lett. **99**, 126804 (2007).
[16] R. Cote, H. A. Fertig, J. Bourassa, and D. Bouchiha, Phys. Rev. B **66**, 205315 (2002); E. Demler, D.-W. Wang, S. Das Sarma, and B. I. Halperin, Solid State Commun. **123**, 243 (2002).
[17] R. R. Du, A. S. Yeh, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **75**, 3926 (1995).