CHIN. PHYS. LETT. Vol. 34, No. 3 (2017) 037301

Observation of an Even–Odd Asymmetric Transport in High Landau Levels *

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(Received 23 November 2016)

Magnetotransport experiments including tilt fields are performed on ultrahigh mobility L-shaped Hall-bar samples of GaAs/AlGaAs quantum wells. The low-temperature longitudinal resistivity (ρ_{xx}) data demonstrate that a striking even–odd asymmetric transport exists along the [1$\bar{1}$0] direction at half filling in $N \geq 2$ high Landau levels. Although the origin for the peculiar even–odd asymmetry remains unclear, we propose that the coupling strength between electrons within the same Landau level and between the neighboring two Landau levels should be considered in future studies. The tilt field data show that the in-plane field can suppress the formation of both bubble and stripe phases.

PACS: 73.43.Fj, 73.43.Nq, 73.43.Qt DOI: 10.1088/0256-307X/34/3/037301

Recently a rich variety of collective phases[1] in high ($N \geq 2$) Landau levels (LLs) have been reported by low-temperature magnetotransport experiments in ultrahigh mobility ($\mu \geq 1000\,\mathrm{m^2/Vs}$) two-dimensional electron gases (2DEGs). These novel phases, characterized by strong anisotropy[2,3] in the longitudinal resistance and re-entrant integer quantum Hall effect[4] (RIQHE) in the Hall resistance, have stimulated considerable interest. Actually, this regime has been a less intensively studied area compared with that in the lowest or first excited LLs, where the fractional quantum Hall effect (FQHE) is present. Theoretical studies including Hartree–Fock (HF) approximation[5–7] and variational method[8] suggested that the electrons in $N \geq 2$ LLs form charge density waves (CDWs) at low temperatures. At half filling ($\nu = 9/2$, $11/2$, etc.) in spin-split $N \geq 2$ LLs, the CDW is expected to form a stripe phase[5–7] or a stripe nematic phase.[9,10] As it breaks the rotational symmetry, the longitudinal resistance exhibits strong anisotropy: a deep minimum along the [110] crystal direction (the 'easy' axis) and a strong peak along the [1$\bar{1}$0] direction (the 'hard' axis). In the flanks of half filling, another kind of CDW phase with the triangular lattice symmetry, a bubble phase is preferred. These two collective phases were responsible for the experimentally observed anisotropic transport and RIQHE, respectively. This picture is basically supported by subsequent experiments[11–18] and theoretical works.[9,19–22] However, most of the existing anisotropic experiments were performed with the van der Pauw measurements, which exaggerates the intrinsic anisotropy[23] due to the current channelling along the easy axis. To better define the current path, Lilly *et al.*[2] conducted the Hall-bar measurements with the bar axis oriented parallel to the [110] and [1$\bar{1}$0] crystal axis in two separate samples.

In this Letter, we report the magnetotransport study in an L-shaped Hall-bar sample. The main findings include: (1) an even–odd asymmetric transport behavior is observed for the first time in the [1$\bar{1}$0] direction at half filling. (2) The transport along the [1$\bar{1}$0] direction is dominated by the stripe phase. (3) An in-plane field can suppress the stripe phase as well as the bubble phase. Our data indicate that the peculiar even–odd asymmetry seems to be related to the different electron–electron coupling strengths in the same Landau level and between the neighboring two Landau levels.

The samples used in this study are the modulation-doped GaAs/AlGaAs quantum wells (QWs) grown by molecular beam epitaxy (MBE). To ensure high homogeneity of the electron density n_e, each wafer was rotated during the growth in the MBE chamber. Each square specimen of $\sim$3 mm$\times$3 mm was firstly cleaved along the [110] direction from an MBE wafer. Then ohmic contacts were realized by depositing Pd(20 nm)/Ge(50 nm)/Au(120 nm) in sequence in a lithographically defined contact area by an electron

*Supported by the National Basic Research Program of China under Grant Nos 2014CB920904 and 2013CB921702, the National Natural Science Foundation of China under Grant Nos 11174340, 11174357, 91221203 and 91421303, the Strategic Priority Research Program B of the Chinese Academy of Sciences under Grant No XDB07010100, the Gordon and Betty Moore Foundation through the EPiQS initiative under Grant No GBMF4420, and the National Science Foundation of MRSEC under Grant No DMR-1420541.

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beam evaporator followed by annealing at 450℃ for 15 min in a 15% hydrogen–85% nitrogen forming gas atmosphere in a self-made rapid thermal annealer. Finally, 100-μm-wide L-shaped Hall-bar patterns were transferred onto the wafers by lithography.

The inset of Fig. 1 displays a typical L-shaped Hall-bar sample used in the asymmetric transport study. The two mutually perpendicular Hall-bar axes are intentionally oriented parallel to the [110] and [1$\bar{1}$0] crystal axis,[24] respectively. The advantage of our sample geometry over the regular square sample is that the current distributions along the two Hall-bars can be strictly defined, which permit us to study the intrinsic current-dependent transport in the two mutually perpendicular Hall-bar axes simultaneously. The sample was mounted on a well-annealed high-purity silver puck connected to the mixing chamber of a ^{3}He/^{4}He dilution refrigerator with the sample in vacuum for temperature-dependent experiments. Tilt-field measurements were performed in a top-loading dilution refrigerator with an 18-T superconducting magnet, with the total magnetic field B applied with an angle θ with respect to the sample normal. Through multi-stage filtering, these two measurement systems have a noise level of ∼15 nV. After a brief red light-emitting diode (LED) illumination at low temperatures, the specimen attained a mobility of $\mu \sim 12(17)\times10^6$ cm^2/Vs and an electron density of $n_e = 3.37(3.38)\times10^{11}$/cm^2 along the [1$\bar{1}$0] ([110]) direction. Standard low frequency lock-in technique was employed to measure the longitudinal resistivity and the Hall resistivity.

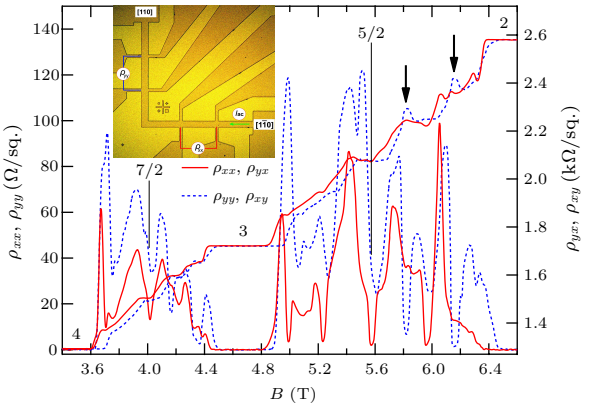

Fig. 1. (Color online) An overview of magnetotranport data is shown for sample A measured at $T = 30$ mK in the first excited Landau level. The red (blue) traces are longitudinal resistivity ρ_{xx} (ρ_{yy}) and corresponding Hall resistivity ρ_{yx} (ρ_{xy}) measured along the [1$\bar{1}$0] ([110]) direction, respectively. Inset: an optical microscopy image of one typical L-shaped Hall-bar sample used in asymmetric transport measurements.

Figure 1 shows the magnetoresistivity and the Hall resistivity of sample A taken at $T = 30$ mK for the first excited Landau level. Throughout this work, ρ_{xx} (ρ_{yy}) refers to the longitudinal resistivity measured along the 'principal axis' [1$\bar{1}$0] ([110]), and ρ_{yx} and ρ_{xy} are the corresponding Hall resistivities. The characteristic features of the even-denominator FQHE states at $\nu = 5/2$ and $\nu = 7/2$ are well developed. In particular, along the [1$\bar{1}$0] direction, at $\nu = 5/2$ even at such a relative high temperature, ρ_{xx} forms a close-to-zero minimum, and concomitantly, with ρ_{yx} forms a quantized plateau at $(h/e^2)/(5/2)$. At the same time, two re-entrant integer quantum Hall states (RIQHSs) denoted by the down arrows in the flanks of $\nu = 5/2$ are developing, which is believed to emerge only at very low temperatures and in very high quality 2DEGs. The above data imply that our sample is very uniform and permits us to study anisotropic transport behaviors at half filling $\nu^* = 1/2$ in high LLs.

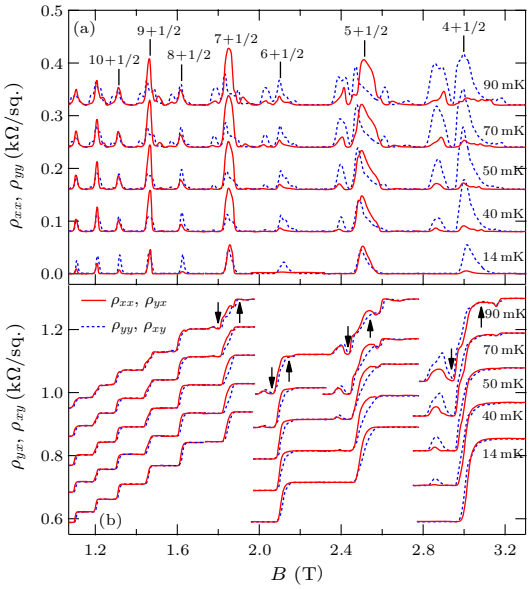

Fig. 2. (Color online) Longitudinal resistivity ρ_{xx} (ρ_{yy}) (upper panel) and corresponding Hall resistivity ρ_{yx} (ρ_{xy}) (lower panel) measured in sample A at five typical temperatures $T = 14$, 40, 50, 70 and 90 mK (from bottom to top). Data are shown in the filling factor range of $4 \le \nu \le 13$. The blue and red curves are the data collected along the [110] and [1$\bar{1}$0] directions, respectively. For clarity, the longitudinal resistivity traces ρ_{xx} (ρ_{yy}) are equally shifted. Similarly, the Hall traces ρ_{yx} (ρ_{xy}) are divided into three groups and each trace is shifted equally in each group. The field positions of half filling from $4+\frac{1}{2}$ to $10+\frac{1}{2}$ are marked in boxes. The up and down arrows in the flank of half fillings indicate the filling factors of $\frac{1}{4}/\frac{3}{4}$.

Figure 2 shows our most striking findings in $2 \le N \le 6$ high Landau levels, corresponding to the filling factor regime of $4 \le \nu \le 12$. We will first discuss the features at half filling $\nu^* = \frac{1}{2}$. At the base temperature $T = 14$ mK, a single peak forms at $\nu^* = \frac{1}{2}$ in ρ_{xx} trace (the bottom red curve in the upper panel of Fig. 2). A close inspection of ρ_{xx} reveals an alternating weak–strong–weak pattern existed at $\nu^* = \frac{1}{2}$ from $N = 2$ to $N = 6$ LL. More importantly, this pattern seems to have close relations with the occupations of Landau levels. Specifically, ρ_{xx} develops a weak hump at $\nu^* = \frac{1}{2}$ when ν changes from even

fillings to odd ones, which is evidenced by a broad weak hump observed at $\nu = 4 + \frac{1}{2}$, $\nu = 6 + \frac{1}{2}$, etc. However, when ν changes from odd fillings to even ones, a contrasting peak in ρ_{xx} is observed. We define the asymmetry parameter as the ratio of the neighboring peak to hump, which can reach as high as 18. We refer this intriguing phenomenon related to even and odd fillings as an even–odd asymmetry. The temperature-dependent data of ρ_{xx} reveal that this kind of asymmetry is rather robust and can survive to 120 mK. As T increases from 14 mK to 90 mK, ρ_{xx} increases but only slightly. To our knowledge, this kind of even–odd asymmetry is experimentally realized for the first time, which is in stark contrast to previously observed in-plane current dependent anisotropy.[2,3,14,25–27] Compared with the characteristics at half fillings between ρ_{xx} and ρ_{yy} curves, we find that the $[1\bar{1}0]$ crystal direction is the hard axis (high resistance). Accordingly, the transport along $[1\bar{1}0]$ is dominated by the proposed stripe phase.

As with ρ_{yy}, at $T = 14$ mK, it resembles ρ_{xx} by forming a single peak at all half fillings present here. However, it exhibits more complex behaviors with T increasing from 14 mK to 90 mK. Here ρ_{yy} undergoes a transition from a sharp peak to a broad valley at $\nu = \text{odd} + \frac{1}{2}$, which is particularly apparent around $7 + \frac{1}{2}$ when $T \geq 40$ mK. This is qualitatively different from previous studies[2,3,14,25–27] where only a resistance minimum were observed at $\nu^* = \frac{1}{2}$ in ρ_{yy}. Moreover, the valley deepens with the filling factor lowered. Similar phenomenon was reported[28,29] in wide quantum wells where two electric subbands were occupied. Different from that, only the lowest subband is occupied in our sample.

For $\nu^* = \frac{1}{2}$, the Hall traces in the [110] and $[1\bar{1}0]$ directions almost share the same behavior. At $T \leq 40$ mK, ρ_{yx} and ρ_{xy} at $\nu^* = \frac{1}{2}$ satisfy the plateau to plateau transition behavior. When $T \geq 50$ mK, we can see that ρ_{yx} and ρ_{xy} begin to deviate from linear relations. The notable kinks appeared near $\frac{9}{2}$, $\frac{11}{2}$, $\frac{13}{2}$, and $\frac{15}{2}$ in the $T = 90$ mK Hall traces prompt us to perform detailed temperature dependence of longitudinal resistivity ρ_{xx} (ρ_{yy}) to search for fractional quantum Hall states (FQHSs) in high LLs. Unfortunately, no thermal activated behaviors (data not shown) were observed at these fractional filling factors. Consequently, no FQHSs were found in $N \geq 2$ high LLs, which is consistent with theoretical calculations.[5,6,8]

Let us now discuss the features around half filling factors $\nu^* = \frac{1}{2}$. At the lowest temperature $T = 14$ mK, only the Hall plateaus and zero magnetoresistances were observed in both crystal axes ([110] and $[1\bar{1}0]$), indicating all electrons condense into a quantum Hall liquid state. When $T \geq 40$ mK, a common feature shared by the Hall traces ρ_{yx} (ρ_{xy}) of the mutual perpendicular directions is the presence of two additional plateaus in the vicinity of $\nu^* = 1/4$ and 3/4, as marked by arrows in the lower panel of Fig. 2. At the same positions, two spikes develop simultaneously in the magnetoresistivity traces. More interestingly, we find that the two plateaus take the values of Hall resistances of the nearest neighboring integer fillings. For example, at $T = 40$ mK around $4 + \frac{1}{4}$ and $4 + \frac{3}{4}$, ρ_{xx} (ρ_{yy}) takes a vanishing value concomitant with a quantized Hall resistance $R_{yx}(R_{xy}) = \frac{h}{\nu e^2}$ where $\nu = 4$ and $\nu = 5$. These features are believed to be the characteristics of re-entrant integer quantum Hall states (RIQHSs),[2,3,25,30–32] and the origin is interpreted as the formation of bubble phase. We will systemically discuss these bubble phases in $N \geq 2$ LLs elsewhere.[33]

The above temperature-dependent data of longitudinal and Hall data indicate that the stripe phase locates at half filling, while the bubble phase distributes in the flanks of half filling. This finding is in excellent agreement with the mean-field phase diagram.[34]

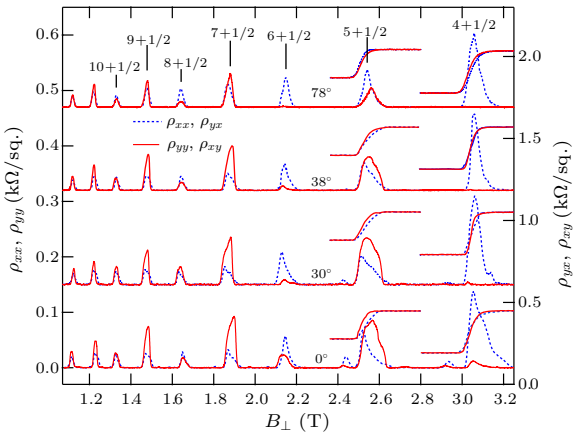

Fig. 3. (Color online) Longitudinal resistivity ρ_{xx} (ρ_{yy}) and Hall resistivity ρ_{yx} (ρ_{xy}) measured at $T = 23$ mK in tilt magnetic fields are shown for the in-plane component $B_\parallel$ along $[1\bar{1}0]$. The blue and red curves are the data collected along the [110] and $[1\bar{1}0]$ directions, respectively. For clarity, all the data are shifted and only the Hall data in $4 \leq \nu \leq 6$ are shown. The field positions of half filling from $4 + \frac{1}{2}$ to $10 + \frac{1}{2}$ are marked in boxes. The tilt angle θ is marked next to the traces.

To gain more insight into the substantial even–odd asymmetric transport in high LLs, we performed tilt-field experiments in a top-loading dilution refrigerator with the in-plane field $B_\parallel = B\sin(\theta)$ directed along $[1\bar{1}0]$. Figure 3 shows the measured magnetoresistivity ρ_{xx} (ρ_{yy}) and Hall resistivity ρ_{yx} (ρ_{xy}) at four typical tilt angles $\theta = 0°$, 30°, 38°, and 78° at our dilution refrigerator's base temperature $T = 23$ mK. The tilt angles are determined by the prominent QHE states, which depend only on the perpendicular magnetic field $B_\perp = B\cos(\theta)$. Though measured in a different system, all the tilt data of ρ_{xx} reveal that the even–odd asymmetry at $\nu^* = 1/2$ exists in the $[1\bar{1}0]$ direction. This suggests that the phenomenon is

robust and has a good reproducibility. In small tilt-fields ($\theta \leq 30^\circ$), the signatures of RIQHSs can also be identified in ρ_{xx} and ρ_{yy} around $\nu = 9/2$ and $11/2$ filling factors, though it is even weaker along $[1\bar{1}0]$ than that along [110]. This verifies the aforementioned fact that the transport along $[1\bar{1}0]$ is dominated by stripe phases. Compared with ρ_{xx} and ρ_{yy}, no features of RIQHSs can be discerned from ρ_{yx} and ρ_{xy} traces, signifying that the longitudinal resistivity is more sensitive to the formation of bubble phases.

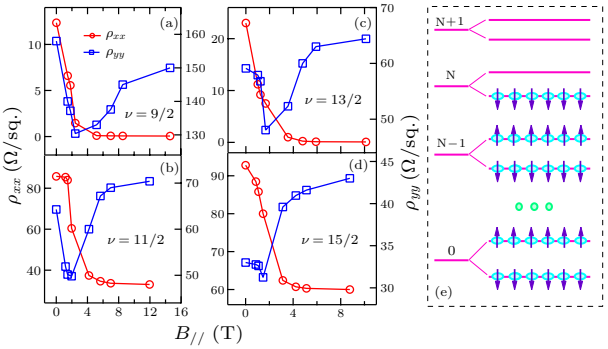

Fig. 4. (Color online) (a)–(d) In-plane magnetic field dependence of ρ_{xx} and ρ_{yy} at $\nu = 9/2$, $11/2$, $13/2$ and $15/2$ at $T = 23$ mK. (e) Schematic diagram of Landau levels. The ellipses symbolize electrons, and arrows their spins.

Figures 4(a)–4(d) summarize the effect of in-plane fields $B_\parallel$ on ρ_{xx} and ρ_{yy}. For the states at $\nu = 9/2$ and $13/2$ (Figs. 4(a) and 4(c)), we find that ρ_{xx} collapses so rapidly that it almost touches zero when $B_\parallel$ is larger than 4 T. On the other hand, for $\nu = 11/2$ and $15/2$ (Figs. 4(b) and 4(d)), ρ_{xx} falls only about 50% at $B_\parallel = 4$ T and then saturates. The contrasting behavior between $\nu = 9/2$ and $11/2$ ($\nu = 13/2$ and $15/2$) is particularly interesting since these two filling factors belong to the same $N = 2$ ($N = 3$) LL. Similar behaviors were observed in previous tilt experiments by Pan *et al.*[26] and Lilly *et al.*[35] but with $B_\parallel$ along [110]. Unlike the case of ρ_{xx}, ρ_{yy} was first suppressed to a minimum strength around $B_\parallel = 2$ T, and then began to rise as $B_\parallel$ was further increased. Finally, ρ_{yy} approaches or exceeds its values at $\theta = 0^\circ$. Another important effect of $B_\parallel$ observed here is that it can suppress bubble phases, demonstrated by the gradual disappearance of RIQHSs in both crystal 'principal axes' as tilt angles θ were increased to 38° or above. In the first excited LL, similar effect of $B_\parallel$ was observed by Eisenstein *et al.*[31] The tilt data demonstrate that the in-plane field has a suppressing effect on the stripe and bubble phases.

The phenomena shown above can be observed in several other samples with electron densities ranging from 1.6 to $3.4 \times 10^{11}/\text{cm}^2$ and low-temperature mobilities $>10 \times 10^6\,\text{cm}^2/\text{Vs}$. By measuring ρ_{xx} with different contact configurations, we find that the orientation of the even–odd asymmetry is fixed to $[1\bar{1}0]$ and is insensitive to field directions as well as thermal cycles. Thus we conclude that the observed even–odd asymmetry is a pervasive feature of high-quality 2DEGs in $N \geq 2$ LLs.

The even–odd asymmetry observed at half fillings of highly excited LLs in high quality 2DEG is of particular interest, because not only it is limited to occur in the $[1\bar{1}0]$ crystal direction, but also it shows close relation to the fillings of Landau levels. However, its origin remains unclear at present. The previously observed huge anisotropy between ρ_{xx} and ρ_{yy} can be easily understood within the context of the theoretically proposed stripe phase[5–7] or stripe nematic phase,[9,10] since it is obviously easier for charge to move parallel to the stripes than perpendicular to them. Though we have shown that the transport along $[1\bar{1}0]$ is dominated by stripe phases, it could not account for the observed even–odd asymmetry. Based on Fig. 4(e), here we give a phenomenological proposal that the electron–electron (e–e) interactions should be considered for future experimental and theoretical studies. Suppose that the Nth LL is the topmost occupied LL, according to Ref. [34] only two kinds of e–e interactions need to be considered: (a) the e–e interaction within the Nth LL and (b) the e–e interaction between the Nth LL and $N-1$th LL. It has been shown that the interaction is larger in (a) than in (b) because the latter is suppressed by the cyclotron gap.[34] The states of $\nu = \text{odd} + 1/2$ and $\nu = \text{even} + 1/2$ correspond to the cases (a) and (b), respectively. Consequently, the transport should exhibit different behaviors at even and odd filling factors.

In summary, we have performed magnetotransport measurements on ultrahigh mobility L-shaped Hall-bar samples of GaAs/AlGaAs quantum wells. The longitudinal resistivity reveals an even–odd asymmetry exists along the $[1\bar{1}0]$ direction at half fillings in $N \geq 2$ high LLs. The intriguing behavior is not understood at present in the absence of theoretical predictions, but our data seems to suggest that the different electron–electron coupling strengths in the same LL and between the neighboring two LLs should be responsible for the observed asymmetric transport related to even and odd fillings.

We would like to acknowledge helpful discussions with Wan Xin, Hu Zhixiang and Zhang Chi.

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