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Stability of the 5/2 fractional quantum Hall state in a Corbino disc sample with in-plane electric fields

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ABSTRACT

Among the various geometries to study the fractional quantum Hall effect in two dimensional electron gas, the Corbino disc owns the advantage to probe the bulk properties directly. In this work we explore the influence of in-plane electric fields on the stability of the 5/2 fractional quantum Hall state realized in Corbino geometry. The effect of weak electric fields is investigated at ultra-low temperatures in order to compare with a theoretical proposal of enhanced Pfaffian state under weak electric fields.

1. Introduction

Since the discovery of the fractional quantum Hall (FQH) effect [1], around 100 FQH states have been observed and most of them are odd-denominator states [2]. In 1987, the first even denominator state, 5/2 FQH state was first observed with a longitudinal resistance minimum and a developing Hall resistance plateau [3], and its exact quantization was reported in 1999 with higher sample quality and lower electron temperature [4]. The even denominator state cannot directly share the theoretical explanation for the odd-denominator states. In the last 30 years, the 5/2 state has been drawing continuous attention both from theoretical and experimental aspects [5,6]. A potential interest in the 5/2 state origins from that its elementary excitations might obey non-Abelian statistics, which makes this state a candidate for fault-tolerant topological quantum computation [7–10]. Numerous candidates with either Abelian or non-Abelian statistics have been proposed for the 5/2 state [8,11–19]. The most theoretical plausible states are the non-Abelian Pfaffian state and its particle-hole conjugate, the anti-Pfaffian state [12–14]. There are also some other candidate states, such as the Abelian 331 state, which is the Halperin's generalization of Laughlin's wave function originally for a bilayer system [15,16].

To identify the wave-function of the 5/2 state or the statistics of its quasi-particles, experiments have been carried out by measuring different properties of the 5/2 states [5,6]. A common approach is to explore the 5/2 state from its edge current. For example, the quantum point contact (QPC) can be used to bring counter-propagating edge currents close to each other and induce quasi-particle tunneling. Shot noise measurements were carried out through QPC and have proved the e/4 charge of quasi-particles at the 5/2 state [20]. Quasi-particle tunneling experiments within a QPC could explore the statistics of the 5/2 state by probing the strength of Coulomb interaction between quasi-particles [21–24]. The results of the latest work [24] indicated that Abelian and non-Abelian states compete at filling factor 5/2. In interference experiments, e/4 and e/2 period interference oscillations supporting non-Abelian statistics have been observed [25,26]. Experiments focused on the edge states have provided important information on the statistics of the 5/2 state, and further experiments to demonstrate the statistics or quasi-particle manipulation are still carrying on.

In addition to the edge, the bulk property also contribute information to identifying the statistics of the 5/2 state. The non-Abelian statistics can be revealed by the entropy carried by quasi-particles [8,27–29], which is related to specific heat measurement at the 5/2 state [30]. Besides, other indirect methods have also been proposed aiming at the bulk properties, including the thermopower [27], temperature dependence of either the electrochemical potential or the orbital magnetization [28], and the anisotropy induced by in-plane magnetic field [31–33]. In the pursuit of bulk properties, the Corbino disc is an appropriate geometry to carry out measurements. The circular symmetry supports the isotropic transport in radial direction and excludes the effect of edge states, thus gives a direct probe to the bulk, which is superior over van der Pauw and Hall bar geometries. However, realization of fractional quantum Hall state in Corbino disc has been technically difficult and the successful attempt of the 5/2 state in Corbino disc is rare, with only one observation of the 5/2 state [34] and one specific heat measurement [30]. In the Hall bar geometry, the

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thermal power signal may be suppressed by the appearance of disorder, while in the Corbino geometry the thermal power signal from only quasi-particles could be measured [35]. Therefore, realization of the 5/2 state in Corbino geometry sample enriches the approach for investigation of quasi-particles' statistics [27,35].

Recently, a theoretical work [36] studied the 5/2 Pfaffian state with in-plane electric fields in Corbino geometry. In that work, an enhancement of the Pfaffian state under sufficiently weak electric fields was predicted, while strong electric fields would destroy the state. Particularly in Corbino geometry an enhancement requires a certain polarity of the applied fields. The verification of this prediction will not only support the Pfaffian theoretical model and non-Abelian statistics, but also serve as a method to stabilize the 5/2 FQH state. Experimentally, this proposal can be realized by the ac differential measurement with a dc voltage bias applied across a Corbino disc.

In this work, we confirm the realization of the 5/2 FQH state in a Corbino device by the corresponding Hall plateau from a van der Pauw sample of the same wafer. Information of the 5/2 energy gap is obtained by varying temperature and electron density is obtained from SdH oscillations. We explore the effect of in-plane electric fields on the 5/2 FQH state at dilution refrigeration temperatures. Under small dc voltage bias, no enhancement of the 5/2 state is observed within our resolution at an excitation of 50 μV; under large dc voltage bias, the 5/2 state is destroyed by strong electric fields as predicted. The stability of the 5/2 FQH state under higher temperature is further explored.

2. Sample and experiment information

The Corbino device was fabricated from a GaAs/AlGaAs heterostructures with quantum well width 25 nm. The density of two-dimensional electron gas (2DEG) is 4.3×10^{11} cm^{-2} and the mobility is 1.2×10^{7} cm^{2}V^{-1} s^{-1}. The Corbino disc owns an inner diameter of 1.8 mm and an outer diameter of 2.0 mm. In the Corbino geometry, pseudo four-terminal differential conductance was measured. As a result, only longitudinal transport with vanishing of conductance at a quantum Hall state is available and the plateau of Hall resistance is absent. We also fabricated a van der Pauw sample from the same wafer and measured together with the Corbino sample, in order to confirm the filling factors.

The measurement setup of the Corbino sample is shown in Fig. 1(a), and that of the van der Pauw sample is shown in Fig. 1(b). The longitudinal conductance of the Corbino sample and the Hall resistance of the van der Pauw sample were measured in the same dilution fridge. The differential measurements were taken using a standard Lock-in technique at 17 Hz with a dc bias applied serving as an in-plane electric field. Between 10 μV and 100 μV, the transport data showed no difference during our test measurement and we used 50 μV for all the final measurements. The base temperature for this work was 30 mK. Before cooling down to the base temperature, the samples were illuminated by a red light-emitting diode at 4.5 K and 15 μA for 1 h.

3. Results

The 2DEG density of the Corbino sample is determined from the SdH oscillations at low magnetic fields (Fig. 1(c)). As a result, the filling factors of the minimums in the longitudinal conductance of the Corbino sample can be labeled. In addition, the integer quantum Hall plateaus in the van der Pauw sample (Fig. 1(b)) coincide with the vanishing of Corbino longitudinal conductance (Fig. 1(a)), which also verified the filling factors we determined from the SdH oscillations. The filling factors of the well-formed minimums of conductance between filling factor 2 and 3 are calculated as 2.671 ± 0.007, 2.540 ± 0.006 and 2.371 ± 0.006. The most likely FQH states should be 8/3, 5/2 and 7/3. The best quality part of the wafer is used for the Corbino sample, and the chip used for the van der Pauw sample is not as high quality as the

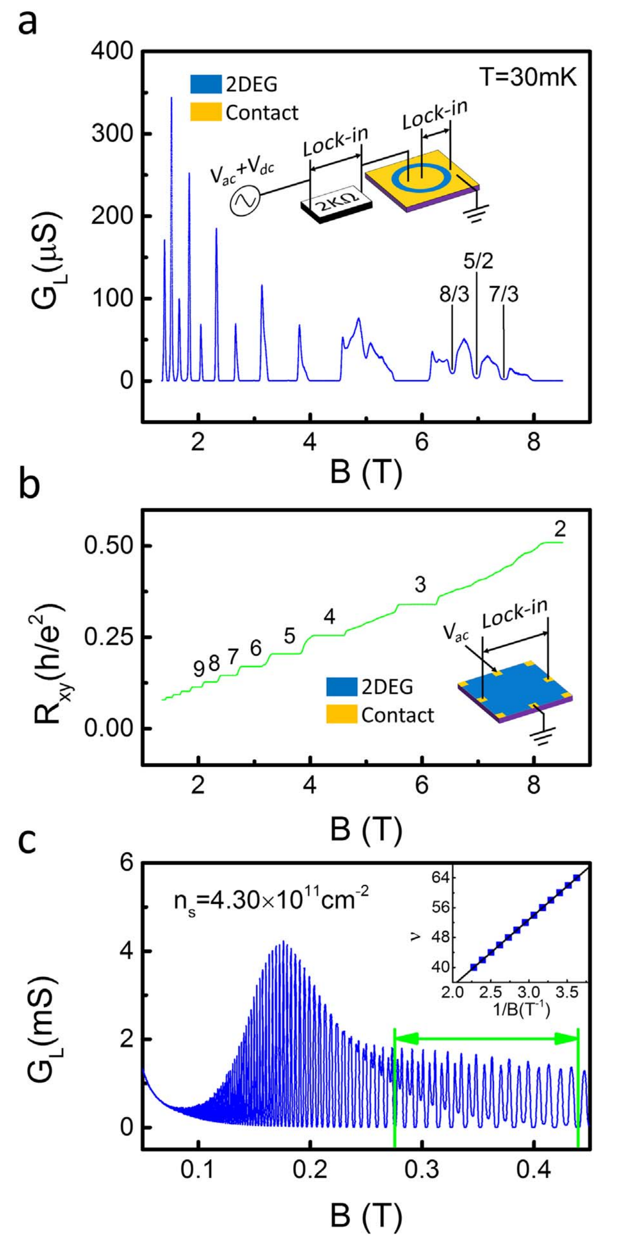

Fig. 1. Magnetic field dependence of the longitudinal differential conductance in Corbino sample and Hall resistance in van der Pauw sample. (a) Differential measurement setup and longitudinal differential conductance for the Corbino sample. (b) Differential measurement setup and Hall resistance for the van der Pauw sample. (c) SdH oscillation of the Corbino sample at low magnetic fields. The 2DEG density n_s is $(4.30 \pm 0.01) \times 10^{11}$ cm^{-2}, fitted within area indicated by green arrows, and the corresponding filling factors are labeled in the inset.

Corbino sample, so the fractional plateaus from the van der Pauw sample in the second Landau levels are not fully developed.

The measurements of longitudinal conductance between the filling factor of 2 and 3 were carried out at different temperatures, as shown in Fig. 2(a). The temperature evolution of FQH states is observed with a deeper dip at a lower temperature. The center of the 5/2 state in magnetic field is determined from the dip of the longitudinal conductance at relatively high temperature, which is 6.992 ± 0.005 T (Fig. 2(b)). From the relation $\sigma_{xx} = \sigma_0 e^{-\Delta/2k_BT}$ at 6.992 T, the energy gap of the 5/2 FQH state can be calculated as 189 mK from the fitting of conductance versus reciprocal of temperature, as shown in Fig. 2(c).

The effect of weak in-plane electric fields on the 5/2 FQH state was explored at 32 mK and at the center of the 5/2 state in magnetic field. Fig. 3(a) exhibits the behavior of conductance under in-plane electric