Physica E: Low-dimensional Systems and Nanostructures 99 (2018) 118–122

Contents lists available at ScienceDirect

Physica E: Low-dimensional Systems and Nanostructures

journal homepage: www.elsevier.com/locate/physe

Coherence length saturation at the low temperature limit in two-dimensional hole gas

Pujia Shan [a], Hailong Fu [a], Pengjie Wang [a], Jixiang Yang [a], L.N. Pfeiffer [b], K.W. West [b], Xi Lin [a,c,*]

[a] International Center for Quantum Materials, Peking University, Beijing 100871, China
[b] Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA
[c] Collaborative Innovation Center of Quantum Matter, Beijing 100871, China

ARTICLE INFO

Keywords:
Two-dimensional hole gas
Integer quantum Hall effect
Plateau-plateau transition
Coherence length saturation
Zero-point fluctuations

ABSTRACT

The plateau-plateau transition in the integer quantum Hall effect is studied in three Hall bars with different widths. The slopes of the Hall resistance as a function of magnetic field follow the scaling power law as expected in the plateau-plateau transition, and saturate at the low temperature limit. Surprisingly, the saturation temperature is irrelevant with the Hall bar size, which suggests that the saturation of the coherence length is intrinsic.

1. Introduction

In the well-known integer quantum Hall (IQH) effect, a quantized plateau develops when the Fermi level is in the localized state, and there is an extended state between two adjacent IQH plateaus [1]. The plateau-plateau transition (PPT) is a localization-delocalization transition occurring at a critical magnetic field B_c, and the localization length ξ diverges with $\xi \propto |B - B_c|^{-\nu}$ when a function of magnetic field is approaching B_c [2–5]. In PPT, the transition is characterized by the slope of the Hall resistance R_{xy}, where $(dR_{xy}/dB)\big|_{B_c} \propto T^{-\kappa}$, $\kappa = p/2\nu$ and p is the temperature exponent of the quantum coherence length, as the coherence length $L_\phi \propto T^{-p/2}$ [3–5]. The scaling power law is usually expected to fail when the coherence length reaches the sample size [4,6], and there has been convincing experimental evidence of the finite size effect in PPT [7,8].

Recently, another study on PPT in a two-dimensional hole gas (2DHG) suggested that the saturation of the slope of the Hall resistance is in good agreement with the assumption of the zero-point fluctuations [9] so that there is an intrinsic saturation of the coherence length at the low temperature limit [10]. There have been substantial experiments witnessing the phase saturation in different systems [7–18], such as one-dimensional metal wire [9,12–14], two-dimensional electron gas [7,8,11], thin film [15,16] and three-dimensional polycrystalline [17,18]. The PPT provides a new approach to study the phase saturation at the low temperature limit [10]. In reference [10], the saturation temperatures of different PPTs are different, which raises the possibility that the finite size effect is not the only cause of the saturation at low temperature in a 2DHG.

In order to systematically study the role of the finite size effect in the PPT of 2DHG, we have carried out transport measurements at high magnetic fields with different Hall bar sizes. The PPTs from IQH plateau 4 to 5 and from IQH plateau 5 to 6 have been studied. The scaling property in the slope of Hall trace as a function of temperature is confirmed at relatively high temperature, and the saturation is also observed at the low temperature limit. The relation between the saturation temperature and the Hall bar width supports that there is an intrinsic mechanism for the coherence length saturation at the low temperature limit.

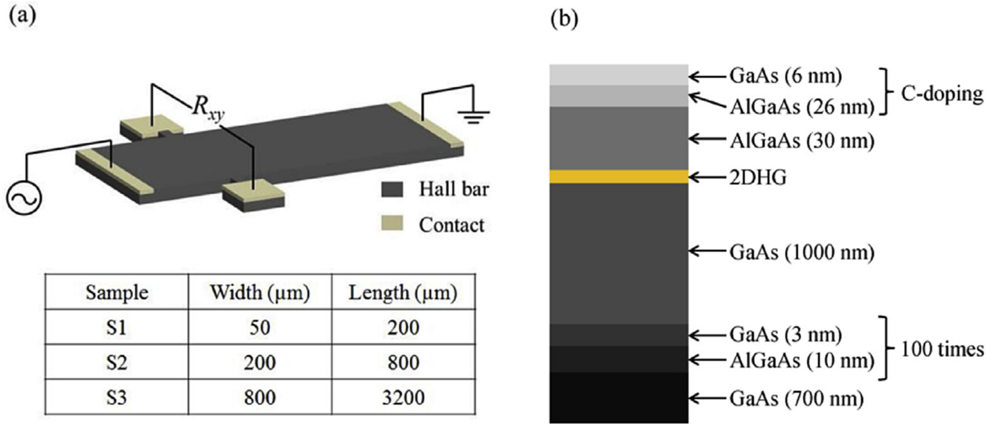
2. Experimental methods

The Hall bars were fabricated on a wafer from the GaAs/AlGaAs heterostructures. The 2DHG is 62 nm below the surface, with a hole mobility of 2.8×10^5 cm^{2}V^{-1}s^{-1} and a density of 2.8×10^{11} cm^{-2}. The Hall bars were shaped by wet etching of H_2SO_4:H_2O_2:H_2O (1:8:240) solution, and the contacts were deposited with Ti/AuBe/Pt/Au by electron-beam evaporator and then were annealed in a rapid thermal processing system at 500 °C. Three Hall bars from the same fabrication process were studied in this work.

Three Hall bars' shape and dimensions are illustrated in Fig. 1. Their widths are 50 μm, 200 μm and 800 μm respectively and the length-to-width ratios are kept as 4:1. A standard four-terminal low-frequency

* Corresponding author. International Center for Quantum Materials, Peking University, Beijing 100871, China.
E-mail address: xilin@pku.edu.cn (X. Lin).

https://doi.org/10.1016/j.physe.2018.01.026
Received 2 October 2017; Received in revised form 21 January 2018; Accepted 25 January 2018
Available online 31 January 2018
1386-9477/



Sample	Width (μm)	Length (μm)
S1	50	200
S2	200	800
S3	800	3200

Fig. 1. (a), the sketch of the measurement circuit and the shape of the Hall bar. The dimensions of three Hall bars S1, S2 and S3 are summarized in the table. The widths of them range from 50 μm to 800 μm, and with the length-to-width ratio kept as 4:1. (b), the structure of the 2DHG wafer doped with carbon.

Lock-in technique was applied in this experiment, with an AC current excitation of 1 nA at 6.74 Hz. The 1 nA excitation was chosen in order to limit the heating effect.

The Hall traces were measured from 24 mK to 500 mK between IQH state 4 to 6. The experiment was performed in a dilution fridge with a base bath temperature lower than 6 mK and the base electron temperature is about 18 mK. Above 20 mK, this fridge's electron temperature is equal to the fridge temperature, and all the temperatures labeled in this work refer to the electron temperature. Before the measurement, the Hall bars were illuminated with red LED for 1 h at around 4 K with an LED current of 20 μA.

3. Results and discussions

3.1. Saturation at the low temperature limit

Fig. 2 shows the Hall traces for the 50 μm, 200 μm and 800 μm Hall bars at different temperatures. Hall traces at different temperatures between the filling factor 4 and 5 (or between the filling factor 5 and 6) tend to cross each other at a magnetic field at the low temperature limit, which is treated as the critical field B_c. The precise B_c is defined by the crossing point of two Hall traces at adjacent temperatures. From Fig. 2, the slope of the Hall resistance $(dR_{xy}/dB)|_{B_c}$ between two neighbor IQH plateaus can be determined as a function of temperature. $(dR_{xy}/dB)|_{B_c}$ vs temperature of three Hall bars for $4\rightarrow5$ transition and $5\rightarrow6$ transition are shown in Fig. 3a and b. The expected scaling power law behavior of $(dR_{xy}/dB)|_{B_c}$ at the high temperature end is apparent, and κ can be determined by $(dR_{xy}/dB)|_{B_c}\propto T^{-\kappa}$.

As temperature decreases, the values of $(dR_{xy}/dB)|_{B_c}$ in three Hall bars saturate. The saturation temperature T_s in this work is defined as Fig. 4a illustrating. Fig. 4b plots the T_s as a function of the Hall bar width. If the saturation results from the finite size effect, the saturation temperature should increase with decreasing Hall bar width. The coherence length $L_\phi\propto T^{-p/2}$ and the temperature exponent of the quantum coherence length p can be obtained [8]. It's generally believed that $p=2$ [8,19] so that $T_s\sim W^{-1}$, which has been experimental observed [8]. However, in Fig. 4b, the saturation temperature qualitatively and quantitatively disagrees with the finite size effect.

External effects, such as the size effect [7,8] and the heating mechanism caused by excitation current [8–11,19], may contribute to this saturation. Internal effects have also been considered comprehensively, such as the electron-electron interaction processes [9] and the magnetic impurities [16,20]. 1 nA excitation was weak enough to avoid the self-heating effect in our temperature range. The noise heating effect can be ruled out because high frequency noise has been filtered by both room temperature and low temperature low-pass filters, and also because our electron temperature can be cooled down to below 20 mK. Therefore, the saturation in our PPT is independent of the heating effect. Besides, the influence of magnetic impurities and the Kondo effect can be disregarded since the IQH effect appears at a relatively high magnetic field. Because we have excluded the finite size effect, we are speculating that the hole in this system may develop intrinsic dephasing and cause the observed slope saturation.

Previous plateau transition of 2DHG study pointed out that besides the finite size effect, the zero-point fluctuations of phase coherent holes

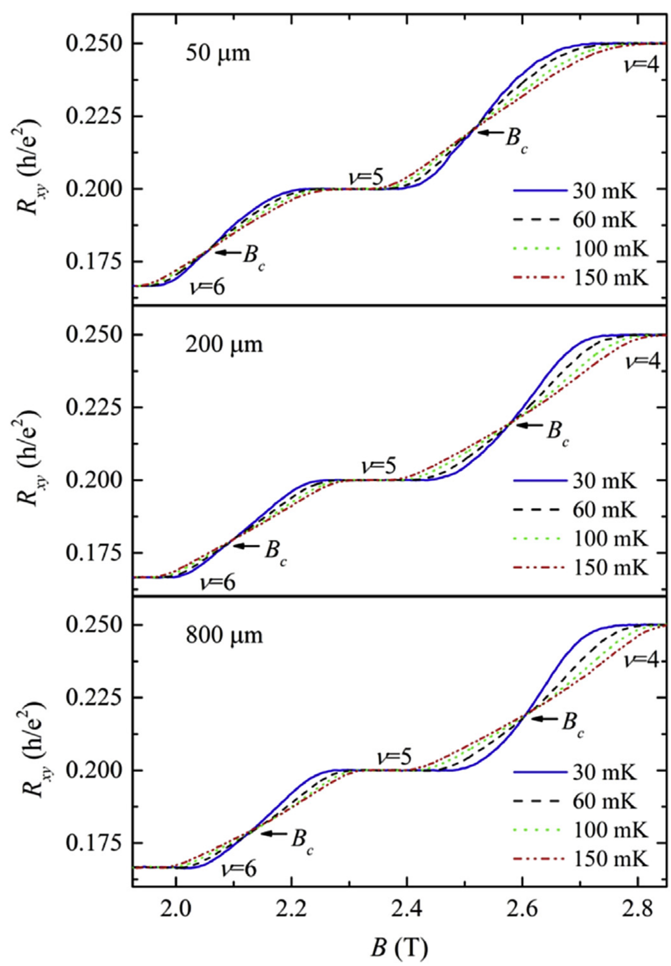


Fig. 2. The Hall resistance R_{xy} vs magnetic field B for the 50 μm, 200 μm and 800 μm Hall bars between the filling factor 4 and 6. Hall traces at different temperatures cross each other at a small magnetic field range at the low temperature limit.