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Physica E: Low-dimensional Systems and Nanostructures

Volume 99, May 2018, Pages 118-122

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

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https://doi.org/10.1016/j.physe.2018.01.026

Highlights

- The plateau-plateau transition is studied in a two-dimensional hole gas (2DHG).
- The saturation … observed at the …
- The saturation … irrelevant to the …
- The size dependence of the coherence length saturation in 2DHG is found different from two-dimensional electron gas.

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.

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Keywords

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

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 when a function of magnetic field is approaching B_c [[2], [3], [4], [5]]. In PPT, the transition is characterized by the slope of the Hall resistance R_{xy}, where , and p is the temperature exponent of the quantum coherence length, as the coherence length [[3], [4], [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], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]], such as one-dimensional metal wire [9,[12], [13], [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 $cm^2V^{-1}s^{-1}$ 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 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.

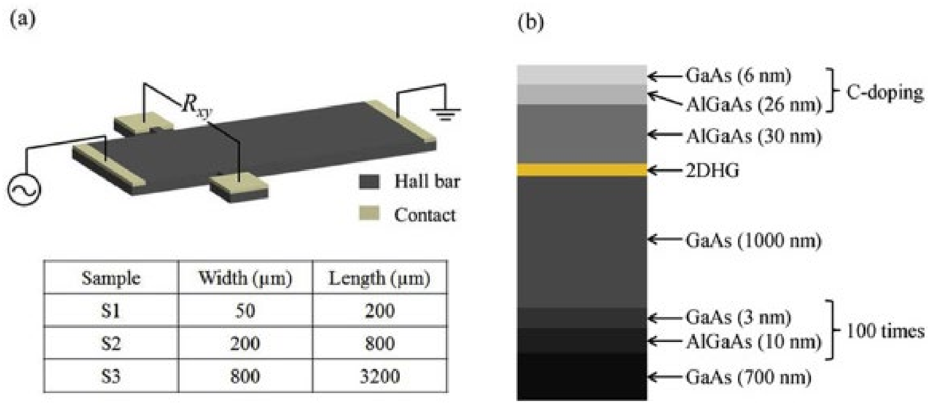

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Fig. 1. (a), the sketch of the measurement circuit and the shape of the Hall bar. The dimensions of three Hall bars S1, S2 and S3 are summarized in the table. The widths of them range from 50 μm to 800 μm, and with the length-to-width ratio kept as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

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 between two neighbor IQH plateaus can be determined as a function of temperature. vs temperature of three Hall bars for 4 → 5 transition and 5 → 6 transition are shown in Fig. 3a and b. The expected scaling power law behavior of at the high temperature end is apparent, and κ can be determined by .

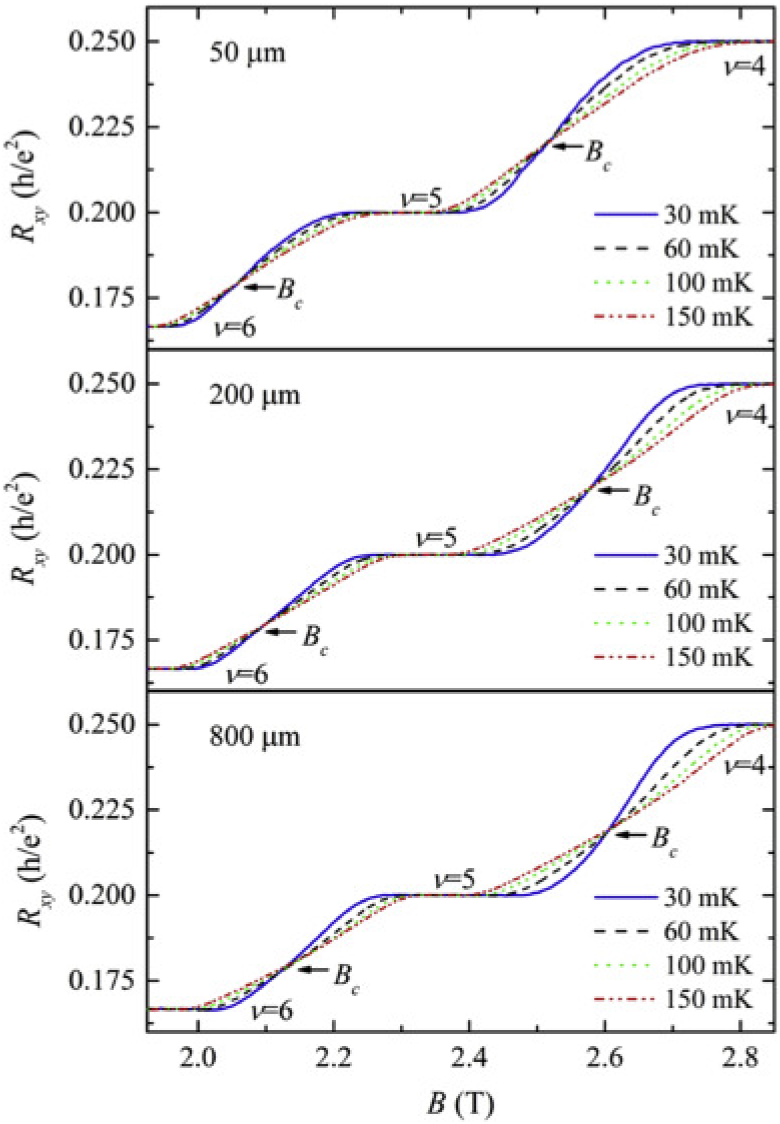

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Fig. 2. The Hall resistance R_{xy} vs magnetic field B for the 50 μm, 200 μm and 800 μm Hall bars between the filling factor 4 and 6. Hall traces at different temperatures cross each other at a small magnetic field range at the low temperature limit.

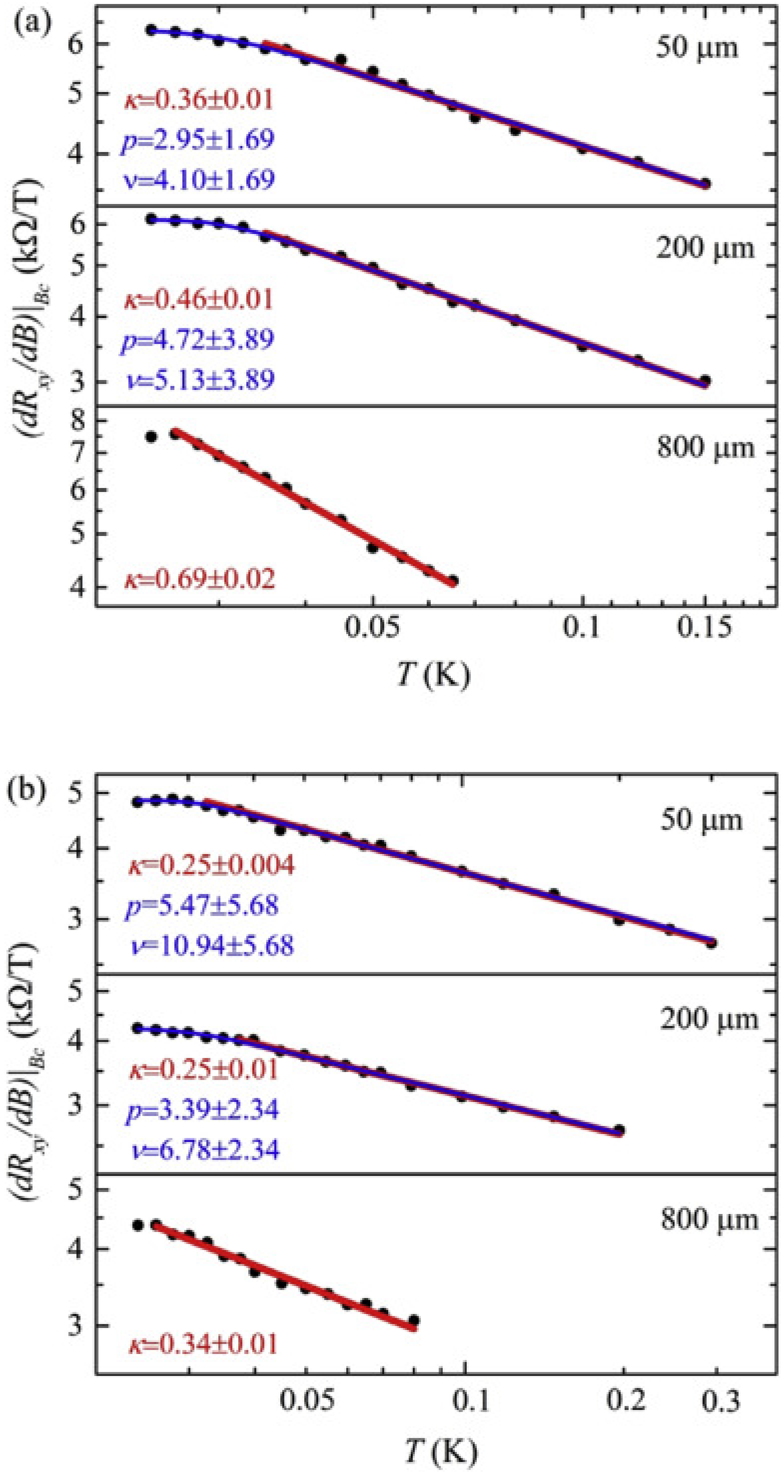

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Fig. 3. as a function of temperature in log-log plots for all three Hall bars. The red lines are fitted by the scaling power law and the blue lines are fitted by the zero-point fluctuations assumption [10]. (a), traces for the filling factor 4 to 5 transition, named as 4 → 5 transition. (b), traces for the filling factor 5 to 6 transition, named as 5 → 6 transition. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

As temperature decreases, the values of 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 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.

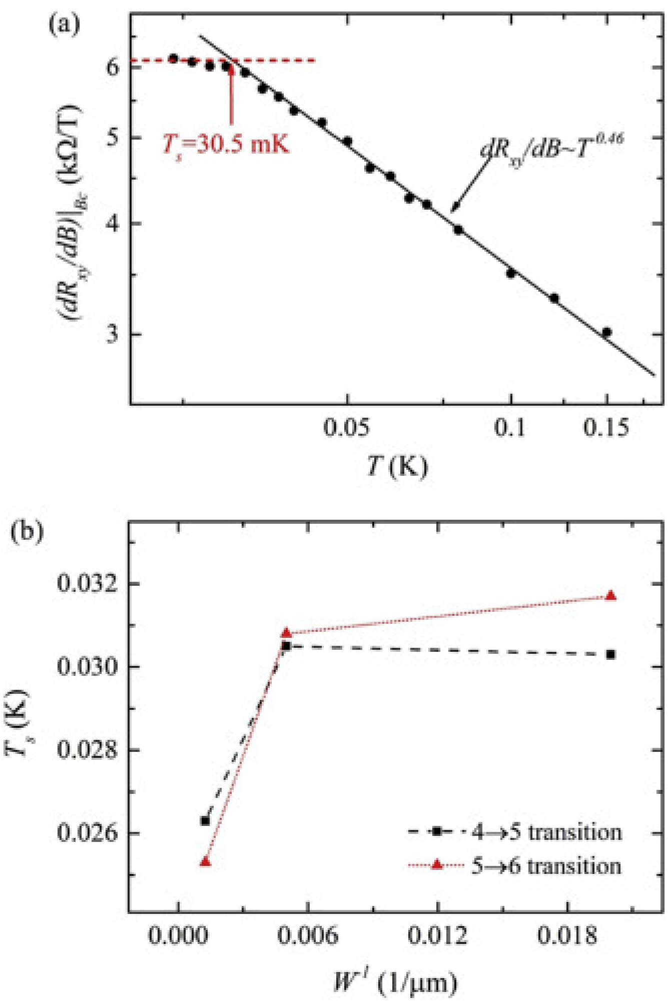

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Fig. 4. (a), values as a function of temperature for 4 → 5 transition in the 200 μm Hall bar. The red arrow indicates the definition of saturate temperature T_S. (b), the saturation temperature T_S as a function of Hall bar width. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

External effects, such as the size effect [7,8] and the heating mechanism caused by excitation current [[8], [9], [10], [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 may play a role [10]. The zero-point fluctuations of holes assumption suggests that the phase coherence length becomes temperature independent at the zero temperature limit [9]. For this reason, the finite size effect is not the only cause of this saturation. The effect of the zero-point fluctuations of phase coherent holes can be described as [10]. The critical exponent κ can be acquired by the scaling power law and p is the temperature exponent of the quantum coherence length. Following the fitting procedure in reference [10], the saturation can be fitted by the same formula as reference [10] in this study. However, it should be noted that the p values from our fittings are far away from the expected number of 2 [8,19]. A possible reason is that the saturation temperature in this work is lower than reference [10], so a reliable fitting is more difficult to achieve, and we do have large uncertainty in determining the p values in Fig. 3. For example, the saturation temperature of the 800 μm Hall bar is too low to even apply the fitting.

It should be noted that B_c may change with temperature at high temperature. In the analyses above, all the B_c defined from two adjacent temperatures saturate at the low temperature limit, as illustrated in Fig. 5. For example, in the 4 → 5 transition of the 200 μm Hall bar, the variation is less than 30 mT below 0.15 K, which is the upper temperature limit when we analyze the scaling behavior in Fig. 3. Above 0.15 K, the values of the crossing points of adjacent temperature curves quickly deviate. B_c is supposed to be independent of temperature, but the irrelevant finite size correction at high temperature [10] can explain this deviation.

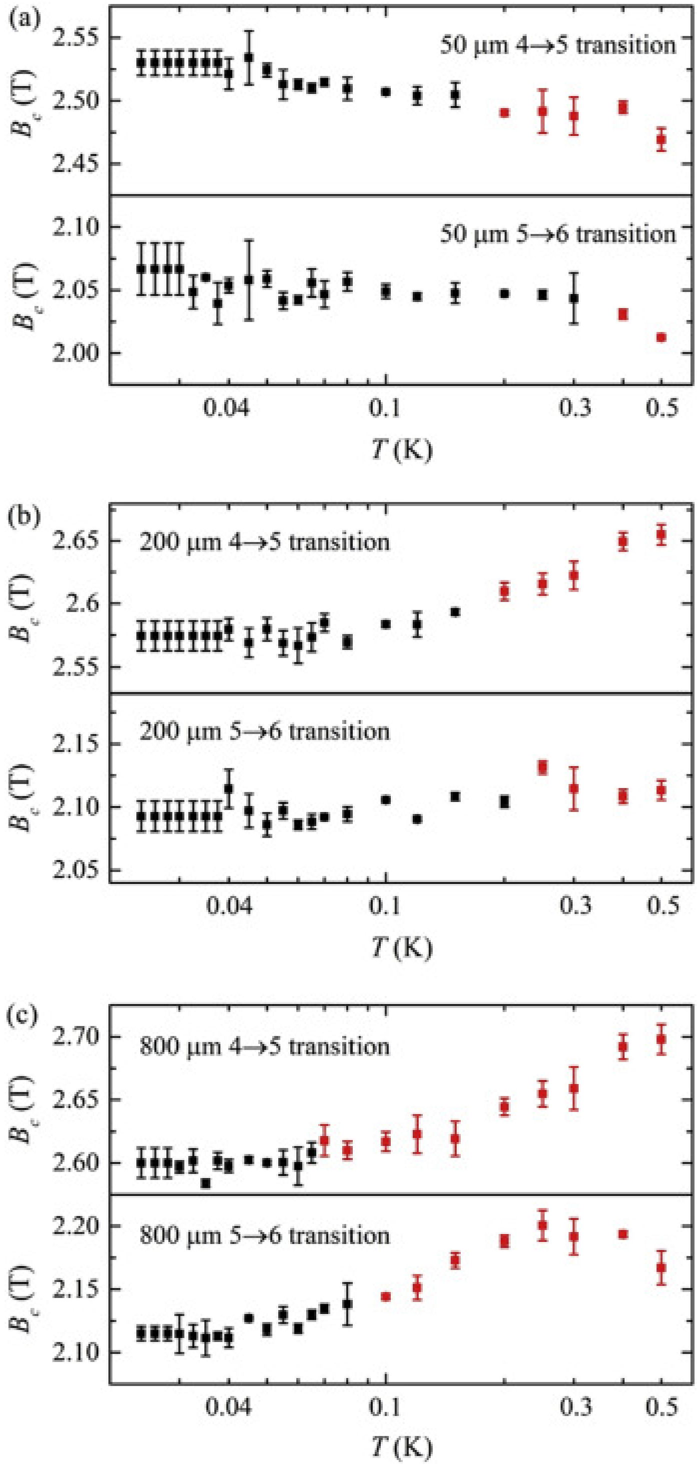

Fig. 5. The critical magnetic field as a function of temperature. When temperature is increasing, the critical magnetic field variation exceeds 30 mT rapidly (red dots). (a), (b) and (c) are the 50 μm, 200 μm and 800 μm Hall bars' critical magnetic fields at different temperatures and filling factors. The black dots are from the same data used in the analysis of Fig. 3. (log-linear plot). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Different values of κ and p

It is believed that in an ideal short-range system, a universal scaling power law can be obtained [8,21]. Consequently, critical exponent *κ* is 0.43, the temperature exponent of the quantum coherence length *p* is 2, and the localization-length exponent *v* is 7/3. The exponents *κ, p and v* should satisfy . In our study, *κ* is not a universal value of 0.43 but varies from 0.25 to 0.69 in different transitions, which is summarized in Fig. 6. It is worth mentioning that there are other experiments finding *κ* ranging from 0.15 to 0.9 in different systems [7,8,10,11,[21], [22], [23], [24], [25], [26], [27]]. There exist a handful of assumptions to explain the variation of *κ*. Some studies pointed out that *κ* is a sample dependent parameter and it will increase with the decreasing mobility [24]. Other studies believed the alloy concentration plays an important role in determining *κ* since it will introduce the long-range Coulomb force into system [7,10,11,22]. What's more, another experiment suggested the inhomogeneity of carrier concentration would affect *κ* seriously [27]. The long-range Coulomb interaction can change the tunneling density of states and lead to a *p* larger than 2, and Coulomb impurities in the system introduce spatial inhomogeneity, which makes *v* less than 7/3 and leads to a larger *κ* [10]. Previous works once achieved various *p* values rather than the expected value of 2 [7,27] and the Coulomb interaction caused by random distribution of disorder scatters may contribute to a larger *p* value [28]. Although the dopant C can play a role as the random scatter in our system, the uncertainty of the *p* values in Fig. 3 is too large to conclude that *p* is different from 2.

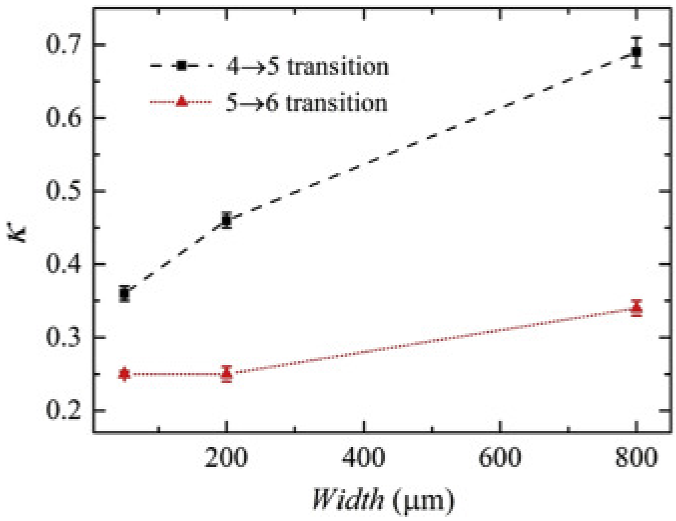

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Fig. 6. κ as a function of Hall bar width for 4 → 5 and 5 → 6 transition.

4. Conclusions

We have studied the quantum Hall plateau transition by measuring the Hall resistance R_{xy} as a function of magnetic field at different temperatures. The slope of R_{xy} saturates at the low temperature limit, which is more relevant to the zero-point fluctuations than the finite size effect. The deviation of the exponent κ from the predicted value is also discussed.

Contributions

Pujia Shan and Hailong Fu fabricated the devices. Pujia Shan, Hailong Fu and Pengjie Wang performed the measurements. L. N. Pferffer and K. W. West prepared and supplied the GaAs wafer. Pujia Shan, Jixiang Yang and Xi Lin analyzed the results and wrote the manuscript. Xi Lin initiated the research.

Acknowledgements

We thank Xin Wan for useful discussions. The work at PKU was funded by NSFC (Grant No. 11674009) and NBRPC (Grant No. 2015CB921101). The work at Princeton University was funded by the Gordon and Betty Moore Foundation through the EPiQS initiative Grant GBMF4420, by the National Science Foundation MRSEC Grant DMR-1420541, and by the Keck Foundation.

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