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1 Introduction

Hysteretic behavior and slow dynamics are not so uncommon in the quantum Hall (QH) state of two-dimensional electron systems (2DESs) [1]. Hysteresis phenomena can occur for various reasons. The most trivial ones are those arising from time delay due to large inductance of a superconducting magnet or from some sort of quasi-systematic temperature change during the up/down sweeps. In the dissipationless QH states, the system can exhibit quite slow response depending on the external circuitry. Slow charge dynamics can also occur, for instance, in bilayer systems or in systems with parasitic charge reservoir [2]. A different and more intriguing class of hysteretic phenomena recently studied are those associated with spin transition of the QH states that involves nuclear spins. The well-known case is the $\nu =$ 2/3 fractional QH state which takes either spin-polarized or unpolarized ground state depending on the magnetic field range in which it occurs. In the intermediate field range, typically around 7 T, the spin-polarized and unpolarized states are sufficiently close in energy so that they form domains. The hysteresis is associated with a slow change in the pattern of such domains [3]. Electrical current flowing across the domain boundary gives rise to electron-nuclear spin flip via hyperfine coupling. The involvement of nuclear spins has been verified by resistively-detected nuclear magnetic resonance (RDNMR) experiments [3]. It has been recognized by extensive studies that phenomena involving nuclear spins are actually ubiquitous in QH systems. A totally different sort of slow evolution may arise from deep electron traps such as the DX center responsible for the so-called persistent photoconductivity. Thus there exist various possible physical mechanisms that can give rise to metastability and slow relaxation.

In this work, we report on hysteretic behavior of two-dimensional hole systems (2DHS) in the QH regime. The phenomenon occurs at dilution refrigerator temperatures and exhibits extremely slow relaxation with time scale on the order of an hour. We discuss the origin of the presently found hysteretic behavior of 2DHS in QH regime in comparison with various hysteretic phenomena hitherto reported in 2DES.

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2 Experimental methods

The 2DHS sample was fabricated from a p-channel GaAs/AlGaAs single heterojunction wafer grown on GaAs (001) substrate. The 2DHS resided at the GaAs/$Al_{0.3}Ga_{0.7}As$ interface which was separated by a 100 nm thick undoped $Al_{0.3}Ga_{0.7}As$ spacer layer from a 100 nm thick Be-doped $Al_{0.5}Ga_{0.5}As$ layer. This structure resulted in a relatively low 2DHS density $n_h = 1.2\times10^{15}$ m^{-2}. Analysis of the low field magneto-transport data revealed the carrier densities of the zero-field spin-split bands (the heavier heavy holes and the lighter heavy holes) to be 7.4×10^{14} and 4.3×10^{14} m^{-2}, respectively. The average transport mobility was $\mu_h = 11$ m^{2}V^{-1}s^{-1} and the quantum mobility of the lighter heavy holes obtained from the analysis of the Shubnikov-de Haas oscillation was $\mu_{q,\,lhh} = 3.3$ m^{2}V^{-1}s^{-1}. The sample was patterned in an L-shaped Hall bar so that the resistivities along the <110> and <1$\underline{1}$0> directions could be measured. Magneto-transport experiments were performed by a standard low-frequency (typically 13 Hz) lock-in technique. The sample was mounted on a rotating stage of top-loading probe which was directly inserted into the mixing chamber of a dilution refrigerator with base temperature ~20 mK. Magnetic fields up to 15 T were applied by a superconducting solenoid. For the search of RDNMR signal, we used the same setup as that described in Ref. [4].

3 Results and discussion

Figure 1 shows the diagonal and Hall resistivity traces of the 2DHS sample taken at a field sweep rate 0.3 T/min with a probe current 10 nA passed along the <110> direction at the base temperature 20 mK. A clear difference is seen between the up-sweep trace (dashed curve) and the down-sweep trace (solid curve) in the high magnetic field range. The trace of ρ_{yy} (resistivity along the <1$\underline{1}$0> direction) is similar except somewhat smaller hysteresis. When the sweep rate was lowered to 0.03 T/min, the difference between the up- and down-sweep traces was much reduced. The reduction occurred in such a way that the slow-sweep trace converged to the up-sweep trace at lower fields and to the down-sweep trace at higher fields. More specifically, the equilibrium state for $B < 5$ T was the "up-sweep state", while it was the "down-sweep state" for $B > 5$ T. Hereafter we call them L-state and H-state for brevity (L and H means stable at low and high fields, respectively). The switching of the stable equilibrium state was found to occur in the vicinity of $\nu = 1$, as we discuss in detail later. The hysteretic behavior was not visible at temperatures higher than about 100 mK or for probe current larger than about 100 nA.

Since the hysteresis was most distinct in the resistivity peak at B=6.8T (corresponding to the QH plateau transition between ν= 1 and ν = 2/3), we chose to use the peak value of ρ_{xx} at this field as an indicator of the system's relaxation to equilibrium. Figure 2(a) shows the time evolution of $\rho_{xx}^{(6.8\mathrm{T})}$ after B was swept up and held at this field. The relaxation toward the equilibrium value followed an exponential time dependence with a time constant τ= 24 min. The relaxation at other arbitrary magnetic field values was measured by the following method. The system was initially kept at a field high enough so that it was well in the H-state. It was then brought down to a lower field B_{wait} and held there for waiting time t_{wait}. The system was then quickly brought to B = 6.8 T and the value of $\rho_{xx}^{(6.8\mathrm{T})}$ was recorded. Figure 2(b) shows the dependence of $\rho_{xx}^{(6.8\ \mathrm{T})}$ on t_{wait} for B_{wait} = 5 T, which shows an exponential t_{wait}-dependence

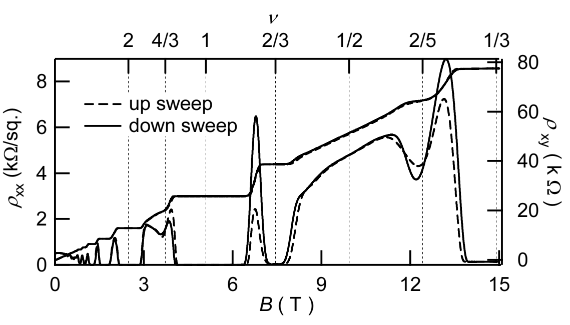

Fig. 1 Magneto- and Hall resistivity traces of the 2DHS sample taken at a field sweep rate 0.3 T/min with a probe current 10 nA at the base temperature 20 mK.

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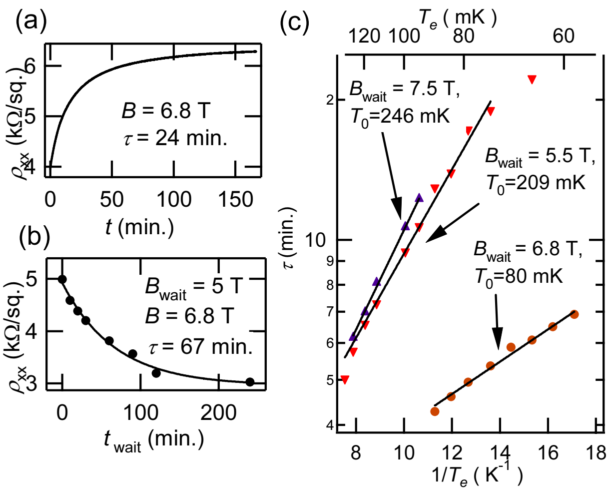

Fig. 2 (a) Time evolution of ρ_{xx} at B = 6.8 T after B is swept from below. The probe current is 10 nA. (b) The dependence of ρ_{xx} at B = 6.8 T on the waiting time t_{wait} at B_{wait} = 5 T. The measurement procedure is given in the text. The curve represents an exponential fit. (c) Temperature dependence of the relaxation time τ at B_{wait} = 6.8 T, 5.5 T, and 7.5 T. The values of thermal activation energy k_BT_0 are given. The probe current is 10 nA. The temperature was controlled using the *rf* coil.

with a time constant τ = 67 min. The measurement procedure concerns the relaxation from the metastable H-state to the stable L-state at B < 5T. The relaxation from the metastable L-state to the stable H-state at B > 5 T was conducted by a similar procedure except that the initialization of the system to the L-state was done at B = 4 T. Figure 2(c) shows the temperature dependence of the relaxation time for selected values of B_{wait}.

The B_{wait}-dependence of relaxation at higher fields are summarized in Fig. 3. The data points given in this figure were taken in the following way. The system was initialized by holding it at B = 4 T for 30 minutes, which made it fully relaxed to the L-state. The system was then brought to different waiting fields B_{wait} and kept there for waiting time t_{wait}. After that, $\rho_{xx}^{(6.8T)}$ was measured to probe the degree of relaxation of the system. A higher value of $\rho_{xx}^{(6.8T)}$ indicates faster relaxation to the H-state at that waiting field. Three sets of data for different waiting times t_{wait} = 60, 30 and 10 min. are shown in the figure. The result clearly shows a rapid change in behavior at ν = 1. The data also shows some structures in the B_{wait}-dependence of the relaxation rate.

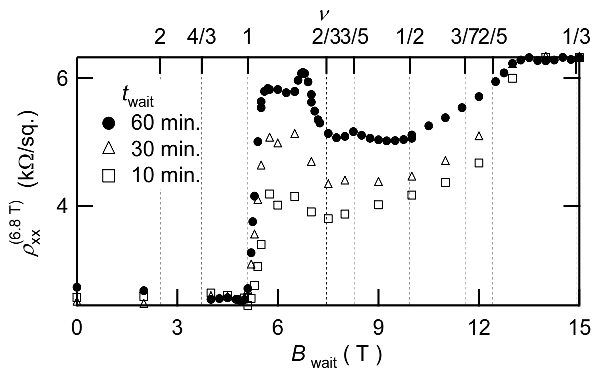

Fig. 3 The different symbols represent the height of the resistivity peak at B = 6.8 T, (which is an indicator of the state of the system) after waiting at various waiting fields B_{wait} for different waiting time t_{wait} = 60, 30 and 10 minutes, respectively.

Let us now discuss the origin of the hysteresis in light of various possible mechanisms stated in the introduction. First of all, slow relaxation of transient current associated with the dissipationless QH states is ruled out because that should be most conspicuous in the zero resistance states. Slow change in the carrier density by charge transfer to and from some sort of charge reservoir is also unlikely, because a carrier density change should show up as lateral shift of the magnetoresistance trace. The extremely long relaxation time on the order of an hour led us to suspect possible involvement of nuclear spins and to conduct RDNMR experiments. However, extensive search for RDNMR response has given negative results, even though the same measurement setup was capable of detecting RDNMR in 2DES samples [4]. The negative result is natural since valence band holes with their predominantly p-character are not

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expected to couple to nuclear spins in any significant manner. Thus, transients associated with vanishing resistivity, a change in the mobile carrier density, and effect associated with nuclear spins, can be eliminated from the list of possible mechanisms. This leaves us to a mechanism that involves a slow change in disorder potential.

Kukushkin *et al*. [5] have observed a phenomenon in 2DES samples which bears some resemblance to the present one. They report that their 2DES samples showed different degree of disorder depending on the cooling path. When the samples were cooled down to the dilution refrigerator temperatures under a high magnetic field, they showed significantly higher quality (smaller disorder) than when they were cooled in zero field. The high quality state was maintained as long as the field was kept in the range $\nu <$ 1, but an excursion to fields lower than $\nu = 1$ quickly brought the system to the zero-field-cooled (lower quality) state. They report that in order to reestablish the high-quality state, they had to warm the sample to ~1.4 K, sweep up the field and then cool down again. The switching of the stable state at $\nu = 1$ is a feature common to both the present case and Ref. [5]. It implies that a relaxation channel opens as soon as opposite spin carriers are introduced. The metastable state may be pictured as follows: When magnetic field is swept, both the electronic states and the self-consistently-screened disorder potential usually readjust themselves in a time scale faster than the sweep rate. As the field is swept up into the $\nu < 1$ range, the readjustment necessarily involves spin flip. If the spin flip process is somehow blocked, the L-state can remain as a metastable state in the $\nu < 1$ range. Since the self-consistent screening is not fully realized in the metastable L-state, it is somewhat more disordered than the fully relaxed H-state.

An important difference between the present observation for 2DHS and that for 2DES in Ref. [5] is the following: The authors of Ref. [5] reports that once the system entered the $\nu > 1$ range and changed to the lower quality state, it never returns to the higher quality state even if field is swept to higher fields as long as it was kept to $T < 1$ K. In our case, by contrast, the system do relax to the H-state even at the lowest temperature 20 mK, as shown in Fig. 2(c). Relaxation is found to be thermally activated with activation energy on the order of 100 mK. We speculate that the difference between the 2DES and 2DHS may be traced to the fact that the lowest Landau level for the valence band has a mixed character containing a small component of the opposite spin [6]. Another possibility is that the metastability in Ref. [5] is related with electron traps at some distance from the 2DES plane, while the hole traps responsible for the presently observed metastability is reside in the region of the 2DHS plane.

4 Conclusions

We have observed a peculiar hysteretic behavior with extremely slow dynamics in 2DHS in the QH regime. The observed switching of the behavior at $\nu = 1$ indicates a spin-related metastable state in the $\nu < 1$ range. Relaxation of the metastable state with a time scale on the order of an hour occurs even at the lowest temperatures.

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