Summary of thesis: Huge Longitudinal Resistance States Induced around Fractional Quantum Hall States

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One of the most intriguing features of the quantum Hall effect (QHE) is that different physical properties, ranging from spin ferromagnetic interactions to quantum phase transitions, arise depending on the Landau level (LL) filling factor ν. Among them, the $\nu = 2/3$ fractional quantum Hall state (QHS) exhibits an interesting effect known as the huge longitudinal resistance state (HLRS), which is described below.

In the $\nu = 2/3$ QHS, degeneracy occurs between the $N = 0$ spin-down composite fermion (CF) LL and the $N = 1$ spin-up CF LL at certain electron densities and magnetic field strengths, where N is the LL index. This degeneracy enables the flipping of the electron spins, which results in a large hysteresis behavior of the longitudinal resistance R_{xx}. Interestingly, it was also revealed that the nuclear spins are dynamically polarized by a relatively large current, a process known as dynamic nuclear spin polarization (DNP), via the hyperfine interaction between the electron spins and nuclear spins, owing to the degeneracy of the CF LLs. This process results in DNP, which in turn affects the domain formation and increases the lengths of the domain boundaries. Furthermore, in recent experiments, it has been demonstrated that DNP can be transferred between layers in bilayer two-dimensional electron gas systems [1]. To date, extensive research aimed toward clarifying the physical origin of the resistance enhancement in the $\nu = 2/3$ QHS has been carried out. However, some aspects of the HLRS are still not comprehensively understood, such as the relationship between the domain morphology and DNP.

In this study, the sample was a GaAs/AlGaAs quantum well grown by molecular beam epitaxy, which had been used in a previous experiment [1]. The width of each quantum well was 20 nm. The sample was processed in the shape of a standard Hall bar having a width of 50 μm and four voltage probes separated by 180 μm. The sample was immersed in a ^{3}He-^{4}He mixture of a dilution refrigerator. The resistances were measured at 62 mK using a standard low-frequency lock-in technique with a frequency of 37.7 Hz. The low-temperature electron mobility was approximately $2 \times 10^6\,\mathrm{cm^2/Vs}$ at a density of $1.0 \times 10^{11}\,\mathrm{cm^{-2}}$. An external magnetic field B_{ext} of strength 7.19 T, at which the spin-unpolarized (SU) to spin-polarized (SP) phase transition takes place at $\nu = 2/3$, was applied by using a superconducting magnet throughout the experiment. The filling factor was controlled by changing the electron density by varying the gate voltage.

We adopted a new method to measure R_{xx} and the Hall resistance R_{xy} accurately [2, 3]. The R_{xx} and R_{xy} values of the HLRS were measured by changing the value of the current to 5 nA to prevent self-heating after the HLRS was induced by applying a large current of 60 nA for 1,800 s at a filling factor ν_{ex}. In this experiment, by repeating the above procedure and varying ν_{ex}, we obtained the saturated values of R_{xx} and R_{xy} in the HLRS. It should be noted that every time we measured the R_{xx} and R_{xy} values of the HLRS, we set the filling factor to $\nu = 0.85$ to reset the nuclear spin polarization using the Goldstone mode in the skyrmion crystals. We observed three peaks in the plot of the HLRS R_{xx} values, and deviations in the values of R_{xy} from the quantized value at $\nu = 2/3$. Intuitively, each peak in the HLRS R_{xx} corresponded to each minimum in the non-HLRS R_{xx}, although there were small shifts in the ν values between the peaks and the minima. The deviations observed in the HLRS R_{xy} are also of significant interest: the R_{xy} values deviated to lower values for $\nu_{\mathrm{ex}} > 0.667$ and higher values for $\nu_{\mathrm{ex}} < 0.667$. A small deviation in R_{xy} at $\nu_{\mathrm{ex}} = 3/5$ was also observed. Our results also reveal that the region in which the HLRS occurs is $0.53 < \nu_{\rm ex} < 0.71$.

Then, the HLRS was induced at $\nu_{\rm ex} = 0.690$ and at $\nu_{\rm ex} = 0.645$. Thus, the original spin configuration corresponded to the SU and SP states, respectively. Subsequently, the ν value was moved instantaneously to $\nu = 0.5$ and swept quickly in the direction of decreasing ν by changing the gate voltage. We also confirmed that the sweep was completed within 50 s before the increased resistance deduced to 10 % of its initial value. From this measurement, we obtained the traces of R_{xx} and R_{xy} for different values of the measuring current I_m as a function of ν. The distinct result is that the R_{xx} of the HLRS produces maxima corresponding to the same ν values as those of the minima of the QHS. The HLRS R_{xx} of a higher I_m is smaller than the corresponding R_{xx} of the lower I_m. It can be seen that the temperature in the larger I_m case is higher. Therefore, the HLRS has insulating properties, even though the QHS has a metallic property. Moreover the value of R_{xy} deviated from the quantized value of $3R_{\rm K}/2$. The deviation is a systematic phenomenon near the $\nu = 2/3$. These results are remarkable because R_{xy} does not quantize to the normal quantized values but to the deviated values. On the otherhand, it is interesting to note that R_{xx} at $1/\nu = 1.45$ still shows a metallic temperature dependence after DNP.

It has been considered that the enhancement of R_{xx} is mainly because of the dissipations and backscattering of electron currents passing through the domain boundaries. We interpreted our measurement results as follow. When the SU state is excited, the main stripe domain is the SU state and the minor one is the SP state. The minor stripe domain is constructed such that the SP "puddle" domains transform to an elongated form and fuses with each other under the Overhauser field $B_{\rm N}$, which is generated by reversing the nuclear spins when an electric current flows between domain boundaries. The $B_{\rm N}$ with the same direction as $B_{\rm ext}$ in the minor domain is higher than the anti-directional $B_{\rm N}$ in the main domain, because the positive and negative nuclear polarizations are balanced and the volume of the main domain is larger than that of the minor domain. On the contrary, when the SP state is excited, the main stripe domain is SP and the minor domain is SU with $B_{\rm N}$ in the direction opposite to $B_{\rm ext}$. From the above construction process, we can deduce that $|B_{\rm N}| \approx 0.5\,{\rm T}$. The HLRS looks like symmetrical to the magnetoresistance of the QHS. We speculate that the main domains of the HLRS should be the corresponding QHSs. The minor domains of these states should be the QHS in the magnetic field shifted by $B_{\rm N}$. For an exceptional metallic state, it can be inferred that the main domain is an SU state and the minor domain is a non-QHS, because the effective magnetic field of the minor domain is lower than $B_{\rm ext}$. The deviation of R_{xy} at $\nu = 2/3$ is explained by stripe domains tilted from the original direction. In this case, the R_{xy} mixes with the R_{xx} and the deviation of the R_{xy} can then be explained by a maximum tilting $\pm 30^\circ$.

In conclusion, the increased R_{xx} shows three maxima that correspond to the quantum Hall minima of the SU phase of $\nu = 2/3$, the SP phase of $\nu = 2/3$, and the $\nu = 3/5$ state. The HLRS shows a deviation in R_{xy}, which depends on the value of $\nu_{\rm ex}$. Our results can be entirely explained by the electron backscattering at the boundaries of the current-induced stripe domains.

References

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