Pump-probe nuclear spin relaxation study of the simplest Ising quantum Hall ferromagnet

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The nuclear spin-lattice relaxation time $T_1$ of the simplest Ising quantum Hall ferromagnet (IQHF) formed at filling factor $\nu = 2$ in a gate-controlled InSb two-dimensional electron gas has been characterized using a pump-probe technique. In contrast to a long $T_1$ of quantum Hall states around $\nu = 1$ and $\nu = 3$ that possesses a Korringa-like temperature dependence, the temperature-independent short $T_1$ of the $\nu = 2$ IQHF suggests the presence of the lowest energy collective spin excitation (skyrmion-like) in domain walls. Furthermore, $T_1$ of this ferromagnetic state is also found to be filling- and current-independent. The interpretation of these results has led to a better understanding of the domain wall dynamics in IQHF.

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The Ising (easy-axis) quantum Hall ferromagnet (IQHF) formed at two energetically-degenerate spin-resolved Landau levels (LLs) in a two-dimensional electron gas (2DEG) has provided an ideal system for understanding itinerant electron ferromagnetism, spin interactions, and domain dynamics\textsuperscript{1-13}. In particular, a resistively detected nuclear magnetic resonance (RDNMR) technique developed in the IQHF of GaAs 2DEGs at filling factor $\nu = 2/3$ (corresponding to a composite-fermion (CF) filling factor $\nu_{\text{CF}} = 2$) has been widely used to investigate the dynamic nuclear polarization (DNP) in semiconductors\textsuperscript{14,15}, to coherently control the nuclear spins in 2DEGs\textsuperscript{16}, and to discover exotic electron phases in quantum Hall systems\textsuperscript{17-19}. Furthermore, this highly-sensitive technique combined with the nuclear spin-lattice relaxation time $T_1$ measurement\textsuperscript{7,8} as a unique probe of low-frequency spin fluctuations can be applied to investigate the domain-wall (DW) structures of IQHF that are poorly characterized, which will lead to a more comprehensive understanding of IQHF. Up to now, the $T_1$ results of IQHF formed at $\nu = 2/3$\textsuperscript{20} and at integers $\nu$ in a two-subband 2DEG (hereafter called two-subband IQHF)$^{21,22}$ are suggestive of low-energy DW excitations but have different properties. Note that intricate CF-CF interactions at fractional $\nu$ (different from electron-electron interactions at integer $\nu$)$^{23}$ and an additional degree of freedom associated with the subband index$^{24}$ may complicate the interpretation of these differences.

More recently, we have performed the RDNMR measurement of the simplest IQHF formed at $\nu = 2$ of the InSb 2DEG\textsuperscript{25,26}. Because the $\nu = 2$ IQHF including only the two lowest LLs can be described by a single-particle picture, it is more appropriate for investigating the DW dynamics of IQHF. Although the preliminary results show that $T_1$ in this IQHF is independent of temperature ($T$), it is unclear whether such a $T_1$ property is unique in the $\nu = 2$ IQHF because the $T_1$ measurement of the non-IQHF states by means of a pump-probe technique is not available due to the difficulty in fabricating the InSb 2DEG with gate control. With recent success in the fabrication of the gate-controlled InSb 2DEG\textsuperscript{27,28} it is of immense interest for us to systematically investigate the $\nu = 2$
IQHF using the pump-probe \( T_1 \) measurement. Here we report on the \( T_1 \) characterization of the \( \nu = 2 \) IQHF and make a comparison to that of other IQHFs.

The pump-probe \( T_1 \) measurement in this study was carried out on two gate-controlled InSb 2DEGs; one with an Al\(_{0.1}\)In\(_{0.9}\)Sb surface layer (Sample 1)\(^{28}\) and the other with an InSb surface layer (Sample 2)\(^{27}\). Both samples were patterned into a Hall bar with a length of \( L = 100 \mu\text{m} \) and a width of \( W = 30 \mu\text{m} \). A low noise preamplifier (Stanford Research Systems, Model SR560) was used for DC magnetotransport and RDNMR measurements. A small RF field \( \sim \mu\text{T} \) (continuous wave mode) matching the NMR resonance frequency of individual nuclei was generated by a single turn coil surrounding the sample (right panel, Fig. 1a). The RDNMR signal was given by the change in longitudinal resistance \( R_{xx} \) of the Hall bar at the resonance condition\(^{29}\). All the measurements were performed at base temperature \( T = 30 \text{ mK} \) (unless otherwise noted) using a dilution refrigerator with an \textit{in situ} rotator. The tilt angle \( \theta \) between the sample normal and the direction of the total magnetic field \( B \) was determined by the Hall measurement at low fields.

The ratio of Zeeman \( (E_z \propto B) \) to cyclotron \( (E_c \propto B_{\text{perp}}, \text{the perpendicular component of } B) \) energies is tuned by \( \theta \) to bring the LLs with opposite spins into degeneracy (right panel, Fig. 1a). Strong electron-electron interactions at the \( \nu = 2 \) LL intersection (including only the \( n = 0 \) and \( n = 1 \) LLs) favor a first-order spin phase transition from an unpolarized state \( (P = 0) \) to a fully polarized state \( (P = 1) \), resulting in the formation of IQHF\(^4\). In this study, a gate voltage \( V_g \) is used to change the electron density \( n_s \) of the InSb 2DEG at a fixed \( B \) and thus the occupation of LLs as defined by \( \nu \).

The dependence of \( R_{xx} \) and transverse resistance \( R_{xy} \) on \( V_g \) for the \( \nu = 2 \) IQHF of Sample 1 is shown in Fig. 1a. Note that charge transport across the DW is expected to produce an emerging peak around \( \nu = 2 \) that is the signature of IQHF\(^{29}\), where the RDNMR signal is detected by aid of the current-induced DNP due to the degeneracy of DW states\(^{30}\). However, it is not distinct in Fig. 1a. We believe that this peak is hidden in the neighboring LL peak at \( \nu \sim 1.5 \) as suggested by the shift of
the LL peak and by a nonzero \( R_{xx} \) in the \( \nu = 2 \) plateau region. This conclusion is further supported by the fact that the RDNMR signal is observed in the region between \( V_g = -0.3 \) V and \( V_g = -0.5 \) V (hereafter called IQHF region, data not shown). The pump-probe \( T_1 \) measurement was performed at \( V_g = -0.4 \) V (corresponding to \( \nu \sim 1.73 \) as defined by \( \nu_p \)), as shown in Fig. 1b. A pump current of 1 \( \mu A \) was applied to polarize the nuclei as indicated by an exponential increase in \( R_{xx} \). \( R_{xx} \) became saturated (\( R_{xx}^{sat} \)) after a time period of \( \tau_p \) (Step I). The current was then switched off and \( \nu_p \) was immediately tuned to the probe filling factor \( \nu_d \) by \( V_g \), where the polarized nuclei were expected to depolarize due to the electron-nuclear hyperfine interaction (Step II). After a time period of \( \tau_d \), the sample was restored to the original pump condition and the nuclei were polarized again as indicated by the change in \( R_{xx} \) with respect to \( R_{xx}^{sat} \) (\( \Delta R_{xx} \), Step III). The plot of \( \Delta R_{xx} \) vs. \( \tau_d \) (Fig. 1c) was obtained by repeating this pump-probe-pump sequence at a certain \( \nu_d \), and a fit to the data gave \( T_1 \).

Figure 2a shows that \( T_1 \) in the IQHF region is constant and is approximately one order of magnitude smaller than that at \( \nu_d = 1 \). Furthermore, \( T_1 \) near \( \nu_d = 1 \) is filling dependent, resembling the results reported in the GaAs 2DEG\(^{31,32} \) where a single-particle model taking account of the disorder-induced LL broadening and the exchange-enhanced activation energy gap accounts for the nuclear spin relaxation. Skyrmions are not expected to contribute to \( T_1 \) near \( \nu_d = 1 \) because they cannot be formed due to large Zeeman splitting of the InSb 2DEG\(^{33,34} \). Note that \( T_1 \) at \( V_g = -0.4 \) V (\( \nu_d \sim 1.73 \)) is the same as that obtained from the time dependence of \( R_{xx} \) in Step I of Fig. 1b, suggesting a current-independent \( T_1 \). Similar results are also obtained in Sample 2 (Fig. 2b). Although layer structures and transport properties of the two samples are different, the results of \( T_1 \) in the IQHF region are the same. These findings cannot be explained by the single-particle model.

A further study was carried out on the temperature dependence of \( T_1 \) for the two samples, as shown in Fig. 3a and 3b. In striking contrast to the decrease of \( T_1 \) with increasing \( T \) around \( \nu = 1 \) and \( \nu = 3 \) that suggests a Korringa-like relaxation process, \( T_1 \) in the IQHF region is found to be
independent of $T$. The temperature-independent $T_1$ is also found in the two-subband IQHF$^{21}$, where the lowest energy charged spin excitations with skyrmion-like configurations in DW are expected to dominate the nuclear spin relaxation. The low-frequency fluctuations in the $XY$ spin components of these excitations may enhance the relaxation and thus result in a short $T_1^{35}$. Note that energetically-degenerate unpolarized and polarized domains of the $\nu = 2$ IQHF do not occur exactly at the LL intersection probably due to the electron exchange interaction$^{20}$, causing a large energy gap at the phase transition$^{26}$. This energy gap is much larger than the thermal energy, ensuring that $T_1$ is independent of $T$ over the range of temperatures investigated$^{26}$. The temperature-independent $T_1$ in the $\nu = 2/3$ IQHF is also implied in Ref. 37. Therefore, we conclude that the $T$-independent $T_1$ is a common feature of IQHF characterized by the RDNMR measurement.

The current study also demonstrates that there are still distinct differences in the $T_1$ properties between different IQHFs that need to be addressed. The $T_1$ measurement of the $\nu = 2/3$ IQHF gives a current-dependent relaxation time constant between 180 s and 1350 s$^{20}$, while that of the $\nu = 2$ IQHF is relatively short (~50 s) and current-independent. Furthermore, $T_1$ of the two-subband IQHF is found to be filling dependent$^{22}$ as contrasted with the $\nu$-independent $T_1$ of the $\nu = 2$ IQHF. It should be noted that the magnetotransport data are indicative of thermally activated transport in both the $\nu = 2/3$ and two-subband IQHFs of the GaAs 2DEG$^{20,22}$. A sharp reduction in activation energy gap at the phase transition suggests the presence of spin-texture excitations (skyrmion-like) in DW that dominate the nuclear spin relaxation and thus $T_1$. Because the precise spin textures depend on the strength of the Zeeman coupling ($\propto B$)$^{34}$, their size and energy should vary with $\nu$ ($\propto 1/B$) that accounts for the filling-dependent $T_1$. Furthermore, a large current is expected to increase the number of these excitations as suggested by optically detected magnetic resonance imaging of the $\nu = 2/3$ IQHF$^{13}$, which will enhance the relaxation efficiency and result in a short $T_1$. In contrast, the variable-range hopping (VRH) rather than the thermally activated transport is dominant in the $\nu = 2$
IQHF of the InSb 2DEG. Although the VRH transport does not provide additional information of the skyrmion-like excitations in the $\nu = 2$ IQHF, the $T_1$ results suggest the size and number of such excitations to be independent of both $\nu$ and current based on the above discussions. Note that the current density typically used in the RDNMR measurement of the InSb 2DEG is at least ten times that of the GaAs 2DEG. Therefore, the number of the skyrmion-like excitations in the $\nu = 2$ IQHF may reach a maximum, accounting for the current-independent $T_1$. Furthermore, the effect of disorder should be taken into account for the skyrmion nucleation in the $\nu = 2$ IQHF of the InSb 2DEG with relatively low electron mobility. The density and size of skyrmions is probably determined by the nature of disorder that is responsible for the $\nu$-independent $T_1$.

Finally, we discuss the effect of spin-orbit coupling (SOC) on $T_1$. The electron transport between domains with opposite spin polarizations is known to be accompanied by the spin-flip process that is usually mediated by electron-nuclear hyperfine interaction or SOC in order to conserve the angular momentum. Although it is evident from the above results and discussions that the hyperfine interaction dominates the spin flip, the effect of SOC cannot be completely excluded. In fact, the possible role of SOC in the nuclear spin relaxation has been investigated using the $\nu = 2/3$ IQHF; the structure inversion asymmetry-induced Rashba SOC is believed to facilitate the spin flip and thus to enhance the nuclear spin relaxation rate (corresponding to a short $T_1$) by fluctuating the hyperfine field. It should be noted that the theoretical analysis of the coupling of LLs due to the Rashba or Dresselhaus SOC was restricted to the electron rather than the CF system. Therefore, the $\nu = 2$ IQHF is more appropriate for investigating the interplay between the hyperfine interaction and SOC in $T_1$. In particular, a strong SOC in InSb is helpful to examine the effect of different types of SOC on $T_1$ by virtue of both in-situ high pressure and gate control approaches, and such a study is currently underway in our laboratory.
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FIG. 1 (color online). (a) Longitudinal resistance $R_{xx}$ and Hall resistance $R_{xy}$ as a function of gate voltage $V_g$ (or filling factor $\nu$) of Sample 1 at $T = 30$ mK, $\theta = 65^\circ$, $B = 15$ T, and a DC current of $I = 35$ nA. The right panel schematically illustrates the measurement setup and the evolution of LLs indexed by $n$ with increasing $\theta$. The Zeeman and cyclotron energy gaps are denoted by $E_z$ and $E_c$, respectively, and a downward (upward) arrow is for spin-down (spin-up). (b) Plot of $R_{xx}$ vs. time for the time sequence of the pump-probe nuclear spin-lattice relaxation $T_1$ measurement. Step I: polarization of nuclei at $\nu_p \sim 1.73$ with a pump current of $I = 1 \mu$A until $R_{xx}$ reaches a saturated value $R_{xx}^{sat}$ after a duration time $\tau_p$; Step II: depolarization of nuclei at the probe filling factor $\nu_d$ in the absence of current for a certain time $\tau_d$; Step III: repolarization of nuclei under the condition of Step I. The change in $R_{xx}$ with respect to $R_{xx}^{sat}$ gives $\Delta R_{xx}$. (c) $\Delta R_{xx}$ vs. $\tau_d$ at $\nu_d = 1$ ($V_g = -0.63$ V). The solid line is an exponential fit to the data.

FIG. 2 (color online). $T_1$ (circles with a thin line as a guide to the eye) and $R_{xx}$ (thick line) of Sample 1 (a) and Sample 2 (b) as a function of $V_g$ (or $\nu_d$). Note that the range of gate-controlled electron density $n_s$ for the two samples is different; that for Sample 1 (Sample 2) varies from $4.05 \times 10^{15}$ m$^{-2}$ to $1.31 \times 2.5 \times 10^{15}$ m$^{-2}$ as $V_g$ is tuned from 0 V to -0.7 (-4) V. In addition, the low-temperature electron mobility $\mu$ of Sample 1 (Sample 2) is about $4.5 \times 10^{15}$ m$^2$/Vs measured at $n_s \sim 2.5 \times 10^{15}$ m$^{-2}$. These results lead to the difference in $\nu_p$ and $\nu_d$ for the pump-probe measurement of the two samples; $\nu_p \sim 1.73$ ($V_g = -0.4$ V) for Sample 1 and $\nu_p \sim 1.86$ ($V_g = -4$ V) for Sample 2. The current used for the $T_1$ and $R_{xx}$ measurements of Sample 1 (Sample 2) are $1 \mu$A (760 nA) and 35 nA, respectively.

FIG. 3 (color online). Temperature ($T$) dependence of $T_1$ for Sample 1 (a) and Sample 2 (b) at different $V_g$ (or $\nu_d$). The solid line is a guide to the eye. The data of $T_1 = 0$ in (b) indicate that depolarization of nuclei at $\nu_d$ is complete within the minimum time interval of $\tau_d = 1$ s.
FIG. 1
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