Spin Phase Transition Studies to Probe Spin Dynamics in Quantum Hall System

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Abstract. We investigate nuclear spin relaxation process in a canted antiferromagnetic state of the bilayer $\nu_{\text{tot}} = 2$ by measuring evolution of the spin phase transition peak of the filling $\nu = 2/3$. We observe a sudden change in the nuclear spin polarization when the nuclear spin is exposed to the canted antiferromagnetic state.

1. Introduction
The bilayer two-dimensional electron systems at total filling factor $\nu_{\text{tot}} = 2$ exhibits low-frequency electron spin fluctuation dynamics from which produce a gapless excitation mode or Goldstone mode. The produced Goldstone mode is due to the interplay between Coulomb energy, Zeeman energy, and inter-tunneling energy gap[1, 2]. An experimental signature of rapid nuclear spin relaxation rate $T_{1}^{-1}$ probed by electrically-detected NMR has confirmed this notion[3, 4]. This rapid relaxation rate is proportional to the transverse components of electron-spin fluctuations at the Larmor frequency of nuclei.

In spite of these interesting experimental proofs, the detection signal was obtained by measuring a change amplitude in resistance at a transition point of the filling $\nu = 2/3$[3, 4, 5, 6, 7]. Since the nuclear spin polarization is not only manifested in the resistance change, thus it only reveals partial information of the true nature of the physical system in questions. In contrast to that approach, we are able to map a minute change in the nuclear spin polarization distribution in a GaAs quantum well by measuring the profile of the transition peak. In this paper, we probe spin dynamics of bilayer GaAs quantum wells by using full record of the spin phase transition peak.

2. Sample and Experimental Methods
Experiments were carried out on two identical GaAs quantum wells sample with 20-nm in width and separated by a 2.2-nm insulation barrier. The sample was patterned into $30 \times 100 \, \mu \text{m}$ Hall bar geometry. Ohmic contact pads were made with AuGeNi alloys annealed at a temperature of $420^\circ \text{C}$. The low temperature mobility is $\mu \sim 1.3 \times 10^6 \, \text{cm}^2/\text{Vs}$ at a carrier density of $n \sim 1.0 \times 10^{11} \, \text{cm}^{-2}$. The electron density in the front- and the back-layer could be tuned from depletion to $3.5 \times 10^{11} \, \text{cm}^{-2}$ by means of applying front and back gate bias voltages, respectively.

We used the spin transition phase peak of the filling $\nu = 2/3$ to induce and detect nuclear polarization. At the transition, two different electronic domains coexist namely spin-unpolarized...
Figure 1. (a) Dynamic nuclear polarization at the transition of the filling factor $\nu = 2/3$. The nuclear spin polarization is manifested in the enhancement of the transition peak after applying a large current $\sim 60$ nA for 500 seconds (red curve). (b) Schematic illustration of the timing sequence of our experiment. (c) Two dimensional plot of $R_{xx}$ highlighted at the total filling factor $\nu_{tot} = 2$ as a function of a back- and front-gate bias voltage measured at 5.75 T and 50 mK. The corresponding electron spin states are shown at the right panel.

and spin-polarized domains[8]. Flowing a relatively high current across two domains results in electron spin flips at the domain wall boundaries which in turn flips the nuclear spin on the site to preserve total angular momentum. Figure 1a displays experimental realization of current induced nuclear polarization at the transition point. The amplitude of the transition peak increased dramatically and the width became very broad after applying a relatively high source-drain current $\sim 60$ nA for 500 seconds (see red curve). The broadening of the transition peak reflects the spatial variation of the hyperfine field $B_N$.

The timing sequence of our experiment is shown in figure 1b. First we set the filling factor to a single layer $\nu_{f} = 0$ and $\nu_{b} = 2/3$ and applied a high current $I \sim 60$ nA for 500 seconds to dynamically polarize the nuclear spin ensemble. The transition developed into a huge peak and was brought out of equilibrium as depicted in figure 1a. Second, we set the electronic system to the bilayer $\nu_{tot} = 2$ with $\delta = 0.15, 0.24$ (see figure 1c) by changing the gate bias voltage. The polarized nuclear spin interacts with the canted antiferromagnetic state in this stage. We interrupted the process by temporary restoring the filling factor to a single layer $\nu_{b} = 2/3$ for a given interval of time "keeping time" and the remaining nuclear polarization was recorded by scanning the transition peak. The remaining polarization is a measure of nuclear spin relaxation.
rate due to interaction with the bilayer electrons.

3. Experimental Results and Discussions

A two-dimensional map of the longitudinal resistance $R_{xx}$ highlighted along $\nu_{\text{tot}} = 2$ as a function of the front- and the back-gate voltages is depicted in Fig. 1c. The magnetic field of 5.75 T was applied perpendicularly to the 2DES. The phase transition between different magnetic phases was driven by altering the charge density imbalance $\delta = n_f - n_b$ while the total density $n_{\text{tot}} = n_f + n_b$ was kept constant. The quantum Hall effect (QHE) was smoothly developed and preserved from the point of no charge imbalance $\delta = 0$, where the system possessed the ferromagnetic (FM) state, to the very large charge imbalance $\delta \gg 0$, where the ground state altered to the spin single (SS) state as the tunneling gap $\Delta_{\text{SAS}}$ overwhelmed the Zeeman energy $\Delta_Z$. In contrast, a single particle energy picture predicts no quantum Hall would be observed due to the expected level-crossing taken place between the crossover from FM to SS states at $\Delta_{\text{SAS}} \approx \Delta_Z$. Such apparent continuously connected QHE is a hallmark of a new class of magnetization namely the canted antiferromagnetic (CAF) state.

Unexpected nuclear spin relaxation behaviour was observed in the CAF state since the initial characteristics of DNP completely disappear as depicted in figure 2 for two different $\delta$ values. The very narrow transition curve shifted to a smaller filling factor $\nu_{tr} \rightarrow 0.62$ after the first second of exposure. As the time passed, the transition curve progressively shifted back to a higher filling factor (i.e equilibrium position at $\nu_{tr} \approx 0.66$) with the curve width remaining almost constantly narrow and extremely small nuclear spin relaxation time. The observed shift to a smaller filling factor with the narrow curve width clearly indicated a sudden change in nuclear spin polarization distribution. The underlying mechanism of this sudden change is not clear yet. This change could signal a sudden burst of the hyperfine field to the electron spins with the Goldstone mode. Alternatively, this change could possibly be due to rapid in-plane nuclear spin diffusion mediated by the Goldstone mode. Future studies will be necessary for both experiment and theory.

The long-ranged nature of the CAF state is expected to break down at high temperature due to vortex-pairs unbinding in the XY plane. At this stage the system undergoes a Kosterlitz–Thouless (KT) transition. U(1) symmetry is restored and the system becomes paramagnetic with no Goldstone mode present. We observed evidence that upon changing the temperature from 50 to 200 mK, the characteristic associated with the CAF state at $\delta = 0.24$ disappeared even though the relaxation time was quite fast (see Fig. 3). It is clearly apparent, particularly from
Figure 3. The evolution of the transition curve exposed to the CAF state with $\delta = 0.24$ at a temperature of 200 mK.

The first second of exposure, the transition curve became very broad making a strong contrast with those obtained in Fig. 2. This could be interpreted as a possibly straightforward signature of a transition between CAF and SS states. The electron spin ordering was destroyed, resulting in incoherent coupling between the nuclear and electron spin. We shall note that the shift of the transition peak equilibrium position to a higher filling factor as the temperature increased was due to the decrease of thermal nuclear polarisation.

4. Conclusions
In conclusion, by measuring the evolution of the transition peak of the filling factor $\nu = 2/3$ we found the sudden change in the nuclear spin polarization when the polarized nuclear spins were exposed to the bilayer CAF state. By ramping up the temperature up to 200 mK, we possibly observed KT transition at $\delta = 0.24$.

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