physica status solidi pss c
www.pss-c.com
current topics in solid state physics

Dispersive lineshape of the resistively-detected NMR in the vicinity of Landau level filling $\nu = 1$

Katsuyoshi Kodera, Hisashi Takado, Akira Endo, Shingo Katsumoto, and **Yasuhiro Iye**
Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Chiba 277-8581, Japan

Received 18 July 2006, revised 18 July 2006, accepted 14 October 2006
Published online 23 January 2007

PACS 73.20.–r, 73.43.–f, 73.63.Hs, 76.60.–k

We report resistively-detected nuclear magnetic resonance studies on GaAs/AlGaAs two-dimensional electron systems in the quantum Hall regime. A peculiar 'dispersive' lineshape that occurs in the vicinity of Landau level filling $\nu = 1$ is found to evolve into a simple dip structure with increasing $|\nu - 1|$. The nuclear spin-lattice relaxation rate exhibits distinct temperature dependences in the respective regions.

phys. stat. sol. (c) **3**, No. 12, 4380–4383 (2006) / **DOI** 10.1002/pssc.200672863

WILEY-VCH

REPRINT

phys. stat. sol. (c) **3**, No. 12, 4380–4383 (2006) / **DOI** 10.1002/pssc.200672863

Dispersive lineshape of the resistively-detected NMR in the vicinity of Landau level filling ν = 1

Katsuyoshi Kodera*, **Hisashi Takado, Akira Endo, Shingo Katsumoto,** and **Yasuhiro Iye**

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Chiba 277-8581, Japan

Received 18 July 2006, revised 18 July 2006, accepted 14 October 2006
Published online 23 January 2007

PACS 73.20.–r, 73.43.–f, 73.63.Hs, 76.60.–k

We report resistively-detected nuclear magnetic resonance studies on GaAs/AlGaAs two-dimensional electron systems in the quantum Hall regime. A peculiar 'dispersive' lineshape that occurs in the vicinity of Landau level filling $\nu = 1$ is found to evolve into a simple dip structure with increasing $|\nu - 1|$. The nuclear spin-lattice relaxation rate exhibits distinct temperature dependences in the respective regions.

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

Quantum Hall (QH) systems, *i.e.* two-dimensional electron systems (2DES) in semiconductor heterostructures subjected to a strongly quantizing magnetic field at low temperature, constitute an inexhaustible source of fascinating physics [1]. In recent years, phenomena associated with the spin degree of freedom have attracted much attention. They include, spin phase transition of fractional quantum Hall states [2] and skyrmion excitations in quantum Hall ferromagnets [3]. In such spin-related phenomena, nuclear spins, which couple to electron spins via hyperfine interaction, often play an important role. Resistively-detected nuclear magnetic resonance (RDNMR) method has proved to be a sensitive tool to probe the low-energy spin excitations of QH systems [4, 5]. In this paper, we present RDNMR data in high mobility 2DES in the QH regime, focusing on the region near the filling $\nu \sim 1$, where skyrmions constitute the low-lying excitation.

2 Experimental methods

A Hall-bar sample with a front gate was fabricated from a GaAs/AlGaAs heterojunction 2DES wafer with mobility $\mu \sim 180$ m^2/Vs. The front gate bias was used to change the electron density over a range from 0.8 to 2.7×10^{15} m^{-2}. The sample was cooled in the mixing chamber of a dilution refrigerator and magnetic fields up to 15 T was applied perpendicular to the 2DES plane. The diagonal and Hall resistances were measured by a standard low frequency *ac* method. An *rf* magnetic field parallel to the 2DES plane was applied by a single turn coil enclosing the sample.

3 Results and discussions

Figure 1(a) shows a typical magnetoresistance trace. RDNMR signals such as shown in Fig. 1(c) were obtained by monitoring the longitudinal resistance while slowly (typically 0.1-0.5 kHz/s) sweeping the *rf* frequency at different fillings. Figure 1(b) shows the observed resonance frequency for the ^{75}As nuclei as

* Corresponding author: e-mail: kodera@issp.u-tokyo.ac.jp

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

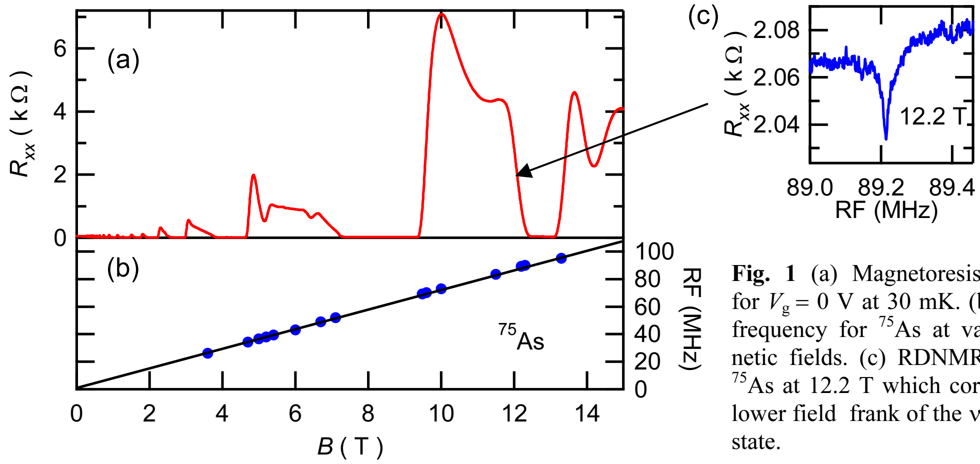

Fig. 1 (a) Magnetoresistance trace for $V_g = 0$ V at 30 mK. (b) RDNMR frequency for ^{75}As at various magnetic fields. (c) RDNMR signal for ^{75}As at 12.2 T which corresponds to lower field frank of the ν = 2/3 FQH state.

a function of magnetic field. Similar signals were obtained for ^{69}Ga and ^{71}Ga. With appropriate tuning, RDNMR signals could be detected over a wide range of filling factor, *i.e.* at flanks of integer and fractional quantum Hall states, albeit with varying signal intensity. For most of the field ranges, the resonance occurred as a small dip ($|\Delta R_{xx}/R_{xx}| < 1\%$) in the *rf*-dependence of the resistance. Particularly large NMR response was observed in the vicinity of ν = 2/3 when it occurred at $B < 8$ T and showed a hysteresis associated with spin transition [2]. This is attributed to effective coupling between electron and nuclear spins at the domain boundaries between spin-polarized and spin unpolarized ground states.

In the vicinity of $\nu = 1$, the RDNMR signal becomes relatively large and takes a dip-and-peak structure shown in Fig. 2(c), which is sometimes referred to as 'dispersive' lineshape [4, 6, 7]. It is likely that

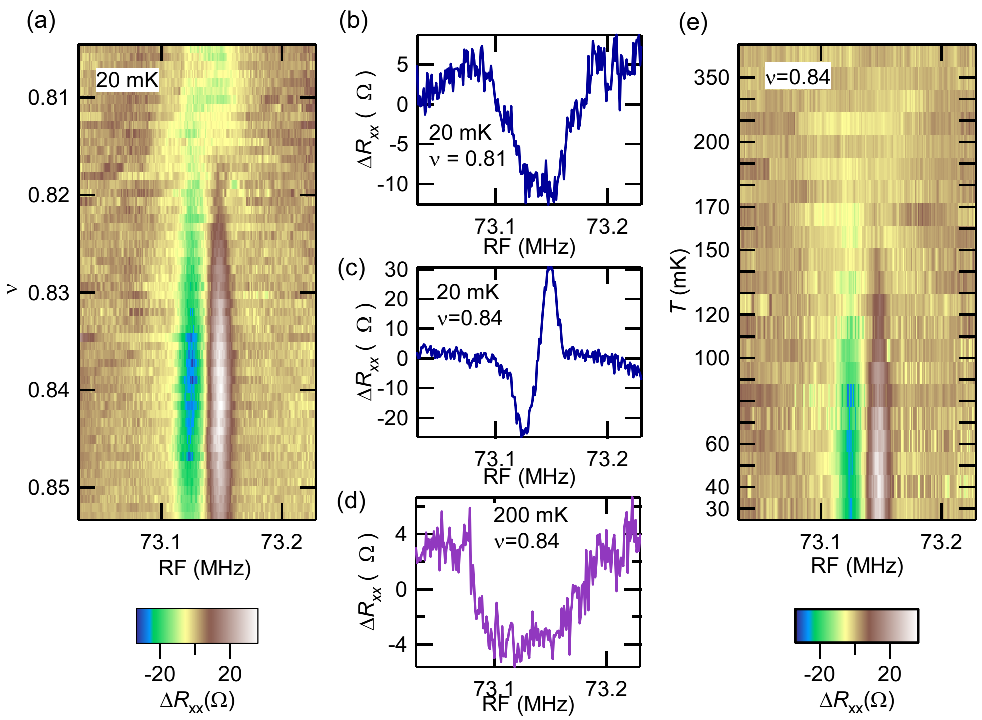

Fig. 2 (a) Color-scale plot showing the evolution of the anomalous RDNMR lineshape with the filling ν. (b) RDNMR signal at $\nu = 0.81$ and $T = 20$ mK, (c) $\nu = 0.84$ and $T = 20$ mK. (d) ν = 0.84 and and $T = 200$ mK. (e) Color-scale plot showing the evolution of the anomalous RDNMR lineshape at $\nu = 0.84$ with temperature.

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

these features originate from the behavior of skyrmions (spin textures) which constitute low-lying excitations in this regime. In what follows, we address this issue by investigating the filling and temperature dependences of the RDNMR.

Figure 2(c) shows a dispersive RDNMR lineshape taken at $\nu = 0.84$ at the base temperature of 20 mK. The probe current was kept below 10 nA in order to avoid Joule heating. Similar lineshape was also observed on the lower-field flank of ν = 1. This dispersive lineshape disappears as one moves further away from $\nu = 1$. Figure 2(b) shows the RDNMR signal at $\nu = 0.81$, where the lineshape is a broad dip. The evolution of the lineshape as a function of ν is summarized in Fig. 2(a) as a color-scale plot. The dispersive lineshape also disappears with increasing temperature. Figure 2(d) shows the RDNMR signal at $\nu = 0.84$ at 200mK. Figure 2(e) is a color-scale plot showing the evolution of the RDNMR signal at $\nu = 0.84$ with temperature. It appears that the filling and temperature ranges where the dispersive lineshape is observed coincide with those where the formation of skyrmion solid is envisaged [8].

Recent experimental studies exploring this region appear to give conflicting results. Gervais *et al.* [6] observed the dispersive lineshape in the vicinity of ν = 1 only at higher *rf* levels. They measured $1/T_1$ under a condition where a dip-only lineshape was observed, and found an anomalous T-dependence, *i.e.* the value of $1/T_1$ increasing with decreasing temperature. They interpreted the observed behavior in terms of melting of skyrmion solid. By contrast, Tracy *et al.* [7] observed the dispersive lineshape at all *rf* levels, but they found $1/T_1$ to exhibit Korringa-like T-dependence.

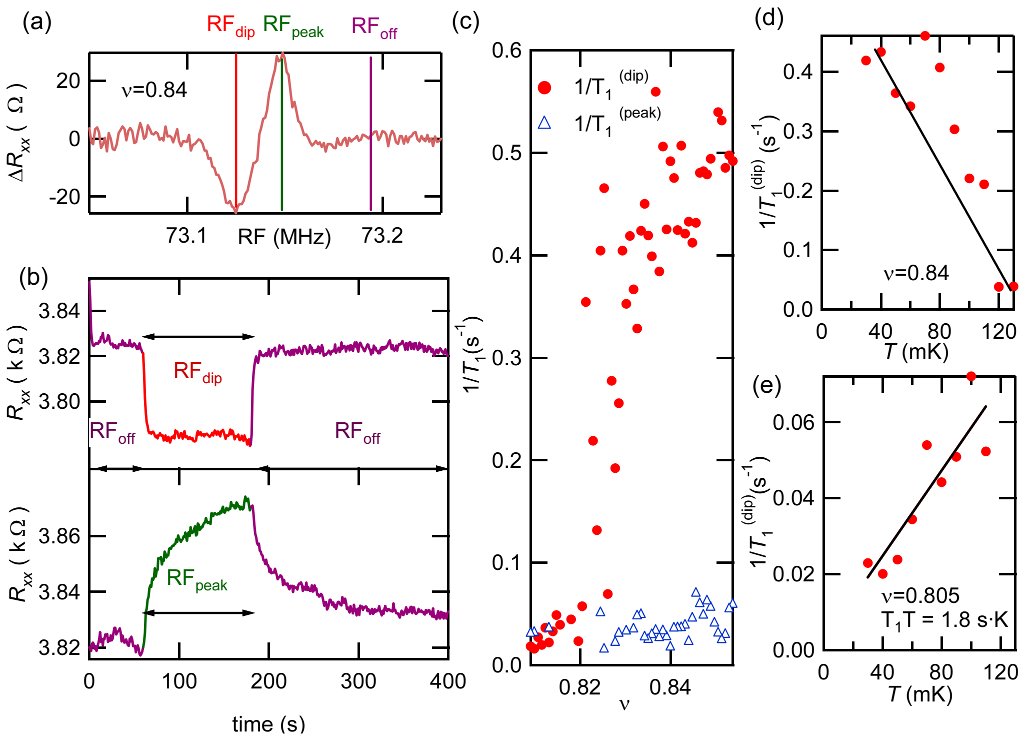

Fig. 3 (a) A typical RDNMR lineshape at B = 10T (ν = 0.84) and T = 20 mK. The vertical lines RF_{dip} (= 73.125 MHz), (RF_{peak} = 73.15 MHz) and RF_{off}(= 73.195 MHz) represent the frequencies used in the relaxation rate measurements described in the main text. (b)Time evolution of ρ_{xx} in response to the frequency switch. (c) $1/T_1^{(dip)}$ and $1/T_1^{(peak)}$ versus ν at 20 mK. (d)(e) Temperature dependence of $1/T_1^{(dip)}$ at $\nu = 0.84$ and 0.805, respectively.

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

We investigated nuclear spin relaxation in this region by a frequency switching technique similar to the other studies [6, 7]. Figure 3(a) shows a typical dispersive RDNMR lineshape observed in the vicinity of $\nu = 1$. The vertical lines labelled RF_{dip} and RF_{peak} indicate the positions of the dip and peak of the dispersive lineshape. The measurement procedure is as follows: Initially, the frequency is set at a certain off-resonant value RF_{off}. The frequency is switched to RF_{dip} for 120 s and then back to RF_{off}. The upper panel of Fig. 3(b) shows the time evolution of ρ_{xx} during this procedure. As long as the change in ρ_{xx} is small fraction, the decay time constant after the switch-back to RF_{off} gives a good measure of the nuclear spin-lattice relaxation time T_1. In this particular trace, the relaxation time is comparable to (or shorter than) the time constant of the measuring circuit. The lower panel of Fig. 3(b) shows a similar trace for RF_{peak} . It is evident that the relaxation time scales differ significantly between the dip and the peak. Figure 3(c) shows the nuclear spin relaxation rates $1/T_1^{(dip)}$ and $1/T_1^{(peak)}$ as a function of ν. It is seen that $1/T_1^{(dip)}$ is strongly enhanced as one moves toward $\nu = 1$. (Note that the apparent saturation of $1/T_1^{(dip)}$ for $\nu > 0.84$ is likely to be due to the time resolution limit of our measuring system.) By contrast, $1/T_1^{(peak)}$ stays low and more or less constant in the same range of ν. The dispersive lineshape and the enhancement of $1/T_1^{(dip)}$ seem to occur concomitantly in the range $\nu > 0.82$. Thus, although the mechanism that gives rise to the dispersive lineshape is yet unidentified, it seems that whatever characterizes the physics in this regime is more strongly reflected in the dip part of the spectrum.

Figures 3(d) and (e) show the temperature dependence of $1/T_1^{(dip)}$ at $\nu = 0.84$ (where the dispersive lineshape is observed) and at $\nu = 0.805$ (where the lineshape is a shallow dip), respectively. In the latter case, the $1/T_1^{(dip)}$ obeys a Korringa-like T-dependence, *i.e.* $1/T_1^{(dip)} \propto T$. At $\nu = 0.84$, by contrast, the $1/T_1^{(dip)}$ exhibits an unusual temperature dependence similar to the one reported by Gervais *et al.* [6]. The enhancement of $1/T_1^{(dip)}$ at low temperatures diminishes at ~100mK. It should be remarked, however, our results and Gervais *et al.*'s differ in respect to the lineshape. On the other hand, in comparison to the report by Tracy *et al.* [7], the experimental results agree in respect to the anomalous lineshape but not in respect to the T-dependence of $1/T_1^{(dip)}$. Further work is obviously needed to clarify the origin of the different outcomes of the RDNMR experiments and to explore their implications in the skyrmion physics.

4 Conclusions

RDNMR experiments on GaAs/AlGaAs 2DES in the vicinity of $\nu = 1$ have revealed a few anomalous features, including the 'dispersive' lineshape, enhanced spin-lattice relaxation rate, and its unusual temperature dependence. These features are thought to reflect the peculiar properties of the system of skyrmions which are envisaged to constitute spin excitations in this regime.

Acknowledgements This work was supported by Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. One of the authors (K.K.) acknowledges the support provided by the Japan Society for Promotion of Science (JSPS) fellowship.

References

[1] S. Das Sarma and A. Pinczuk (Eds.), Perspectives in Quantum Hall Effects (John Wiley & Sons, NY, 1997).
[2] S. Kromüller et al., Phys. Rev. Lett. **81**, 2526 (1998); Phys. Rev. Lett. **82**, 4070 (1999).
[3] S. E. Barrett et al., Phys. Rev. Lett. **74**, 5112 (1995).
[4] W. Desrat et al., Phys. Rev. Lett. **88**, 256807(2002).
[5] K. Hashimoto et al., Phys. Rev. Lett. **88**, 176601 (2002).
[6] G. Gervais et al., Phys. Rev. Lett. **94**, 196803 (2005).
[7] L. A. Tracy et al., Phys. Rev. B **73**, 121306(R) (2006).
[8] L. Brey et al., Phys. Rev. Lett. **75**, 2562 (1995); R. Cote et al., Phys. Rev. Lett. **78**, 4825 (1997).

 © 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim