Resistively detected NMR with dispersive lineshape in single InSb quantum wells

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Abstract. We present a DC measurement of resistively detected NMR (RDNMR) in a single InSb/AlInSb quantum well. Dynamic nuclear polarization has been demonstrated around the resistance spike, which is the signature of the pseudospin quantum Hall ferromagnet at the filling factor of two. The RDNMR signals with dispersive lineshape occur on each side of the spike, but show the shape inversion. The dispersionlike lineshape is found to be independent of measurement conditions (current intensity, temperature, and RF power), provided the polarized nuclei are in equilibrium.

1. Introduction
The contact hyperfine coupling between electrons and nuclei supports electron-nuclear flip-flop and thereby dynamic nuclear polarization (DNP). The polarized nuclei produce an effective magnetic field $B_N$, which modifies the Zeeman energy $E_Z$ of electron spins in a two-dimensional electron gas (2DEG) via the Overhauser shift, and accordingly changes the longitudinal resistance $R_{xx}$. This simple picture is used to account for resistively detected nuclear magnetic resonance (RDNMR), an emerging high-sensitivity NMR approach for probing the dynamics of electron and nuclear spins in low-dimensional semiconductor structures [1-3]. The RDNMR signal usually shows a dip or a peak in $R_{xx}$ response to the applied radio-frequency (RF) field (continuous wave mode). However, more complicated RDNMR signals with anomalous dispersive lineshape (a dip-peak structure) have been observed in the GaAs 2DEG recently [4-11]. This dispersionlike RDNMR lineshape was first demonstrated near the $\nu = 1$ quantum Hall (QH) state and was assigned to be a signature of Skyrmions [4], while similar RDNMR lineshape observed at other filling factors casted doubt on this interpretation [5, 6]. In particular, the RDNMR study of the $\nu = 1$ QH state in a tilted magnetic field strongly suggests that there is no correlation between the dispersionlike lineshape and the Skyrmion formation [7]. The origin of this anomalous RDNMR lineshape still remains unclear.

More recently, we have successfully demonstrated DNP and RDNMR in single InSb quantum wells (QWs) [12]. The large g factor of the InSb 2DEG enables construction of quantum Hall ferromagnet (QHF) with domain structures at $\nu = 2$ using tilted magnetic fields. The ferromagnetism
formed at \( \nu = 2 \) is characterized as the simplest Pseudospin QHF (PQHF) because only the pseudospin-down \([n, \sigma] = (0, \downarrow)\) and pseudospin-up \([n, \sigma] = (1, \uparrow)\) sublevels are involved, where \( n \) and \( \sigma \) are the orbit and spin indices, respectively. The PQHF is featured by a resistance spike (or peak) within persistent R\(_{xx}\) minima. A large AC current induces the resistance change of the spike with respect to DNP, allowing us to observe the RDNMR signals of both In and Sb with a dip or a peak feature. Domain structures are shown to play a dominant role in the DNP process. Here we focus on the DC measurement of RDNMR in the InSb 2DEG. In contrast to the results in the AC measurement, the DC-induced RDNMR shows a dip-peak structure. We describe properties of the dispersionlike RDNMR signal under different temperature, current, and RF conditions. A comparative study of this anomalous RDNMR lineshape in different 2DEG systems will enhance our understanding of its underlying mechanism.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) Longitudinal resistance R\(_{xx}\) vs. total magnetic field B\(_{tot}\) at \( \theta = 64.5^\circ \), \( T = 100 \) mK, and I\(_{DC}\) = 870 nA. The resistance spike of the \( \nu = 2 \) PQHF locates around 12.5 T. Inset: Setup of tilted-field experiments. Tilt angle \( \theta \) was determined from the Hall resistance. (b) R\(_{xx}\) vs. B\(_{tot}\) at several temperatures.

### 2. Experimental details

Our 2DEG sample is a 20-nm-wide InSb QW with asymmetrically silicon delta-doped Al\(_{0.2}\)In\(_{0.8}\)Sb barriers and has a low-temperature electron mobility of \( \mu = 13.6 \) m\(^2\)/Vs and an electron density of \( n_e = 2.56 \times 10^{15} \) m\(^{-2}\). The RDNMR measurement in a tilted magnetic field is performed using a dilution refrigerator with an in-situ rotator. A DC bias is applied to measure R\(_{xx}\) and to polarize the nuclei. A small RF field \( \sim \mu \)T (continuous wave mode) matching the NMR frequency of individual nuclide is generated by a single turn coil wound around the Hall bar (inset of figure 1 (a)). To minimize heating effects, the sample is irradiated by the RF field with a small power of -6 dbm, unless noted otherwise.

### 3. Dispersive RDNMR lineshape

We perform the RDNMR measurement on the resistance spike of the \( \nu = 2 \) PQHF. As a typical example, we present the results obtained from the resistance spike at \( \theta = 64.5^\circ \) (figure 1 (a)). A large DC current of I\(_{DC}\) = 870 nA is kept constant at fixed B\(_{tot}\) around the spike (11.6 T or 13.7 T) till R\(_{xx}\) becomes saturated. Then, the RF field is applied while sweeping the frequency through the Larmor resonance of \( ^{115}\)In at 6 kHz/min. The RDNMR signals are thus obtained, as shown in figures 2(a) and 2(b). It is clear that the RDNMR signal on each side of the spike exhibits the dispersive lineshape. More interestingly, these two RDNMR signals show inverted dip-peak structure. Similar results have already been obtained around the \( \nu = 1 \) state of the GaAs 2DEG, where the shape inversion is attributed to the sign change of the derivative of temperature (T)-dependent R\(_{xx}\) (dR\(_{xx}\)/dT) [8]. In our
case, however, the spike amplitude monotonously increases with increasing temperature (figure 1 (b)). Therefore, the shape inversion around the spike cannot be simply attributed to the thermal effect.

**Figure 2.** RDNMR signals of $^{115}$In attained at 11.6 T and 13.7 T in figure 1 (a) with different RF sweep rates. The spectra of (a) and (b) were obtained at a slow rate of 6 kHz/min, while (c) and (d) at a high rate of 120 kHz/min. The quadrupole splitting of $^{115}$In are partially resolved in (a) and (c). The arrow indicates the scan direction.

We systematically probe properties of the dispersive lineshape response to various measurement conditions (current intensity, temperature, RF power, and sweep rate). It is found that the RDNMR signal exhibits dispersionlike lineshape over a wide range of current intensity (from 300 nA to 3 μA), temperature (from 100 mK to 4 K), and RF power (from -30 dBm to 2 dBm), provided the signal is distinguishable. This result is different from the observation in the GaAs 2DEG, where the RDNMR lineshape strongly depends on the current intensity and the RF power [9, 10]. Nevertheless, the RDNMR spectra depend on the scan direction at a relatively high RF sweep rate of 120 kHz/min (figure 2 (c) and (d)). For instance, the RDNMR signal at 11.6 T shows the dispersionlike lineshape for the upward scan (black arrow, figure 2(c)), while a normal dip in $R_{xx}$ appears for the downward scan (gray arrow, figure 2(c)). Similar findings are observed at 13.7 T (figure 2(d)). This result compared with that of the slow RF scan indicates that the RDNMR spectra obtained at relatively high sweep rate are out of equilibrium, i.e., $R_{xx}$ is recorded at the level below its saturation value.

4. **Conclusion**

In summary, we have demonstrated the dispersive RDNMR lineshape in the simplest PQHF of the InSb 2DEG by a DC measurement. The RDNMR on each side of the resistance spike (signature of the
PQHF) exhibits inverted dispersionlike lineshape. The monotonous increase of the spike resistance with increasing temperature rules out the possibility that the thermal effect accounts for the shape inversion as described in [8]. At slow RF sweep rate, the dispersionlike RDNMR lineshape is robust irrespective of temperature, current, and RF power. This is different from the findings in the GaAs 2DEG. Although the origin of the anomalous RDNMR lineshape is still unknown, our results obtained from the 2DEG made of material other than GaAs will contribute to a better understanding of its underlying mechanism.

References
[1] Smet J H et al., 2002 Nature 415 281.
[2] Hashimoto K et al., 2002 Phys. Rev. Lett. 88 176601; Yusa G et al., 2005 Nature 434 1001.
[3] Hirayama Y et al., 2009 Semicond. Sci. Technol. 24 023001.
[4] Desrat W et al., 2002 Phys. Rev. Lett. 88 256807.
[5] Gervais G et al., 2005 Phys. Rev. B 72 041310(R).
[6] Stern O et al., 2004 Phys. Rev. B 70 075318.
[7] Bowers C R et al., 2010 Phys. Rev. B 81 073301.
[8] Tracy L A et al., 2006 Phys. Rev. B 73 121306(R).
[9] Dean C R et al., 2009 Phys. Rev. B 80 15331.
[10] Dean C R et al., 2008 Physica E 40 990.
[11] Kodera K et al., 2006 phys. Stat. sol. (c) 3 4380.
[12] Liu H W et al., 2010 Phys. Rev. B 82 241304 (R).