High-sensitive optical measurement of spin polarization in a quantum Hall system

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Abstract. Spin polarization measurement is important for the study of a variety of spin states in quantum Hall system. Kerr rotation is proportional to spin polarization, so we developed a high sensitive measurement of Kerr rotation by using homodyne detection and a variety of modulation techniques. Furthermore, we developed Kerr rotation spectra measurement system base on the multi-channel homodyne detection, which enables the assignment of the optical transitions and semi-quantitative estimation of spin polarization by integrating the spectra over the specific optical transition. The spin polarization presents a rapid spin depolarization on both sides of \( \nu = 1 \) due to Skyrmionic excitation. However the top of spin polarization presents a narrow flat region. Furthermore the spin polarization around \( \nu = 3 \) also shows a rapid spin depolarization which suggest the existence of Skyrmion at higher odd filling factor.

1. Introduction
In the quantum Hall system, the freedom of kinetic motion is quenched due to Landau quantization and the electron-electron interaction brings a variety of condensed states, like fractional quantum Hall states. Especially for the electrons in GaAs/AlGaAs quantum well where the Zeeman energy is much smaller than the electron-electron interaction, a variety of spin states appears in the quantum Hall system. The existence of quantum Hall ferromagnet and Skyrmion were first demonstrated by the spin polarization measurement due to Knight shift in NMR experiment [1]. However, because of the low sensitivity, the NMR measurement needs a special sample of multi quantum wells. In order to measure the spin polarization in a single quantum well, a variety of spin polarization measurement methods were developed such as polarization analysis of photo luminescence [2] and optical absorption [3]. However, luminescent measurement is not a direct method, and absorption measurement also needs a special sample and the sensitivity is not high enough. So, we still have unsolved problems, like instability of ferromagnetic state at \( \nu = 1 \) [3] and the existence of Skyrmionic excitation at higher odd filling factor [4, 5]. In order to clarify these problems, a more sensitive and reliable measurement method of spin polarization in a quantum well layer is highly desired.
2. High-sensitive measurement of Kerr rotation by homodyne detection

Kerr rotation is the phenomenon that polarization of the reflected beam is rotated from that of the incident beam, and the angle is proportional to the magnetization along the optical axis. In the non-magnetic material, such as GaAs/AlGaAs, the Kerr rotation angle is proportional to the difference of the electron spin population. In the quantum Hall system, the angle is in the order of mill-radian. So we developed a high sensitive Kerr rotation measurement method by homodyne detection. The sample was single side δ–doped GaAs/AlGaAs quantum well. The g-factor was measured to be 0.23 by TRKR experiment for the 15nm quantum well [6]. The electron density can be changed in the range of 1.45~3.2x10¹¹ cm⁻² by a back gate voltage and the mobility is about 1 ×10⁶ cm²/Vs.

At first, we introduced a gate voltage modulation technique for the Kerr rotation measurement. Figure 1 shows the experimental setup (a), the modulation signal as a function of magnetic field (b) and the estimated spin polarization as a function of filling factor (c). Kerr rotation for the 810nm radiation from a tunable laser was observed in Faraday configuration at 1.5K by using a balanced detector and lock-in detection. The gate modulation signal shows a dispersive profile around odd integer filling factor, where the quantum ferromagnetism is expected.

The spin polarization against filling factor is derived from the gate modulated Kerr signal in the following procedure. We define the spin polarization function per particle as $\gamma_0 = S(E)/N$. Assuming the spin polarization function per particle is same for N and N+$\Delta N$, i.e. $\gamma(N+\Delta N) = \gamma(N)$, the gate modulated Kerr signal is expressed as,

$$\Delta \theta_k = a\gamma(N+\Delta N) \times N + \gamma(N) \times \Delta N$$

where a is a proportionality constant. Gate modulated Kerr signal contains the components induced by the change of $\Delta N$ and $\Delta N$ as seen in Eq.(1). $\gamma(N)$ satisfies the following integral equation,

$$\gamma(N) = \int \frac{d\gamma(N)}{d\nu} \times \nu$$

So we derive $\gamma(N)$ self-consistently by an iteration method with the starting function $\gamma(N) = 0$ at each even filling factor.

Spin polarization presents a rapid spin depolarization on both side of $\nu$=1, reflecting existence of Skyrmion. However in this method, gate voltage modulation disturbs the electron system and precise determination of the filling factor dependence of spin polarization is difficult because the spin polarization is averaged over the modulation depth.

![Figure 1. Kerr rotation measurement by gate modulation: (a) Experimental setup, (b) Gate modulation signal, (c) Estimated spin polarization vs. filling factor](image-url)
So, we employed a light phase modulation technique in the Kerr rotation measurement as shown in Fig.2 (a). Filtered radiation from super luminescent diode was used for this experiment. Rapid phase modulation by a photo elastic modulator enables a very high-sensitive measurement of Kerr rotation. A sharp peak at $v=3$, and some fine structure around $v=1$ are clearly seen in Fig.2 (b).

Kerr rotation measurement for the radiation around a specific wavelength enables a high sensitive detection of spin polarization. However the sensitivity depends on a magnetic field and wavelength of the light. So, for the quantitative measurement of spin polarization and detailed analysis of spin states, we need whole Kerr rotation spectrum.

3. Kerr rotation spectrum measurement by multi-channel homodyne detection

Figure 3 (a) shows the experimental setup for Kerr rotation spectrum measurement. Broad band light from super-luminescent diode (SLD) was introduced to the sample in Faraday configuration. The incident light was polarized by Glan laser prism. Optical pass of the reflected light was separated from the incident pass by non-polarizing beam splitter and analyzed by another Glan laser prism after passing through the liquid crystal retarder. Finally, the beam is introduced to the spectrometer with CCD multi channel detector. Unnecessary radiation from SLD was eliminated by spectrum filter and

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the intensity of incident beam was kept below 1μW for 50μmφ spot to minimize the optical disturbance to the quantum Hall system.

Figure 3 (b) shows the phase sensitive measurement of reflection spectra by liquid crystal retarder and the Kerr rotation spectra. Two spectra were measured by changing the relative phase between signal and reference axis by π. Kerr rotation spectra are derived from the spectra with the following equation

\[
\theta_k(\lambda) = \frac{\cos \phi}{2 \sin \phi} \frac{I_{\pi/2}(\lambda) - I_{-\pi/2}(\lambda)}{I_{\pi/2}(\lambda) + I_{-\pi/2}(\lambda)},
\]

where \(\phi\) is the angle between the analyzer axis and the signal axis. The measurement was repeated and Kerr rotation spectra are averaged in order to decrease shot noise. We can choose the Kerr rotation spectra and magnetic dichroic spectra by adjusting the center phase of phase retarder. Hereafter, we focus on the magnetic dichroic (MD) spectra.

Figure 4 (a) shows magnetic dichroic spectra observed at \(v=1\) and 1.5K. We also measured optical absorption spectra for \(\sigma^-\) and \(\sigma^+\) polarized light by photo luminescent excitation method to check the correspondence between the MD spectra and the absorption spectra. In Fig.4 (b), upper trace shows the absorption for \(\sigma^-\) polarization and lower trace show the absorption for \(\sigma^+\) polarization. MD spectra correspond to the difference between \(\sigma^-\) and \(\sigma^+\) absorption. Figure 4 (c) shows the assignment of the optical transition according to Fromer [7].

Figure 5 is 2D plot of MD intensity as a function of magnetic field and photon energy. We can see the magnetic field dependence of the optical transitions. Lowest energy transition is heavy hole state to \(N=0\) electron Landau level, and the next lower energy transition is heavy hole state to \(N=1\) electron Landau level. The Landau fan is strongly deviated from simple Landau fan. Furthermore we can see the optical transitions become sharper at integer filling factor, and absorption line presents splitting at integer filling factor. However, these are not the subject of this paper, so move to the evaluation of spin polarization.

**Figure 4.** MD spectra and optical transitions observed at \(v=1\) and 1.5K: (a) MD spectra, (b) Absorption spectra, (c) Assignment of optical transition

**Figure 5.** Gray scale plot of MD intensity observed at 1.5K as a function of magnetic field and photon energy.
4. Evaluation of spin polarization from magnetic dichroic spectra

Intensity of $V^-$ transition is proportional to the density of unoccupied spin up states and intensity of $V^+$ transition is proportional to that of unoccupied spin down states. So, we can derive the spin polarization by integrating the MD spectrum intensity across the optical transitions from the heavy hole state to the lowest unoccupied electron Landau level.

Figure 6 (a) shows the filling factor dependence of the spin polarization ratio in the range of $Q=0.95\sim1.9$, which is obtained by integrating the MD spectra intensity across of the transition to N=0 Landau level. The solid line is the spin polarization calculated based on the non interacting electron gas model at T=0. Dotted line is the expected spin polarization due to Skyrmionic excitation according to Barrett model where the Skyrmion size is assumed to be 4.0\cite{1}. Circles show the spin polarization ratio obtained in the present experiment, whose vertical scale is adjusted to the Barrett model. Spin polarization measurement by Kerr rotation reconfirmed the Skyrmionic excitation around $Q=1$. However, spin polarization has a flat region at the top, which means the existence of non polarized spins at $Q=1$ as shown in the Fig 6 (b). Similar result was recently reported by P.Plochocka at 1.6K \cite{3}. These unusual filling factor dependence suggest the existence of an intriguing spin state at $Q=1$, where a stable quantum ferromagnetic state is expected.

![Spin polarization vs Filling Factor](image1)

**Figure 6.** Filling factor dependence of spin polarization estimated from MD spectra:
(a) Spin polarization in the range of $v=0.95\sim1.9$, (b) At the top region of $v=1$

Figure 7. MD spectra and spin polarization in the range of $v=2\sim4$
(a) MD spectra observed at $v=3.3$ (b) Spin polarization around $v=3$
Figure 7 (a) shows the MD spectrum observed at $v=3.3$. In this magnetic field, the lowest absorption line is the transition from the heavy hole state to lowest unoccupied Landau level, $N=1$. On the low energy side of this transition, a peak corresponding to $\sigma^-$ absorption was observed. This indicates the unoccupied spin up state, which reflects the existence of Skyrmion around $v=3.3$. Figure 7 (b) shows the spin polarization obtained around $v=3$ ($v=1$) for the electron density $1.6 \times 10^{11}$ cm$^{-2}$. The rapid spin depolarization was also observed on both sides of $v=3$. The existence of Skyrmion at higher odd filling factor is theoretically predicted for the finite well width [4, 5]. The obtained result seems to support the theoretical prediction, however, there is some significant discrepancies between them. To confirm the existence of Skyrmion at higher integer odd filling factor, we need a more systematic study of spin polarization at lower temperature.

We are now developing a fiber based Kerr rotation spectra measurement system which is applicable to the dilution refrigerator. Kerr rotation spectra at mill-Kelvin may solve the unsettled problems and reveal the new spin condensed states in the quantum Hall states.

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