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Real-space Mapping of Spin-resolved Quantum Hall Chiral Edge States by Near-field Scanning Optical Microscopy

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Abstract

The quantum Hall edge states are formed in the vicinity of the edge of a sample that hosts two-dimensional electron system (2DES) in a perpendicular magnetic field at low temperature. The bulk 2DES states rise up due to the confinement potential near the edge and intersect with the Fermi-level, forming current carrying compressible states. The compressible states are separated by insulating incompressible states. The distribution of the compressible/ incompressible states has been investigated by various scanning probe microscopy, however, there have been few reports on real-space mapping of spin-resolved quantum Hall edge states. Here we report on the first observation of spin-resolved chiral quantum Hall edge states by a low-temperature near-field scanning optical microscope.

1. Introduction

Continuous efforts have been made to directly image alternating strips of the compressible and the incompressible states in the vicinity of a sample edge [1,2], for example, by scanning single electron transistors [3], subsurface charge accumulation [4], scanning force microscope [5-7] and near-field scanning optical microscope (NSOM) [8]. It has been revealed how the compressible-incompressible states develop with magnetic field, and the condition for the formation of the edge states are clarified at the presence of disorders [8].

The quantum Hall chiral edge states carry not only currents but also spins. Observation of spin-polarized edges has been attracting much interests after the recent discovery of the quantum spin Hall effect [9] and the quantum anomalous Hall effect [10]. The spin splitting has been predicted to change the distribution of the compressible and the incompressible edge states. The real-space distribution of the spin-split edge states depends sensitively on screening and exchange energy-enhanced *g*-factor [11]. Thus we have conducted a direct measurement of the spin resolved quantum Hall chiral edge states.

Local probe methods based on optical excitations have been investigated to map the quantum Hall chiral edge states [12-15]. The ability to access states at a specific energy by tuning the wavelength of the laser light is one of the advantages of the optical excitation method, however, this has not been utilized in the previous reports. Moreover, The optical approach was demonstrated to be a strong tool for the straightforward measurement of spin polarizations of the electrons in the edge states [16]. In this paper, we report on Hall photovoltage mappings of the spin-resolved quantum Hall chiral edge states using a circularly polarized near-field scanning optical microscope at low temperature.

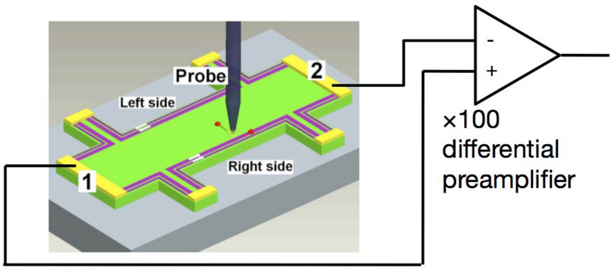

Fig. 1 Schematics of the measurement setup and the sample structure.

2. Experiment

The sample was a standard Hall-bar structure of a GaAs/AlGaAs modulation-doped single heterojunction with a mobility of 178 m^2/Vs and a density of 4.6×10^{11} cm^{-2}. The width and the length of the Hall bar were 25 and 300 μm, respectively. The sample on the scanning stage was illuminated with a tunable semiconductor diode laser light through a double tapered optical fiber probe [17] under a shear force feedback control in a dilution refrigerator at the base temperature of 70 mK. An aperture with a diameter of about 100 nm was created by focused ion beam slicing of the apex of a metal-coated NSOM probe tip. The scanning range of the tube piezoscanner was 2.1 μm. The polarization of the incident beam was controlled by a Berek compensator and a polarizer. Two-terminal photovoltage was amplified by a differential preamplifier as schematically shown in Fig. 1 and was measured synchronously with a lock-in-amplifier. The sample temperature during the measurements was 250 mK.

3. Mapping of quantum Hall chiral edge states

Upon local illumination of the sample through an NSOM probe, electron-hole pairs are created. The electron-hole pairs are dissociated due to the vertical confinement potential of the single heterojunction sample. The optically created electrons rapidly relax to the Fermi-level, and diffuse across the tunnel barrier between the edge and the bulk states. Slight change of the local electron density by diffusion current is balanced by the build-up of the Hall voltage [14], which is measured as a function of the position of the illumination spot. The optically created holes move to the rear side of the sample and contribute to the background of the photovoltage. Based on the Onsager-Casimir reciprocity theorem [18], the photovoltage profile reflects the potential profile.

Figure 2 shows magnetic field (B) dependence of a mapping of the spatial derivative of the photovoltage (dV/dx) by irradiating unpolarized light at 1.5194 eV. The position with large |dV/dx| (red) corresponds to the position of the incompressible strips. In-between the incompressible strips with even local filling factor (ν_L), the photovoltage signals due to odd ν_L are clearly observed at around B=3.50, 2.62, and 2.06 T. Circular polarization dependence of the photovoltage signals has been investigated by irradiating polarized light at 1.5140 eV near the onset of the absorption. The obtained photovoltage mappings clearly indicate that spin polarized electrons are injected to the sample.

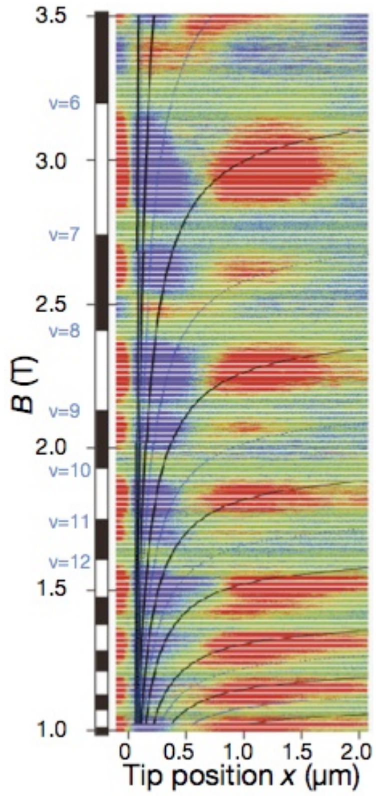

Fig. 2 Magnetic field dependence of a mapping of dV/dx at E_p=1.5194 eV at T = 250 mK.

3. Conclusions

We have performed real-space mappings of spin resolved quantum Hall chiral edge states by an NSOM. Our results open up a novel method to investigate mappings of the edge states of topological quantum liquids.

Acknowledgements

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References

[1] B. I. Halperin, Phys. Rev. B **25**, 2185 (1982)

[2] D. Chklovskii, B. Shklovskii, and L. Glazman, Phys. Rev. B **46**, 4026 (1992).

[3] N. Zhitenev, T. Fulton, A. Yacoby, H. Hess, L. Pfeiffer, and K. West, Nature **404**, 473 (2000).

[4] S. Tessmer, P. Glicofridis, R. Ashoori, L. Levitov, and M. Melloch, Nature **392**, 51 (1998).

[5] K. L. McCormick, M. T. Woodside, M. Huang, M. Wu, P. L. McEuen, C. Duruoz, and J. S.Harris, Phys. Rev. B **59**, 4654 (1999).

[6] P. Weitz, E. Ahlswede, J. Weis, K. von Klitzing, and K. Eberl, Physica E **6**, 247 (2000).

[7] J. Hedberg, A. Lal, Y. Miyahara, P. Grtter, G. Gervais, M. Hilke, L. Pfeiffer, and K. West, Appl. Phys. Lett. **97**, 143107 (2010).

[8] H. Ito, K. Furuya, Y. Shibata, S. Kashiwaya, M. Yamaguchi, T. Akazaki, H. Tamura, Y. Ootuka, and S. Nomura, Phys. Rev. Lett. **107,** 256803 (2011).

[9] M. Knig, S. Wiedmann, C. Brne, A. Roth, H. Buhmann, L. W. Molenkamp, X.-L. Qi, and S.-C. Zhang, Science **318**, 766 (2007).

[10] C.-Z. Chang, J. Zhang, X. Feng, J. Shen, Z. Zhang, M. Guo, K. Li, Y. Ou, P. Wei, L.-L. Wang, Z.-Q. Ji, Y. Feng, S. Ji, X. Chen, J. Jia, X. Dai, Z. Fang, S.-C. Zhang, K. He, Y. Wang, L. Lu, X.-C. Ma, and Q.-K. Xue, Science **340**, 167 (2013).

[11] A. Manolescu and R. R. Gerhardts, Phys. Rev. B **51**, 1703 (1995).

[12] R. Merz, F. Keilmann, R. J. Haug, and K. Ploog, Phys. Rev. Lett. **70**, 651 (1993).

[13] R. J. F. van Haren, F. A. P. Blom, and J. H. Wolter, Phys. Rev. Lett. **74**, 1198 (1995).

[14] A. A. Shashkin, A. J. Kent, J. R. Owers-Bradley, A. J. Cross, P. Hawker, and M. Henini, Phys. Rev. Lett. **79**, 5114 (1997).

[15] H. van Zalinge, B. Özyilmaz, A. Böhm, R. W. van der Heijden, J.H. Wolter, and P. Wyder, Phys. Rev. B **64**, 235303 (2001).

[16] S. Nomura and Y. Aoyagi, Phys. Rev. Lett. **93**, 096803 (2004).

[17] T. Saiki, S. Mononobe, M. Ohtsu, N. Saito, and J. Kusano, Appl. Phys. Lett. **68**, 2612 (1996).

[18] H. Casimir, Rev. Mod. Phys. **17**, 343 (1945).