Final Technical Report

Project Title:
Experiments on Quantum Hall Topological Phases in Ultra Low Temperatures (DE-FG02-06ER46274)
Funding Period: 02/15/2011 to 02/14/2015
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Project Scope

This project is to cool electrons in semiconductors to extremely low temperatures and to study new states of matter formed by low-dimensional electrons (or holes). At such low temperatures (and with an intense magnetic field), electronic behavior differs completely from ordinary ones observed at room temperatures or regular low temperature. Studies of electrons at such low temperatures would open the door for fundamental discoveries in condensed matter physics. Present studies have been focus on topological phases in the fractional quantum Hall effect in GaAs/AlGaAs semiconductor heterostructures, and the newly discovered (by this group) quantum spin Hall effect in InAs/GaSb materials.

This project consists of the following components: 1) Development of efficient sample cooling techniques and electron thermometry: Our goal is to reach 1 *mK* electron temperature and reasonable determination of electron temperature; 2) Experiments at ultra-low temperatures: Our goal is to understand the energy scale of competing quantum phases, by measuring the temperature-dependence of transport features. Focus will be placed on such issues as the energy gap of the 5/2 state, and those of 12/5 (and possible 13/5); resistive signature of instability near 1/2 at ultra-low temperatures; 3) Measurement of the 5/2 gaps in the limit of small or large Zeeman energies: Our goal is to gain physics insight of 5/2 state at limiting experimental parameters, especially those properties concerning the spin polarization; 4) Experiments on tuning the electron-electron interaction in a screened quantum Hall system: Our goal is to gain understanding of the formation of paired fractional quantum Hall state as the interaction pseudo-potential is being modified by a nearby screening electron layer; 5) Experiments on the quantized helical edge states under a strong magnetic field and ultralow temperatures: our goal is to investigate both the bulk and edge states in a quantum spin Hall insulator under time-reversal symmetry-broken conditions.

Summary of Accomplishments

• *Studies of 5/2 State in the Limits of Small Zeeman Energy*
Using very -high mobility QWs having various densities n_e, we have investigated the 5/2 plateau in the high- and low-magnetic field limits and its response to a tilted magnetic field. During this

funding period, we focused on the limit of small Zeeman energy, where we have observed an enhancement of 5/2 quantum Hall plateau in small tilt fields. This work (in collaboration with Loren Pfeiffer group at Princeton) is published in *Phys. Rev. Lett. 108, 196805 (2012)*.

The proposed Pf (or APf) wavefunction for 5/2 requires the spin being at least partially-polarized. Recent numerical results indicate that at 5/2 in realistic systems is spin-polarized even in the limit of vanishing Zeeman energy. It is anticipated that increasing the Zeeman energy would help to stabilize the spin-polarized ground state in the presence of fluctuations. Therefore, a tilted magnetic field is supposed to enhance the FQHE at 5/2. However, to date all the experimental results have been contradicted to this simple prediction: 5/2 FQHE are found to be weaken in a tilted field. Competition with a striped many-electron phase could be responsible for the complex response of the 5/2 state to a tilted field. Surprisingly, we have observed a $\nu = 5/2$ FQHE at a magnetic field $B = 1.5 \sim 1.7$ T, and found that its energy gap values increase in an in-plane magnetic field. Based on our results, we discuss the relevance of a Skyrmion spin texture at $\nu = 5/2$ associated with small Zeeman energy in wide quantum wells.

•High Magnetic Field and Ultralow Temperature Experiments on the Helical Edge States in InAs/GaSb Bilayers

Topological insulators are a novel class of materials with nontrivial surface or edge states Time-reversal symmetry (TRS) protected TIs are characterized by the Z_2 topological invariant. The fate of the Z_2 TIs under broken TRS is a fundamental question in understanding the physics of topological matter but remains largely unanswered. Here we show, a two-dimensional TI is realized in an inverted electron-hole bilayer engineered from InAs/GaSb semiconductors which shows quantized edge conductance in mesoscopic size devices. More surprisingly, the TI retains robust helical liquid (HL) edge states under a strong magnetic field. The results are published in *Phys. Rev. Lett.113, 026804 (2014)* (in collaboration with Kathryn Moler group at Stanford) and *Phys. Rev. Lett. 114, 096802 (2015)*.

Wide conductance plateaus of $2e^2/h$ value are observed; they persist to 10T applied in-plane field before transitioning to a trivial semimetal. In a perpendicular field up to 35T, broken TRS leads to a spatial separation of the movers in Kramer's pair and consequently the intra-pair backscattering phase space vanishes, i.e., the conductance increases from $2e^2/h$ in strong fields manifesting chiral edge transport. For a given field, gap closing at the boundary between integer quantum Hall (QH) and quantum spin Hall (QSH) is observed as a function of chemical potential, consistent with a topological phase transition. Our findings suggest that once established, the HL is remarkably resilient and only undergoes adiabatic deformation under TRS breaking. Our study presents a compelling case for exotic properties of QSH insulators beyond current theoretical understanding.

Our more recent experiment (in collaborations with Gábor Csáthy group at Purdue) shows that the helical edge states in the TI made of InAS/GaSb is a new class of strongly interacting 1D electronic system, and ultralow temperature nonlinear transport results indicate that the properties of such a system may be understood by helical Luttinger liquid theory. The results are published in *Phys. Rev. Lett. 115, 136804 (2015)*.

Publications Supported by This Grant

1. Enhancement of the ν = 5/2 Fractional Quantum Hall State in a Small In-Plane Magnetic Field, Guangtong Liu, Chi Zhang, D. C. Tsui, Ivan Knez, Aaron Levine, R. R. Du, L. N. Pfeiffer, and K. W. West, ***Phys. Rev. Lett*. 108**, *196805 (2012)*.

2. Images of edge current in InAs/GaSb quantum wells, Eric M. Spanton, Katja C. Nowack, Lingjie Du, Gerard Sullivan, Rui-Rui Du, and Kathryn A. Moler, ***Phys. Rev. Lett. 113***, *026804 (2014)*.

3. $2k_F$-Selected Conductance Oscillations of High-Mobility Two-Dimensional Electron Gas in Corbino Devices, Xiaoxue Liu, Yuying Zhu, Lingjie Du, Changli Yang, Li Lu, Loren Pfeiffer, Ken West, and Rui-Rui Du, ***Appl. Phys. Lett. 105***, *182110 (2014)*.

4. Observation of Robust Quantum Spin Hall States in InAs/GaSb Bilayers, Lingjie Du, Ivan Knez, Rui-Rui Du, and Gerard Sullivan, ***Phys. Rev. Lett. 114***, *096802 (2015)*.

5. Landau Level Crossing in Spin-Orbit Coupled Two-Dimensional Electron Gas, Xing-Jun Wu, Ting Xin Li, Chi Zhang, and Rui-Rui Du, ***Appl. Phys. Lett. 106***, *012106 (2015)*.

6. Depinning transition of bubble phases in a high Landau level, Xuebin Wang, Hailong Fu, Lingjie Du, Xiaoxue Liu, Pengjie Wang, L. N. Pfeiffer, K. W. West, Rui-Rui Du, and Xi Lin, ***Phys. Rev. B 91***, *115301 (2015)*.

7. Observation of a Helical Luttinger Liquid in InAs/GaSb Quantum Spin Hall Edges, Tingxin Li, Pengjie Wang, Hailong Fu, Lingjie Du, Kate A. Schreiber, Xiaoyang Mu, Xiaoxue Liu, Gerard Sullivan, Gábor A. Csáthy, Xi Lin, and Rui-Rui Du, ***Phys. Rev. Lett. 115***, *136804 (2015)*.

8. Scaling properties of the plateau transitions in the two-dimensional hole gas system, Xuebin Wang, Haiwen Liu, Junbo Zhu, Pujia Shan, Pengjie Wang, Hailong Fu, Lingjie Du, L. N. Pfeiffer, K. W. West, X. C. Xie, Rui-Rui Du, and Xi Lin, ***Phys. Rev. B 93***, *075307 (2016)*.

Invited Talks Based on Research Supported by This Grant

1. "New Quantum Spin Hall Insulator in InAs/GaSb", Stanford Condensed Matter Seminar, January 26, 2012

2. "Helical Edge Modes in Inverted Electron-Hole Bilayers", 31th Intl' Conf. on Semicond. Phys., Zurich, July 29-Aug. 3, 2012

3. "Creating Majorana Fermions on the Edge of InAs/GaSb", MIT Chez Pierre CM seminar, April 22, 2013

4. "Creating Majorana Fermions on the Edge of InAs/GaSb Quantum Wells", Symposium on Quantum Hall Effects and Related Topics, on the occasion of 70th birthday of Prof. Dr. K. v. Klitzing, Max-Planck-Institute for Solid-State Research in Stuttgart, Germany, June 26-28, 2013

5. Symposium on Majorana Physics in Condensed Matter, Ettore Majorana Center, Erice, Italy, July 12-18, 2013

6. "Quantized Edge States in InAs/GaSb Bilayers", Microsoft Station-Q Meeting, Santa Barbara, December 6, 2013

7. "Superconductor Proximity-Coupled Helical Edges in InAs/GaSb Bilayers", Int'l Workshop on Emerging Phenomena in Quantum Hall Systems – EPQHS-5, Weizmann Institute of Science, Israel, July 7-9, 2014

8. "Proximity-Coupled InAs/GaSb Quantum Wells as a Platform of Majorana Zero-Modes", Inte'l Workshop, Institute of Advanced Studies, Hong Kong University of Science and Technology, Jan. 9, 2014

9. "Robust Helical Edge States in InAs/GaSb Bilayers", 21th Int'l Conf. on the Physics of High Magnetic Fields, Aug. 3-8, 2014, Panama City, FL, USA

10. "Robust Quantum Spin Hall Effect in Gated InAs/GaSb Bilayers", European Materials Research Society Fall 2014 Conf. Sept. 17, 2014, Warsaw, Poland

11. "Helical Edge States and Beyond in InAs/GaSb Bilayers", Workshop on Majorana Zero - Modes and Beyond, Princeton Center for Theoretical Science, Oct. 29-31, 2014

12. "InAs/GaSb Quantum Spin Hall Insulators", invited Talk, American Vacuum Society, Jan. 2015, Salt Lake City, USA

13. "Robust Helical Transport in InAs/GaSb", Invited Symposium Talk, APS March Meeting, March 2015, San Antonio, USA

14. "Helical Luttinger Liquid", invited talk, IAS Workshop on Topological Matter, HKUST, Hong Kong, July 2015

15. "InAs/GaSb Quantum Spin Hall Insulator and Beyond", invited talk, Max Plank Society Summer School, Stuttgart, July 2015

16. "Helical Luttinger Liquid", invited talk, Int'l Workshop on Interaction and Topology in 1D, Mark Planck Institute, Dresden Germany, Sept. 2015