SAND2015-8027PE

Program Title: Quantum Electronic Phenomena and Structures
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Program Scope

This project is to discover and understand emerging quantum phenomena and states in novel electronic device structures that are governed by the laws of quantum mechanics. The project includes research of quantum transport studies in low dimensional electron systems, carrier transport dynamics, optical properties, and high quality materials synthesis. We investigate electron physics at the nano and mesoscopic scales that occurs due to strong electron-electron and electron-disorder interactions, and focus on important areas, such as novel fractional quantum Hall physics, exotic many-body states in coupled quantum structures, the impact of disorder in strongly correlated ground states, topological transport properties in Dirac materials, the valley degree of freedom in high quality Si/SiGe quantum wells, and THz quantum Hall effects in two dimensional electron/hole systems. These research topics are at the frontier of the field of condensed matter physics and will undoubtedly yield new discoveries and new understanding of emergent quantum states and behaviors.

The proposed research activities are categorized in three synergistically integrated tasks. Task 1, *Quantum Transport in Structured Semiconductors*, seeks to nano-engineer new types of quantum electronic structures and to discover and understand novel collective electron states and their quantum properties in these low-dimensional systems. Task 2, *Syntheses and Electronic Properties of Topological Nanostructures*, seeks to grow high quality topological insulator nanostructures and to probe their exotic quantum electronic properties. We will also perform transport studies in mono-layer InN quantum wells and InN nanowires in the context of topological properties. The long term vision of Task 3, *Transport Dynamics in heterostructures*, is to discover new quantum phase transitions and to understand vertical charge transport dynamics in type II heterostructures.

Recent Progress:

Second Generation Fractional Quantum Hall Effect: The search for novel fractional quantum Hall effect (FQHE) states, for example, non-abelian FQHE states, continues to attract a great deal of interest since they were first discovered in 1982. To date, studies on non-Abelian FQHE states have mostly been limited to the second Landau level. A little over ten years ago, observation of the signature of the FQHE at ν=4/11, however, generated new excitements on the existence of non-Abelian FQHE states in the lowest Landau level. This state has been viewed as an FQHE state of composite fermions (CFs). Yet, its origin remains elusive. Several proposals have been made. Among them, the numerical simulations by Wójs, Yi, and Quinn (WYQ) showed that a spin-polarized 4/11 FQHE state is an unconventional FQHE state of CFs and, possibly, a new non-Abelian state.

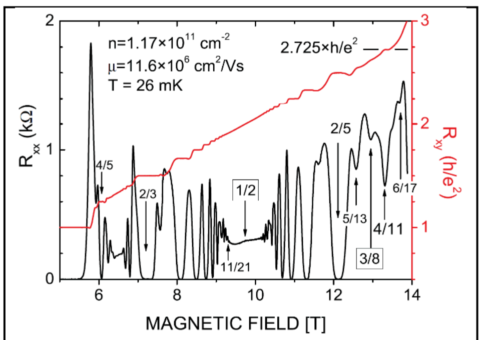

Fig. 1: Magneto-resistance R_{xx} and Hall resistance R_{xy}. A quantized plateau is observed at ν=4/11.

Despite a significant amount of theoretical work on this novel 4/11 FQHE state, experimentally, a definitive observation, in the form of an accurately quantized Hall plateau with activated longitudinal resistance, has been lacking. Recently, with new improvements in wafer growth, a high electron mobility of ~ 12×10^6 cm^2/vs has been achieved at an electron density of ~ 1.2×10^{11} cm^{-2}. In this high-quality low-density sample, we observed at ν=4/11 activated magnetoresistance R_{xx} and quantized Hall resistance R_{xy}. Our results thus confirm that the 4/11 state is a true FQHE state. Furthermore, we studied the spin polarization of this new FQHE state, utilizing the well-developed in-situ tilt magnetic field technique. Results from two quantum well samples of different well thickness (40 nm versus 50 nm) show that the 4/11 state is most likely spin polarized in the density range of n~1×10^{11} cm^{-2}, consistent with previous numerical results [Barlam et al, PRB **91**, 045109 (2015)]. Our results thus suggest that the 4/11 state is a WYQ state, a new non-Abelian state in the lowest Landau level. [Publication #9]

Terahertz magneto-optical spectroscopy of two-dimensional hole system: Two-dimensional hole systems (2DHS) are known to have an advantage in their use in the burgeoning areas of quantum computing and spintronics, as the *p*-type hole valence band has a reduced hyperfine interaction with the nuclei, leading to longer spin coherence times for holes. Furthermore, the Rashba effect can be made much stronger in a 2DHS than in a two-dimensional electron system (2DES). Consequently, it is particularly important to explore 2D hole physics in depth. We have performed the first temperature-dependent THz magneto-optical spectroscopic measurements on two-dimensional hole gases, revealing significant differences in the dependence of the cyclotron frequency on magnetic field as compared to the more commonly studied two-dimensional electron gases, particularly at higher temperatures. In addition, our ultrafast microscopic measurements on single GaN nanowires were also published in Appl. Phys. Lett. We then built upon these results by performing ultrafast optical microscopy (UOM) on single GaN/InGaN core/shell nanowires, providing new insight into carrier relaxation in radial multiple quantum well systems. [Publication #10, #12]

Electron bilayers in undoped Si/SiGe double quantum wells: Additional degrees of freedom often bring about new physical phenomena in the quantum Hall regime. Spins and valleys have both been shown to play an important role in integer and fractional quantum Hall states. Layers are another degree of freedom that can be engineered into a 2D electron system. In GaAs this has led to a plethora of inter-layer correlation effects, the most famous one being the Bose-Einstein condensation of excitons. A bilayer system also serves as the platform for building coupled quantum wires. This architecture has long been employed to study Luttinger liquid physics in 1D electron gas.

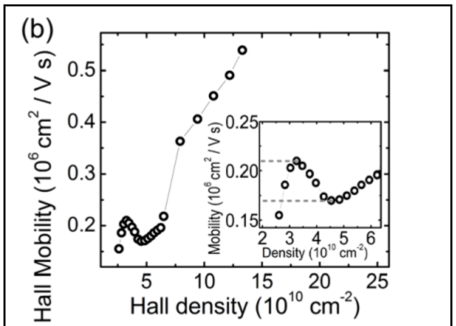

Fig. 2: the mobility dip indicates the onset of population of the second layer.

In Si/SiGe, no high-mobility electron bilayer system has been reported. The main difficulty is in material growth, since bottom-side modulation-doping of a Si/SiGe double-quantum-well structure does not work well due to surface segregation of dopants. The segregated dopants travel along the growth front and are incorporated throughout the structure, spoiling the mobility. We circumvent this difficulty by employing a dopantless architecture. The architecture, together with high-quality material growth, has led to record mobility in Si-based systems. By carefully choosing the barrier and quantum well thicknesses, two layers of electrons can be capacitively induced and coexist under certain gate bias conditions. As shown in Fig. 2, a mobility dip is observed with increasing electron density. The dip is a signature of the onset of inter-layer scattering and occurs at a density consistent with our self-consistent Schrodinger-Poisson simulations, thus proving the existence of an electron bilayer system in Si. We also observed a ν=2 integer quantum Hall state. Factoring in the material and structure parameters, we think this state could arise from inter-layer correlation but inter-layer tunneling could render the state single-layer-like. The new material should allow us to unambiguously identify inter-layer correlation-induced quantum Hall states. [Publication #11]

Reversible Bandgap Tuning in GaN Nanowire Lasers: We demonstrated dynamic and continuous tuning of single nanowire lasers by application of hydrostatic pressures up to ~7 GPa. A wide ~30 nm range of reversible wavelength tuning was achieved in a single GaN nanowire laser. The wavelength tuning is caused by an increase in the direct bandgap of GaN with increasing pressure and is precisely controllable to subnanometer resolutions. The observed pressure coefficients of the NWs are ~40% larger compared with GaN microstructures fabricated from the same material or from reported bulk GaN values, revealing a nanoscale-related effect that significantly enhances the tuning range using this approach. [Publication #15].

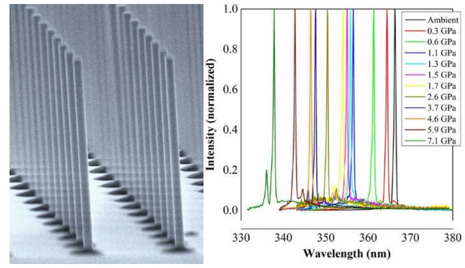

Fig. 3: Left panel shows GaN nanowires with controlled dimensions fabricated by two-step dry + wet top-down approach. Right panel shows lasing spectra of GaN nanowires under hydrostatic pressure.

Future Plans:

Fractional quantum Hall effect at ν=3/8: Surprisingly, very little experimental data are available for this possible even-denominator fractional quantum Hall state in the lowest Landau level. On the other hand, numerical calculations have revealed many possible exotic ground states at this filling factor, for example, an anti-Pfaffian state in the second CF Landau level. Thus, a better understanding of the nature of this novel FQHE will have important implications in fault-tolerant topological quantum computation. We plan to systematically study this state in our ultra-high mobility two-dimensional electron systems. We will explore its spin polarization utilizing the tilted magnetic field technique and density dependence studies. In particular, we will examine whether there exists a spin transition as predicted in numerical calculations.

Si/SiGe bilayer material: We will perform low-temperature magneto-transport studies on the new Si/SiGe bilayer material with suppressed inter-layer tunneling and search for evidence of inter-layer correlation. An electron bi-wire Si/SiGe sample has been fabricated and is ready to be measured. We will study 1D-1D tunneling and 1D-1D drag in this system with a valley degree of freedom. We are also working toward selective modulation doping through STM-based hydrogen lithography, which will allow us to introduce position correlation in the remote charge layer. Theoretically this should lead to higher 2DEG mobilities than with a random distribution of ionized donors.

Terahertz magneto-optical spectroscopy: We have re-optimized our ultrafast optical microscopic setup and will perform UOM measurements on InN nanowires in the near future. We are also adapting our system to perform ultrafast optical Faraday rotation measurements on single nanowires, with the goal of exploring spin-orbit coupling in these systems. We have also begun optical-pump, THz probe experiments in a magnetic field on 2DEG and 2DHG, revealing novel photo-induced quantum states.

Topological properties in Dirac materials: We will begin a new synthesis effort in topological materials. Our initial focus will be on SnTe nanostructures, which have been predicted to have topological states on the high symmetry facets. We will explore the growth of SnTe nanostructures by thermal vapor deposition, examining the effects of substrate, metal catalyst, and growth conditions on nanostructure formation. Quantum transport properties of topological surface states in these materials will be studied. In addition, high frequency transport studies, which have extensively been used to manifest quantum phases and phase transitions, will be carried out in understanding quantum properties in topological nanostructures coupled with photons. We have begun THz magneto-optical measurements on other 2D nanosystems, including MoS2, topological insulators, and Dirac/Weyl semimetals. Finally, we plan to theoretically explore the effect of realistic disorder on the current-carrying edge modes of a topological insulator. We will use actual measured device geometries, where appropriate, in numerical simulations to compare candidate disorder models with the results of experiment.

Publications intellectually led by this FWP (October'13 to September'15):

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3) G.C. Dyer, G.R. Aizin, S.J. Allen, A.D. Grine, D. Bethke, J.L. Reno, E.A. Shaner, *Interferometric measurement of far infrared plasmons via resonant homodyne mixing*, Optics Express **22**, 16254 (2014).
4) D. Laroche, G. Gervais, M.P. Lilly, and J.L. Reno, *1D-1D Coulomb Drag Signature of a Luttinger Liquid*, Science **343**, 631 (2014).
5) N. S. Selby, M. Crawford, L.A. Tracy, J.L. Reno, and W. Pan, *in-situ Biaxial Rotation at Low-Temperatures in High Magnetic Fields*, Rev. Sci. Instrum. **85**, 095116 (2014).
6) S.K. Lyo and W. Pan, *Miniband transport in a two-dimensional electron gas with a strong periodic unidirectional potential modulation,* Solid State Communications **196**, 51 (2014).
7) W. Pan, E. Dimakis, G.T. Wang, T.D. Moustakas, and D.C. Tsui, *Two-dimensional electron gas in monolayer InN quantum wells*, Appl. Phys. Lett. **105**, 213503(2014).
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12) P.C. Upadhya, J.A. Martinez, Q. Li, George T. Wang, B.S. Swartzentruber, Antoinette J. Taylor, and Rohit P. Prasankumar, *Space-and-time-resolved spectroscopy of single GaN nanowires*, APL **106** , 263103 (2015).
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14) Brian L. Brown, Patricia Martinez, Anvar A. Zakhidov, E.A. Shaner, and Mark Lee, *Microwave Conductance Properties of Aligned Multiwall Carbon Nanotube Textile Sheets*, J. Appl. Phys**.** **118**, 014308 (2015).
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Collaborative publications (October'13 to September'15)

16) O. Mitrofanov, W. Yu, R.J. Thompson, Y. Jiang, I. Brener, W. Pan, C. Berger, W.A. de Heer, and Z. Jiang, Probing terahertz surface plasmon waves in graphene structures, Appl. Phys. Lett. 103, 111105 (2013).
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20) C.S.F. Cobaleda, X.Y. Xiao, D.B. Burckel, Ronen Polsky, D. Huang, E. Diez, and W. Pan, *Superconducting properties in Tantalum decorated three-dimensional graphene and carbon structures*, APL **105**, 053508 (2014).
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