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Quantum Electronic Phenomena and Structures

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Future Plans:

Spin polarization of the fractional quantum Hall states in the first excited Landau level: Surprisingly, very little data are available for the spin polarization of the fractional quantum Hall (FQH) states in this Landau level. On the other hand, answers to this question will help us to better understand the nature of these FQH states, in particular the 5/2 and 12/5 states, which are believed to be of non-Abelian and have potential applications in fault-tolerant topological quantum computation. We plan to systematically study the spin polarization utilizing the tilted magnetic field technique in ultra-high mobility two-dimensional electron systems. In particular, we will examine whether the transition from a FQH state to an anisotropic state at 5/2 is a first order quantum phase transition, predicted by a theoretical model. Possible spin transition under tilt magnetic fields will also be examined for the 12/5 state, a possible candidate of the more exotic parafermionic FQH state.

Double Quantum Wires: With the goal of studying 1D correlation physics we will use the new samples to measure 1D-2D tunneling, 1D-1D tunneling for a single subband and Coulomb drag between 1D wires. These transport measurements will probe the density of states and interwire electron-electron scattering due to Coulomb interactions. These effects should depend on the nature of the 1D ground state, and provide a useful tool to access Luttinger liquid effects. In addition to these dc transport techniques, we have developed a high frequency (~GHz) reflectometry technique for quantum computing measurements. While this is primarily for the detection of single electron events in quantum dots, we will try to make conductance measurements of single long quantum wires on the time scale of 100 nanosec to 1 microsec. The combination of double wire experiments and fast transport measurements has significant potential for new studies of quantum wires.

Spin Physics in 2D Holes: Building on recent successes in growth of high-mobility two-dimensional hole systems (2DHS) via C doping of (100) oriented GaAs/AlGaAs heterostructures, we propose to develop 2DHS at Sandia for experiments investigating the spin degree of freedom in nanostructures. After successful development of 2DHS, we propose to perform experiments investigating hole spins in bulk 2D systems. For example, measurements of the spin-orbit coupling can be made via magnetotransport. Another goal would be to experimentally determine the coupling between hole and nuclear spins in the host semiconductor using nuclear magnetic resonance (NMR) techniques, such as resistively-detected NMR, to verify the magnitude and form of the coupling predicted by theory.

Growth and Electronic Properties of Nanowires: We will focus on growth and characterization of core-shell nanowires, primarily Al(Ga)N/GaN and patterned InGaAs/GaAs nanowires, in order to continue our study of interface manipulation and engineering of nanowires, and the resulting effects on their electrical and optical properties. These core-shell nanowires will allow us to examine the novel structure and physics of 1D and 2D electron and hole gases that may be formed at the heterointerfaces in free-standing semiconductor nanowires, as predicted by our recent theoretical work (Ref 34). We will also fabricate and study the properties of Al(Ga)N/GaN nanowire heterostructures using a recently-developed top-down nanowire fabrication technique, which may yield nanowires with fewer point defects. Obtaining better understanding of and control over these phenomena could enable the development of ultrafast and ultraefficient nanowire-based electronic and photonic devices.

Ultrafast Dynamics in Nanowires: We will use terahertz (THz) time-domain spectroscopy (THz-TDS) to measure the conductivity of core-shell nanowires in a non-contact manner, which will enable us to study 1DEG/2DEG formation in these systems. Optical-pump terahertz-probe measurements will enable us to temporally resolve conductivity dynamics in these nanomaterials after ultrafast photoexcitation. Additionally, we will continue our pump-probe experiments on individual nitride nanowires. Our initial focus will be to optimize the spatial resolution of this technique, which should enable us to image carrier dynamics in individual nanowires with sub-100 fs temporal and sub-micron spatial resolution. Performing such measurements will enable us to directly image, for example, the effects of radial heterostructuring on charge transport in a single GaN core/AlGaN shell nanowire, with direct impact on the use of these nanowires in nanoscale transistor and waveguide applications.

Selected Publications (2008-2011):

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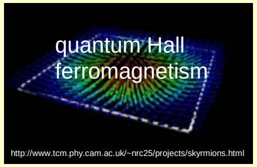
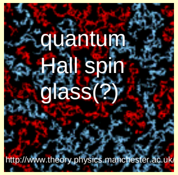
Interplay between disorder and electron-electron interactions in quantum Hall regime

Quantum Hall ferromagnetism in presence of tunable disorder



Increasing → disorder

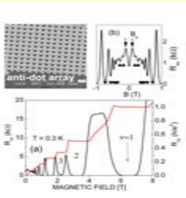


(a quantum phase transition)

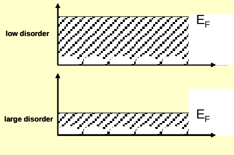
Background

- electron-electron (e-e) interaction and the interplay between disorder and e-e interaction are the main theme in quantum condensed matter physics.
- no experimental evidence to a long-predicted, *disorder induced* quantum phase transition from the many-body quantum Hall ferromagnetic state to quantum Hall spin glass state at ν=1 integer quantum Hall effect (IQHE) state.
- Experimental verification helps better understanding of quantum phase transition physics.

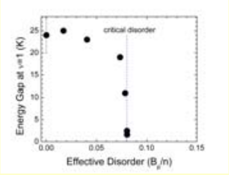
Results:



- Uniform anti-dot array fabricated by interferometric lithography.
- Commensurate oscillations as well as Shubnikov-de Haas oscillations seen at low magnetic fields.
- Well developed quantum Hall effect states at Landau level fillings ν=1,2,3…

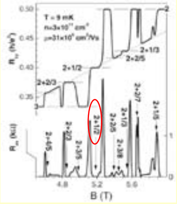


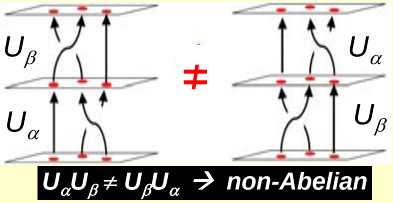
- Due to antidots, modulated bottom of energy band (voids) by strength of ΔV in energy vs. position plot, as large scattering centers for electron transport.
- Tunable disorder strength by varying Fermi level E_F relative to ΔV.



- Slow change in ν=1 energy gap in weak effective disorder regime.
- Sharp drop at apparent critical effective disorder.
- Evidence of a first order quantum phase transition from quantum Hall ferromagnetic ground state to quantum Hall spin glass state

Impact of disorder on the 5/2 fractional quantum Hall state

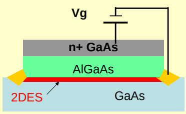


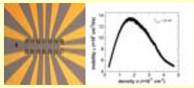


Background

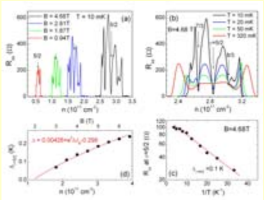
- Even-denominator FQHE state, probably due to pairing of composite fermions.
- Quasiparticles of this state believed to obey *non-abelian* statistic, application in topological quantum computation.
- Need to understand impact of disorder on this state to achieve largest energy gap (larger gap → small error rate and higher operational temperature).

Results:

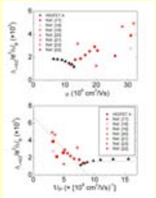




- High quality heterojunction insulated-gate field-effect transistor (HIGFET).
- No modulation doping. Electron density induced by gate voltage, V_g.
- 2D density tunable from 2×10^{10} to $\sim5\times10^{11}$ cm^{-2}, with a peak mobility of $\sim14\times10^6$ cm^2/Vs.

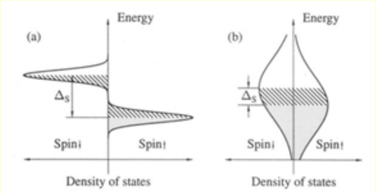


- Density dependence of 5/2 FQHE state performed.
- Thermally activated 5/2 state observed in HIGFETs and thus true energy gap measured.
- Density dependent data of energy gap consistent with a spin-polarized 5/2 ground state.



- Normalized energy gap decreases sharply with increasing disorder in modulation doped samples (red symbols), where sample disorder is of long range.
- Weak disorder dependence in HIGFET, where the disorder is of short-range and dominantly caused by charge-neutral surface roughness scattering.
- Very different roles in affecting the 5/2 energy gap for long-ranged Coulombic and short-ranged charge-neutral disorders.

Collapse of spin splitting in quantum Hall effect

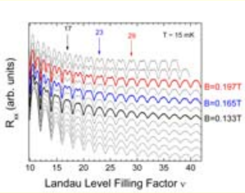


Fogler and Shklovskii, PRB 52, 17366 (1995)

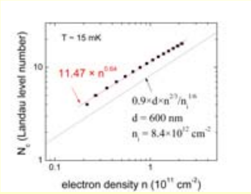
Background

- Current interest in electron spin physics in semiconductors for quantum computation applications.
- QHE being a unique system due to its tunability in spin population and thus strength of exchange interaction.
- Exchange interaction enhanced g-factor responsible for energy gaps of odd filling factor (ν) QH states being large.
- Disorder induced collapse of spin splitting at odd ν's, a quantum phase transition.

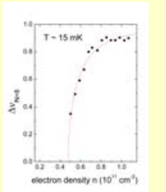
Results:



- R_{xx} versus ν at different magnetic fields.
- Magnetic field from top to bottom – 0.239, 0.229, 0.197, 0.176, 0.165, 0.144, 0.133, 0.122, 0.111, 0.101, 0.090, and 0.079T.
- Three traces at B = 0.197, 0.165, and 0.133T highlighted, showing the collapse of spin splitting at ν = 29, 23, and 17, respectively.



- Landau level number as a function of the critical electron density where the collapse of spin splitting occurs.
- Red line – power-law dependence fit.
- Theoretical prediction shown as dotted line.
- Discrepancy between experimental result and theoretical prediction probably due to finite g-factor in GaAs.



- $\Delta\nu_{N=8}$ as function of density for two peaks flanking ν=17 quantum Hall state.
- Solid line – a fit to equation $\Delta\nu_N = a\times\coth[a\times(n-c)^{1/2}] - b\times\coth[b\times(n-c)^{1/2}]$, which resembles the behavior of the Brillouin function .

Basic Energy Sciences

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