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Final Report on LDRD: MBE Growth and Transport Properties of Carbon-doped High Mobility Two-dimensional Hole Systems

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Abstract

This LDRD's purpose was to provide a scholarship to John Watson at Purdue University as part of the Campus Executive Program. This report will present a summary of his work at Purdue during the length of the scholarship.

Utilizing a new high mobility GaAs growth facility at the Birck Nanotechnology Center (BNC) at Purdue University, a systematic investigation of molecular beam epitaxy (MBE) growth of carbon-doped high mobility two-dimensional hole systems (2DHS) was performed. New physics and new device applications often follow from advances in material synthesis. The recent development of efficient resistive carbon doping filaments allow for the construction of extremely high quality two-dimensional hole systems on the high symmetry (100) face of GaAs. The initial studies focused on determining the parameters that presently limit low temperature mobility in carbon-doped 2DHS. The work included MBE growth, structure modeling, and low temperature transport measurement of MBE grown samples.

CONTENTS

NOMENCLATURE

[Sample list:]

MBE	Molecular Beam Epitaxy
2DHS	Two-dimensional hole system
2DHG	Two-dimensional hole gas
DOE	Department of Energy
SNL	Sandia National Laboratories

1. INTRODUCTION

New physics and new device applications often follow from advances in material synthesis. The recent development of efficient resistive carbon doping filaments allow for the construction of extremely high quality two-dimensional hole systems on the high symmetry (100) face of GaAs. Yet there is still much to learn about structure optimization and many physical phenomena remain to be explored. Initial studies focused on determining the parameters that presently limit low temperature mobility in carbon-doped 2DHS. The worked include MBE growth, structure modeling, and low temperature transport measurement of MBE grown samples. Furthermore, the samples grown in the course of the study have found utility for experiments studying electron-electron interactions in low dimensional systems. The benefits of the research are numerous. The rich spin structure of the GaAs valence band is of interest to physicists studying spin related phenomena in lower dimensional systems. Samples grown may allow for the exploration of new 2DHS-based semiconductor nanostructures. 2DHS based nanostructures have not been as widely investigated as electron systems. In addition to being of fundamental interest, these GaAs hole systems may have many applications in next generation technologies. For instance, the lower hyperfine coupling of holes (e.g. as compared to electrons) to atomic nuclei is of great importance for schemes for solid state quantum computation which require spin systems largely decoupled from their environments

Begin sections on odd, right-hand pages unless your document is short, in which case, you can run the sections together and begin them on odd or even-numbered pages.

2. FIRST YEAR ACCOMPLISHMENTS

My work towards these goals proceeded along several lines. My first project involved the setup of a vacuum preparation chamber. This chamber was used for thermally cleaning material sources before they were installed in my group's other MBE used for growth of GaN samples. This chamber will also be of vital importance when we install the sources in our new MBE because the cleanliness of the sources themselves sets, in part, a limit on the ultimate purity of the resulting sample.

My second, more lengthy, project was to set up my group's ^{3}He cryostat which allows us to make magneto-transport measurements at low temperatures (T = 300mK). This involved preparation of the lab space, plumbing vacuum lines and the helium recovery system, and setup of the electronics equipment used in the transport measurements. Parallel to this project, I also set up our annealing equipment which is used to make electrical contact to the semiconductor samples, and I calibrated our equipment and established our recipe for making electrical contacts to our samples.

Once this lab was setup, we began low temperature magnetotransport measurements of several samples Dr. Manfra brought from Bell Labs. Over the course of these measurements we encountered two challenges. The first (minor) complication was due to a faulty power supply for our superconducting magnet. Solving this problem involved switching out the power supply for a different power supply borrowed from another professor and rewriting some of the software used to run the experiment. The second, more significant complication was due to what we initially thought was electrical interference. However, after an exhaustive search of our lab and measurement circuits for sources of interference we concluded that the poor signal quality we observed was due to poor electrical contact to the samples and was not due to our electronics. Nonetheless, this exercise was a useful one in that I learned a great deal about sources of electrical interference and made adjustments to our setup to avoid such problems in the future.

Despite the complications described above, I was able to collect a significant amount of valuable data on one of the samples. The literature review and analysis of this data lasted for the next few months and was presented at the American Physical Society (APS) March Meeting in Portland, Oregon. In analyzing the transport data, we found that hole mobility drops off at low density faster than we can account for theoretically in a manner very similar to that observed by Sandia researchers in an electron-hole bilayer as reported in *Applied Physics Letters* **90**, 052103 (2007). We plan to present this data to our collaborators and submit our results to a journal for publication.

Most importantly, our new MBE arrived in March only slightly behind schedule. While we are still waiting for the manufacturer to complete three of the gate valves, our preparation has been in full swing. My work has involved several projects. First, I have been re-cleaning our previously mentioned prep chamber which was contaminated when its cryo-pump compressor failed and caused the pump to vent its trapped contaminants into the prep chamber. Second, I have designed and am in the process of overseeing the installation of an ultra-high purity argon gas line which is necessary for venting the various vacuum chambers on the MBE. This is a crucial project at this point in time in particular because we cannot install any of the gauges, pumps, or valves on the MBE without backfilling the vacuum chamber with clean argon gas to prevent contamination from the outside atmosphere. Finally, I have had many other small projects associated with the installation such as the setup of a ‘clean hood’ which will be used for sample preparation prior to growth and the placement and installation of liquid nitrogen lines for the cooling shroud in the growth chamber of the MBE.

3. SECOND YEAR ACCOMPLISHMENTS

This year has been one of enormous progress in our group as we are now able to produce 2-dimensional electron systems (2DESs) and 2-dimensional hole systems (2DHSs) that display fraction quantum Hall effect (FQHE) physics that is among the best in the world. After finishing the installation of our machine, initial machine calibration growths began at the beginning of the calendar year, and by the end of February we were able to achieve an electron mobility of 1.5×10^6 cm^2/Vs at liquid helium temperatures. Progress over the intervening few months has been rapid with peak electron mobilities of 15×10^6 cm^2/Vs at T = 300mK and peak hole mobilities of 2×10^6 cm^2/Vs at T = 50 mK and density 6.2×10^{10} cm^{-2}. The hole mobility in particular is impressive in that it is comparable to the highest quality samples reported in the literature at this density. In addition to our growth efforts, I have completed analysis with the help of collaborators of transport measurements I made on an extremely high mobility hole sample my adviser Dr. Michael Manfra grew at Bell Laboratories. This analysis indicates that in hole systems the low temperature transport characteristics can be dominated by effects that are negligible in electron systems of similar carrier density. This result is clear evidence that there is still much to be understood about 2DHSs and underlines the importance of my proposed work to further advance the state of the art in 2DHSs. We are currently in the process of submitting these results to Physical Review B for publication.

4. THIRD YEAR ACCOMPLISHMENTS

1) High mobility two-dimensional hole gases (2DHGs)

- Wrapped up initial work with 2DHGs to determine dominant factors limiting the low-temperature mobility
- Achieved T = 300 mK mobility of 2.3 x 10^6 cm^2/Vs at density of 6.5 x 10^{10} cm^{-2} - among the highest mobility ever reported for 2D holes
- Found that unlike electron mobility, hole mobility follows a complicated density dependence due to the interplay of interface roughness scattering, remote impurity scattering, alloy scattering, and background impurity scattering
- Published paper in Phys. Rev. B (see section 5)
- Have plans to further study these samples in dilution refrigerator under construction (see below)
- So far have sent portions of these wafers to two different collaborators
- Plot of mobility and transport relaxation time vs. 2D hole density of samples grown in the experiment:

2) Work on various heterostructures for collaborators (including structure simulation, growth, and initial characterization)

- State-of-the-art structures for experiments in correlated-electron physics such as the fractional quantum Hall effect and various schemes of quantum computation
- Maximum 2DEG mobility achieved thus far: 22 x 10^6 cm^2/Vs
- Set record for largest energy gap (570 mK) of the $\upsilon = 5/2$ fractional quantum Hall state

3) Gallium-outgassing chamber

- Designed custom ultra-high vacuum chamber and stand and worked with vendor to have the chamber built
- Specified and ordered all auxiliary equipment for chamber
- Assembled chamber and stand, baked, and leak-checked chamber
- Final chamber pressure: 3.5 x 10^{-11} Torr (e.g. achieved goal of ultra-high vacuum)
- Chamber currently awaiting use to purify gallium source material during next source material reload

4) Dilution refrigerator

- Began construction of dilution refrigerator to perform electrical transport experiments at T ~ 20 mK
- My work included lab space preparation (working with physical facilities to dig out rebar in floor and install a chain hoist), helium recovery line installation, specification and purchase of dewar and stand, testing of all existing system components, maintenance and wiring of vacuum pumps, room temperature signal wiring and electrical filtering, extensive vacuum leak checking, and design and fabrication of sample mount
- First cool-down of fridge expected in September 2012

5) In-situ back-gated 2DEGs

- Goal to position electrical gate close (< 2 microns) to 2D channel to allow tuning of electron density while leaving surface of wafer free for nanostructure patterning
- Progress thus far: first wafer grown, lithographic mask designed, cleanroom, lithography, and evaporator training received, first set of devices fabricated
- First device tested is gate-able
- Further work needed in minimizing electrical contact resistance and maximizing mobility

5. PUBLICATIONS AND PRESENTATIONS BY JOHN WATSON WHILE ON CAMPUS EXECUTIVE SCHOLARSHIP

Scattering mechanisms in a high-mobility low-density carbon-doped (100) GaAs two-dimensional hole system
J. D. Watson, S. Mondal, G. A. Csathy, M. J. Manfra, E. H. Hwang, S. Das Sarma, L. N. Pfeiffer, and K. W. West
PHYSICAL REVIEW B **83**, 241305(R) (2011)

Quantitative analysis of the disorder broadening and the intrinsic gap for the $\nu = 5/2$ fractional quantum Hall state
N. Samkharadze, J. D. Watson, G. Gardner, M. J. Manfra, L. N. Pfeiffer, K. W. West, and G. A. Csathy
PHYSICAL REVIEW B **84**, 121305(R) (2011)

Exploration of the limits to mobility in two-dimensional hole systems in GaAs/AlGaAs quantum wells
J. D. Watson, S. Mondal, G. Gardner, G. A. Csathy, and M. J. Manfra
PHYSICAL REVIEW B **85**, 165301 (2012)

Magnetoplasmon resonance in a two-dimensional electron system driven into a zero-resistance state
A. T. Hatke, M. A. Zudov, J. D. Watson, and M. J. Manfra
PHYSICAL REVIEW B **85**, 121306(R) (2012)

Density dependence of mobility in a high quality Carbon-doped GaAs two-dimensional hole system
John Watson, Sumit Mondal, Gabor Csathy, Michael Manfra, Loren Pfeiffer, and Kenneth West
American Physical Society March Meeting, Portland, OR, March 18, 2010

Density dependence of mobility in a high quality Carbon-doped GaAs two-dimensional hole system
John Watson, Sumit Mondal, Gabor Csathy, Michael Manfra, Loren Pfeiffer, and Kenneth West
University Government Industry Micro/Nano Symposium (UGIM), Purdue University, June 30, 2010

Exploration of the mobility limits in two-dimensional hole systems in (001) GaAs/AlGaAs quantum wells
John Watson, Sumit Mondal, Gabor Csathy, Michael Manfra
Electronic Properties of Two-Dimensional Systems Conference (EP2DS), Florida State University July 25, 2011

Exploration of the mobility limits in two-dimensional hole systems in (001) GaAs/AlGaAs quantum wells

John Watson, Sumit Mondal, Gabor Csathy, Michael Manfra
North American Molecular Beam Epitaxy Conference (NAMBE), University of California at San Diego, August 16, 2011

Exploration of the mobility limits in two-dimensional hole systems in C-doped (001) GaAs/AlGaAs quantum wells

John Watson, Sumit Mondal, Geoff Gardner, Nodar Samkharadze, Gabor Csathy, Michael Manfra
Aspen Winter Conference - New Paradigms for Low-Dimensional Electronic Materials, Aspen Center for Physics, Aspen, CO, February 6, 2012

Exploration of the limits to mobility in two-dimensional hole systems in GaAs/AlGaAs quantum wells

John Watson, Sumit Mondal, Geoff Gardner, Gabor Csathy, Michael Manfra
American Physical Society March Meeting, Boston, MA, February 29, 2012

6. CONCLUSIONS

The Campus Executive Scholarship provided by this LDRD has allowed John Watson of Purdue to make a significant start on his Ph.D. He has been able to bring the lab up from scratch and begin research on 2DHS. So far this work has led to 4 publications and six presentations. John hopes to graduate in May of 2014.

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