Transport in Near-Surface Two-Dimensional Electron Systems

Ryan McMorris

Chemical Engineering, University of Washington

NNIN REU Site: Nanotech, University of California, Santa Barbara, CA
NNIN REU Principal Investigator: Christopher Palmstrøm, Departments of Electrical and Computer Engineering and Materials, University of California at Santa Barbara
NNIN REU Mentor: Borzoyeh Shojaei, Department of Materials, University of California at Santa Barbara
Contact: rjmcmorr@uw.edu, cpalmstrom@ece.ucsb.edu, borzoyeh@gmail.com

Abstract:

Near-surface two-dimensional (2D) electron gases are enabling platforms for controlling single electrons in quantum dots and using electron spin as a quantum bit in quantum computation. The requirements for the material system that forms the 2D electron gas are low levels of disorder to reduce scattering, the 2D electron gas be as close to the surface as possible to lead to abrupt confinement potentials created by depletion top gates, and spacer layers between the 2D electron gas and surface have low leakage currents under an applied gate bias. The design of a sub-50 nm deep modulation doped AlGaAs/GaAs heterostructure that forms a 2D electron gas at the AlGaAs/GaAs interface is presented. Magneto-transport measurements in a sub-50 nm deep 2D electron gas formed at the interface of a modulation doped AlGaAs/GaAs heterostructure grown by molecular beam epitaxy are presented. The addition of a high-κ dielectric layer was implemented with the purpose of decreasing gate leakage. Characterization of the dielectric and processing techniques are presented and discussed.

Background:

Our project had two primary goals and we approached these independently. First we wanted to grow and characterize a sub-50 nm deep two-dimensional electron gas or 2DEG. Second we wanted to explore deposition techniques for high-κ dielectrics on top of III-V heterostructures. Motivation for this project included a previously successful qubit, created via a double quantum dot design in the same material system. This design by Weperen, et al., was at a depth of 110 nm. This deeper 2DEG functioned well, but needed to be shallower in order to improve scalability.

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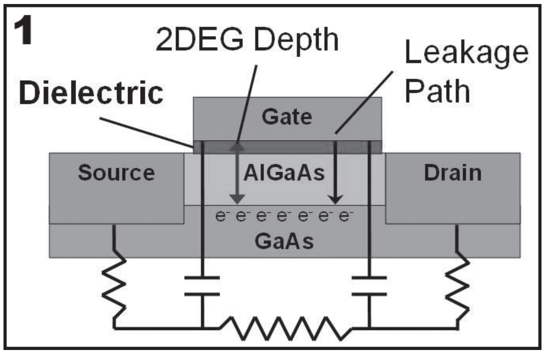

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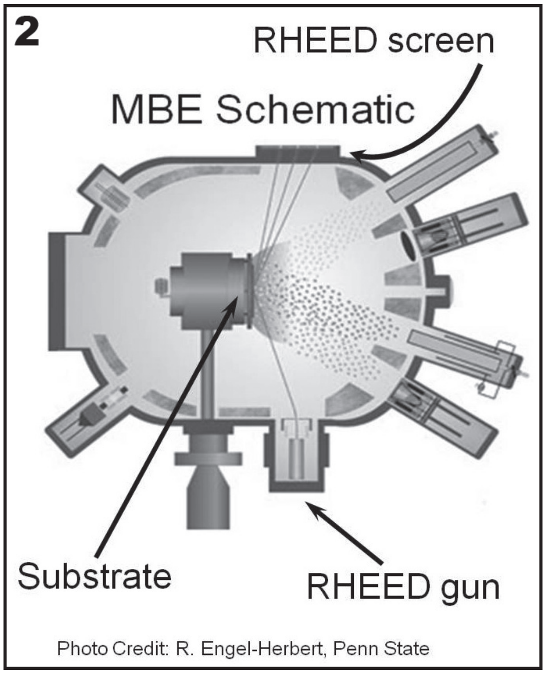


Photo Credit: R. Engel-Herbert, Penn State

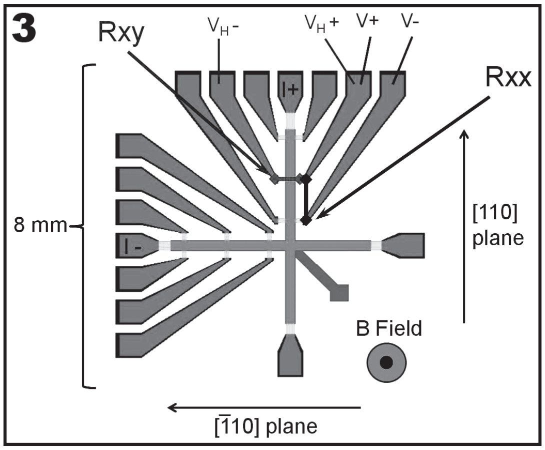
Experimental Procedures:

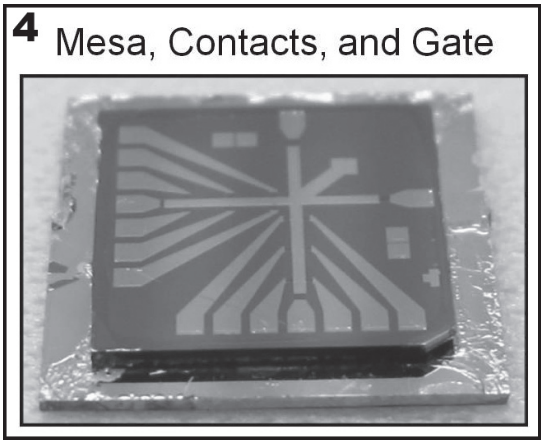
Samples were grown by molecular beam epitaxy. This process uses high purity elemental sources under ultrahigh vacuum to grow precise monolayers of material on a substrate. Reactive high energy electron diffraction or RHEED was used to calibrate the growth rate for each layer as RHEED can identify specific surface interaction effects which exist for the various surface states. This process works by real time analysis of the surface of the substrate as growth occurs.

Photolithography was then used to pattern the surface of the samples with our Hall bar design. This technique was effective as it is relatively easy to etch through the 40 nm of material above the 2DEG, thus controlling the conduction pathways in the sample. This type of experiment was useful as it told us how effectively and efficiently our 2DEG was functioning.

Transport Measurements on 40 nm Deep 2DEG:

We primarily measured 40 nm deep 2DEG's and used a Hall bar setup in order to perform measurements. Measurements included basic transport such as sheet resistance and mobility





as well as an analysis of Shubnikov de Haas oscillations and Hall plateaus. The schematic above shows how the Hall bar design was used to take basic voltage measurements which can be used to calculate sheet resistance, carrier density, and mobility.

Before taking these measurements however, we used theoretical modeling with the purpose of improving the 2DEG's design, and recognizing likely problems within the system. We used a 1D self consistent Schrodinger-Poisson solver developed by Greg Snider. Results of this modeling indicated that a parallel conduction pathway might form in the delta-doping layer, hindering performance. However, further analysis showed that an applied gate voltage would quickly eliminate the problem.

Our first set of measurements was a sheet resistance vs. temperature analysis. This measurement showed that the 2DEG had truly metallic character, with resistance falling close to 0 at low temperature (lowest of ~ 3K) as was expected in a functioning 2DEG. Further data analysis showed that low temperature carrier density and mobility were both in the ranges expected at 3.4×10^{11} (cm^{-2}) and 239,000 ($cm^2/V\times s$) respectively. These results matched with the previously mentioned theoretical modeling quite well and indicated a high quality 2DEG.

Lastly, an analysis of the measured voltages under a varying magnetic field from 0 up to 7 Tesla was performed at 1.8 K. As expected, our 2DEG showed Shubnikov de Haas oscillations and Hall plateaus.

Results such as these further confirm the high quality of the system and its design.

Characterizing High-k Dielectric Deposition:

For the second part of the project, we needed to deposit a thin layer (~ 10 nm) layer of our chosen dielectric. We used aluminum oxide and deposited by atomic layer deposition. This technique was used due to its high precision in depth and high quality thin films. Using the trimethylaluminum precursor and H_2O purge gas, we deposited our 10 nm layer. Characterization of this surface was done by ellipsometry and x-ray photoelectron spectroscopy (XPS). The ellipsometer showed that we had successfully deposited 10.5 nm. Additionally XPS analysis showed that our surface was 64% oxygen and 36% aluminum. Obviously this was not the 3 to 2 ratio that we would expect, so further work is necessary in this area.

Summary:

In conclusion, we successful grew a 40 nm deep 2DEG and characterized the transport properties. Additionally we developed and studied dielectric depositions over near surface 2DEG's in III-V heterostructures.

Short term future work will include exploring an anneal step as a solution to the oxygen rich dielectric layer, taking low temperature gated magneto-transport measurements, and comparing hafnium oxide over aluminum oxide in place of the aluminum oxide alone.

Long term efforts will include measuring leakage and noise using a quantum point contact and measuring the level of screening caused by the dielectric using a quantum point contact in proximity to a quantum dot.

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References:

[1] van Weperen, B. D. Armstrong, E. A. Laird, J. Medford, C. M. Marcus, M. P. Hanson, and A. C. Gossard, Phys. Rev. Lett. 107, 030506 (2011).