Characterization of Quantum Confined Two-Dimensional Electron Gasses

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Introduction:

Spintronics, or spin electronics, which depend on electron spin, could be faster, smaller and more energy efficient than traditional charge-based electronics. Here, two-dimensional sheets of electrons, or two-dimensional electron gasses (2DEGs), were characterized. They showed properties important to spintronics, such as high electron mobilities and long mean free path. Quantum confined 2DEGs formed in gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) heterostructures were simulated using a Poisson/Schrödinger equation solver before the heterostructures were grown by molecular beam epitaxy (MBE). Hall bars were fabricated using photolithography, etching and metal contact formation for use in magnetotransport measurements. The Integer Quantum Hall Effect was observed in these devices and temperature dependence of electron mean free path, mobility and density were studied. These results will be used to develop better material systems for next-generation electronics and spintronics.

Experimental Procedure:

The four basic steps in characterizing two-dimensional electron sheets are design of material structures for quantum confinement, growth of materials, fabrication of Hall bar devices and measurement and analysis.

In the design stage, a Poisson/Schrödinger equation solver [1] was used to simulate the heterostructures. A heterostructure was made up of two or more kinds of dissimilar materials layered on top of one another [2], in this case—materials with different energy band gaps. Gallium arsenide (GaAs) has a relatively low band gap of 1.424 eV at 300 K. Aluminum arsenide (AlAs) has a band gap of 2.12 eV at 300 K [3]. For the heterostructures used here, GaAs was layered with AlGaAs, because the band gap of AlGaAs can be adjusted by changing the Al content.

Two different quantum wells were used, a square well, and an inverted well. The square well had a symmetric layer structure, with gallium arsenide layer in between layers of aluminum gallium arsenide. The inverted quantum well had only one layer of gallium arsenide, with one GaAs/AlGaAs interface, as seen in Figure 1. This differs from a triangular, or conventional quantum well, in that the low band gap material was at the surface, rather than the higher band gap material.

After a design was chosen, the heterostructure was grown by MBE. Elemental source materials were used and the environment was kept at ultra high vacuum, enabling sharply defined interfaces, sub-monolayer control of thickness, precise control of material composition and minimization of unintentional impurities. This process was essential in achieving the high quality heterostructures necessary for 2DEGs displaying high electron mobility and long mean free path.

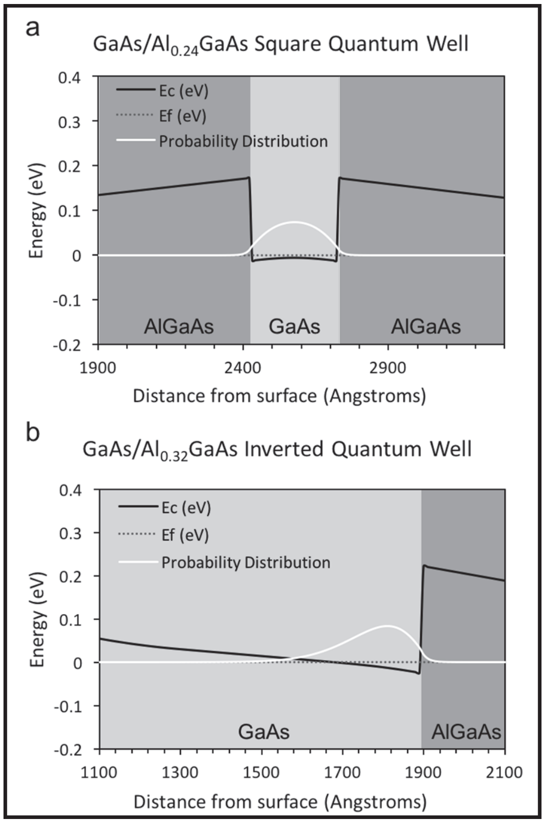

Figure 1: This image shows the conduction bands, Fermi levels and electron waveform probability distribution for; a. a square well, and b. an inverted quantum well.

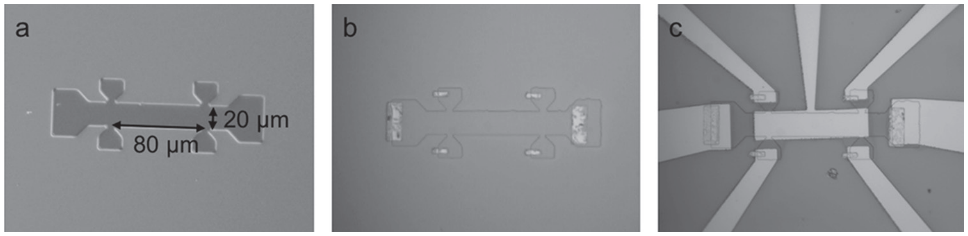

Figure 2: This is a Hall bar; a. after chemical wet etch, b. after metal contact deposition, lift-off and anneal, and c. after metal lead deposition and lift off. Note that the dimensions are 80 × 20 µm.

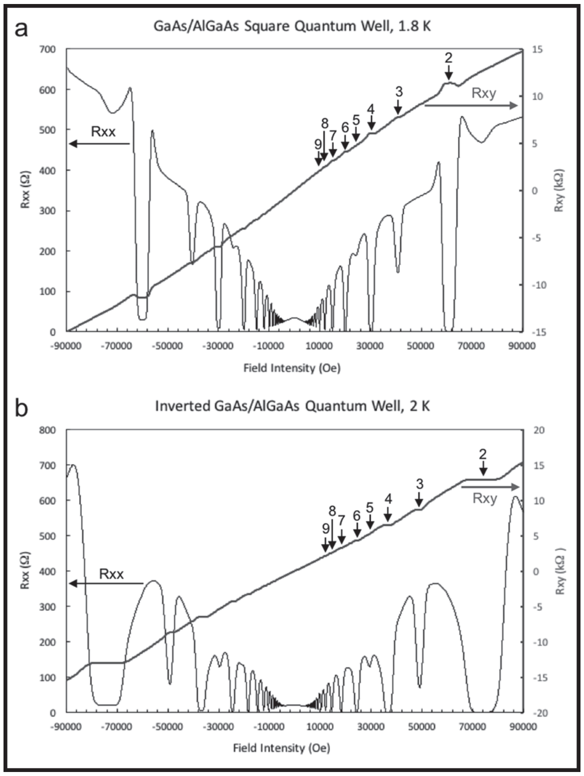

Figure 3: The Integer Quantum Hall Effect observed in; a. a square well, and b. an inverted well. Plateaus in R_{xy} correspond to dips in R_{xx} and occur where R_{xy} is equal to 1/i times $h/e^2 \approx 25.813$ kΩ, i being an integer.

Hall bars were fabricated using photolithography. They were simple devices, consisting of a basic rectangle, with connection points for voltage probes and current sources.

Figure 2 shows a Hall bar at various points in fabrication. Figure 2a. shows the pattern after the unnecessary material has been etched away using a chemical wet etch, leaving behind a Hall bar shaped mesa. Figure 2b. shows the device after the deposition of metal contact pads by electron beam deposition and subsequent annealing. The annealing step is necessary to form an ohmic contact, or one that is linear in current/voltage relationship, between the semiconductor and the metal. Finally, metal leads are deposited, as seen in Figure 2c. Their purpose is to connect to the pads and provide a larger surface area to which wires can be bonded.

To determine electron mobility and mean free path, measurements were taken for a range from -9 to 9 Tesla magnetic field and from 1.8 to 300 K for temperature. An alternating current was sourced and lock-in amplifiers were used to measure AC voltages in order to reduce electrical noise. Two resistances were measured: parallel to current, R_{xx}, and perpendicular to it, R_{xy}, defined as the perpendicular voltage, V_{xy}, divided by longitudinal current, I_{xx}. These values were used to calculate electron mobility, electron sheet density, and mean free path.

Results:

The Integer Quantum Hall Effect, which is a hallmark of 2D electron transport, was observed for the samples tested [4]. Figure 3 shows some of the measured results.

The fact that this effect was observed shows that the structure produced successfully confined the electrons to a two-dimensional sheet. For the two samples whose results are shown, the mobility and mean free path at 2 K for the square well were 870,000 cm^2/Vs and 5.48 µm and for the inverted quantum well, 1,200,000 cm^2/Vs and 7.6 µm.

Conclusion and Future Work:

These results were typical for the structures that achieved 2DEG confinement, indicating that these samples show promise for future spintronics research. The next steps in this research would be to investigate spin injection into these quantum wells, using ferromagnetic contacts.

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