Fabrication of a Stable Tunable Fabry-Perot Interferometer in the Fractional Quantum Hall Regime

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Abstract:

Electronic Fabry-Perot interferometers on high mobility gallium arsenide / aluminum gallium arsenide heterostructures have recently been used in attempts to detect non-Abelian statistics in the fractional quantum Hall regime. Though successful in the integer quantum Hall regime, these devices appear to lack the electrostatic stability needed for interference measurements at fractional filling factors. This is likely due to the fact that the doping of the material is optimized for high mobility, leading to poor gateability. Here we report on the development of a new generation of devices where gates are deposited in etched trenches rather than on the surface of the chip, allowing them to operate at smaller voltages where they are more stable.

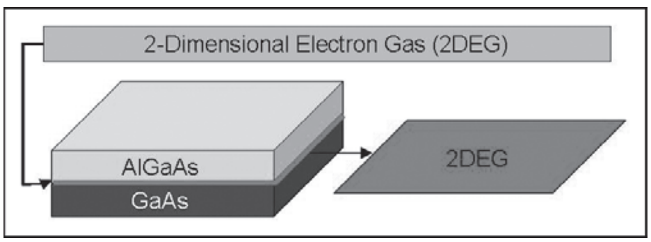

Figure 1: A two-dimensional electron gas.

Introduction:

Under exchange of identical particles, fermions have an anti-symmetric wave function whereas bosons have a symmetric wave function. This difference in symmetry properties is responsible for the characteristics of different particles, such as photons and electrons. However, particles that are neither fermionic nor bosonic, termed anyons, have been hypothesized to occur in the fractional quantum Hall regime [1]. The filling factor 5/2 has received particular attention since the anyons there are believed to be non-Abelian and therefore potential building blocks for a topological quantum computer [2].

In the Hall effect, a current in a two-dimensional (2D) electron gas (Figure 1) running orthogonal to a magnetic field generates a Hall resistance, perpendicular to both the current and the magnetic field, due to the Lorentz force. At low enough temperatures and high enough magnetic fields, quantization of the energy spectrum leads to plateaus in the Hall resistance known as the quantum Hall effect.

Furthermore, it has been observed that certain quantized Hall resistances most likely result from the formation of correlated states where charge is carried by anyonic quasiparticles whose charge is a fraction of an electron's. For these fractional quantum Hall states to form, a high-mobility 2D electron gas is required. Such a 2D electron gas can be created at the interface of a gallium arsenide/aluminum gallium arsenide heterostructure [3]. An interference device, seen in Figure 2, defined by negative voltages applied to metal gates on the surface of the chip, has been proposed to detect the non-Abelian anyons required for topological quantum computing via their effect on the relative phase of interfering trajectories. So far, a major obstacle has been the electrostatic stability of the device.

Here, etching the interferometer into the chip is explored as a possible way to reduce the needed gate voltages, possibly increasing stability.

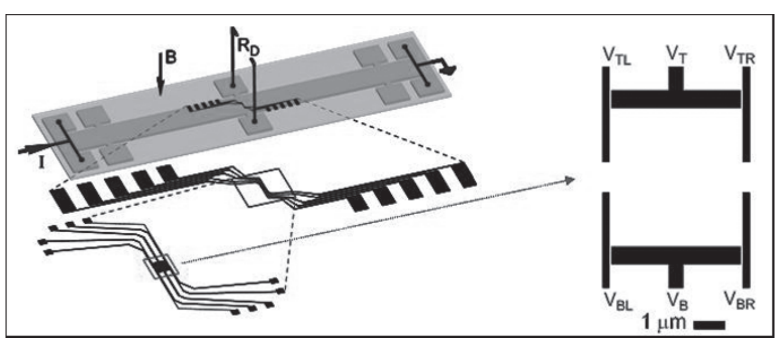

Figure 2: An electronic interferometer device is shown on typical Hall bar used in quantum Hall measurements [4].

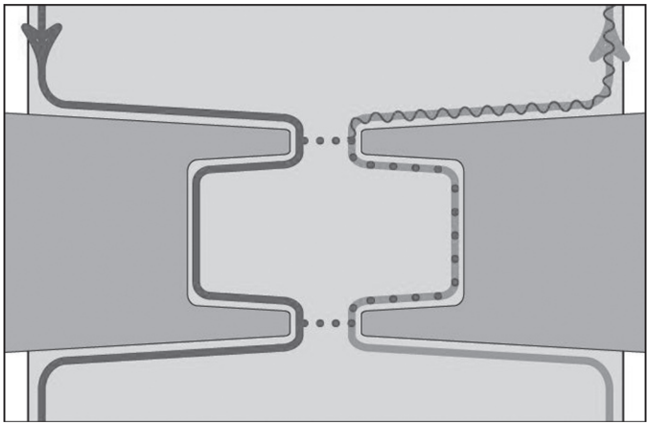

Figure 3: Charges in the two-dimensional electron gas travel along the edges of the device. Tunneling at the two quantum point contacts leads to interference [5].

Methods:

Previous fabrication methods of the electronic interferometer deposited the gates on the surface of the heterostructure. The gates' large distance to the 2D electron gas and screening from the donor layer necessitate the use of relatively large gate voltages, resulting in unstable, "switchy" device behavior. By depositing the gates in etched trenches instead of on the surface, both of these problems may be alleviated. The drawback of this method is that etching the interferometer features becomes difficult when dealing with separations of short distances (in our case, 140 nm). If etched too far, the gates could become shorted due to lateral etching. If etched too little, no advantage is observed.

In order to find the optimal fabrication parameters, multiple devices were written onto a chip using electron beam lithography at different exposure doses. After developing, the chip was then etched some distance. This procedure was repeated using multiple chips, where for each chip, the distance etched was varied. Finally, titanium/gold gates were deposited via thermal evaporation.

After fabricating devices that passed visual inspection in the scanning electron microscope, the gates were tested by measuring the device resistance as a function of gate voltage at 4 K. A sharp rise in resistance signals depletion of the 2D electron gas under the gates. Comparing the gate voltage at which depletion occurs in etched versus unetched samples provides a quantitative measure of the effect of the etching.

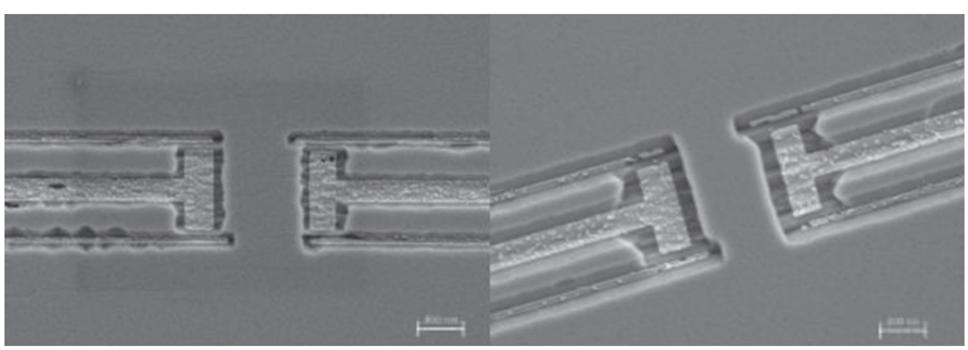

Figure 4: The left device is etched ~ 60 nm and the right device is etched ~ 115 nm.

Results and Conclusions:

The farthest distance etched so far was 115 nm. Since the distance from 2D electron gas to the surface of the heterostructure is 200 nm, the distance to the gates is 85 nm. As seen in Figure 4, despite the etched features being connected, the gates do not short. Modeling the gates and the 2D electron gas as a parallel plate capacitor suggests that the absolute value of the depletion voltage in the etched device should be reduced by 0.386V from that in the unetched device. Experimentally, a decrease of 0.3 V is observed. However, the depletion voltage in both cases is roughly 1 V more negative than that predicted from this simple model, suggesting that screening from the donor layer may still be an issue.

Future Work:

The next set of devices can be etched farther in order to further reduce the gate voltages needed. Once an optimal etch depth is chosen, the device will be cooled in a dilution refrigerator and used for fractional quantum Hall interferometry. If the etching has led to increased stability, non-Abelian statistics may finally be observed.

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References:

[1] Wilczek, F. Fractional Statistics and Anyon Superconductivity. World Scientific, Singapore, 1990.

[2] Kitaev, A. Y. "Fault Tolerant Quantum Computation by Anyons", Annals of Physics, 303, 2- 30 (2003).

[3] Stormer, H. "Nobel Lecture: The Fractional Quantum Hall Effect" Reviews of Modern Physics, 71, 875-889 (1999).

[4] McClure, D. et al. "Edge-State Velocity and Coherence in a Quantum Hall Fabry-Perot Interferometer" (2009), arXiv:0903.5097 [5] Illustration by Douglas McClure.