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High-Mobility 2D Hole Systems for Quantum Computing Applications

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Abstract

One of the leading candidates for a solid-state quantum bit is the spin of a single electron confined in a semiconductor. Coherent control of individual electron spins has already been demonstrated in quantum dots in high-mobility 2D electron systems in GaAs/AlGaAs heterostructures. The major source of decoherence in such experiments is coupling between electron spins and nuclear spins in the host GaAs semiconductor. It has been proposed that hole spins in GaAs would be better suited for such experiments due to a lesser coupling between hole and nuclear spins. Building on recent successes in the growth of high-mobility 2D hole systems (2DHS) via carbon doping of (100) oriented GaAs/AlGaAs heterostructures, we have developed 2DHS at Sandia to enable experiments investigating the physics of hole spins in GaAs, looking towards eventual applications in the area of quantum computing.

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INTRODUCTION

To date, experiments looking at the possibility of using spins in semiconductors as quantum bits have primarily focused on electron spins. It was only recently suggested that hole spins in GaAs might provide better decoherence times. One of the main reasons that there are relatively few experiments on holes in GaAs, as compared to electrons, is the difficulty of growing high-quality two-dimensional hole systems (2DHS) that can be used to fabricate stable hole nanostructures (such as quantum dots). However, recent advances in growth of 2DHS via carbon doping provide a new possible route to obtaining material of comparable quality to current high-mobility 2D electron systems in GaAs.

One of the motivations for investigating single hole transistors in GaAs is the potential improvement in spin coherence time for holes vs. electrons. Figure 1a shows a GaAs double quantum dot device formed by surface gates and Fig. 1b shows a cartoon of the two electrons confined in the double quantum dot potential and presence of background nuclear spins [1]. As alluded to in the introduction, in electron quantum dots in GaAs, interaction of electron and nuclear spins in the host semiconductor is a major source of electron spin decoherence [1]. Figure 1c illustrates the difference between the electron and hole wavefunctions in GaAs. The lack of overlap of the hole wavefunction with the nucleus leads to a much weaker interaction between the nuclear and hole spin, as compared to the electron spin, which makes hole spins a promising candidate for spin-based quantum bits [2,3].

Figure 1. a) SEM image of metallic gates on the surface of GaAs/AlGaAs heterostructure, defining a double quantum dot structure in the 2D electron gas below (adapted from Ref [2]). b) Sketch of two electrons confined in the double dot potential, showing host semiconductor nuclei. c) Cartoon of electron (left) vs. hole (right) wavefunction, illustrating the difference in the overlap of the wavefunction with the nucleus, which strongly affects the coupling of electron vs. hole spins to the nuclear spins.

In this project, we have fabricated and characterized 2DHS and hole nanostructures using carbon doped GaAs/AlGaAs heterostructures. We have demonstrated the growth of high mobility carbon-doped 2D hole systems (2DHS) that can be locally depleted with patterned surface gates with negligible leakage current. These 2DHS have a low-temperature mean free path of $\sim 1 \mu\text{m}$, a length larger than typical nanostructure dimensions, which should aid in the formation of low-disorder few hole nanostructures.

The initial phase of this project involved developing the capability to grow 2DHS via carbon doping of GaAs/AlGaAs heterostructures. The use of a resistively-heated carbon filament to create high-mobility 2DHS is a fairly recent development (~ 2005) and very few research groups worldwide have this capability. Mobilities as high as $10^6 \text{ cm}^2/\text{Vs}$ at a density of $\sim 1 \times 10^{11} \text{ cm}^{-2}$ have been achieved in these structures [4]. Earlier work on 2DHS in GaAs relied either on Be doping, which typically results in lower mobilities due to diffusion of Be, or Si doping of (311)A oriented structures, which gives rise to 2DHS with complicated band structure, mobility anisotropies, and mobilities that may be limited by interface roughness.

ACCOMPLISHMENTS

High Mobility 2DHS

Initial experiments focused on basic characterization of the material, looking at carrier density and low-temperature mobility. We initially aimed for a hole mobility $> 10^5 \text{ cm}^2/\text{Vs}$, corresponding to a mean free path $> 0.5 \mu\text{m}$ at typical hole densities, which should be long enough to allow for the fabrication of nanostructures (e.g., quantum dots) that are not dominated by impurities or defects. We have demonstrated a 2DHS with mobility $\sim 5 \times 10^5 \text{ cm}^2/\text{Vs}$ at a density of $6.5 \times 10^{10} \text{ cm}^{-2}$ and temperature of 0.35 K. This mobility corresponds to a mean free path of about $\sim 1 \mu\text{m}$.

Figure 2a shows resistance versus perpendicular magnetic field at a temperature $T = 0.35 \text{ K}$, showing the quantum Hall effect in our 2DHS. We observe plateaus in the hall resistance and minima in the longitudinal resistance at the expected magnetic field values for a single 2D hole layer.

A second key ingredient to fabricating nanostructures is the ability to control the hole density via Schottky gates on the surface of the heterostructure. A major hurdle facing current hole nanostructures in GaAs is achieving stable devices with the use of surface gates [5]. Therefore, we have tested the ability to control 2D hole density with surface gates, both in bulk 2D devices using large gates to control the overall density, and eventually, with nano-patterned gates used to define quantum dots or quantum point contacts (a building block of quantum dots). Figure 2b shows mobility versus density for a 2DHS, where the hole density is tuned over a large range by use of a global aluminum surface gate.

Figure 2. a) Magnetotransport in Sandia GaAs 2DHS showing the quantum Hall effect, where the positions of the minima in R_{xx} and plateau in R_{xy} are as expected for a single hole layer. b) Mobility of 2DHS versus density at $T = 0.35$ K.

Quantum Point Contact Device

After demonstrating the ability to control the 2D hole density with a global surface gate, we fabricated a simple quantum point contact structure and measured the conductance versus gate voltage at $T = 0.35$ K. Figure 3a shows a SEM of the aluminum depletion gates on the surface of the GaAs/AlGaAs heterostructure, fabricated via electron beam lithography and lift-off..

Figure 3. a) SEM image of the depletion gates on the surface of the GaAs/AlGaAs heterostructure. b) Conductance versus depletion gate voltage for a hole qpc device.

Figure 2b shows transport in a quantum point contact device fabricated from a 2D hole heterostructure. We are able locally deplete the 2D hole density in this device with surface gates with no noticeable leakage current between the gates and 2D hole layer. The data shows some hints of steps due to conductance quantization, however, the positions of the steps indicate that

the conductance is not perfectly ballistic. Decreasing the depth of the 2D hole layer would help to maintain a higher density and thus mobility inside the qpc constriction, hopefully improving the quantization of the conductance steps.

Shallow 2DHS

To form nanostructures with sharp electrostatic confinement in the 2D layer, it is necessary to use a relatively shallow 2D layer. The distance between the Schottky gate and the 2D layer should be on the order of or less than the width of the desired confinement potential in the 2D layer. Using shallow 2D layers will help to form ballistic quantum point contacts and create small quantum dots with few hole occupation.

Our initial 2DHS with $5 \times 10^5 \text{ cm}^2/\text{Vs}$ mobility was relatively deep, where the 2D layer was $\sim 280 \text{ nm}$ below the heterostructure surface. In order to obtain a more shallow 2D layer, we characterized a series of GaAs/AlGaAs heterostructures with decreasing 2D hole layer depth. As depth decreases, the 2D layer will eventually be forced closer to the top doping layer. This will tend to decrease mobility due to scattering from the Coulomb potential due to the ionized acceptors in the doping layer [6]. However, we were able to obtain a 2D hole layer at a depth of 120 nm from the surface with a low temperature mobility ($T = 0.35 \text{ K}$) of $\sim 2 \times 10^5 \text{ cm}^2/\text{Vs}$ at a density of $2.8 \times 10^{11} \text{ cm}^{-2}$.

Quantum Dot Devices

We next used our 120 nm deep 2DHS to fabricate quantum dot devices. We deposited aluminum Schottky gates onto the heterostructure surface with $50 - 100 \text{ nm}$ linewidth using electron-beam lithography and lift-off. Figure 4a shows a SEM of a representative device. The gate design was based off of designs that have been successful for forming electron quantum dots devices in GaAs/AlGaAs heterostructures [7].

Figure 4. a) SEM of representative device, showing the depletion gates on the surface of the GaAs/AlGaAs heterostructure and cartoon of location of quantum dot (red region). b) Transport through quantum dot device A, sweeping the CP gate, with static gate voltages $L = 2.7 \text{ V}$, $R = 1.6 \text{ V}$, $LP = RP = 0.5 \text{ V}$. Capacitance between CP and the quantum dot is 6 aF . c) Transport through quantum dot device B, sweeping the RP gate, with static gate voltages $L = R = 1 \text{ V}$, $LP = CP = 0.5 \text{ V}$. Capacitance between RP and the quantum dot is 9 aF .

Figures 4b and c show transport through two different quantum dot devices fabricated on our 120 nm deep 2DHS heterostructure. These devices actually have a 30 nm ALD Al_2O_3 layer between the heterostructure surface and the gates, for reasons that will be discussed in the next section. The transport in both Figures 4b and c show clear Coulomb blockade oscillations, demonstrating that we have successfully formed a quantum dot.

From the period of the Coulomb blockade oscillations we can determine the capacitance between the quantum dot and swept depletion gate. For the symmetrically biased device, (device B), the capacitances from the dot to the three lower plunger gates were all similar, 9 ± 1 aF, suggesting that the dot is positioned symmetrically within the device, as expected for a lithographically defined quantum dot. Device A required more voltage on gate L versus gate R in order to balance conductance through the left versus right dot tunnel barrier. We speculate that this may be due to a defect in the aluminum liftoff of the nano-patterned gates.

We are also able to tune the gates such that an isolated quantum dot is formed on one side of the structure. The T and CP gates are biased in order to form a tunnel barrier in the middle of the quantum dot device. Figure 5a shows a SEM image of the gates on a representative device where the red region indicates the approximate (not to scale) location of the quantum dot formed only on the right side of the device. Figure 5b shows transport through the quantum dot with clear Coulomb blockade oscillations. The period of the oscillations gives a capacitance from the dot to the RP gate of 2.4 aF. This capacitance is smaller than for the case of the larger dot formed in the center of the device (for which this capacitance was 9 aF). This is presumably due to the fact that the dot formed on the right side of the device is smaller than the dot formed in the center.

Figure 5. a) SEM of representative device, showing a cartoon of the location of the quantum dot formed on the right side of the device (red region). b) Transport through quantum dot device versus RP gate voltage, with static gate voltages $L = LP = 0$ V, $R = 1$ V, $T = 0.7$ V, $CP = 3.1$ V.

Charge Noise

A current hurdle facing hole nanostructures in GaAs is the ability to form devices with surface depletion gates that are stable [5]. In both electron and hole nanostructures in GaAs, the conductance can drift over time or exhibit telegraph noise, depending on the device design and

GaAs/AlGaAs heterostructure. The mechanism behind the conductance drift and/or noise is not well understood. There is some evidence that the noise may be related to leakage current between the gates and the 2D layer [8], so we decided to try adding an insulating layer of ALD Al_2O_3 between our depletion gates and the heterostructure surface. Indeed, we found that it was difficult to observe Coulomb blockade in devices fabricated without this additional insulating layer. We speculate that the insulating layer may help improve the stability of the device conductance, allowing us to observe Coulomb blockade which would be masked by charge noise in devices fabricated with gates placed directly on the heterostructure surface.

Even in devices with an Al_2O_3 layer, charge noise is currently preventing tuning of the device to the double quantum dot or charge sensing regime. Figure 6 shows dot conductance versus time for device A with a 30 nm Al_2O_3 layer. The magnitude of the telegraph-like fluctuations is the same order of magnitude as the baseline conductance.

Figure 6. Dot conductance versus time for device A, showing telegraph-like noise. Gate voltages are $L = 1.2$ V, $R = 0.7$ V, $T = CP = RP = LP = 0.6$ V.

CONCLUSIONS

In conclusion, we have demonstrated shallow high mobility 2DHS in C-doped GaAs/AlGaAs heterostructures that can be used to form hole nanostructures. The mobilities are high enough such that the mean free path of the holes is $\sim 1 \mu\text{m}$, which is larger than typical nanostructure dimensions. We have fabricated hole quantum dots using surface depletion gates and observed Coulomb blockade oscillations. In future work we plan to fabricate quantum dots with few hole occupation and try to determine the dot occupation with a nearby charge sensor. This would enable investigation of few hole spin physics in GaAs hole nanostructures. Reduction of charge noise in depletion mode nanostructures will be key to enabling these experiments.

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