Ballistic Transport in 5 µm Quantum Wires

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Motivation—In very low disorder two dimensional electron systems, the mean free path of the electron determined from transport measurements can exceed 100 µm. In the same material with a one dimensional (1D) constriction, electrons will travel ballistically (i.e., without scattering) a much shorter distance. Maximizing the length for ballistic transport, and understanding the nature of diffuse transport in longer wires will be crucial for studies of interacting nanostructures such as coupled quantum wires. We present transport results on the ballistic to diffuse crossover in low disorder long single quantum wires.

Accomplishment—Quantum wires of varying length are fabricated in 2D electron systems using a pair of metallic gates separated by a narrow gap where the wire forms (see SEM image in Fig. 1). Low background disorder in the nanostructure is achieved by using semiconductor heterostructures grown by molecular beam epitaxy where the embedded 2D electron system can have a mobility exceeding 10^7 cm^2/Vs. The conductance of a short wire is shown in Fig. 1. In the main panel, the 2D electron gas is initially unconstrained, and the conductance is very high. For $V_{gate}<-0.7$ volts, electrons must flow through the 0.5 µm wide gap between the gates. Further reduction of the gate voltage narrows the wire until the conduction ceases at $V_{pinchoff} \approx -3.0$ volts. Before pinchoff, many plateaus in the two-terminal conductance data are observed. After correction for contact resistance, the plateaus form steps that are spaced by integer values of $2e^2/h$, where e is the charge of the electron and h is Plank's constant. These equally spaced steps in the conductance indicate that transport is ballistic in the 1D wire. For the short wire in Fig. 1, over 14 conductance steps are observed. The large number of steps testifies to the high quality of the quantum wires fabricated at Sandia.

As the length of the quantum wires are increased scattering in the wire becomes important, and eventually a transition from ballistic to diffuse transport occurs. In Fig. 2, data corrected for contact resistance are shown for wires of length 0.5, 5 and 10 µm. In the 5 µm wire, the higher conductance steps are washed out, but the last 4 steps remain quantized at integer multiples of $2e^2/h$, indicating that current flows through the this longer wire without scattering. The absence of quantized steps for the 10 µm suggest that the 1D mean free path is between 5 and 10 µm. We are exploring the role of phonons, roughness and impurity scattering for the significant reduction from the 2D mean free path. Even though conductance steps are not observed for the 10 µm quantum wire, magnetoconductance measurements show some evidence that even for long wires a fraction of the electrons continue to behave ballistically.

Significance—For the high quality 1D wires fabricated at Sandia, electrons travel ballistically in quantum wires exceeding a length of 5 µm. The long 1D mean free path observed in single wires enables the fabrication of more complicated interacting nanostructures. These types of structures are expected to provide the basis for future ultra-low noise detectors and other novel electronics, possibly even quantum computing.

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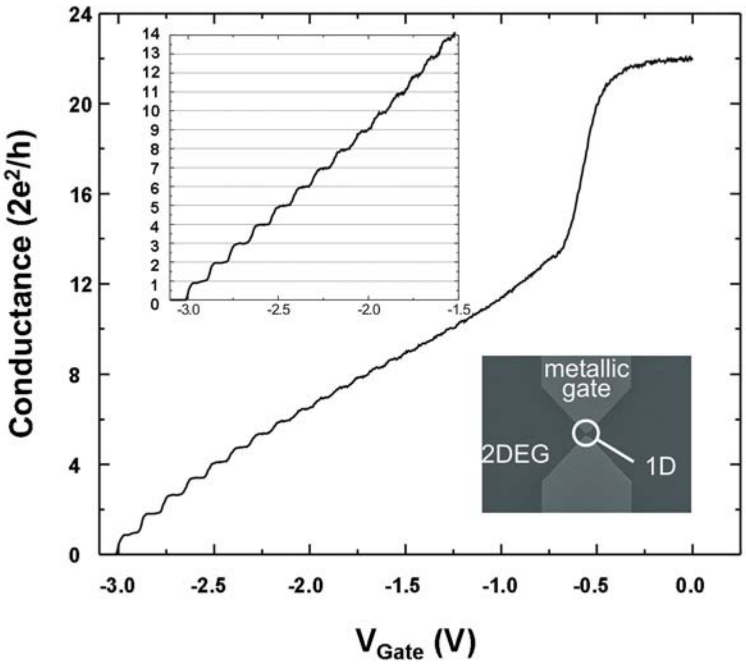

Figure 1. Conductance at $T = 0.3\ K$ as a function of split gate voltage for a quantum wire of length 0.5 μm and width 0.5 μm (SEM image). For $V_{Gate} < -0.7$ V we observe a 2D-1D transition, and as we further deplete the 2D electrons we observe the onset of steps. Upper inset: Quantized conductance steps at integer values of $2e^2/h$ (after correction for contact resistance).

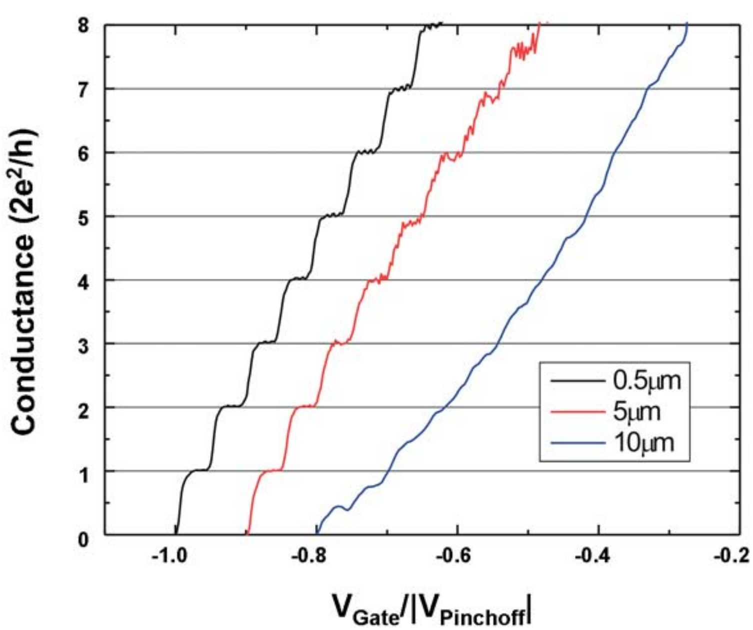

Figure 2. Conductance steps (corrected for contact resistance) for several quantum wires of different length. The gate voltage has been normalized to the voltage where conductance drops to zero ($V_{pinchoff}$) and each curve is offset by 0.1 for clarity. We observe a transition from ballistic to diffuse transport as we increase the length of the wire.