

## Ballistic hole transport in a quantum wire

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We report ballistic hole conduction in 2  $\mu\text{m}$  long GaAs quantum wires of nominal cross-section 15 nm by 15 nm. In each of eight test wires, we observe several quantized conduction steps of approximate height  $0.77 e^2/h$ . The wires were fabricated using the cleaved edge overgrowth molecular-beam epitaxy process, and the modulation-doped acceptors were incorporated using a carbon filament as the source of atomic carbon. © 2005 American Institute of Physics.

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It has been nearly a decade since the first measurements of electron transport in a ballistic quantum wire made by cleaved-edge-overgrowth (CEO) molecular-beam epitaxy (MBE) were reported.<sup>1</sup> That work has since blossomed into a series of ever more subtle and sophisticated experiments, now including complex wire-to-wire quantum tunneling experiments<sup>2-4</sup> and the realization of true four-terminal resistance measurements on a clean quantum wire.<sup>5,6</sup> Here, we report on what we believe are the first transport results for ballistic *holes* in such ideal CEO quantum wires. Because holes greatly differ from electrons in effective mass,  $g$ -factor, and spin-orbit interactions with the lattice,<sup>7,8</sup> we expect these new results to open up many avenues of research in one-dimensional (1D) physics.

The free hole carriers in this work were obtained by modulation doping the AlGaAs barriers adjacent to the GaAs conduction channel using a carbon filament source of our own design to produce the atomic C flux. The flux was calibrated by doping a GaAs bulk layer at  $1 \times 10^{18}$  acceptors/cm<sup>3</sup>, as it was epitaxially growing at 0.283 nm/s. Under these conditions, the total power emitted by our filament was 120 W. The C source is important in this work because, as we shall see below, the completed structure requires that acceptors be incorporated during MBE growth on the (110) cleaved surface. Without a C source, this requires using either the highly diffusion-prone Be dopant, or the Si acceptors, which impose drastic compromises away from the optimal (110) MBE growth conditions.<sup>9</sup>

The quantum-wire structure was fabricated using a three-step MBE process called CEO. First, an AlGaAs/GaAs multilayer structure is grown onto a (100) GaAs substrate by conventional MBE. In the second step, the wafer is removed from the growth chamber, and lithographically patterned to lay down various W-metal gates. The substrate is then thinned from the back to about 90  $\mu\text{m}$ , and cleaved in air into pieces nominally 1 cm on a side. An additional short scratch mark is then inscribed on each piece at the intended position of a future cleave to be made later in the MBE vacuum. These pieces are then mounted using Ga-solder against a low Ta-metal wall in the MBE machine so that the top edge of each piece faces the elemental sources. When the

MBE is again brought to the proper growth conditions, a mechanical arm sweeps across these freely standing pieces, cleaving them at the pre-established scratch marks, thereby exposing a fresh (110) crystalline surface. Step 3 is started within a few seconds as the MBE source shutters are opened and the initiation of the second MBE growth begins on the newly exposed (110) cleaved edge.

The details of the first multilayer sequence MBE grown at 640 °C on the (100) substrate are as follows: A 500 nm GaAs buffer, a 100 period superlattice consisting of 3 nm GaAs and 10 nm Al<sub>0.32</sub>Ga<sub>0.68</sub>As, a 15 nm wide quantum well, a 40 nm Al<sub>0.32</sub>Ga<sub>0.68</sub>As spacer barrier, a delta-doping layer consisting of  $3.1 \times 10^{11}$  C atoms/cm<sup>2</sup>, a 350 nm Al<sub>0.32</sub>Ga<sub>0.68</sub>As spacer barrier, a delta-doping layer consisting of  $5.7 \times 10^{11}$  C atoms/cm<sup>2</sup>, a 50 nm Al<sub>0.32</sub>Ga<sub>0.68</sub>As spacer barrier, and a 10 nm GaAs cap layer. This layer sequence is comprised of a fully complete modulation-doped quantum-well structure whereby the C-acceptors located at the As sites in the AlGaAs barrier modulation dope the 15 nm quantum well with free holes. The resulting two-dimensional (2D) hole mobility was  $1.5 \times 10^6$  cm<sup>2</sup>/V s at a density of  $1.6 \times 10^{11}$  holes/cm<sup>2</sup> measured in a standard van der Pauw geometry at 250 mK.

As described above, this completed substrate was removed from the MBE machine and, after testing a small piece, the remainder of the substrate was patterned with evaporated W-metal gates by photolithography. Each gate under sufficient positive bias can fully deplete the 2D hole gas directly below, and thus divide the 2D hole gas into two separate and isolated regions that will later be bridged by a quantum wire defined by the cleave and the second MBE growth.

Figure 1 is a microphoto of a typical W-gate pattern on a portion of a thinned piece ready for reinstalling into the MBE for the CEO. The piece will be cleaved in the MBE growth chamber on the dashed line shown in the microphoto, and the second MBE growth will occur on the newly established (110) surface formed by the cleave. The 13 fine W-lines crossing the cleave site are each 2  $\mu\text{m}$  wide and separated by 2  $\mu\text{m}$  wide fingers of ungated semiconductor containing the 2D hole gas. Each gate can be used to form a 2  $\mu\text{m}$  long quantum wire bridging the depleted 2D region under the gate. An unbiased gate leaves the 2D hole gas

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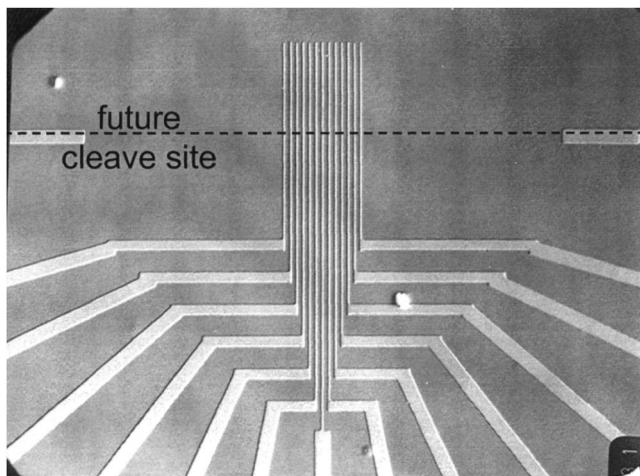


FIG. 1. Microphoto of the W-gate pattern on a portion of a thinned 10 mm by 12 mm piece of substrate shown after the first MBE growth, ready for reinstalling into the MBE for cleaving and the second MBE growth. The 13 W gates intersecting the future cleave are each  $2\ \mu\text{m}$  wide and  $2\ \mu\text{m}$  apart resulting in a total collective length of  $50\ \mu\text{m}$  along the cleave.

intact. Thus, the two macroscopic 2D hole layers on both sides of this gate can be used as contacts to this quantum wire. Notice the W-metal gates are self-aligned in the sense that because the gates extend past the intended cleave site, it is assured that each gate will break at the cleave and thus extend exactly to the cleave. We also note here that the use of lithographically patterned W-gates on our GaAs samples has resulted in no observable compromise to the cleanliness of our MBE environment or to the mobility of the CEO samples produced.

The upper two drawings of Fig. 2 show the sequence of steps involved in the fabrication of the completed hole wire structure. The GaAs substrate after receiving its patterned W-metal gates is cleaved in the MBE growth chamber at the  $490\ ^\circ\text{C}$  growth temperature required for the second MBE growth. This CEO growth has the following multilayer sequence: First, a 300 nm GaAs buffer layer is grown on the (110) monitor wafer mounted with the cleave, the samples are cleaved, then a 35 nm  $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$  spacer barrier, a delta-doping layer consisting of  $1.9 \times 10^{12}\ \text{C atoms/cm}^2$ , a 5.4 nm  $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$  spacer barrier, a delta-doping layer consisting of  $1.9 \times 10^{12}\ \text{C atoms/cm}^2$ , a 200 nm  $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$  spacer barrier, and a 10 nm GaAs cap layer are grown on both the cleaved edge and the monitor wafer. This creates a 2D hole gas on the monitor wafer that we can use to establish the parameters for (110) growth on the cleaved edge. Our measurements of this (110) monitor wafer at 300 mK show a surprisingly high-quality 2D hole layer with a hole mobility of  $1.2 \times 10^6\ \text{cm}^2/\text{V s}$  and a density of  $2.6 \times 10^{11}\ \text{holes/cm}^2$ .

The W-metal gates are contacted with In solder and the 2D hole gases between the gates are contacted using In-Zn. The lower part of Fig. 2 shows how the sample is affected by the biasing of the gates. Because the W-gate  $G_2$  is unbiased, the 2D hole gas is unaffected. In contrast, the gate  $G_1$  is shown with sufficient positive bias to fully deplete the 2D hole gas in a strip below the gate, thus separating 2D-1 and 2D-2. However, the two sheets are still bridged by the quantum wire that is formed by modulation doping during the second growth. Electrical contact to this quantum wire is actually made in several stages. First, the In-Zn contact is

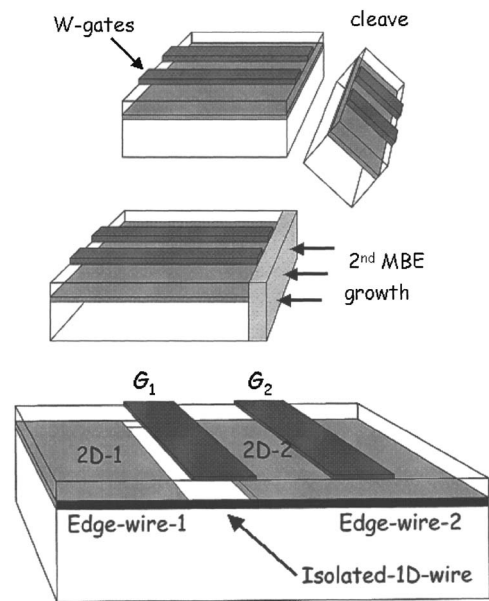


FIG. 2. The upper two drawings show the sequence of fabrication steps for our quantum wire: A prepatterned multilayered structure, containing a 2D hole gas is cleaved in the MBE chamber. Additional layers are then overgrown onto the freshly cleaved crystallographic facet. The lower drawing shows the formation of the quantum wire by biasing one of the W gates. Gate  $G_1$  is biased positively depleting the 2D hole gas directly underneath, thus creating two separate 2D hole gases labeled 2D-1 and 2D-2. For a range of  $G_1$  gate voltages, the depleted strip is bridged by the isolated 1D quantum wire shown in black. As this gate voltage is made ever more positive, the hole wire also gradually becomes depleted. (See Fig. 3.) The unbiased gate,  $G_2$ , has no effect.

made to the 2D hole gases on both sides of gate  $G_1$ . Then, contact is made between the two 2D hole gases and the two 1D edge wires labeled in the figure. Finally, the two edge wires contact the ends of the isolated 1D wire bridging the depletion region under the gate  $G_1$ . A nice feature of this structure is that the hole density in the quantum wire is controllable by adjusting the positive voltage bias  $G_1$  in excess of that needed for local 2D depletion under the W gate.

The inset of Fig. 3 shows source-drain hole-conduction data taken at 250 mK for three CEO quantum wires plotted versus bias on their various top W gates. The conductance steps closely overlap in this plot from one wire sample to another, attesting to the fidelity of our fabrication process. In the main part of Fig. 3, we show the characteristics of one of these wires. Several quantum conductance steps are visible. The height of the lowest step ranges from 70 to 80% of the conductance quantum,  $2e^2/h$ , in the eight wires tested on two separate cleave samples. This indicates that the wires are each single mode in the lowest quantum-wire state.

Although the step heights become less clear for the third, and higher steps, all quantized conductance steps appear to be about equal to the height of the first step. Yet, the conductance plateaus that we observe for our hole wires are not exact multiples of  $2e^2/h$ , as one might have expected. Non-universal values of conductance plateaus are also observed for *electron* quantum wires fabricated by CEO MBE and contacted by 2D electron gases at the source and drain.<sup>1</sup> In the electron case, it is now established<sup>5,6</sup> that these nonuniversal values arise from a competition between the 1D-2D wave function mismatch and the inevitable residual disorder along the ungated wire regions. It is likely that the 0.7–0.8

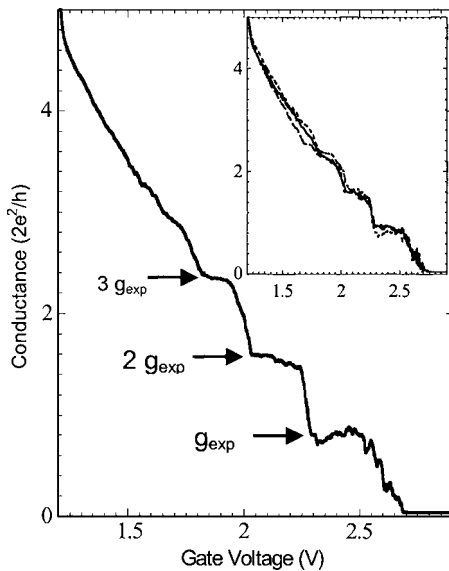


FIG. 3. Conductance plotted against the voltage applied to one of the  $2\ \mu\text{m}$  wide gates. Clear steps are seen at multiples of  $g_{\text{exp}} \approx 0.77$  of the quantum of conductance ( $2e^2/h$ ). Inset: Data from the device in the main figure (dashed-dotted line) and from two other devices (dashed and solid lines). Note the self-similarity of the three data sets. All data were taken at  $T \approx 250\ \text{mK}$  with an ac excitation of  $20\ \mu\text{V}$  and  $17.7\ \text{Hz}$ .

prefactor that we observe in our hole wire plateaus has a similar origin.

Quantized conductance steps have been seen in short 1D constrictions in 2D hole gases as early as 1994.<sup>7,8</sup> Here, however, each of our W gates is  $2\ \mu\text{m}$  in width, creating  $2\ \mu\text{m}$  long wires. Hence, the backscattering length in our wires exceeds 130 times the confinement dimension. This confirms that our wires are truly 1D.

We expect this work to open up exciting new avenues of 1D research for ballistic holes. For example, recent work on the mobility of holes in two dimensions suggests that the hole effective mass can be varied by changing the width of the quantum well.<sup>10</sup> Presumably, this effect—originating from confinement in the presence of strong spin-orbit interactions in the GaAs valance band—will also occur in quantum wires. If this is indeed the case, as the wire cross section is varied, the hole effective mass and the kinetic-to-Coulomb energy ratio will change.

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