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Electron transport in AlGaAs/GaAs V-groove quantum wires

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Abstract

We fabricated modulation doped GaAs-AlGaAs V-groove heterostructures incorporating quantum wires (QWRs), using organometallic chemical vapor deposition on corrugated substrates. Electron-beam lithography was employed to isolate a single QWR and to apply Schottky gates to the QWR and to the V-groove sidewalls. We observed a two-step sequence of carrier depletion, first from the sidewalls and then from the QWR, when a progressively more negative gate voltage was applied. In the regime of QWR depletion the conductance decreases in steps which attain 90% of the quantized value $2e^2/h$. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: 1D transport; Quantum wire; Quantized conductance

V-groove quantum wires (QWRs), produced by organometallic chemical vapor deposition (OMCVD) overgrowth of a GaAs/AlGaAs heterostructure on corrugated substrates, have been extensively studied in the past. In particular, the structure and optical properties of undoped QWRs were characterized, showing excellent interface quality and distinct one-dimensional (1D) subbands in luminescence and absorption spectra [1,2]. In this paper we report on electron transport measurements in modulation doped V-groove QWRs. We observe the quantization of conductance in gated structures with gate length ~ 2 μm at low temperatures (4 K). Similar to etched [3,9] and T-shaped wires [4], the conductance step values in our QWRs deviate from the "canonical" multiples of $G_0 \equiv 2e^2/h$.

The QWRs were produced by self-ordered growth of GaAs/AlGaAs heterostructures, using OMCVD on undoped (0 0 1) GaAs substrates with 3 μm pitch V-grooves oriented in the $[0\,1\,\bar{1}]$ direction. Details of the growth and structure of such undoped QWRs are given elsewhere [1]. Our doped structures contain a 50 nm Si doped (2×10^{18} cm^{-3}) AlGaAs layer on both sides of the GaAs QW layer, spaced by 15 and 80 nm, respectively. Additionally, relatively thick (500 nm) superlattice and AlGaAs buffer are used to trap impurities. We obtained mobility values in the two-dimensional electron gas (2DEG) on planar GaAs grown simultaneously, as well as on the sidewalls of the corrugated structure, of 2×10^5 cm^2/Vs at 4.2 K. The electron density was $\sim 5\times10^{11}$ cm^{-3} for the 2DEG on the sidewalls, and $\sim 3\times10^{11}$ cm^{-3} on planar substrates, as measured by Hall effect and Shubnikov-de-Haas oscillations. The cross section of the heterostructure is presented in a transmission electron microscope (TEM) image (Fig. 1), where the different parts of the structure can be identified. The sidewall quantum wells (QWs) are 12 nm thick, while the QWR in the center is thicker, about 19 nm, due to the larger surface diffusion length of Ga adatoms, as compared with that of Al [1].

For transport measurements, Hall bar geometry samples were fabricated using standard photolithography with Au/Ge/Ni ohmic contacts. Mesa etching and Ti/Au Schottky gate deposition were implemented using electron-beam lithography (EBL), which allowed us to fabricate smaller and more complex structures that are

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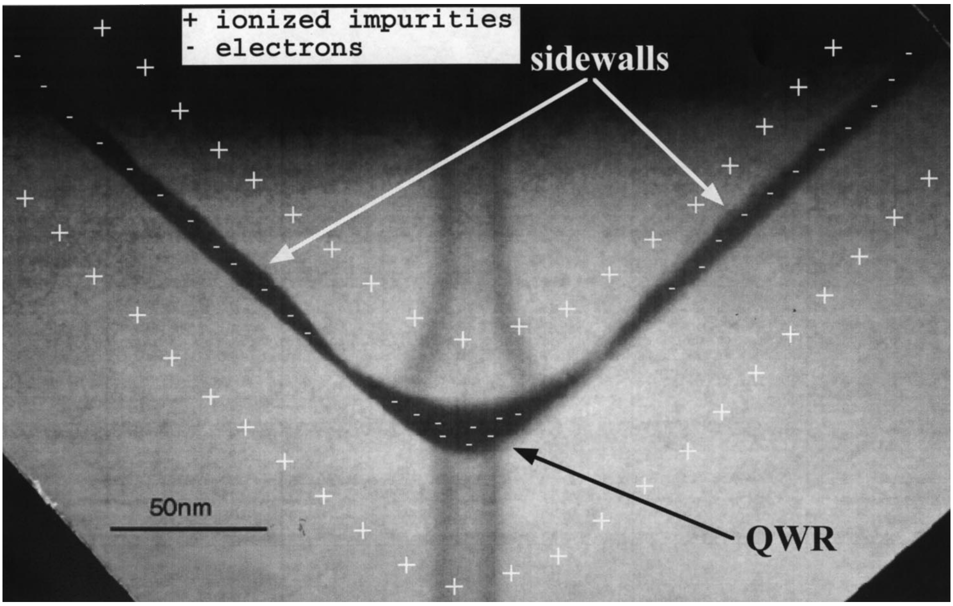

Fig. 1. Cross-sectional TEM image of the QWR region, on which the charge distribution due to the doping is schematically shown.

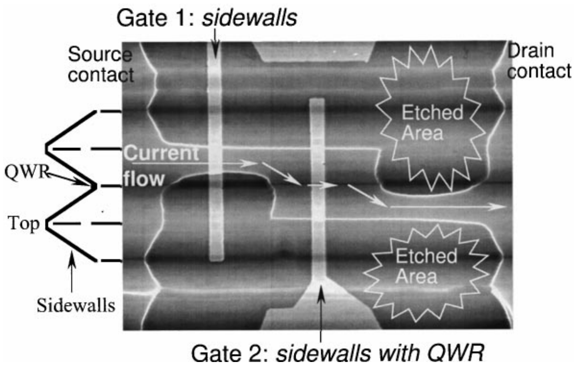

Fig. 2. Top SEM view of a QWR device. Gate 1 covers only the sidewall, gate 2 covers two sidewalls and one QWR. The arrows show current flow through the etched mesa structure. On the left, the V-groove structure is shown schematically.

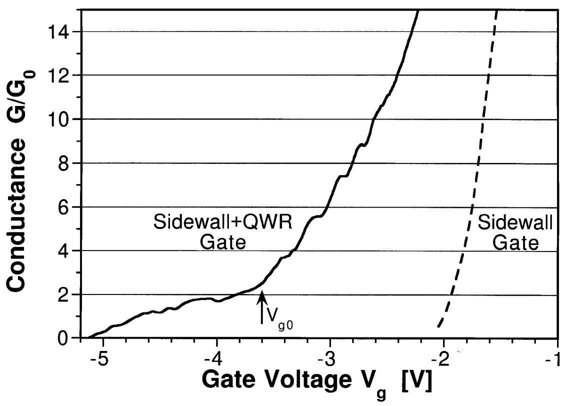

Fig. 3. Conductance (in units of $G_0 \equiv 2e^2/h$) versus gate voltage V_g for the device shown in Fig. 2. The dashed line shows gating of the sidewalls only, and the solid line corresponds to gating of the sidewalls and QWR. The arrow indicates the change of slope at V_{g0}.

precisely aligned with the QWRs [5]. To measure the conductance of the QWRs, we developed a new device configuration, which is the S-shaped mesa structure depicted in Fig. 2. In this device, the current is forced to pass from one sidewall QW, through the QWR, to the other sidewall QW. Two separate Schottky metal gates of length 2 μm are deposited so that one (left) depletes only a QW sidewall, whereas the second (right) depletes both sidewall QWs and the QWR. The devices were measured at $T = 4.2$ K using a lock-in four terminal technique.

In the absence of a technique for directly contacting the QWRs, we made use of the 2DEG on the sidewalls, which is connected to the QWR via a constriction. Ohmic contacts were applied to the 2DEG, and a gate placed on the entire V-groove structure was used to deplete the carriers from the 2DEG and the QWR. The electrostatics of the V-groove heterostructure capacitor results first in a complete depletion of the 2DEG, the point at which only a 1D conduction channel, whose length is determined by the gate, remains. The dashed curve in Fig. 3 shows the conductance of the 2DEG on a sidewall, measured using gate 1 in Fig. 2, indicating complete depletion at $V_g \sim -2$ V. For a gate placed over the full V-groove (like gate 2 in Fig. 2), we observe finite conductance beyond this negative voltage, representing transport in the QWR 1D channels (solid line in Fig. 3). In this gate configuration, we first observe depletion of the 2DEG, followed by sequential depletion of the QWR channels for $V_g < -2$ V. Complete depletion of the electrons from the QWR is attained at $V_g \sim -5$ V, the point at which the conductance vanishes. The electrostatics of the V-shaped capacitor is also the origin of a lateral confining potential [6], which adds to the built-in QWR confining potential due to the GaAs layer tapering.

The conductance of the QWR region, measured at gate voltages below -2 V (solid line in Fig. 3), shows a step-like dependence on gate voltage, indicating sequential depopulation of the 1D subbands. In the range of gate voltages between -2.5 V and -3.5 V, the value of the conductance steps are $\sim 0.9G_0$, suggesting ballistic transport in these wires up to ~ 2 μm in length [7]. Deviations from exact G_0 step values were observed in other 1D structures, like etched [3] and T-shaped wires [4]. Below a certain voltage $V_{g0} \sim -3.6$ V (marked by an arrow in Fig. 3) the overall slope of the $G(V_g)$ curve is changed, and the lowest 4 steps are suppressed in value (each $\sim 0.4G_0$). Systematic measurements of conductance in similar V-groove structures of different thickness indicate that this suppression is probably due to imperfect (non-adiabatic) connection between the 2D contacts and the 1D channels in these systems [8].

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