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Direct evidence for quantum contact resistance effects in V-groove quantum wires

D. Kaufman[a,*], B. Dwir[a], A. Rudra[a], I. Utke[a], A. Palevski[b], E. Kapon[a]

[a] *Physics Department, Swiss Federal Institute of Technology (EPFL) CH-1015 Lausanne, Switzerland*
[b] *School of Physics and Astronomy, Tel-Aviv University, Tel Aviv, Israel*

Abstract

The effect of quantum contact resistance on one-dimensional (1D) electrical conductance was investigated in quantum wires (QWR) realized with V-shaped GaAs/AlGaAs heterostructure. The transition length between the electron reservoir and the QWR was controlled by employing an electric field. The required transition length is found to decrease with increasing overlap between the 2D states in the reservoir and the 1D states in the QWR.

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In recent years, considerable research effort has been concentrated on electronic transport in low-dimensional systems [1,2]. One of the striking phenomena in one-dimensional (1D) structures is the quantization of the electrical conductance in canonical units of $G_0 \equiv 2e^2/h$, according to the Landauer picture [3]. Quantized conductance in these units is experimentally observed, however, only when the carrier reservoirs are connected *adiabatically* to the 1D conductive channel, as in the case of a point contact structure [4,5]. In all other reports dealing with “rigid” QWR structures, which are connected to two-dimensional electron gas (2DEG) reservoirs in a more abrupt way, conductance steps of less than the canonical value have been observed [6–8]. Several mechanisms explaining this anomalous behavior have been proposed, including electron scattering due to wire potential scattering and electron–electron interaction (e.g. spin splitting in zero-magnetic field [9–11]). However, recent studies support the conjecture that electron scattering at the 1D/2D interface between the contacts and the wire is responsible for many of the observed lower conductance features [12,13]. In the present paper, we report results of transport experiments in novel V-groove QWR structures which directly evidence this quantum contact resistance effect at the 1D/2D interface.

Our structures consist of modulation doped GaAs/AlGaAs V-groove QWRs grown by organometallic chemical vapor deposition on corrugated

* Corresponding author. Tel.: +41-21-6935423; fax: +41-21-6935480.
E-mail address: david.kaufman@epfl.ch (D. Kaufman)

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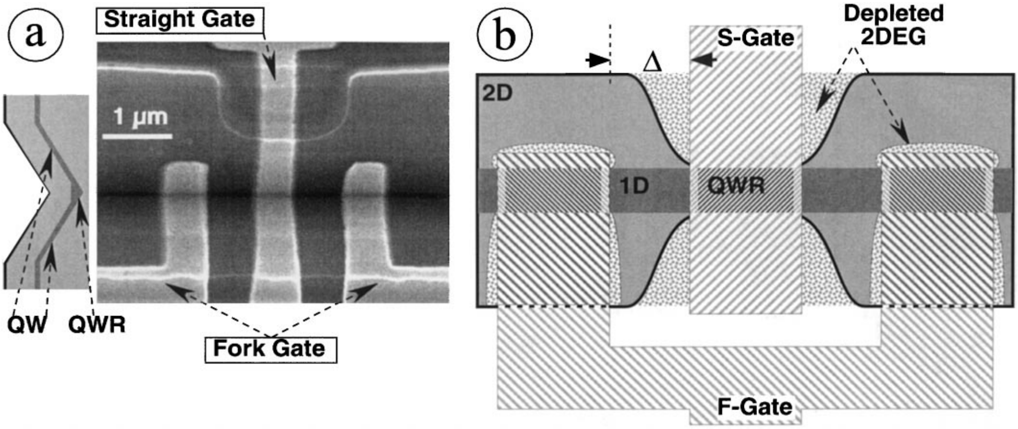

Fig. 1. (a) SEM image of an isolated single V-groove top-gated by the two independent gates. (b) A schematic illustration showing the QWR definition by the straight gate and the access length Δ defined by the fork-shaped gate. The QWR is connected to two electron reservoirs in which the conductance proceeds in parallel in 2D and 1D regions.

substrates. The QWR is formed in the conducting QW layer deposited at the bottom of the V-groove. Mesa structures containing a single QWR were fabricated using photolithography followed by electron-beam lithography [14]. The QWR is electrically connected via the 2DEG on the sidewalls of the V-grooves. A Schottky gate in the form of a narrow (~ 0.6 μm for the samples reported here) stripe is employed to define the length of the QWR channel (see Fig. 1(a)). This straight gate (SG) is used both for depleting the electrons from the sidewalls located underneath it, thus isolating a QWR section for measurement, and (at more negative voltages) for controlling the Fermi level in the wire (see Fig. 1(a) and Refs. [14,15]). In previous experiments [15], we observed ballistic quantized conductance for SG lengths less than the mean free path in these structures (~ 1.5 μm). The conductance steps were smaller than G_0 for the lower lying 1D states, and closer to G_0 for the higher energy subbands. Furthermore, the deviation from the canonical value decreased with increasing wire thickness. This was interpreted as due to the imperfect overlap between the electron wave functions in the 2DEG contacts and the 1D wave functions in the wires, which introduces electron scattering and effectively adds to the contact resistance of the device. Whereas the lower energy states in thinner wires are strongly confined and therefore exhibit poor overlap with the 2D states, the higher energy subbands and the states in thicker wires are weakly confined, mainly due to the electric field distribution in the V-shape structure [15–17].

In our QWR heterostructures, the electrons are scattered into (or from) the QWR within a transition region of length Δ between the 2D reservoirs and the 1D channels (see Fig. 1(b)). In the previous experiments the transfer length between the 2D electrons and the 1D ones was a function of the thickness of the QW layer and could not be further tuned once this thickness had been fixed. In the experiments reported here, we have added a fork-shaped gate (FG) on both sides of the SG (see Fig. 1(a)). This gate is designed in such a way that when it is negatively biased, it depletes the QWR region at the bottom of the V-groove, but does not cut off the conduction in one of the sidewall 2DEG. The electron “access” length Δ is defined as the distance of the FG from the SG measured along the QWR axis (see Fig. 1(b)). In this way, we could determine the length of the 1D–2D transition zone and observe the effect of controlling it on the conductance step value.

We measured the conductance of samples with nominal QW thicknesses $t_{nom} = 12$ and 26 nm, which corresponds to “strong” and “weak” heterostructure confinement potential, respectively. Conductance measurements were performed at 4.2 K using an AC four terminal lock-in technique. The results for $t_{nom} = 26$ nm and for $\Delta = 0.5$ and 1 μm are shown in Fig. 2, where the conductance is plotted as a function of V_{SG} with V_{FG} as a parameter. For each one

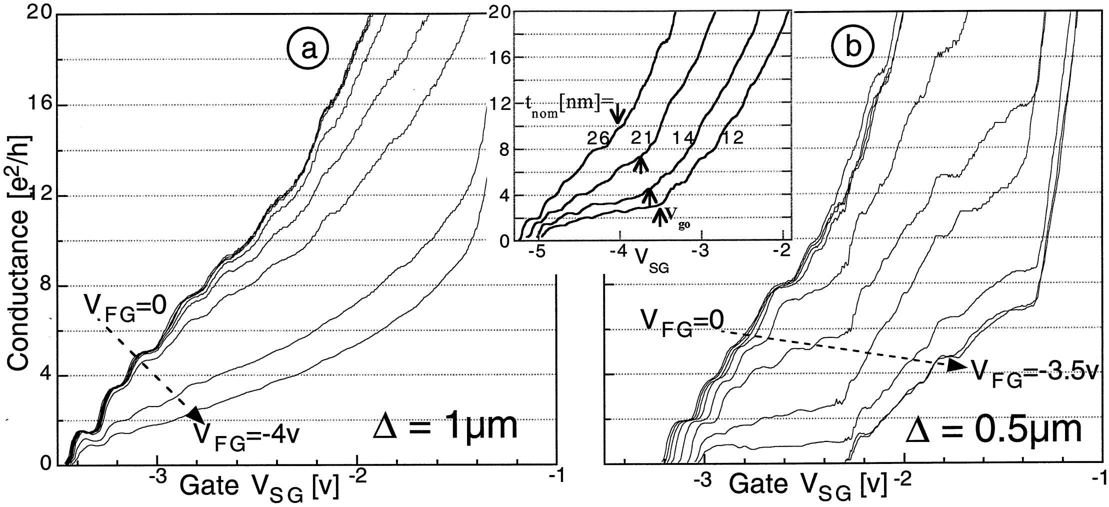

Fig. 2. Conductance versus straight-gate voltage measured for the sample with nominal QW thickness of 26 nm at 4.2 K while the fork-shaped-gate voltage is the tuning parameter (mostly in steps of 0.5 V). The QWR "access" length Δ is 1 μm in (a) and 0.5 μm in (b). In the inset, the conductance is plotted for structures different nominal QW thickness (12, 14, 21 and 26 nm).

of these curves, the initial resistive component measured at $V_{SG} = 0$ was subtracted before calculating the conductance G.

The behavior of G as a function of V_{SG} and V_{FG}, for both values of t_{nom}, can be qualitatively divided into three regimes, depending on the value of Δ. For values of Δ larger than a certain value Δ_{serial}, no significant effect on the conductance curves was observed for any value of V_{FG}. The value of Δ_{serial} was about 3 μm for $t_{nom} = 26$ nm and about 7 μm for $t_{nom} = 12$ nm. This indicates that for coupled 2D/1D reservoir sections longer than these values of Δ_{serial} the mechanism of electron scattering into the wire is unchanged and the FG influence is limited to adding a constant serial resistance.

For $\Delta < \Delta_{serial}$, the effect of the FG operation becomes very significant. The conductance behavior is different in two regimes of Δ, namely $\Delta_{critical} < \Delta < \Delta_{serial}$ and $\Delta < \Delta_{critical}$, where $\Delta_{critical}$ is about 1 μm for $t_{nom} = 26$ nm and about 2.5 μm for $t_{nom} = 12$ nm. For $\Delta_{critical} < \Delta < \Delta_{serial}$ (see Fig. 2(a) for the case $t_{nom} = 26$ nm) one first observes a monotonic decrease of the conductance of the QWR as V_{FG} becomes more negative. A saturation value of V_{FG} is reached beyond which further decrease of V_{FG} does not influence the conductance curve. Regardless of the V_{FG} value, all the curves still show complete depletion of the QWR at approximately the same $V_{SG} = V_{dep}$ ($V_{dep} \approx -3.3$ V for the case of Fig. 2).

For samples where $\Delta < \Delta_{critical}$, there is a certain value of V_{FG} for which a complete depletion of the QWR by the SG occurs at $|V_{SG}|$which is substantially less than $|V_{dep}|$ (see Fig. 2(b)). This complete depletion is observed for V_{FG} very close to V_{dep}, implying that the wire under the FG is then completely depleted. Moreover, the V_{SG} value for which the QWR is fully depleted coincides with the voltage where the conductance curve exhibits a slope change. This voltage (V_{go}, see inset of Fig. 2) designates the point for which the nature of the confining potential at the QWR changes from electrostatic ("weak") to heterostructure ("strong") confinement [15]. In Fig. 3 we summarize the observed dependence of the conductance of the ground level on Δ for the two QWR structures measured. The three regimes in the step-like curve are evident as well as the threshold distances $\Delta_{critical}$ and Δ_{serial}.

This behavior of the conductance versus Δ can be understood in the framework of the following simple model. Contact with the QWR segment of our structures is accomplished via the 2D electron gas on the sidewalls of the groove. The electrons couple from these 2D reservoirs into the 1D channel due to scattering at the 2D/1D interface. The coupling be-

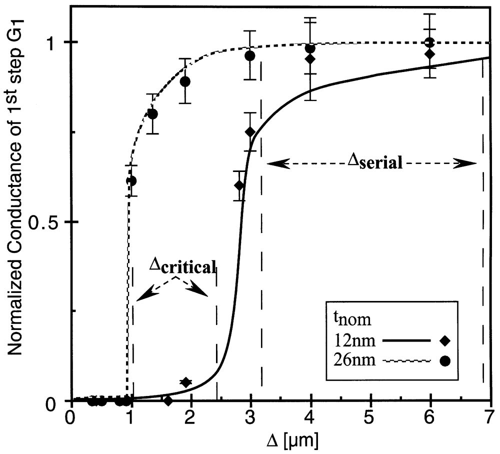

Fig. 3. The normalized conductance of the first step versus the QWR "access" length D, for structures with different QW nominal thickness (12 and 26 nm) corresponding to different strength of 1D confinement (symbols). The curves serve as a guide-to-the-eye to clarify the characteristic lengths Δ_{critical} and Δ_{serial}.

tween the 2D reservoirs and the 1D channels can be effectively described by introducing a contact transmission factor $T<1$ that reduces according to the conductance step heights. For structures with sufficiently long Δ, this 2D–1D transmission coefficient is sufficiently large such that the values of the conductance steps is unaffected. Conductance in structures with insufficiently long Δ can be tuned via the number of 1D channels allowed into the access zone by FG. As long as $\Delta < \Delta_{\text{critical}}$, all 1D states have reduced but enough scattering probability to be coupled into the QWR even when the 2D–1D coupling under the FG is quenched. Once $\Delta < \Delta_{\text{critical}}$ the application of FG permits to turn off the transmission of the strongly confined 1D states due to the lack of sufficient scattering along such a short path. Therefore, the minimal path, estimated by Δ_{critical}, becomes longer as the 1D/2D mismatch increases, as observed for the structures with different t_{nom}.

We can thus conclude that electron transport through QWR structures with sufficiently tight lateral confinement connected to 2D reservoirs exhibits quantized conductance steps lower in values than the canonical ones due to electron scattering at the 2D–1D interface zone. The length of this zone should exceed a critical value in order to allow for a sufficient number of scattering events that can couple the electrons into the 1D wire channels. This minimal length increases with the strength of the QWR confinement potential.

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