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Quantized conductance and intersubband scattering in serially connected quantum wires

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Abstract. – We studied the conductance of quantum wires (QWRs) with rigid confinement potential in different configurations, including single QWRs, QWRs with restricted access to the 2D reservoirs, and serially connected QWRs. We explain the deviations of quantized conductance values from $2e^2/h$ as coming from the lack of 1D/2D coupling. The role of intersubband scattering in establishing contact between the QWR and 2D reservoirs is demonstrated. The achievement of conductance step values close to $2e^2/h$ in these wires depends on establishing strong intersubband scattering without significant backscattering.

Introduction. – Electron transport in one-dimensional (1D) systems has drawn considerable attention over the last decade since it exhibits new physics related both to the quantum confinement and to the modified electron interaction resulting from the reduced dimensionality. In a non-interacting 1D electron system, the conductance is quantized in units of $G_0 \equiv 2e^2/h$, corresponding to perfect electron transmission *via* 1D channels [1–3]. Such quantized conductance has been observed in quantum point contact (QPC) devices in which extremely narrow conducting channels are defined in a high-mobility 2D electron gas (2DEG) using a negatively biased split gate [4, 5]. In these structures, there is an adiabatic transition from the few, well-separated 1D channels between the gates, through a multitude of closely spaced 1D states, to the continuum of 2D electron states away from the constriction, which act as an effective reservoir. However, all attempts to observe the same conductance values in wires with "rigid" confining potential (CP), such as etched-and-regrown [6], cleaved-edge-overgrown [7] and V-groove [8] quantum wires (QWRs) failed, showing conductance step values that are lower than G_0 with non-universal deviations [8, 9]. The major difference between QWRs and QPCs is the coupling between the 1D and 2D states, the latter ones being so far the only means to contact experimentally 1D states. In an ideal QWR with rigid CP, and in the absence of scattering, the 1D states are very weakly coupled to the 2D states and through them to the external contacts. Therefore, a scattering-free QWR system, which shows the universal values of conductance steps $n \cdot G_0$, would be impossible to contact through 2D states. In such wires, one could thus only attempt to approach the ideal conductance values by searching for a compromise between strong 1D/2D coupling and small backscattering. The momentum transfer required by a 1D/2D scattering is on the order of k_F, since the entire

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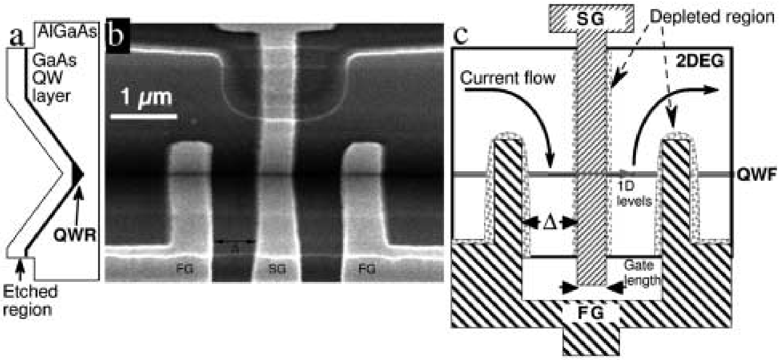

Fig. 1 – a) Schematic cross-section of a QWR device. b) Scanning electron micrograph (top view) of a device with a straight gate SG and a fork gate FG at an inter-gate distance Δ. c) Schematic diagram of the device, showing the current path and depleted regions.

kinetic energy along the wire has to be transferred to the perpendicular direction. Scattering events involving such large momentum transfer are therefore only due to strong interactions, which would also be responsible for backscattering (involving a momentum exchange of $2k_\mathrm{F}$). However, if the CP is not very strong, thus allowing for many 1D subbands with small energy separation between them, the 1D/2D coupling could be achieved by a cascade of intersubband scattering events involving a small momentum transfer. Such weak scattering events would not cause backscattering in a 1D system.

In this letter, we demonstrate that QWRs with rigid CP, which so far show the highest values of conductance steps, indeed, exhibit significant intersubband scattering over distances short compared to the 1D/2D contact length. We use a system of two serially connected V-groove QWRs, where we can vary independently the channel population in each QWR, to show that the transmission of the combined system can be explained only by invoking intersubband scattering.

We have used in this work AlGaAs/GaAs/AlGaAs QWRs, grown by OMCVD in $3\,\mu$m pitch V-grooves etched in GaAs substrates. The details of V-groove growth and properties have been published elsewhere [8, 10]. The crescent-shaped QWRs, typically $35 \times 120\,\mathrm{nm}^2$ in cross-section, were modulation-doped to $1.8 \times 10^6\,\mathrm{cm}^{-1}$. Typical 1D subband spacing is $3.3\,\mathrm{meV}$, and the mean free path is $2.4\,\mu$m. The resistance of a single V-groove device (isolated by mesa etching) was measured at $4.2\,\mathrm{K}$ by a 4-probe AC lock-in technique, using excitation current of $10\,\mathrm{nA}$. Au/Ti gates were applied to the QWR by electron-beam lithography [11].

In order to demonstrate the weakness of 1D/2D coupling in QWRs with a strong CP, we first performed a series of measurements on QWRs with a specially designed dual-gate configuration [12], as shown in fig. 1. As in all our devices, the current and voltage leads are connected to the 2DEG on the sidewalls of a single V-groove, defined by an isolating mesa etch. We have already established [8, 10] that about $-1.5\,\mathrm{V}$ is needed for depletion of the sidewall 2DEG, while about $-3.5\,\mathrm{V}$ is needed to deplete the QWR. Therefore, when the straight gate (SG in fig. 1) voltage is below $-1.5\,\mathrm{V}$, the 2DEG underneath it is completely depleted and all the current must pass through the QWR. In order to define the region of the current entrance and exit to/from the QWR, we added a fork-shaped gate (FG in fig. 1), which can deplete only the QWR (and the 2DEG on one sidewall), but never completely the 2DEG (on the other sidewall). When this FG is biased below $-3.5\,\mathrm{V}$, we are sure to cut off any electron flow in the QWR at a known distance Δ from the straight gate SG. All current flowing through the

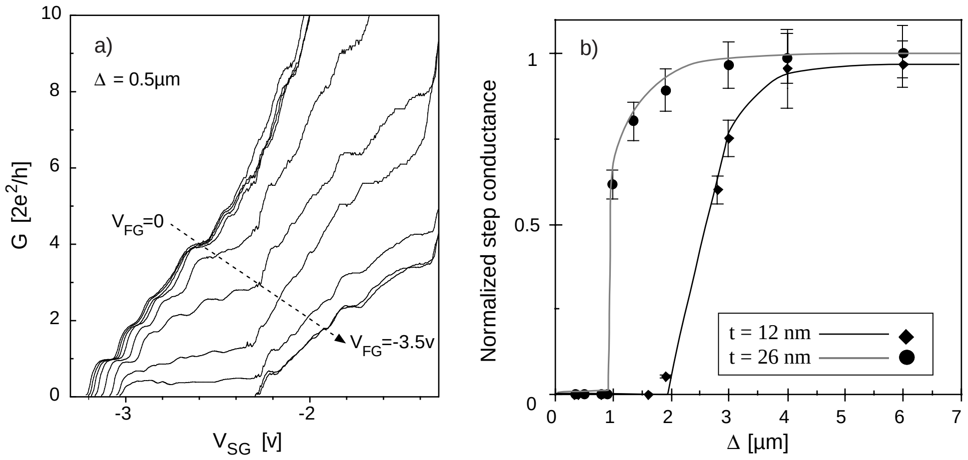

Fig. 2 – a) Conductance (in units of $2e^2/h$) of the device of fig. 1, as a function of the straight gate voltage V_{SG}, with the fork gate voltage V_{FG} as parameter. b) Conductance of many such devices, all measured when the SG allows only one channel to pass, and FG cuts off the QWR (values are normalized to the conductance when SG allows only one channel to pass and $V_{\mathrm{FG}} = 0$), plotted as a function of the inter-gate distance Δ. The solid and dashed lines are guides to the eye.

device must then flow along the path illustrated in fig. 1c), entering the QWR from the 2DEG only along a distance Δ. For each of two QWR thicknesses ($t = 12,\ 26\,\mathrm{nm}$), we measured ten devices having different gate distances Δ between 0.4 and 6 μm. The resulting conductance of one of these devices, with $\Delta = 0.5\,\mu\mathrm{m}$, is shown in fig. 2a). We observe that as the fork gate FG cuts off the conductance of the QWR under it, the conductance of the low-lying states under the straight gate SG vanishes, whereas the conductance of higher states remains finite. The conductance value of the first plateau, measured under the above conditions (FG cutting off the QWR but not the 2DEG) in different devices, is plotted in fig. 2b) as a function of the distance Δ. It is clear that for $t = 12\,\mathrm{nm}$ the 1D/2D contact resistance for the low-lying states becomes enormous for distances below $2\,\mu\mathrm{m}$, whereas for $t = 26\,\mathrm{nm}$ (weaker CP) the same occurs at a distance of $1\,\mu\mathrm{m}$. The large contact resistance to the low-lying subbands is the evidence for the lack of scattering with large momentum exchange over small distances. The higher QWR subbands do not exhibit such resistance, showing that they are much better coupled to the 2DEG. These observations are also consistent with recently published results in T-shaped QWRs [13, 14].

We concentrate now our studies on 26 nm QWRs, which show better 2D/1D coupling, as is manifested by the higher values of conductance steps. A typical example is shown in fig. 3a), where we show the conductance (in units of $2e^2/h$) of several devices with different gate lengths. It is clear that, for QWR length below $1.5\,\mu\mathrm{m}$, the conductance of one channel is length independent and close to $0.9 \cdot G_0$, while from $1.5\,\mu\mathrm{m}$ it starts falling down ($G = 0.85$ at $1.5\,\mu\mathrm{m}$). This behavior indicates that QWRs shorter than about $1.5\,\mu\mathrm{m}$ can be regarded as ballistic, meaning that backscattering effects are small. Having assessed the ballistic transport on a length scale of up to $1.5\,\mu\mathrm{m}$, we fabricated a series of samples with two straight gates (which we call RG and LG, see fig. 3b), each $0.25\,\mu\mathrm{m}$ wide and spaced $0.7\,\mu\mathrm{m}$ apart. In this device, we can bias each gate in an independent way, and our main interest is in the regime where both gates are negatively biased to the point of allowing only a few channels to pass. The small total length of the device ($1.2\,\mu\mathrm{m}$) keeps overall transport within the ballistic regime (total length $< 1.5\,\mu\mathrm{m}$). Moreover, the small gate spacing ($0.7\,\mu\mathrm{m}$) ensures that no

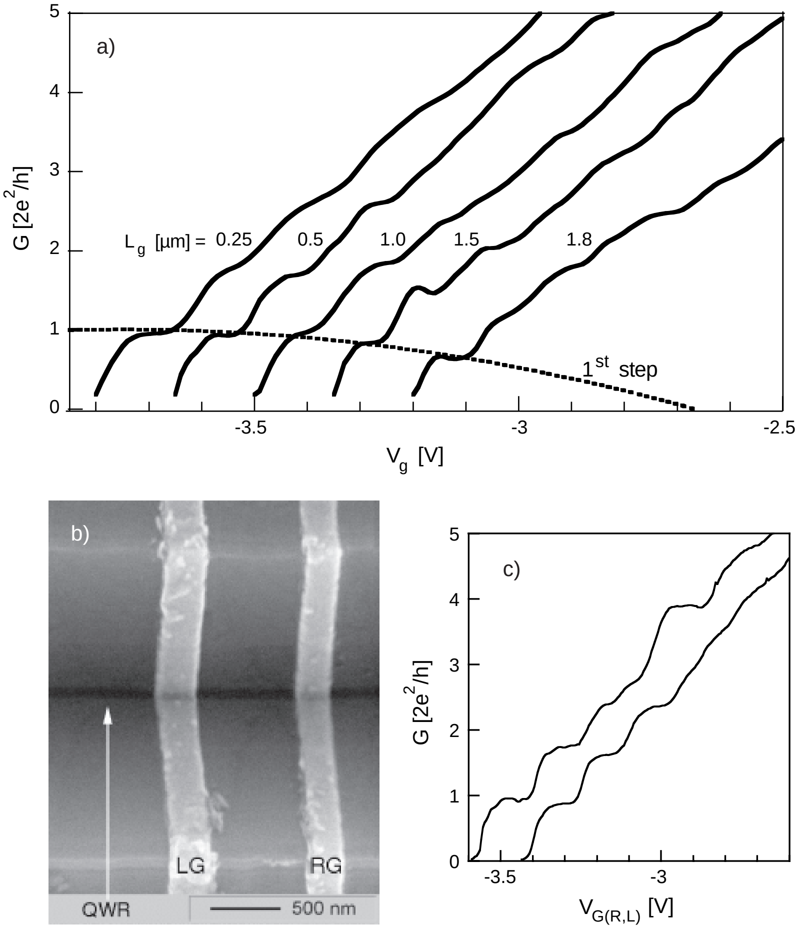

Fig. 3 – a) Conductance (in units of $2e^2/h$) of QWR sections of lengths 0.25–1.8 μm, as defined by the length of a single gate (similar to SG in fig. 1). The line connecting the first plateaus is a guide to the eye. b) Scanning electron micrograph (top view) of a device with two straight gates, RG (right) and LG (left). c) Conductance (same units) of the device in fig. 1a) *vs.* voltage of each of the two gates, while the other gate is maintained at 0 V.

interaction takes place between the low-lying electron states in the QWR and the 2DEG (as shown in fig. 2b), 1 μm is needed). A typical plot of conductance (in units of $2e^2/h$) as a function of gate voltage, for each of the two gates, is shown in fig. 3c). The values of the first few conductance steps are about 90% of $n \cdot G_0$, indicating the good 2D/1D coupling.

When both gates are negatively biased, as shown in fig. 4a), the conductance curves (G *vs.* $V_{\rm LG}$) show lower and lower values as gate RG becomes more negatively biased. The most important feature observed in fig. 4a) is the bunching of the conductance curves, which indicates electrostatic influence of each gate on the conductance under the other one. For each subsequent curve (lower $V_{\rm RG}$) the curve shifts to the right (higher $V_{\rm LG}$), producing a strong visual bunching effect at the plateau values of RG. Consequently, it is easy to take into account the electrostatic cross-talk between the gates: each bunch thus indicates the variations of conductance of the combined 2-gate system, when the conductance under gate RG is kept at its plateau value and $V_{\rm LG}$ is varied. One can see that the combined conductance of the two-gate

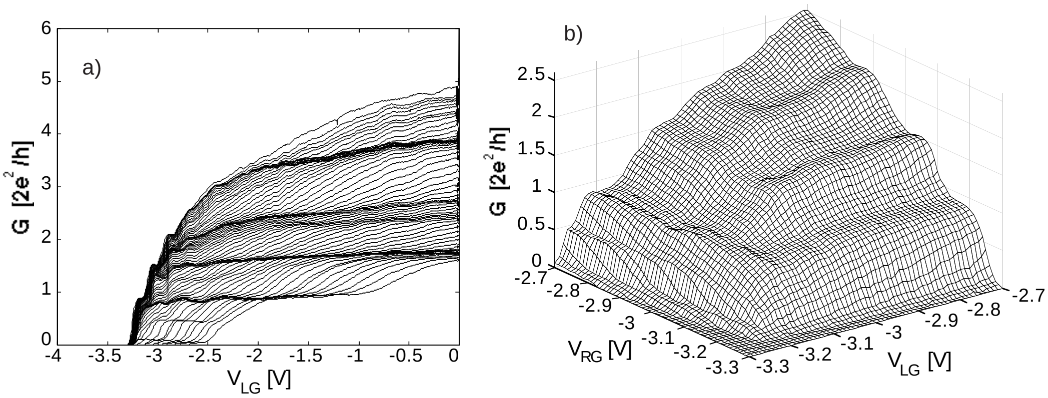

Fig. 4 – a) Conductance (in units of $2e^2/h$) of the device in fig. 3b) *vs.* gate LG voltage, with gate RG voltage as parameter (curves from top to bottom correspond to V_{RG} varying from $-2.7\,\mathrm{V}$ to $-3.3\,\mathrm{V}$ at $0.01\,\mathrm{V}$ intervals). b) Conductance (in units of $2e^2/h$) of the device in fig. 3b) *vs.* the voltage on both gates (varying from $-2.7\,\mathrm{V}$ to $-3.3\,\mathrm{V}$ at $0.01\,\mathrm{V}$ intervals).

system varies slowly (as a function of V_{LG}), as long as the number of open channels under LG is higher than the number of those open under RG. The combined conductance is also much higher than what would be expected from a serial connection of the two QWR sections, *e.g.*, by a contact to a 2D reservoir between them. This observation is consistent with the previously observed effect of the lack of 1D/2D contact on the device's length scale [12]. In a similar way, we can plot the conductance *vs.* V_{RG}, with V_{LG} as parameter (not shown); however we prefer showing the influence of the two gates on equal footing in a 3D plot (fig. 4b). Using this picture, it is easy to identify the values of combined conductance which correspond to plateaus under both gates. It is remarkable that, although the combined conductance of the system with one and two channels under each gate is much higher than it would be in the case of serial connection, it is lower than for a ballistic transmission through two barriers. This fact is the proof that electrons passing through the first two channels are scattered to higher subbands already in the short distance between the gates. Indeed, without subband scattering, the only possible way to lower the transmission of the first 1D channel under LG, by reducing the number of populated subbands under RG, would be through energy-dependent transmission of the 1st channel under RG. However, we know (from fig. 3c) that the transmission of this channel is no less than $T_1 \approx T_2 \approx 0.9$, so the combined transmission of the system without subband scattering should have been at least $\frac{T_1 T_2}{1-R_1 R_2} \approx 0.82$ ($R \equiv 1-T$ and we suppose that the phase relaxation rate is much higher than the scattering rate). Therefore, the observed transmission of 0.7 when both gates allow a single-channel population, is a clear indication of significant intersubband mixing.

Unfortunately, it is impossible to obtain quantitative evaluation of the scattering rates for each subband and their energy dependence. Yet, an over-simplified approach, neglecting multiple reflections between the gates, can give us bounds for T_{12}, *i.e.* the fraction of electrons scattered between the 1st and 2nd subband of the QWR: $0.075 < T_{12} < 0.27$. This figure decreases significantly for scattering from the 1st to higher subbands. The origin of the observed intersubband scattering could be related to either static potentials (interface roughness, impurities) or to electron-electron interaction. We believe though, that electron-phonon interaction could be excluded, due to the low measurement temperature relative to the Debye temperature. It should also be noted that in T-shaped QWRs with much stronger

CP [13, 14], the deviations from ballistic transport in serially connected 1D regions occur at much longer distances, where the contact to the 2DEG is already established. This is due to the larger subband separation in the QWR, which reduces subband scattering, leading to stronger deviation from $n \cdot G_0$ values.

As a last remark, we note the appearance of a "half-plateau" in the range $V_{\mathrm{LG}} \approx -3.25\,\mathrm{V}$, $-2.7\,\mathrm{V} < V_{\mathrm{RG}} < -3.0\,\mathrm{V}$ (see left side of fig. 4b). This conductance feature, at about $0.5 \cdot G_0$, is similar to the one observed in QPCs by many groups since 1991 [15] and which is still studied today [16]. Its exact nature is still under controversy, but it is interesting to note the appearance of such plateau in a strong-confinement system like our QWR, in a similar way to the one observed in weak-confinement systems (QPCs).

To summarize, we claim that the contact of QWRs with rigid confinement potential to the 2DEG is established *via* a cascade of scattering from the low to higher subbands, the latter ones being better coupled to the 2DEG. Since backscattering can occur only at high subbands, due to the relatively weak scattering potential in our samples, the probability to backscatter (after a multitude of such events) to the original low-energy subband, is extremely small. This situation is analogous in some sense to the problem of electron reflection in QPCs, where it is known that the precise quantized G_0 value can be observed only in high-mobility 2DEG, where the mean free path is much larger than the length of the constriction. In such samples, backscattering can occur only as a cascade of many small-angle scattering events. Therefore, the probability to be scattered back into the same point in space is extremely small. On the other hand, for low-mobility samples, although the mean free path is still larger than the constriction length, each scattering event can cause backscattering; therefore, the return probability is much higher, which eventually results in strong deviations from G_0. The mechanism of subband scattering remains open for future studies, *e.g.*, through the temperature dependence of the conductance in a 2-gate system.

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