0.7 anomaly and magnetotransport of disordered quantum wires

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Abstract – The unexpected “0.7” plateau of conductance quantisation is usually observed for ballistic one-dimensional devices. In this work we study a quasi-ballistic quantum wire, for which the disorder-induced backscattering reduces the conductance quantisation steps. We find that the transmission probability resonances coexist with the anomalous plateau. The studies of these resonances as a function of the in-plane magnetic field and electron density point to the presence of spin polarisation at low carrier concentrations and constitute a method for the determination of the effective $g$-factor suitable for disordered quantum wires.

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It is expected that quantum point contacts (QPC) and quantum wires (QW) will act as active components of future nano-electronic devices and circuits. Therefore, the renewed interest in transport and spin properties of one-dimensional (1D) systems recently takes place in the mesoscopic physics community. In those studies, special attention is directed towards the long-standing problem of quantum transport — the so-called “0.7 anomaly” [1] most often, but not exclusively, observed for devices fabricated on modulation doped GaAs/AlGaAs heterostructures. Usually, anomalous behavior is observed in transport data as a “kink” on the conductance $G$ vs. the device width curve, occurring for the low carrier densities, when $G \sim 0.7 \times 2e^2/h$, here $-e$ is the electron charge and $h$ is the Planck constant. The origin of this effect is currently under active debate since this anomaly seems to be a universal, but still unexplained feature of one-dimensional mesoscopic transport. Experimentally, the magnetic field dependence of the additional plateau is common for all studied systems — by applying a parallel in-plane field the 0.7 feature evolves gradually towards $0.5 \times 2e^2/h$ conductance step, when only one spin-polarised level is occupied [1–6]. Therefore, it has been suggested that such an anomalous plateau is due to spontaneous spin polarisation of one-dimensional electron liquid, caused by exchange interactions among carriers in the constricted geometry of the device [2,7]. If it is so, the 1D systems may be used as an efficient spin filter with possible practical applications. This point of view is supported by magnetic focusing data obtained for the $p$-type device, which reveal the static spin polarisation of holes transmitted through the constriction [8]. Furthermore, recent shot-noise measurements carried out for $n$-type QPC [9] show that distinct transport channels exist at $G < 2e^2/h = G_0$, presumably related to spin, exhibiting quite different transmission probabilities.

Many experiments, however, bring out rather contradictory observations regarding the temperature dependence of the additional plateau. Already Thomas and co-workers [1] revealed that the 0.7 “kink” disappears when temperature is lowered, typically below few hundreds milikelvins. Such unusual low-temperature behaviour is accompanied by the zero-bias peak in the differential conductance, which is typical for the Kondo effect for quantum dots [3,10]. Nevertheless, the Kondo-type features appear to be typical for the point contacts only, i.e. for devices for which $L/W \sim 1$, where $L$ and $W$ are the physical length and width of the conducting

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channel, respectively [6,11,12]. On the contrary, for longer quantum wires, when \( L/W \gg 1 \), the 0.7 anomaly becomes even more pronounced, when the temperature is lowered and zero-bias anomaly is not observed [13–15]. Additionally, the anomalous plateau does not always occur at \( G = 0.7 \) (in \( G_0 \) units), there is some evidence that the value decreases with the length of the wire approaching the “quantized” value \( \sim 0.5 \) [13,15]. This may suggest that additional plateau is generic for 1D systems. The Kondo physics shows up only, when the source-drain distance is reduced towards zero and the confining potential forms a smooth saddle point in the 2D landscape.

Usually, the “0.7–0.5” anomaly is observed for ballistic point contacts and wires, i.e., when \( L \ll \ell \), where \( \ell \) is the mean free path of electrons (or holes). As a consequence, in the analysis of the possible origin of this anomaly, the role of disorder is ignored. The aim of our work is to study the 0.7 plateau for quasi-ballistic devices and to detect the fate of the mysterious conductance “kink”, when the back-scattering events operate within the 1D channel.

For this purpose we have fabricated quantum wires with \( L \sim \ell \) from a wafer containing a modulation doped AlGaAs/GaAs/AlGaAs quantum well. We show here that the “0.7 anomaly” is very robust against the disorder. The analysis of linear and non-linear transport measurements enables us to observe the characteristic anomalous plateau for devices with \( L/W \approx 20 \) in spite of the fact that the disorder reduces the magnitude of the overall conductance and leads to the appearance of transmission resonances. Actually, as we show here the presence of the resonances allows one to determine the evolution of spin polarisation with the in-plane magnetic field and electron density. Employing this method, we determine the electron Landé factor \( g \) at relatively high carrier concentrations. At the same time, we find that splitting of the resonances is absent when the conductance is reduced below \( G \lesssim 0.8 \). This observation is in agreement with the explanations of the 0.7 anomaly in terms of spontaneous spin polarisation of low-density 1D carrier liquid.

The four-terminal quantum wires are patterned of an MBE-grown (by the Veeco GEN-II system) 20nm AlGaAs/GaAs/AlGaAs:Si quantum well located at 101 nm below the surface. The 60 nm top barrier results in the electron concentration \( n_{2D} = 1.8 \times 10^{11} \text{ cm}^{-2} \) and carrier mobility \( \mu = 2.45 \times 10^5 \text{ cm}^2/\text{Vs} \) as measured in the dark at \( T = 2.8 \text{ K} \). The wires of length \( L = 0.6 \mu \text{m} \) and lithographic width \( W_{\text{liq}} = 0.4 \mu \text{m} \) are patterned by \( \epsilon \)-beam lithography and shallow-etching techniques. The physical width of the wires is controlled by means of the top metal gate which is evaporated over the entire device. The differential conductance \( G = \partial I_{sd}/\partial V_{sd} \) measurements are conducted in a He-4 cryostat and He-3/He-4 dilution refrigerator by employing a standard low-frequency lock-in technique with ac voltage excitation of 10 \( \mu \text{V} \). The source-drain voltage \( V_{sd} \) and current \( I_{sd} \) are measured by employing battery-powered, low-noise \( \text{dc} \) amplifiers. Data are collected at zero magnetic field and also with in-plane field \( B_{||} \) applied parallel to the current through the 1D constriction.

Figure 1 presents the conductance \( G \) as a function of the gate voltage \( V_g \) obtained at zero \( \text{dc} \) source-drain bias. The quantized conductance plateaux are observed, which correspond to the successive population/depopulation of the 1D electric subbands. However, the height of particular steps deviates from the quantized values, \( N \times G_0 \), where \( N \) is an integer corresponding to the number of occupied subbands. We find from our measurements that the perfect quantisation cannot be recovered by subtracting a constant resistance from the raw experimental data. The unknown part of such series resistance, which depends on gate voltage, is rather small and further decreases for positive \( V_g \) since the top gate covers only the wire area and a narrow margin (≈ 5 \( \mu \text{m} \)) around it. Furthermore, the gate dependent and independent contributions to the total contact resistance are effectively eliminated by the application of a 4-terminal method of measurements. Some authors have considered the influence of electron-electron interactions in 1D systems on conductance quantisation but the prevailing view is that a reduction in plateaux heights results from elastic backscattering, occurring within the disordered quantum channel [16,17]. We conclude, therefore, that in our wire \( G \) is diminished by backscattering, \( G = (2e^2/h)NT \), where \( T \approx 0.81 \) is the transmission probability similar for each channel up to \( N = 10 \).

However, the disorder not only reduces uniformly the conductance magnitude, but also results in the appearance of conductance resonances at sufficiently
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low temperatures, which originate from interference of scattering amplitudes. The coexistence of these two effects was already observed experimentally in quasi-ballistic quantum wire [18–20] and is also present for the device studied here. Figure 2 shows conductance measured at various temperatures in the He-4 cryostat and the dilution refrigerator. With lowering temperature, the Ramsauer-like resonances clearly show up. This pattern undergoes a change when the sample is warmed up and cooled down again, as scattering centres move or change their charge state [17]. We conclude, therefore, that our sample is indeed in the quasi-ballistic regime, $L \sim \ell$.

The important aspect of our findings is that, despite the strong effects of disorder, the anomalous “0.7” conductance step is visible on the the $N = 1$ plateau. In our case it assumes the value of $G \approx 0.06G_0$. As expected, when the in-plane magnetic field $B_\parallel$ is applied, the height of this additional plateau decreases, as shown in the inset to fig. 1.

A question arises, whether the conductance step in question is not a resonance peak persisting up to 2K. In order to address this issue, we have carried out dynamic-conductance measurements as a function of source-drain bias [21], as it is known that the “0.7” plateau becomes even wider for non-zero bias and can survive up to $V_{sd} \approx 10$ meV [11,14]. Figure 3 shows the evolution of differential conductance with the bias and gate voltage. Quantized plateaux are visible as collections of lines, which for $G < 0.8$ the aggregation of lines is identified as the “0.6” anomaly, discernible also for non-zero biases. The distinction between the additional plateau and any interference effect is evidenced in fig. 4, where the transconductance $dG/dV_g$ at $T = 0.025$ K is shown as a function of gate voltage and bias. Together with the distinctively diamond-shaped regions, bordered by high transconductance (bright) areas, also the additional bright strip which crosses the borderline between integer and half-integer conductance diamonds is clearly visible. According to previous studies such characteristic high transconductance line forms when the “0.7–0.5” plateau evolves toward the normal one and it is observed up to biases comparable with the energy gap between 1D levels. Therefore we conclude that the “0.6” anomaly is present also at low temperatures, provided $V_{sd} > 1$ mV. In fig. 4(a) the anomalous plateau is visible as a darker region on the left side of the dashed curve. At low source-drain voltages, however, the anomaly is masked by transmission resonances which show-up due to the presence of disorder. As a result, the characteristic high transconductance line is replaced by the “sub-diamond” pattern, which forms because the interference pattern splits in energy. Distinct branches for electrons injected from left and right are marked with dashed lines in fig. 4(b). One of these lines (the second to the left) seems to coincide with the transition region where the anomalous plateau changes over to the normal one i.e. looks like a continuation of the dashed curve from fig. 4(a). Nevertheless, both lines are most probably not related, because the interference pattern observed for $V_{sd} < 1$ mV changes after a cool-down cycle, whereas the “0.6” line visible for $V_{sd} > 1$ mV does not.

Recently, Bielejec [22] et al. have reported a reduction of the conductance step (down to 0.84) and the presence of the “0.7” anomaly for a long and very high-mobility split-gate device. However, no Ramsauer-like transmission
resonances were found at low temperatures. For the data reported here, we can observe a stronger reduction of conductance, the “0.6” anomaly, and transmission resonances. It seems that the wires patterned by shallow etching are well suited for such studies because the 1D confining potential is much stronger comparing to the transition regions between plateaux (or transmission resonance peaks). Transition points between plateaux \( N \to N + 1 \) splits with the bias because for left- and right-moving electrons it occurs at different gate voltages, as marked by solid black lines. The dashed line labels the range where anomalous plateau changes over to normal one. (b) The enlarged part corresponding to the \( N = 1 \) plateau with superimposed interference peaks, dashed lines mark the “sub-diamond” structure, which is related to such conductance resonances at \( V_{sd} \lesssim 1 \text{ mV} \).

If the interference pattern splits when left- and right-moving electrons start to differ in energy, we may ask if the Zeeman splitting induced by the external field, will lead to a similar effect. Actually, the influence of spin splitting upon mesoscopic conductance fluctuations was observed for diffusive transport in quantum wires of diluted magnetic semiconductor (Cd,Mn)Te:In [23]. It was found that the correlation field \( B_c \) of the universal conductance fluctuations scales with the \( s\)-\( d \) exchange spin splitting of the conduction band. Therefore, we expect that in non-magnetic materials the interference pattern will also split at a sufficiently high in-plane magnetic field — when the Zeeman energy exceeds the separation of fringes. Relevant data for our sample is presented in fig. 5 where the evolution with the magnetic field of the first two conductance steps is shown.

Figure 5(a) shows that already at \( B_\parallel = 6 \text{T} \) the lower conductance plateau corresponds to fully spin polarised electron transport. As regards the transmission resonances, the first impression is that the interference pattern has changed completely. However, it is not true. As seen...
The amplitude of the two most prominent peaks only fluctuates (∆G), and then the number of peaks is approximately constant. On resonances do not split— the amplitude of fluctuations is enhanced by the exchange interaction [2, 4]. For our sample we obtained |g∗| = 1.2 ± 0.1 (as compared to 0.44 in bulk GaAs), which is in very good agreement with recent data for ballistic QPCs [6]. The advantage of the proposed method is that it can be applied for long, quasi-ballistic quantum wires. The disadvantage is, of course, the non-reproducibility of the observed interference pattern, which changes after subsequent warming-up and then cooling-down.

In summary, we studied the conductance quantization of quasi-ballistic (L ≈ ℓ), large-aspect-ratio (L/W ≈ 20) quantum wire. Due to the disorder present in our sample, we observed reduced conductance steps [(0.81 ± 0.01) × G0] and transmission resonances on the onset of quantized plateaux, caused by the interference of incoming and reflected electron waves. With the application of source-drain bias spectroscopy, we showed, that the backscattering of electron waves and reduction of transmission probability through the sample do not destroy the existence of the so-called 0.7 (in our case 0.6) anomaly. The additional conductance plateau was clearly observed in the temperature range from 1.8 to 0.025 K. Furthermore, we proposed the single electron effect (splitting of the interference peaks with in-plane magnetic field) as a suitable tool for studying the enhancement of electron g-factor in quantum wires which is a collective phenomenon, observed before for ballistic point contacts. Finally, the Zeeman splitting of the conductance transmission resonances was not observed on the onset of the first plateau suggesting that for B = 0 and G < 0.8 the spin degeneracy is already lifted. This observation supports hypothesis that it is a spontaneous spin polarisation which is responsible for the “0.5–0.7” anomaly.

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