Luttinger liquid behavior in weakly disordered quantum wires

E. Levy,1,∗ A. Tsuchernik,2 M. Karpovski,1 A. Palevski,1 B. Dwir,3 E. Pelucchi,3 A. Rudra,3 E. Kapon,3 and Y. Oreg4

1School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel
2University Research Institute for Nanoscience and Nanotechnology, Tel Aviv University, Tel Aviv 69978, Israel
3Ecole Polytechnique Federale de Lausanne (EPFL), Laboratory of Physics of Nanostructures, CH-1015 Lausanne, Switzerland
4Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

We have measured the temperature dependence of the conductance in long V-groove quantum wires (QWRs) fabricated in GaAs/AlGaAs heterostructures. Our data is consistent with recent theories developed within the framework of the Luttinger liquid model, in the limit of weakly disordered wires. We show that for the relatively low level of disorder in our QWRs, the value of the interaction parameter \( g \approx 0.66 \), which is the expected value for GaAs. However, samples with a higher level of disorder show conductance with stronger temperature dependence, which does not allow their treatment in the framework of perturbation theory. Fitting such data with perturbation-theory models leads inevitably to wrong (lower) values of \( g \).

The electrical conductance through noninteracting clean quantum wires (QWRs) containing a number of one-dimensional subbands is quantized in the universal unit \( \frac{e^2}{h} \), as observed in narrow constrictions in 2D electron gas (2DEG) systems \( 2,3 \). For such short and clean narrow wires, the e-e interactions described by the so-called Luttinger liquid (LL) model \( 4 \) do not affect the value of the conductance, namely it is temperature and length independent as indeed was shown experimentally \( 2,3 \). In the presence of disorder in sufficiently long QWRs, suppression of the conductance is expected at low temperatures. A number of theoretical papers addressing this issue \( 2,3,5,8 \) predict a negative correction to the conductance versus temperature \( G(T) \), which increases with \( T \) and obeys a power law: \( T^{g-1} \), where \( g < 1 \) is an interaction parameter.

The validity of the implications of the LL theory has been recently demonstrated in a number of experiments \( 3,10 \). The most evident proofs of the predictions were shown in tunnelling experiments performed in T-shaped cleaved-overgrown GaAs quantum wires \( 6 \) and in carbon nanotubes \( 10 \). Earlier non-tunnelling experiments, in which suppression of conductance occurs in the linear response regime, did not unambiguously prove the validity of the theory, and the value of the \( g \) parameter could not be deduced from the experimental data \( 11,12,15 \). Several complications are encountered in such experiments. For sufficiently disordered wires, where the correction to \( G(T) \) is expected to be large, the value of the conductance at the plateau is not well defined due to the specific realization of the disordered potential in the wire, as was the case for the long wires of Tarucha et al. \( 11 \). Moreover, in the intermediate regime, namely for disorder level for which the conductance plateau could be well defined but the corrections to \( G(T) \) are already significant for a relatively narrow temperature range, \( g \) cannot be extracted by applying a perturbation theory. If however, the disorder is very weak so that the plateaus are well defined at all temperatures \( 11,12 \), the variation of its value versus temperature is so weak that the \( g \) parameter cannot be reliably determined. Therefore, if one wishes to compare \( G(T) \) to the theory, a wire possessing just the right amount of disorder is needed.

In this work, we present an experimental study of the conductance in single mode V-groove GaAs QWRs. The variation of conductance was measured over a wide temperature range. Our results are consistent with the theories \( 2,3,5,8 \) based on the LL model for weakly disordered wires, allowing us to deduce the value of \( g = 0.66 \), as expected for interacting electrons in GaAs and as was observed experimentally in tunneling experiments \( 9 \). We show results for QWRs displaying different amounts of disorder, thus enabling us to show the importance of the degree of disorder and the limits of perturbation theory.

The QWRs studied here were produced by low pressure \( (20 \text{ mbar}) \) metalorganic vapor phase epitaxy (MOVPE) of GaAs/AlGaAs heterostructures on undoped (001) GaAs substrates patterned with V-grooves oriented in the [01-1] direction, fabricated by lithography and wet chemical etching \( 14 \). The heterostructure consisted of a 150 \( \text{nm} \) AlAs/GaAs buffer layer, 1 \( \mu \text{m} \) \( \text{Al}_{0.27}\text{Ga}_{0.73}\text{As} \) lower barrier layer, 14 \( \text{nm} \) GaAs quantum well (QW) layer, 160 \( \text{nm} \) \( \text{Al}_{0.27}\text{Ga}_{0.73}\text{As} \) upper barrier layer, and a 10 \( \text{nm} \) GaAs cap layer. All layers were nominally undoped, except for two 20 \( \text{nm} \) Si doped \( \left( \approx 1 \times 10^{18} \text{ cm}^{-3} \right) \) regions in the \( \text{Al}_{0.27}\text{Ga}_{0.73}\text{As} \) barriers, spaced by 80 and 60 \( \text{nm} \), respectively, from the lower and upper GaAs QW interface, serving as modulation doping regions. The layer thicknesses refer to growth on a planar (100) sample. Growth of the GaAs QW in V-grooves yields a crescent-shaped QWR flanked on both sides by \( (111)A \) oriented QWs (see inset of Fig. 1). The modulation doping yields
a 1D electron gas confined to the wire, laterally connected to 2DEG systems that form on the \{111\}A QW's.

The QWRs were contacted using the scheme illustrated schematically in Fig. 1. Source and drain Au/Ge/Ni pads were fabricated using standard photolithography techniques with a mesa etched along the QWR, providing ohmic contacting to the 2DEG regions. Additionally, narrow (0.5 \( \mu \)m) Ti/Au Schottky gates were formed using electron beam lithography in order to isolate the QWR and control the number of populated 1D subbands in it.

The conductance was measured by the four-terminal method using a low noise analog lock-in amplifier (EG&G PR-124A). The excitation current was kept at \( I = 0.1 \) \( nA \) ensuring that the voltage drop across the wire never exceeded \( \frac{2e^2}{h} \) at the lowest temperature. Without application of gate voltage \( V_g \), the transport in our system is carried by electrons in the 2DEG on the sidewalls and in parallel with those in the 1D QWR. Application of a sufficiently large negative \( V_g \) depletes the electrons at the sidewalls and creates a 1DEG confined to the V-groove QWR underneath the gate \[15\]. At a certain range of still more negative voltage, a single populated 1D channel is realized. As was demonstrated \[10\], the electrons remain at their one-dimensional state during a transition length \( \Delta \) (see Fig. 1) on both sides of the gate. This transition length arises from the weak coupling between the 1D states and the located 2DEG, which acts as an electron reservoir. This transition length, defined as the length required for electrons to be scattered into/from the 2DEG, was found to be as large as \( \Delta = 2 \) \( \mu \)m \[16\]. It is thus reasonable to conclude that the effective length of the 1D wire exceeds the actual width of the gate (0.5 \( \mu \)m) by about 2 \( \mu \)m on each side of the gate.

Fig. 2 shows the variation of the conductance with gate voltage \( V_g \), in the range where electrons populate only a single 1D sub-band, at temperatures between 100 \( mK \) and 4.2 \( K \). The temperature was measured using a calibrated carbon thermometer (Matsushita 56 resistor). The electronic temperature of GaAs 2DEG does not deviate from the bath temperature for \( T > 100 \) \( mK \) as shown in our previous studies \[17\]. The data was taken at stabilized temperatures of the bath while the \( V_g \) was swept through the entire range. A series resistance of 180 \( \Omega \), measured at \( V_g = 0 \), has been subtracted from all curves. At 4.2 \( K \) the conductance plateau is smooth with \( G = 0.94 \times \frac{2e^2}{h} \), indicating that only weak disorder is present in our samples. At lower temperatures, some small undulations of the conductance values appear at the plateau, but its average value is well defined with the standard deviation being much less than the average value (see error bars in Figs. 3 and 4). A similar phenomenon, namely the appearance of such structures at lower temperatures and their disappearance at higher temperatures, was also recently observed in clean cleaved-edged overgrown wires \[18\]. The variation of the plateau value (approximately 20\%) through the wide temperature range (1\frac{1}{2} decades), allows us to make a meaningful comparison of the data to the theories derived in the appropriate limit of weak disorder. Fig. 3 shows the measured variation of conductance versus temperature.

Early theories, particularly those of Kane and Fisher \[9\] (and of Ogata and Fukuyama \[6\]), proposed that for relatively small barriers (weak disorder, which is assumed to result in relatively small corrections), the conductance of a sufficiently long, single mode 1D spinfull Luttinger liquid system decreases with temperature in the manner

\[
G'(T) = \frac{2e^2}{h} \cdot g \left[ 1 - \left( \frac{T}{T_0} \right)^{g-1} \right]
\]

Here, \( g < 1 \) is a dimensionless parameter, which is a

![FIG. 1: Schematic diagram of the device’s geometry. The QWR is located at the bottom of the V-groove. The inset shows a cross-sectional TEM image of the wire, on which the charge distribution is schematically depicted.](image)

![FIG. 2: Conductance vs. gate voltage \( V_g \) for 0.5 \( \mu \)m gate width at various temperatures, after subtraction of series resistance.](image)
The theory of Maslov [7], the interaction parameter \( g \) is given roughly by the expression \( g = \frac{1}{\sqrt{1 + \epsilon e^{-U/L}}} \), where \( U \) is the Coulomb interaction energy between neighboring electrons. \( T_0 \) is a parameter describing the strength of the backscattering (disorder) in the wire; at \( T \approx T_0 \) the corrections to \( G(T) \) become of order \( \frac{2e^2}{h} \). Both theories predict a correction of \( g \frac{2e^2}{h} \) even for ballistic wires at relatively high temperatures. These imply that for sufficiently long wires, one cannot observe values close to \( \frac{2e^2}{h} \) in GaAs, since the value of \( g \) is expected to be of the order of \( \approx 0.7 \) in such wires, as was already pointed out by Tarucha et al. [11].

This contradiction was also addressed in detail in several theoretical papers [7, 8, 10, 21, 22]. According to the theory of Maslov [7], the interaction parameter \( g \) of the wire determines the exponent of the temperature variation, whereas the pre-factor \( g \) in equation (11) should be set to 1 (noninteracting reservoirs). Fig. 3 (dashed line) shows the curve calculated from this modified equation.

A different but numerically equivalent result was derived by Oreg and Finkel’stein [8]. They also demonstrated that for an infinite clean wire, the conductance keeps the universal value \( \frac{2e^2}{h} \) per mode, even in the presence of interactions. According to their theory, because of the electric field renormalization by the interactions, the results given by Kane and Fisher [5] of equation (11) are modified in the following way:

\[
G(T) = \frac{2gG'(T)}{2h(g-1)G'(T) + 2g} \tag{2}
\]

As can be easily verified, the leading term in the temperature variation of the conductance of equation (2) leads to the same results given by Maslov [7].

As one can see from Fig. 3 an excellent fit is obtained for both theories [7, 8], and we obtain \( g = 0.64 \pm 0.05 \), as is expected for electrons in GaAs wires. Indeed, this value is consistent with the experiments in Ref. [9], showing \( g \) values between 0.66 and 0.82. Moreover, using the Fermi energy \( E_F \approx 1.5 \pm 0.5 \text{ meV} \) (half of level spacing between 1D sub-bands estimated in our previous experiments [12]), we calculate the corresponding electron densities at the middle of the plateau, obtaining \( n_{1D} = 3.2 \pm 0.5 \times 10^{11} \text{ cm}^{-1} \). Substituting the above value for \( n_{1D} \) into \( U = \frac{e^2}{\tau} \times n_{1D} \) we get \( U = 3.85 \pm 0.60 \text{ meV} \) which yields the values of \( g = 0.66 \pm 0.04 \), consistent with our fit to the LL model.

Disorder in V-groove QWRs stems mainly from interface roughness brought about by lithography imperfections on the patterned substrate and peculiar faceting taking place during MOVPE on a nonplanar surface [22]. The disorder results in potential fluctuations along the axis of the wire, and manifests itself in localization of excitons and other charge carriers as evidenced in optical spectroscopy studies of these wires [23]. Optical and structural studies indicate the formation of localized potential wells along the wires with size in the range of several 10 nm [24]. The specific features of the disorder in the QWRs studied here, in terms of depth and size of the localization potential, are expected to vary from sample to sample. In fact, the degree of disorder is represented in our analysis of the temperature dependence of the conductance by the parameter \( T_0 \). Repeating the analysis of Fig. 3 for several samples, we observed in all the wires having small amount of disorder, namely showing \( T_0 < 2 \text{ mK} \), similar values of \( g \), namely \( g = 0.66 \). However, other wires with stronger disorder (\( T_0 > 2 \text{ mK} \)), showed lower values of \( g \), around \( g = 0.5 \). Fig. 4 summarizes the values of \( g \) vs. \( T_0 \) obtained for our different wires. The values of the total change \( \Delta G \) were calculated for each wire in the temperature range 0.1–4.2 K and are also shown in Fig. 4. Note that there is an agreement between the two indicators for the strength of the disorder, \( T_0 \) and \( \Delta G \). The transition between \( g = 0.66 \) and \( g = 0.5 \) at \( T_0 \approx 2 \text{ mK} \) occurs for \( \Delta G \approx 23\% \). We believe that above \( T_0 \approx 2 \text{ mK} \) the disorder in the wires is strong enough so that the description by perturbation theory is no longer valid. Trying to fit such data with perturbation-theory equations gives inevitably lower (and wrong) values of \( g \). For such wires, one should use other theories concerning stronger disorder due to many impurities [23], or stronger backscattering [20] in the system. The results of conductance measurements in GaAs wires reported recently by Rother et al. [13] also correspond to highly disordered samples, and also give \( g = 0.5 \). Indeed, analyzing their data, we estimate the value of \( T_0 \approx 15 \text{ mK} \) (marked by a star in Fig. 4) and the change in the conductance \( \Delta G/G \approx 10\% \) over a small temperature range (1–3 K). These values are even larger than corresponding values for our most

![Fig. 3: Conductance values of the first plateau vs. temperature in the wire of Fig. 2 (points with error bars). Both theoretical expressions are plotted for the same parameters, e.g. \( g = 0.64 \) and \( T_0 = 0.7 \text{ mK} \) of equation (2).](image-url)
The wrong values of g, expressed in %, are shown for each point. The star represents the theoretical values of 0 for the second and the third plateaux, respectively, which agree with the experimental data.

We however observe that the 2DEG to the 1D subbands in the ungated region, we conclude that the observed decrease of the conductance is due to the interactions in the LL model.

In conclusion, we have measured the temperature dependence of the electrical conductance in single mode quantum wires. We find that our data is consistent with theoretical calculations based on the LL model, in the limit of weak disorder in the system. We showed that the use of the perturbative result (namely $G' \propto T^{-1}$) in order to estimate $g$, is valid only for wires produced with a moderate amount of disorder ($T_0 < 1 \text{mK}$).

We thank Dganit Meidan for constructive discussions of our results. This research was partially supported by the Israel Science Foundation, founded by the Israel Academy of Sciences and Humanities Centers of Excellence Program and by ISF grant 845/04.