Fermi liquid behavior of GaAs quantum wires

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1. Introduction

The electrical conductance through noninteracting clean quantum wires containing a number of one-dimensional subbands is quantized in the universal units $2e^2/h$[1,2] . As the number of the subbands is changed, the conductance varies in a step-like manner (with the plateaus at integer values of the universal unit), as was observed in narrow w constrictions in 2D electron gas (2DEG) systems [3, 4]. Typically, the size of the constrictions is comparable to the Fermi length λ_F , and is much shorter than the mean free path in the 2DEG. For such short and clean narrow wires, the e-e interactions described by the so-called Luttinger liquid (LL) model [5]
do not affect the value of the conductance, namely it is temperature and length independent as indeed was shown experimentally [3, 4]. In the presence of disorder in sufficiently long (containing at least a few electrons) quantum wires (QWRs), suppression of the conductance is expected at low temperatures. A number of theoretical papers addressing this issue [6–9] predict a negative correction to the conductance versus temperature $G(T)$, which obeys a power law: T^{g-1}, where $g< 1$ is an interaction parameter. Eventually, at T = 0, the above theories predict vanishing conductance. These theories use all perturbation treatment of the disorder and are thus limited to the cases of relatively small disorder. No theoretical treatment beyond perturbation theory has been suggested so far.

The validity of the implications arising from the LL theory has been recently demonstrated in a number of experiments [10, 11]. The most evident proofs of the theoretical predictions were shown in the *tunnelling* experiments performed in T-shaped cleaved-edged overgrown GaAs quantum wires[10] and in carbon nanotubes[11]. 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[12–14]. Several complications are encountered in such experiments. For sufficiently disordered wires, where the correction to the conductance 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*. [12]. Moreover, in the intermediate regime, namely, for the disorder level for which the plateau could be well defined but the corrections to G(T) are already significant for a relatively narrow temperature range, the parameter g cannot be extracted by applying a perturbation theory. The attempt to extract g from such samples by applying the theory in the limit of weak disorder would result in reduced values of g as we believe was the case[14]. If however, the disorder is very weak so that the plateaus are well defined at all temperatures, [12, 13] the variation of its value vs. 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 order to avoid the above difficulties. On one hand, the disorder should be weak enough to give well defined plateaus, while on the other hand, the overall weak variation of G(T) should be observed over the extended temperature range so that the perturbation theory could be applied.

In this work, we present an experimental study of the conductance in single mode GaAs QWRs grown on a V-groove substrate. The variation of the conductance was measured over a wide temperature range. Our results are consistent with the theories [8, 9] 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 [10]. We show results coming from QWRs displaying varying amounts of disorder, thus enabling us to show the importance of the degree of disorder in fitting to perturbation theory and to show its limits.

2. Sample preparation and the experimental setup

The QWRs studied in this work were produced by self-ordered growth of GaAs/AlGaAs heterostructures, using low pressure (20 mbar) metalorganic vapor phase epitaxy (MOVPE) on undoped (001) GaAs substrates with a few isolated V-grooves oriented in the [01-1] direction, fabricated by electron-beam and UV lithography, followed by wet chemical etching [15]. The heterostructure consisted of a 230 *n*m GaAs buffer layer, followed by a one micron thick $Al_{0.27}Ga_{0.73}As$ layer. 20 *n*m Si doped ($\approx 1\text{x}10^{18}$ cm^{-3}) $Al_{0.27}Ga_{0.73}As$ layers on both sides of the GaAs quantum well layer, spaced by 80 and 60 *nm*, respectively in the growth order, provide the electrical charge to the quantum well. The quoted thicknesses are "nominal", as calibrated on a planar (100) sample. Fig. 1(a) shows a cross-sectional TEM image of the QWR's region of a typical sample used in our experiments. We observe that the thickness of the quantum well varies along the direction perpendicular to the plane, thus strengthening the confinement. In this way the QWR is formed at the bottom of the V-groove. For the transport measurements, multiple contact samples were fabricated using standard photolithography techniques with a mesa etched along the QWR and with

Au/Ge/Ni ohmic contacts, as shown in Fig. 1(b). Additionally, narrow (0.5 μm) Ti/Au Schottky gates were formed using electron beam lithography in order to isolate the QWR and control the number of 1D subbands in it.

The conductance of the wire was measured using a four-terminal AC method and lock-in amplifier detection [schematically shown in Fig. 1(b)]. If the 2DEG is not depleted in the sidewalls, the electronic transport in our system is carried by both the electrons in the 2D sidewalls and in the 1D quantum wire in parallel. By applying negative voltage to the Schottky gate deposited on top of the mesa, one can fully deplete the 2DEG in the sidewalls and thus isolate a section in which there are electrons only in the 1D wire[16]. At a certain range of the negative voltage a single populated 1D channel is realized. It would be natural to think that the length of the 1D region is determined by the width of the gate. However, as was demonstrated in our studies [17], the electrons remain at their one-dimensional state during a transition length Δ [see Fig. 1(b)] on both sides of the gate. This transition length arises from the poor coupling between the 1D states and the 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 extensively studied in our previous experiments [17], and was found to be as large as $\Delta = 2\ \mu m$. From the above discussion it is reasonable to conclude that the effective length of the 1D wire (although not being accurately defined) actually exceeds the actual width of the gate (0.5 μm), since the electrons stay on average for another 2 μm in the QWR before being scattered to the 2DEG on each side of the gate.

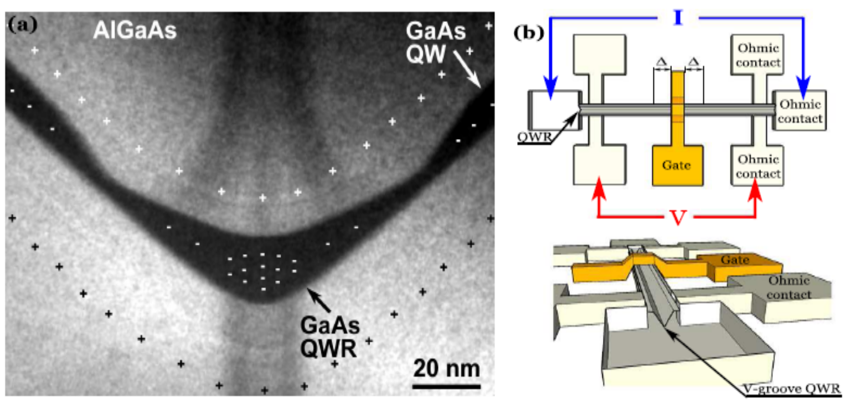

Figure1. (a) Cross-sectional TEM image of the QWR's region, on which the charge distribution due to the doping is schematically shown. (b) Top and perspective view schematic images of the device's geometry. The QWR is present at the bottom of the V-groove aligned with the mesa structure.

3. Experimental Results

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

100mK and 4.2 K. The electronic temperature of GaAs 2DEG does not deviate from the bath temperature for T>100 mK as shown in our previous studies[18]. 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 Ω, measured at V_g=0, has been subtracted from all curves. At 4.2 K the conductance plateau is smooth with $G=0.94\cdot 2e^2/h$, 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.[19] The variation of the plateau value (approximately 20%) through the wide temperature range (1.5 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.

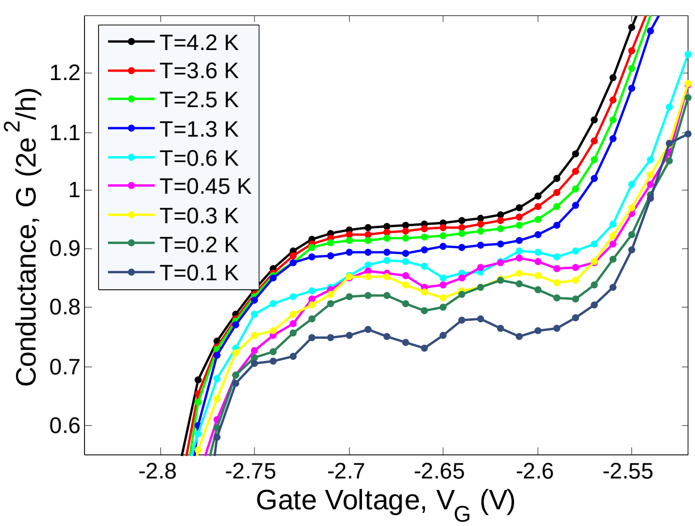

Figure 2. Conductance vs. gate voltage V_g for 0.5 μm gate width at various temperatures, after subtraction of series resistance.

Early theories, particularly those of Kane and Fisher[6] (and of Ogata and Fukuyama[7]), 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

$$G'(T)=g\cdot(2e^2/h)\cdot[1-(T/T_0)^{g-1}] \tag{1}$$

Here, $g<1$ is a dimensionless parameter, which is a measure of the strength of the interactions. For repulsive interactions, g is given roughly by the expression $g^2=1/[1+(U/2E_F)]$, 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 $T\sim T_0$ the corrections to G(T) become of order $(2e^2/h)$. Both theories predict a correction of $g\cdot(2e^2/h)$ even for ballistic wires at relatively high temperatures. These imply that for sufficiently long wires, one cannot observe values close to $2e^2/h$ in GaAs, since the value of g is expected to be of the order of ≈ 0.7 in such wires, as was already pointed out by Tarucha *et al.*[12]
This contradiction was also addressed in detail in several theoretical papers.[8,9,20-22]
According to the theory of Maslov,[9] the interaction parameter g of the wire determines the exponent of the temperature variation, whereas the pre-factor g in equation (1) should be set to 1 (for non-interacting 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.[9] They also demonstrated that for an infinite clean wire, the conductance keeps the universal value $2e^2/h$ 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 (1) are modified in the following way:

$$G(T)=2g\cdot G'(T)/[(h/e^2)\cdot(g-1)\cdot G'(T)+2g] \quad (2)$$

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.[8]
As one can see from Fig. 3, an excellent fit is obtained for both theories,[8,9] and we obtain $g=0.64\pm0.05$, as is expected for electrons in GaAs wires. Indeed, this value is consistent with the experiments in Ref. 10, showing g values between 0.66 and 0.82. Moreover, using the Fermi energy $E_F\approx 1.5\pm0.5$ meV (half of level spacing between 1D sub-bands estimated in our previous experiments,[16] we calculate the corresponding electron densities at the middle of the plateau, obtaining $n_{1D}=3.2\pm0.5\cdot10^5$ cm^{-1}. Substituting the above value for n_{1D} into $U=(e^2/\varepsilon)\cdot n_{1D}$ we get $U=3.85\pm0.60$ meV which yields the values of $g=0.66\pm0.04$, 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.[23] 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.[24] Optical and structural studies indicate the formation of localizingpotential wells along the wires with size in the range of several 10 nm.[25]
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 $T_0<2$ mK, similar values of g, namely $g=0.66$. However,

other wires with stronger disorder (T_0>2 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.

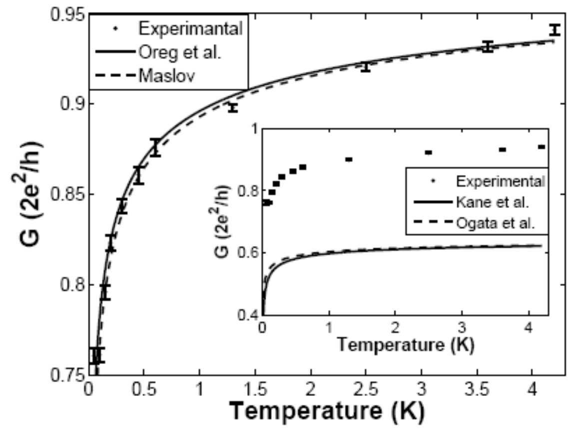

Figure 3. Conductance values of the first plateau vs. temperature in the wire of Fig. 2 (points with error bars). Both theoretical expressions are plotted for the same parameters, e.g. g=0.64 and T_0=0.7 mK of equation (2).

The values of the total change in ΔG/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 a complete correspondence between the two indicators for the strength of the disorder, T_0 and ΔG/G.

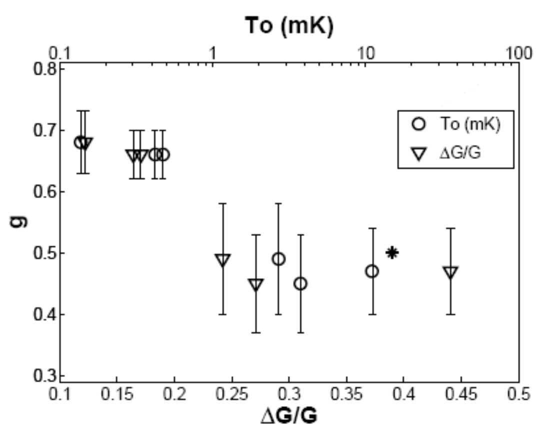

Figure 4. Interaction parameter g vs. disorder parameter T_0. and the values of ΔG/G (in the temperature range 0.1-4.2 K) The star represents an estimate for the strength of the disorder of the results reported in Ref. 14. The wrong values of g≈0.5 (at high disorder) are established by using the perturbation formula in a region where it is inapplicable.

The transition between g=0.66 and g=0.5 at $T_0 \approx 2$ mK occurs for $\Delta G/G \approx 23\%$. We believe that above $T_0 \approx 2$ 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,[25] or stronger backscattering[26] in the system. The results of conductance measurements in GaAs wires reported recently by Rother *et al.*[14] also correspond to highly disordered samples, and also give g=0.5. Indeed, analyzing their data, we estimate the value of $T_0 \approx 15$ 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 disordered sample in the same temperature range.

It is highly unlikely that the observed temperature dependence could be attributed to the contact resistance between the 2DEG and the 1D subbands outside the gated region for the reasons outlined below:

a) if the contact resistance is treated quantum mechanically,[13] namely as a change of the transmission from the 2DEG to the 1D subbands in the ungated region, we would expect that $\Delta G/G$ would be similar for any number of 1D channels under the gate. We however observe that $\Delta G_1/G_1$ of the first plateau is much smaller than $\Delta G_2/G_2$ of the second plateau at the same temperature range. The latter, however, is consistent with the expected result of the Luttinger model when the scattering occurs under the gated region, since the effect of the Coulomb interaction on the transmission depends on the number of 1D subbands. Indeed, from an analysis of higher steps in the conduction depletion curve, used in a smaller temperature range (0.1-0.6 K, where the plateaux are better resolved), we deduce the values g=0.55 and g=0.47 for the second and the third plateaux, respectively, which agrees with the theoretical values of 0.54 and 0.47.[9]

b) if the decrease of the conductance is considered as an additional contact resistance added in series to the wire (i.e., treated classically), than the values of the transmission for each channel at low temperature at the second plateau would increase with lowering temperature and eventually exceed unity for each channel. Therefore, we conclude that the observed decrease of the conductance is due to the interactions in the LL model.

4. Conclusions

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[8,9] based on the LL model, in the limit of weak disorder in the system. We showed that the use of the perturbative result (namely $G' \propto T^{g-1}$) in order to estimate g, is valid only for wires produced with a *moderat*e amount of disorder (T_0<1 mK).

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