Luttinger-Liquid Behavior in Weakly Disordered Quantum Wires

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We have measured the temperature dependence of the conductance in long V-groove quantum wires fabricated in GaAs/AlGaAs heterostructures. Our data are 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 quantum wires, the value of the interaction parameter $g \cong 0.66$, 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.

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The electrical conductance through noninteracting clean quantum wires (QWRs) containing a number of one-dimensional subbands is quantized in the universal unit $2e^2/h$ [1], 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 [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 [9,10]. The most evident proofs of the predictions were shown in *tunneling* experiments performed in T-shaped cleaved-edged overgrown GaAs quantum wires [9] and in carbon nanotubes [10]. Earlier *nontunneling* 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 [11–13]. 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 the 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 [7,8] 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 mbar) metal-organic 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 230 nm GaAs buffer layer, a 1.1 μm $Al_{0.27}Ga_{0.73}As$ lower barrier layer, a 14 nm GaAs quantum well (QW) layer, a 160 nm $Al_{0.27}Ga_{0.73}As$ upper barrier layer, and a 10 nm GaAs cap layer. All layers were nominally undoped, except for two 20 nm Si-doped ($\approx 1 \times 10^{18}$ cm^{-3}) regions in the $Al_{0.27}Ga_{0.73}As$ barriers, spaced by 80 and 60 nm, respectively, from the lower and the 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 in Fig. 1). The modulation doping yields a 1D elec-

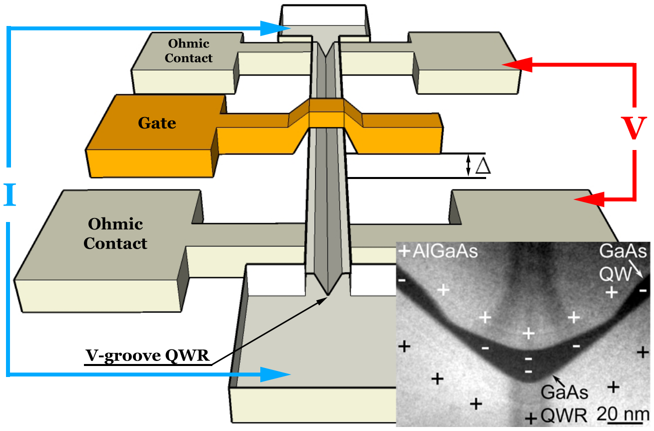

FIG. 1 (color online). Schematic diagram of the device's geometry. The QWR is located at the bottom of the V groove. The inset shows a cross-sectional TEM image of the wire, on which the charge distribution is schematically depicted.

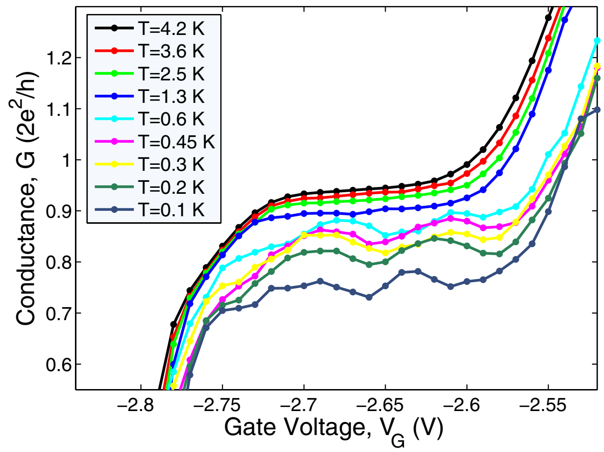

FIG. 2 (color online). Conductance vs gate voltage V_g for 0.5 μm gate width at various temperatures, after subtraction of series resistance.

tron gas confined to the wire, laterally connected to 2DEG systems that form on the $\{111\}A$ QWs.

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 μm) 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 $k_B T/e$ 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 [16], the electrons remain at their one-dimensional state during a transition length Δ (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 or from the 2DEG, was found to be as large as $\Delta = 2$ μm [16]. It is thus reasonable to conclude that the effective length of the 1D wire exceeds the actual width of the gate (0.5 μm) by about 2 μm on each side of the gate.

Figure 2 shows the variation of the conductance with gate voltage V_g, in the range where electrons populate only a single 1D subband, 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 were 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 $G = 0.94 \times (2e^2/h)$, 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 appear-

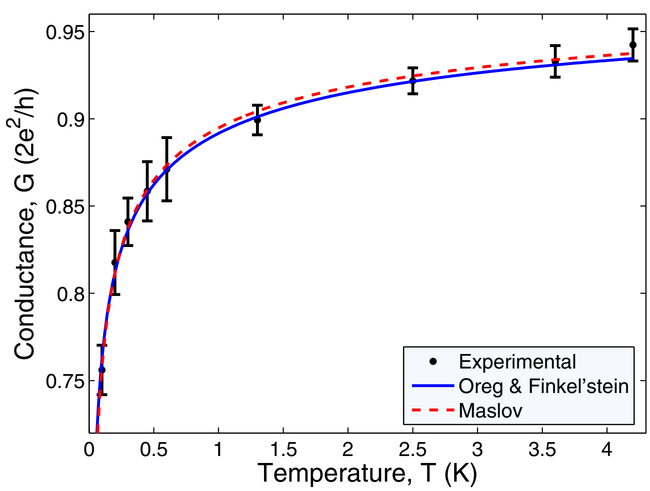

FIG. 3 (color online). Conductance values of the first plateau vs temperature in the wire of Fig. 2 (points with error bars). Both theoretical expressions are plotted for the same parameters, e.g., $g = 0.64$ and $T_0 = 0.7$ mK of Eq. (2).

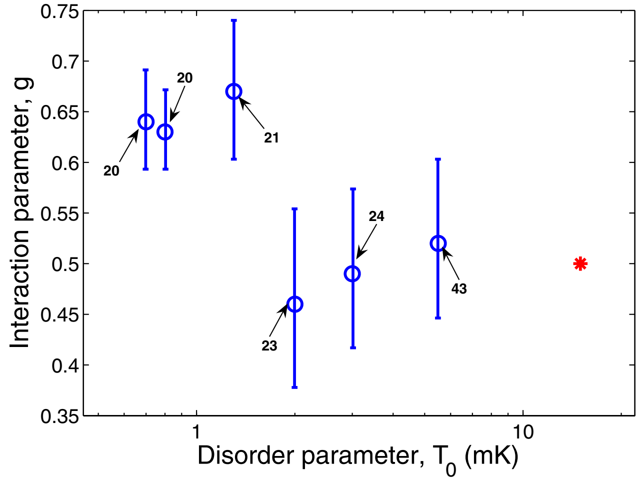

FIG. 4 (color online). Interaction parameter g vs disorder parameter T_0. The values of $\Delta G/G$ (in the temperature range 0.1–4.2 K) expressed in percentage are shown for each point. The star represents an estimate for the strength of the disorder of the results reported in Ref. [13]. The wrong values of $g \approx 0.5$ (at high disorder) are established by using the perturbation formula in a region where it is inapplicable.

ance 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. Figure 3 shows the measured variation of conductance versus temperature.

Early theories, particularly those of Kane and Fisher [5] (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

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

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 $g = 1/\sqrt{1 + (U/2E_F)}$, 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 $g(2e^2/h)$ 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 $\simeq 0.7$ in such wires, as was already pointed out by Tarucha *et al.* [11].

This contradiction was also addressed in detail in several theoretical papers [7,8,19–21]. According to the theory of Maslov [7], the interaction parameter g of the wire determines the exponent of the temperature variation, whereas the prefactor g in Eq. (1) should be set to 1 (noninteracting reservoirs). Figure 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 $2e^2/h$ 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 Eq. (1) are modified in the following way:

$$G(T) = \frac{2gG'(T)}{\frac{h}{e^2}(g-1)G'(T) + 2g}. \tag{2}$$

As can be easily verified, the leading term in the temperature variation of the conductance of Eq. (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 $E_F \cong 1.5 \pm 0.5$ meV (half of the level spacing between 1D subbands estimated in our previous experiments [15]), we calculate the corresponding electron densities at the middle of the plateau, obtaining $n_{1D} = 3.2 \pm 0.5 \times 10^5\ \mathrm{cm}^{-1}$. Substituting the above value for n_{1D} into $U = (e^2/\varepsilon) \times n_{1D}$, we get $U = 3.85 \pm 0.60$ 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 localizing 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 the 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 of the wires having a 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 $g = 0.5$. Figure 4 summarizes the values of g vs T_0, obtained for our different wires. The values of the total change $\frac{\Delta G}{G}$ were calculated for each wire in the temperature range 0.1–4.2 K and are also shown in Fig. 4. Note that the wires showing stronger temperature dependence correspond to lower values of g, whereas the wires showing moderate temperature dependence, namely, $\frac{\Delta G}{G} \approx 20\%$, correspond to $g \approx 0.66$. The strength of the temperature dependence is an indicator for the amount of disorder in our wires. The transition between $g = 0.66$ and $g = 0.5$ at $T_0 \approx 2$ mK occurs for $\frac{\Delta G}{G} \approx 23\%$. 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.* [13] also correspond to highly disordered samples and also give $g = 0.5$. Indeed, analyzing their data, we estimate the value of $T_0 \approx 15$ mK (marked by a star in Fig. 4) and the change in the conductance $\frac{\Delta G}{G} \approx 10\%$ 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 [12], namely, as a change of the transmission from the 2DEG to the 1D subbands in the ungated region, we would expect that $\frac{\Delta G}{G}$ 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 [8]. (b) If the decrease of the conductance is considered as an additional contact resistance added in series to the wire (i.e., treated classically), then the values of the transmission for each channel at low temperature 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.

In conclusion, we have measured the temperature dependence of the electrical conductance in single mode quantum wires. We find that our data are consistent with theoretical calculations [7,8] 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 *moderate* amount of disorder ($T_0 < 2$ mK).

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