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Evidence of Luttinger liquid behavior in GaAs/AlGaAs quantum wires

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Abstract

We present low-temperature measurements of the ballistic transport in high-quality quantum wires. As the Fermi energy is varied, the conductance of these wires exhibits quantized plateaus at values lower than integer multiples of $2e^2/h$. We observe Luttinger liquid power laws in the temperature dependence of the plateau conductances as well as in the non-linear current–voltage characteristics. From these power laws we extract the Luttinger liquid scaling exponent α_N as a function of the Fermi energy and the number of occupied subbands. © 2000 Elsevier Science B.V. All rights reserved.

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One of the most important features of ballistic transport in non-interacting one-dimensional electron systems (1DES) is the quantization of the conductance in integer multiples of $G_0 = 2e^2/h$ [1]. In real 1DES electron–electron interaction is expected to lead to a considerable deviation from this exact quantization. These 1DES are theoretically described in the framework of the Luttinger liquid theory. According to this theory the electron–electron interactions show up in the conductance of the quantum wire (QWR) in a twofold manner. First, the interactions lead to a renormalization of the conductance $G = g \cdot G_0$ by an interaction-dependent factor g. It has been shown, however, that this renormalization of the conductance does not take place when Fermi liquid contacts are attached to the QWR [2,3]. Second, in combination with a small amount of disorder, which is inevitably present in real samples, the electron–electron interactions are expected to lead to a characteristic power-law dependence of the conductance on the temperature or the applied voltage [4,5]. The scaling exponent of these power laws is a characteristic fingerprint of the electron–electron interaction in the QWR. While deviations from the exact quantization have been observed in other experiments [6,7], no systematic search for the predictions of the Luttinger

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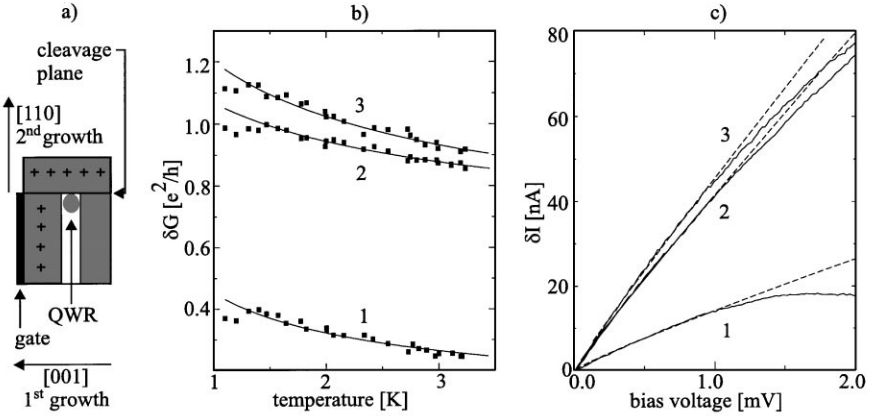

Fig. 1. (a) The schematic drawing of the sample structure shows the modulation doped quantum well grown in the first growth step on the GaAs [0 0 1] plane and the modulation doping sequence grown in the second growth step on the [1 1 0] cleavage plane. Applying a negative bias voltage to a narrow gate on the sample surface separates the two-dimensional electron gas, generated in the quantum well by the modulation doping in the [0 0 1] plane, into two sheets. These two-dimensional electron systems then serve as contacts to the QWR whose electron density can be varied by the same gate. The width of the gate thus defines the length of the QWR which was 2 μm in our experiments. (b) The temperature-dependent deviation of the conductance from the exact quantization in integer multiples of $2e^2/h$ for the lowest three subbands. The solid lines indicate a fit with the Luttinger liquid power law. (c) The deviation of the current from the current corresponding to exact quantization versus the bias voltage. The curves were taken at the same electron densities in the lowest three subbands as the temperature dependence in plot (b). The dashed lines indicate a fit of the Luttinger liquid power law at voltages less the 1 mV.

liquid theory has been carried out so far. In this paper we present an experimental determination of the scaling exponent as a function of the Fermi energy and the number of occupied subbands in the QWR both from measurements of the temperature dependence of the conductance and of the non-linear current–voltage characteristics.

We have fabricated high-quality QWRs using molecular beam epitaxy (MBE) and the cleaved edge overgrowth technique [8]. This fabrication process has been described in detail in Ref. [7]. We start with a modulation doped quantum well of 400 Å thickness on the GaAs [0 0 1] surface. This sample is then cleaved in situ in the MBE chamber and a modulation doping sequence is grown on the atomically smooth GaAs [1 1 0] surface immediately after the cleavage step. A schematic drawing of the sample structure is shown in Fig. 1(a). The QWR is then confined by the quantum well potential and by the triangular potential arising from the modulation doping sequence on the cleavage plane. A gate on the [0 0 1] surface allows the continous variation of the electron density within the 2 μm long QWR. As a function of the gate voltage and therefore the 1D electron density our QWRs show quantized plateaus at conductance values significantly smaller than expected for exact quantization.

Fig. 1(b) shows the deviation $\delta G = NG_0 - G$ of the differential conductance from the exact quantization as a function of the temperature measured with standard lock-in techniques at an excitation voltage of 10 μV. These temperature dependencies were measured roughly in the middle of the conductance plateaus of the lowest three subbands. For a QWR subject to slight disorder with Fermi liquid contacts Luttinger liquid theory predicts, that these deviations exhibit a power-law behavior as the temperature is changed: $\delta G \propto T^{-\alpha_N}$ [5]. The solid lines indicate a fit of this power law to the experimental data. We now perform this analysis for all gate voltages within the individual conductance plateaus and therefore obtain the scaling exponent α_N as a function of the Fermi energy and the number of occupied subbands N. Care must be taken to choose the proper temperature range for the evaluation of the data because the finite length of the QWR leads to a cut-off to Luttinger liquid behavior at temperatures below $T_c = \hbar v_F/(k_B L)$ [4]. Here v_F denotes the Fermi velocity, L the length of the QWR and k_B the Boltzmann constant. This cut-off temperature can be estimated to be less than 1 K for our QWRs. At temperatures higher than approximately 5 K thermal broadening hinders the evaluation, so we use a fitting range $1.5\ \mathrm{K} < T < 4\ \mathrm{K}$.

Since the scaling exponent α_N is a fundamental parameter of the Luttinger liquid, it also shows up in other quantities of the 1DES which are experimentally accessible. One of these quantities is the current–voltage characteristic. The current is expected to vary non-linearly with the applied bias voltage V, following a power-law similar to the power law describing the temperature dependence, i.e. the deviation $\delta I = I_0 - I$ of the current I from the current $I_0 = NG_0V$ corresponding to exact quantization is given by $\delta I \propto V^{1-\alpha_N}$ [4]. Fig. 1(c) shows this deviation versus the bias voltage at a temperature of 0.35 K for the same electron densities in the lowest three subbands, where the temperature-dependent measurements of Fig. 1(b) have been taken. Again we use the appropriate power law to extract the parameter α_N from these non-linear *IV* characteristics as a funtion of the Fermi energy and the subband number N. Up to voltages of 1 mV the current can be fitted very well with a power-law characteristic whereas at higher bias voltages the current can no longer be described with a power law.

As a result we obtain the Luttinger liquid scaling exponent α_N as a function of the gate voltage as shown in Fig. 2. The solid line represents the conductance of the QWR and is shown to identify the individual subbands. We find that the α_N obtained from the temperature dependence of the conductance (filled squares) and the α_N obtained from the non-linear current–voltage characteristics (open squares) agree very well. The only exception is the first subband whose width is quite small and thus hampers proper measurement of *IV* characteristics. The values of α_N are in the range of 0.1 to 0.5 which indicates repulsive electron–electron interaction. The value of 0.5 for α_1 in the first subband, though exceptionally large as compared to the other subbands, is in good agreement with the value given by Tarucha et al. [6]. Within the indiviual subbands α_N stays approximately constant. This comes as a surprise, because the electron–electron interaction is expected to depend strongly on the electron density resulting in a Fermi energy dependency of α_N. One could speculate, that a part of the Luttinger liquid behavior takes place in the contact regions where the electron states of the QWR overlap with the electron states of the contact areas. Since these regions are not influenced by the gate voltage, their temperature-dependent influence on the conductance would be independent of the gate voltage. However, this clearly contradicts the experimental finding of different scaling exponents for the individual subbands occupied as a function of the gate voltage. As the subband number N is increased, α_N shows a slight variation but no clear increase or decrease. The $1/N$-behavior predicted by the theory cannot be observed [9,10]. However, this behavior is expected in the limit $N \gg 1$. In the few channel regime realized in the experiment, the properties of the individual subbands, expressed by their wave functions and electron densities, may dominate the general $1/N$-behavior.

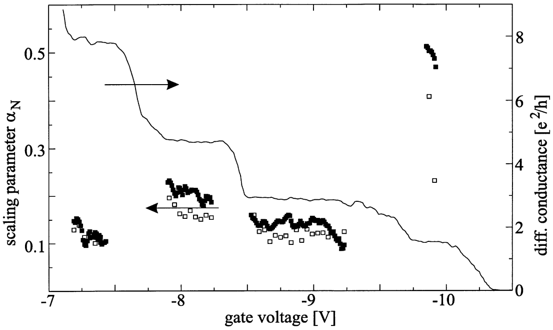

Fig. 2. The scaling exponent α_N as a function of the gate voltage and therefore as a function of the Fermi energy and the subband number N in the QWR. The filled squares show the α_N values obtained from the temperature dependence of the conductance, the open squares show α_N obtained from the non-linear current–voltage characteristics. The solid line shows the conductance of the QWR versus the gate voltage.

In summary, we have observed a power-law temperature dependence of the quantized conductance plateaus and of the non-linear current–voltage characteristics in high-quality ballistic QWRs. From these power laws we calculate the Luttinger liquid scaling exponent α_N as a function of the Fermi energy and the number of occupied subbands. The values for α_N obtained from both of these independent measurements agree very well. The scaling exponent α_N stays approximately constant within each individual subband and shows no monotonic behavior as the subband number is changed.

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