Nonuniversal Conductance Quantization in Quantum Wires

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We have measured the transport properties of high-quality quantum wires fabricated in GaAs-AlGaAs by using cleaved edge overgrowth. The low temperature conductance is quantized as the electron density in the wire is varied. While the values of the conductance plateaus are reproducible, they deviate from multiples of the universal value of $2e^2/h$ by as much as 25%. As the temperature or dc bias increases the conductance steps approach the universal value. Several aspects of the data can be explained qualitatively using Luttinger liquid theory although there remain major inconsistencies with such an interpretation. [S0031-9007(96)01675-4]

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One-dimensional (1D) electronic systems, so-called Luttinger liquids, are expected to show unique transport behavior as a consequence of the Coulomb interaction between carriers [1–4]. Even for Coulomb energies smaller than the electron kinetic energy correlated electron behavior is expected. Because of the large quantum mechanical zero point motion of the electrons, these correlations are short ranged and their spatial extent is expected to increase in a power law manner as the system's temperature is lowered [4]. The longer correlation length causes the system to be more susceptible to pinning by local impurities. Therefore the conductance of a 1D system is expected to be suppressed at low temperature even for a wire with just a few impurities [4–6]. This remarkable results as well as many other non-Fermi liquid properties of the Luttinger model remain largely untested by experiments due to the lack of a suitable 1D wire [7].

One of the fingerprints of a noninteracting 1D conductor is its quantized conductance in multiples of the universal value $G_O = 2e^2/h$ [8]. This quantization results from an exact compensation of the increasing electron velocity and the decreasing density of states as the number of carriers increases. Therefore, as subsequent 1D electronic subband are filled with electrons, the conductance appears as a series of plateaus or steps with values equal to G_Q multiplied by the number of partly occupied wire modes (N).

In an earlier publication, mainly focusing on our novel wire fabrication process, we determined the transport mean free path as well as the energy and mode spectrum in the wire using magneto-transport spectroscopy [9]. The exceptionally long transport mean free path in excess of 10 μm and the exceedingly large subband spacing of 20 meV make these wires ideal for studying effects of electron-electron $(e\text{-}e)$ interactions in 1D. Here we present results of such an investigation as temperature and bias voltage are varied.

Transport through the wires at low temperatures (0.3 K) presents a significant mystery. Although the wire's conductance is quantized in equal steps showing plateaus that are flat to within 5%, the quantized conductance is reproducibly lower than NG_Q. This reduction is of fixed amount for a particular wire width and can be as large as 25%. At higher temperatures and dc biases the conductance approaches NG_Q. We discuss three different models to put our unexpected findings in their proper context. While some aspects of the data can be reproduced qualitatively, none of the scenarios provides a satisfactory interpretation of all our observations.

The exceptional quality of the 1D wires is central to our ability to obtain high quality, reproducible data. For this reason we reiterate the intricate fabrication process.

Wire fabrication by cleaved edge overgrowth [10] and the unique, *in situ* contacting scheme are shown in Fig. 1. The starting point is a modulation doped GaAs quantum well of 14, 25, or 40 nm thickness embedded between two

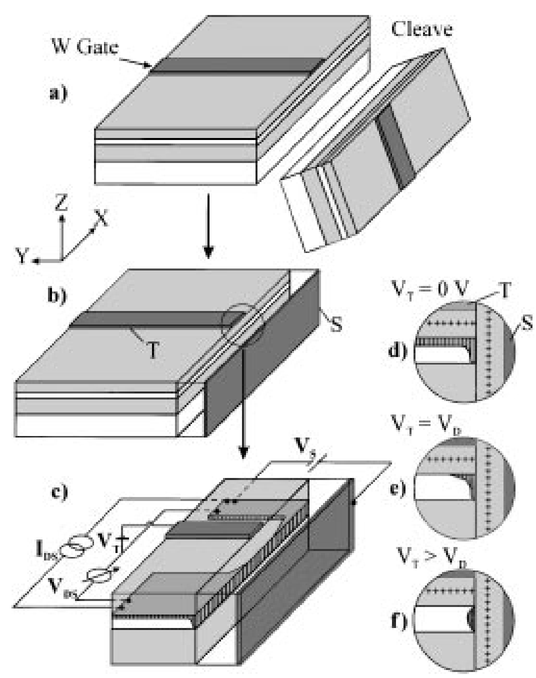

FIG. 1. (a) Wire preparation by cleaved edge overgrowth of GaAs-AlGaAs by molecular-beam epitaxy. For details see text.

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thick AlGaAs layers and doped from the top [Fig. 1(a)]. The resulting two-dimensional electron gas (2DEG) resides 500 nm below the top surface, has an electron density $n \approx (1-2) \times 10^{11}$ cm^{-2}, and a mobility $\mu \geq 3 \times 10^6$ cm^2/V sec. A long and narrow evaporated tungsten stripe [Fig. 1(a)] will later define the 1D wire region. The quantum wire itself is fabricated by cleaving the specimen in ultrahigh vacuum and overgrowing the smooth cleavage plane with a second modulation doping sequence [Figs. 1(a) and 1(b)]. This introduces electrons at the edge of the quantum well [see Fig. 1(d)] creating one or more confined edge states along the cleave. Strong overlap between the 2DEG and the edge states couple both systems intimately along the entire edge. The 1D wire region is obtained by decoupling the edge states from the 2DEG with the help of the tungsten gate (T), which, after the cleave, extends exactly to the edge of the quantum well. Figure 1(c) shows a blowup of the critical device region under suitable bias conditions. In essence, the top gate (T) separates the 2DEG into two sheets that connect, through the edge states, to the 1D wire. The side gate (S), only 200 nm from the cleaved edge, primarily serves to vary the electrons density along the edge.

Figures 1(d), 1(e), and 1(f) show a sequence of schematic cross sections of charge distributions in the wire region for different top-gate voltages V_{T}. As V_{T} is biased increasingly negative the 2DEG is separated and the 1D wire becomes firmly confined in two dimensions: in the z direction by the quantum well and in the y direction by the strong triangular potential of the cleaved-edge modulation-doping sequence. Electrons in such cleaved edge overgrowth wires are confined on three sides by atomically smooth barriers and on the fourth side by a strong electric field. It is important to realize that the top gate affects only the density in the *wire region* and the side gate affects the density in the *entire edge.* For strongest 1D confinement the top gate is biased negatively and the side gate strongly positively pushing the electrons against the cleaved edge of the quantum well.

Electronic transport measurements on the quantum wires are performed in a pumped He^3 cryostat using an excitation voltage of $V_{\mathrm{ex}} = 10\ \mu$V at 16 Hz in the contact configuration shown in Fig. 1(c). Figure 2 shows the linear response conductance of a wire embedded in a 25 nm quantum well as a function of V_{T}. Clear conductance quantization is observed. Importantly, the values of the conductance plateaus are markedly different from NG_Q (dotted lines) and seem to be quantized in units of $0.85 \times (2e^2/h)$. This nonuniversal value is reproducible to within 5% in all wires fabricated from the same quantum well material even if it was cleaved and overgrown in separate runs. However, wires made with different quantum well widths give different values. The 40, 25, and 14 nm quantum wells have prefactors 0.9, 0.85, and 0.8, respectively. The plateaus are flat to within 5% and their existence demonstrates that deviations from universality are independent of electron density in the wire. Constant step height between

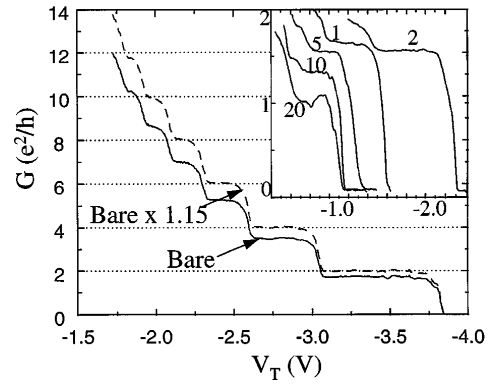

FIG. 2. Linear response conductance of a 2 μm long wire in a 25 nm quantum well vs the top-gate voltage (V_T) measured at a temperature of 0.3 K. The solid line is the measured conductance. The dashed curve is the measured conductance multiplied by an empirical factor of 1.15. Inset: Linear response conductance of the last plateau for wires of different lengths fabricated consecutively along the edge of a single 25 nm cleaved edge overgrowth specimen. The numbers denote the wire length in microns.

plateaus rules out a single series resistance as the origin of nonuniversality. In such a case the step height would have to decrease for the higher modes.

The effect of temperature on the wire conductance is shown in Fig. 3. At high temperatures the higher plateaus degrade due to the thermal population of the more closely spaced upper subbands [8]. However, the lowest plateau remains flat even at 20 K with a value approaching G_Q at high enough temperatures. The rigid rise, preserving the plateau, suggests once more that there is no dependence on the electron density in the wire. The temperature dependence of the higher plateaus, $G_N(T)$, is stronger and appears to be given by $G_N(T) = NG_1(T)$. This suggests that each mode contributes an equal amount to the total

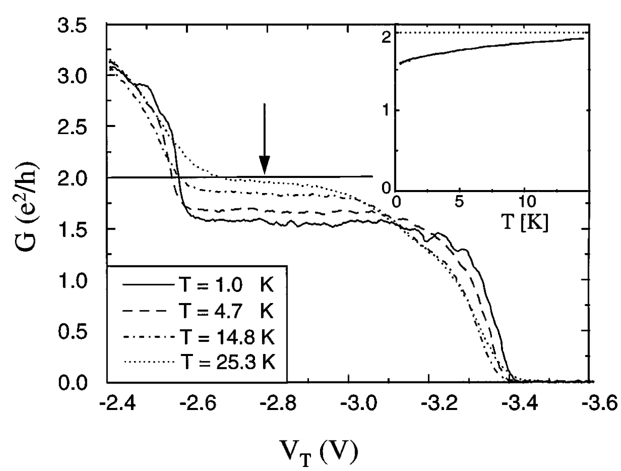

FIG. 3. Differential conductance of a 2 μm long wire in a 25 nm quantum well vs top-gate voltage (V_{T}). The different curves correspond to different temperatures. Inset: The differential conductance vs temperature for a value of V_{T} marked by the arrow.

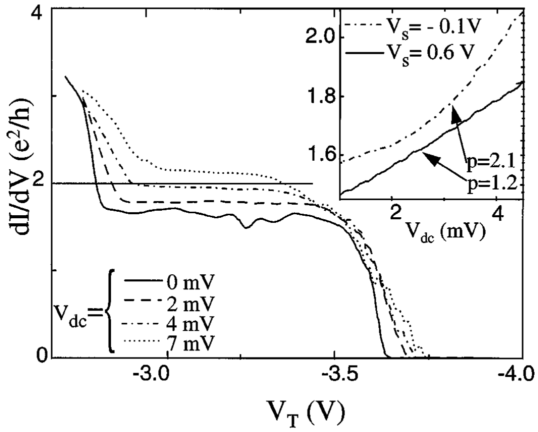

FIG. 4. Differential conductance of a 2 μm long wire in a 25 nm quantum well vs top-gate voltage (V_{T}). The different curves correspond to different dc biases. Inset: Differential conductance vs dc bias. The different curves correspond to different side-gate voltages and hence different density of the edge modes. The differential conductance is fitted to a power law ($dI/dV = c + AV_{\mathrm{dc}}^{p}$). The value of p for each of the densities is noted.

conductance at any given temperature. The inset to Fig. 3 contains the temperature dependence of the lowest plateau for a fixed V_T (marked by an arrow in Fig. 3).

A similar increase is observed in the nonlinear differential conductance (dI/dV) shown in Fig. 4. dI/dV is directly measured by superimposing an ac signal on the dc bias (V_{dc}). Again, the plateaus rise rigidly with dc bias, suggesting no dependence on wire density. At sufficiently large biases dI/dV even exceeds G_Q. However, the dc conductance (I/V) remains below G_Q throughout the entire range of dc bias studied.

Our findings can be summarized as follows: (1) The wire conductance is quantized in equal steps that differ reproducibly from the universal value by as much as 25%, i.e., $G(V_{\mathrm{T}}) = Ng(2e^2/h)$, where $g < 1$. (2) The conductance plateaus are flat implying insensitivity to electron density. They remain flat at elevated temperatures and dc biases. (3) The wire conductance approaches the universal values as the temperature increases. (4) The nonlinear differential conductance increases with increasing bias and even exceeds the universal value of $2e^2/h$. The dc conductance approaches $2e^2/h$. (5) The behavior summarized above is observed in all 15 wire samples we studied.

We discuss now three different theoretical models in an attempt to explain our results. In the first model we assume noninteracting electrons both in the wire and in the contact regions. Landauer's formula in the absence of disorder and, hence, for ideal transmission probability predicts conductance quantization, namely, $G = NG_Q$. Reduced conductance of our wires may then arise from a nonideal electron transmission [8]. Two experimental observations speak against such a possibility. The observation of flat plateaus implies energy independent transmission probability; a very unlikely possibility. Also, the observed strong temperature dependence rules out such an unlikely interpretation. It is a very general ingredient of any noninteracting theory that for an energy independent transmission probability the conductance is also temperature independent [8]. This is in contradiction with experiment.

The second model considers the role of e-e interactions in the wire. In Luttinger liquid theory interaction effects in an *infinite* wire reduce the conductance to below $2e^2/h$ [3,4]. However, for a *finite* wire without disorder, *coupled to Fermi liquid (noninteracting) leads,* the predicted conductance is always $2e^2/h$ [11–13]. Therefore, within this framework, one must invoke disorder in order to explain the lower conductance [7]. Such a situation was recently studied theoretically by Maslov [14] and experimentally by Tarucha *et al.* [15] who found the conductance to decrease from $2e^2/h$ in a power law fashion as $T \rightarrow 0$. Moreover, the zero temperature conductance is expected to be finite and to decrease with increasing wire length, qualitatively agreeing with the data in the insets of Figs. 2 and 3. However, in Maslov's theory as in Luttinger liquid theory in general [4] both the strength of the e-e interactions and the scale of the temperature dependence are determined by the electron density; in contradiction with the observed flat plateaus and the conductance steps of equal height. Therefore, e-e interactions in a finite disordered wire can account only for a subset of the experimental observations.

The assumption of Fermi liquid behavior in the leads, underlying Maslov's model, is not necessarily met in our experiment. The cleaved edge overgrowth geometry forces the electrons against the cleavage plane creating 1D edge states along the *entire* edge: in the wire as well as in the 2DEG. Since these edge states are part of the leads, non-Fermi liquid behavior may indeed exist. Exact modeling of such a system is beyond our ability. However, we can evaluate some aspects of the lead configuration and compare the implications with experiment. We therefore consider a third model which associates the reduced conductance with the competition between the scattering from the 2DEG to the edge modes and the backscattering in them. Electron transport through the wire should be viewed as a sequential process of scattering from the 2DEG into the edge states, proceeding along the edge modes while coupled to the 2DEG, entering and traversing the wire, exiting the wire, and preceding along the edge modes on the opposite side of the wire until being scattered out into the other 2DEG contact. The 2DEG states and the edge modes are orthogonal, and the Fermi energy in the edge states ($>$20 meV) far exceeds E_F in the 2DEG ($\approx$10 meV). Therefore, the momenta of electrons at the Fermi level in both systems are highly disparate and electron transfer between them requires a scattering process involving an impurity or defect along the edge.

We model this transport by taking a Boltzmann approach. For simplicity we consider only one mode along the edge and in the wire. We define the local density of right and left movers in this mode as $\mathbf{n}_R(x)$ and $\mathbf{n}_L(x)$, respectively, and introduce two phenomenological scattering rates. The first is the edge mode backscattering rate per unit length Γ_{BS} which scatters a right mover into a left mover and vice versa. The second coefficient Γ_{2D} describes the scattering rate per unit length between the 2DEG and either the right or left movers. The steady-state Boltzmann equation for the right movers in contact with the 2DEG to the right of the wire is $v_R \frac{\partial \mathbf{n}_R}{\partial x} = \mathbf{n}_R^{\mathrm{2D}} \Gamma_{\mathrm{2D}} + \mathbf{n}_L \Gamma_{\mathrm{BS}} - \mathbf{n}_R(\Gamma_{\mathrm{2D}} + \Gamma_{\mathrm{BS}})$, where v_R is the velocity of the right movers (also equal to the Fermi velocity, v) and $\mathbf{n}_R^{\mathrm{2D}}$ is the effective density of the 2DEG to the right of the wire [16]. Similar equations can be written for the left movers and for both movers in contact with the 2DEG to the left of the wire. Solving this set of equations for the current through the wire, defined as $I = ev[\mathbf{n}_R(L) - \mathbf{n}_L(-L)]$, yields $I = ev(\mathbf{n}_R^{\mathrm{2D}} - \mathbf{n}_L^{\mathrm{2D}})/\sqrt{1 + 2\Gamma_{\mathrm{BS}}/\Gamma_{\mathrm{2D}}}$ and hence $G = G_Q/\sqrt{1 + 2\Gamma_{\mathrm{BS}}/\Gamma_{\mathrm{2D}}}$. Therefore, the conductance of the system is indeed lower than the universal one. Note that in the absence of backscattering the predicted conductance is G_Q. Since such a coupling between a wire and the equilibrating reservoirs has not been considered in the literature, it is unclear whether the conductance in this case should be the universal one or the reduced value expected for the case on an infinite wire [3,4]. This model can be easily extended to account for more than one mode. However, the only way to generically obtain conductance steps of equal height is to assume that the modes are completely uncoupled from each other and that the scattering rates associated with each mode are the same. The different density in each of the edge modes make this possibility highly unlikely.

A qualitative understanding of the temperature and dc bias dependence may be obtained in this model by considering the effect of interactions on the scattering rates. Luttinger liquid theory predicts [4] that backscattering along the entire edge is enhanced at low temperatures suggesting a larger Γ_{BS}. Also, scattering from the 2DEG into the edge modes is suppressed at low temperatures due to the vanishing of the tunneling density of states, suggesting a smaller Γ_{2D}. Therefore, the conductance is expected to decrease as the temperature is lowered which is in qualitative agreement with the measurements. This reduced conductance in *not* due to interactions within the wire. In fact, we assume the perfect transmission through the wire not to be altered by interactions provided the scattering mean free path exceeds the wire length. Therefore, the conductance should also not depend on wire density, as is observed in experiment. Furthermore, the conductance is expected to depend on the electron density in the edge modes which can be varied by the side gate S as is indeed found to be the case. The inset to Fig. 4 shows the differential conductance of the wire at fixed V_T at the center of the last plateau for various side-gate voltages V_S. Clearly, the differential conductance increases significantly with dc bias. An empirical fit, $\frac{dI}{dV} = c + AV_{\mathrm{dc}}^p$ yields $p = 1.2$ for the high density case increasing continuously to $p = 2.2$ at the lowest measured edge mode density. Such a behavior is in qualitative agreement with Luttinger liquid theory. Lower densities are expected to generate larger interaction effects manifested through larger powers of the dc bias or temperature [4,5,14]. Two important results, however, are not explained by this Boltzmann-transport model. The first is the observed dependence of plateau value on wire length (see inset to Fig. 2). Since the reduced conductance is a result of the coupling between the edge states and the 2DEG it is unclear why increasing the wire length suppresses it. The second observation is the apparently finite conductance at zero temperature. Since the edge modes are effectively infinite, Luttinger liquid theory [4] predicts that $\Gamma_{\mathrm{2D}} \rightarrow 0$ with decreasing temperature and hence zero conductance. This behavior is clearly not observed, suggesting the onset of coherence between the 2DEG and the edge modes at low temperatures.

It appears that our experimental data on quantized conductance in high quality quantum wires cannot be understood within existing models of either noninteracting or interacting electrons in 1D.

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