Experimental Evidence for Resonant Tunneling in a Luttinger Liquid

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(Received 9 September 1999)

We have measured the low-temperature conductance of a one-dimensional island embedded in a single mode quantum wire. The quantum wire is fabricated using the cleaved edge overgrowth technique and the tunneling is through a single state of the island. Our results show that while the resonance line shape fits the derivative of the Fermi function the intrinsic linewidth decreases in a power law fashion as the temperature is reduced. This behavior agrees quantitatively with Furusaki's model for resonant tunneling in a Luttinger liquid.

PACS numbers: 73.20.Dx, 71.10.Pm, 73.23.–b, 73.50.Jt

One-dimensional (1D) electronic systems are expected to show unique transport behavior as a consequence of the Coulomb interaction between carriers [1]. Unlike in two and three dimensions [2], where the Coulomb interaction affects the transport properties only perturbatively, in 1D it completely modifies the ground state from its well-known Fermi-liquid form, and the Fermi surface is qualitatively altered even for weak interactions. Today, it is well established theoretically that the low-temperature transport properties of interacting 1D-electron systems are described in terms of a Luttinger liquid rather than a Fermi liquid [3–7]. The difference between a Luttinger liquid and a Fermi liquid becomes dramatic already in the presence of a single impurity. According to Landauer's theory, the conductance of a single channel wire with a barrier is given by $G = |t|^2 e^2/h$, where $|t|^2$ is the transmission probability through the barrier. This result holds even at finite temperatures, assuming the transmission probability is independent of energy, as is often the case for barriers that are sufficiently above or below the Fermi energy. In 1D, interactions play a crucial role in that they form charge density correlations. These correlations, similar in nature to charge density waves [8], are easily pinned by even the smallest barrier, resulting in *zero* transmission and, hence, a vanishing conductance at zero temperature. At finite temperatures, the correlation length is finite and the conductance decreases as a power law of temperature, $G(T) \propto T^{(2/g)-2}$ [5,6]. Here $g \approx 1/\sqrt{1 + U/2E_F}$, where U is the Coulomb energy between particles and E_F is the Fermi energy in the wire. Despite the deep theoretical understanding of Luttinger liquids, only a handful of experiments have been interpreted using such models. For example, in clean semiconductor wires prepared by the cleaved edge overgrowth (CEO) method [9], contrary to theory, the conductance is suppressed from its universal value [10]. Although not fully understood, this suppression is believed to be a result of Coulomb interactions that suppress the coupling between the reservoirs and the wire region. Other measurements done on weakly disordered wires [11] show a weak temperature dependence of the conductance that is attributed to the Coulomb forces between electrons in the wire. Finally, The strongest manifestation of interaction in the clean limit comes from tunneling experiments such as the one recently reported on single walled carbon nanotubes [12] and those performed on the chiral Luttinger liquid [13].

In this work, we have focused on the transport properties through confined states in a 1D wire, namely, when a 1D island is embedded in a 1D wire. The 1D island is formed at low densities such that the disorder potential in the wire exceeds the Fermi energy at several points along the wire. Resonant tunneling (RT) has previously been studied experimentally in a chiral Luttinger liquid when the resonant level width was larger than the electron temperature [14,15]. However, an unequivocal verification of the theoretical prediction has not been obtained. Theoretically, the problem of RT has been considered by Kane and Fisher [5] and was later extended by Furusaki [16] to include many resonant levels and the effects of Coulomb blockade (CB). Our measurements probe the intrinsic width, Γ_i, of several resonant states as the temperature is lowered. In contrast to conventional CB theory [17], where Γ_i is temperature independent, we find that Γ_i decreases as a power law of temperature over our entire temperature range (2.5 to 0.25 K). The measured behavior is in quantitative agreement with the theoretical prediction of Furusaki [16].

The 1D wires are fabricated by the CEO method (see Fig. 1a and [9]). The electrons are confined by a 25 nm square well potential in one direction and by a triangular potential well approximately 10 nm wide (binding them to the cleaved edge). To create a 1D island within our wire, we have chosen to study 5 μm long wires that show disorder induced deviations from the conductance plateaus (see Fig. 1b). The wire conductance is measured as a function of its density (by negatively biasing the top gate, see Fig. 1a) using standard lock-in techniques. A fixed excitation voltage of 10 μV is applied across the wire and the corresponding current is measured. As the density of electrons in the wire is reduced, the 1D modes are depopulated one by one until only a single mode remains

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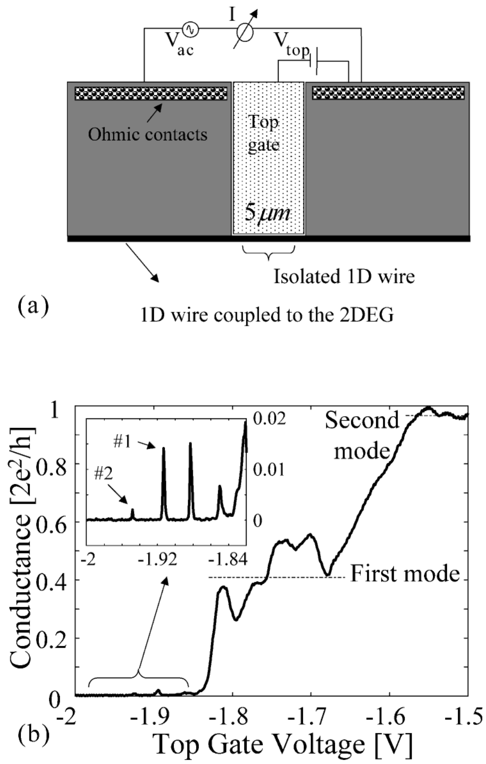

FIG. 1. (a) Top view layout of the wire and its contacting scheme. The sample is fabricated using the CEO method. The 1D wire (thick black line) exists along the cleaved surface and overlaps a 2DEG over the entire edge. The metallic gate depletes the 2DEG over a 5 μm wide segment, thereby, forming an isolated 1D wire that is coupled at its ends to the overlapping 2DEG. A further increase in the top gate voltage reduces the wire density continuously to depletion. (b) Conductance of the wire as a function of the top gate voltage. Inset: A zoom-in of the conductance of the wire in the subthreshold region.

partially populated. Several broad resonances appear superimposed on the "last plateau" with an average conductance of $0.45 \times 2e^2/h$. We attribute the broad resonances to above barrier scattering when the Fermi energy is higher than the disorder potential. The deviation of the conductance plateau from the universal value has been studied in detail in [10]; however, a detailed theoretical explanation is still lacking. It should be noted that, on similar but cleaner wires, we have previously reported [9,10] plateau conductance values of $\approx 0.8 \times 2e^2/h$. The larger deviation observed here suggests that disorder plays an important role in the suppression of the value of the conductance plateaus. As the density is further reduced, the highest potential barrier in the wire crosses the Fermi energy, the last mode is pinched off, and the wire splits into two parts. Upon further decrease in density, a second barrier crosses the Fermi energy, thereby, forming a 1D island, and transport occurs through resonant states. Of course as the density is reduced even further, more islands will form in the wire. However, for transport to occur through them, at least one confined state in each island must be concurrently aligned with the Fermi energy. Since this condition is very unlikely, the wire is expected to be completely pinched off when more than one island has developed. Therefore, the sharp resonances in the subthreshold region, being almost equally spaced in gate voltage, are attributed to CB resonances through a *single* 1D island.

The conductance due to RT of a particle between two Fermi-liquid leads is easily calculated using the Landauer formula, $G_{\rm FL} = \frac{e^2}{h} \int |t(\varepsilon)|^2 \frac{\partial f}{\partial \varepsilon}\, d\varepsilon$, where $|t(\varepsilon)|^2$ has the Breit-Wigner line shape centered around the resonant energy ε_0, $|t(\varepsilon)|^2 = \Gamma_i^2/[(\varepsilon - \varepsilon_0)^2 + \Gamma_i^2]$, and f is the Fermi function. When $k_B T \gg \Gamma_i$, the case of interest here, one finds that $G_{\rm FL} = \frac{e^2}{h} \Gamma_i \frac{\pi}{4k_B T} \cosh^{-2}(\frac{\varepsilon_0 - \mu}{2k_B T})$, with μ the chemical potential in the leads. The main outcome of this analysis is the line shape of the resonance being the derivative of the Fermi function, its full width at half maximum equals $3.53 k_B T$, and the area under the peak (or the peak height multiplied by $k_B T$) is proportional to Γ_i. In the conventional theory of CB [17], Γ_i depends on the transmission probabilities through the individual barriers, which are independent of temperature and, hence, should lead to a peak area independent of temperature. In the case of RT from a Luttinger liquid, the individual transmission probabilities are suppressed as the temperature is lowered [5,6]. Therefore it is expected and has been shown theoretically [16] that the extracted Γ_i should drop to zero as $\Gamma_i \propto T^{(1/g)-1}$. The resonance line shape, however, in the case of $k_B T \gg \Gamma_i$, has been shown [15,16] to be only slightly modified by the interactions, and the change is too small to be detected experimentally. We, therefore, deduce the electron temperature (in units of gate voltage) from the full width at half maximum that we obtain by fitting the resonances to the derivative of the Fermi function. The width of all the resonances in Fig. 1b is the same and follows linearly the ^{3}He refrigerator temperature, as clearly shown in Fig. 2. Such a fit also allows us to

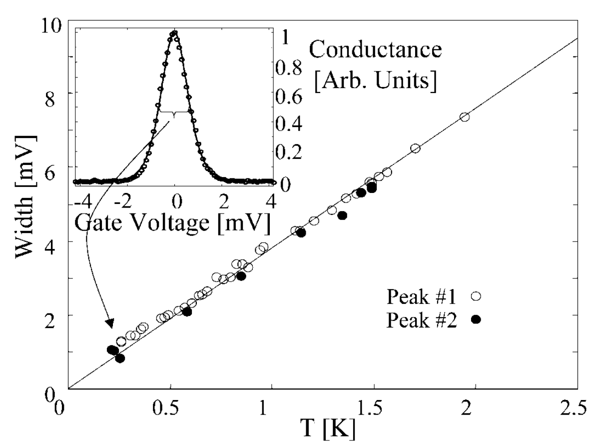

FIG. 2. The full width at half maximum of the resonances marked in Fig. 1b vs the refrigerator temperature. The inset shows an example of a typical fit to the derivative of the Fermi function, from which the width is extracted.

calibrate the gate voltage in units of energy thereby extracting the charging energy (distance between peaks), estimated to be 2.2 meV. Knowing the cross section of the wire, we estimate the length of the island from the charging energy to be 100–200 nm. It is, therefore, likely that the 1D island is connected on both sides to two 1D conductors that are several microns long. Figure 3 shows the extracted Γ_i for the peaks marked in Fig. 1b. It is clear that Γ_i is not constant but rather drops as a power of temperature. The extracted values of g for the two peaks are 0.82 (peak #1 in Fig. 1b) and 0.74 (peak #2 in Fig. 1b). The change in g results from the change in density induced in the 1D wire when moving from one peak to the next. Similar power law behavior is observed for all measured resonances in three different wires. The observed power law behavior is direct proof of Luttinger-liquid behavior in our CEO wires.

At sufficiently high temperatures the assumption of tunneling through a single resonant state breaks down, and we should expect an increase of the extracted Γ_i due to transport through a few excited states of the 1D island [16]. The possibility of an excited state affecting the temperature dependent conductance is of interest since it allows a better test of Furusaki's model. The excited state spectrum of the 1D island is extracted from differential conductance measurements at finite source drain voltage, V_{ds}. Figure 4 shows a gray scale plot of the differential conductance as a function of the top gate voltage and V_{ds} for two peaks.

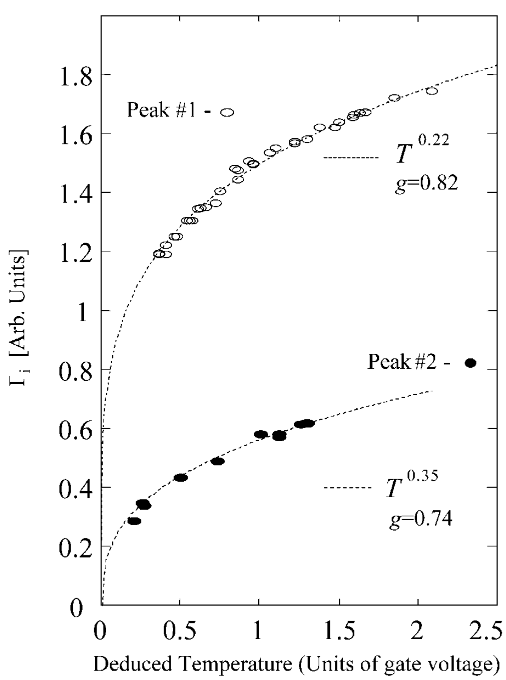

FIG. 3. The intrinsic linewidth of the resonance Γ_i, vs temperature (in units of gate voltage). Both parameters are extracted from a fit to the derivative of the Fermi function. Γ_i is seen to decrease as a power law of the temperature indicating Luttinger-liquid behavior. The dashed lines are a power law fit to the data.

For peak #1 (in Fig. 1b) several excited states can be observed in Fig. 4a. The lowest three, at $V_{ds} = -0.4$ meV, $V_{ds} = -0.7$ meV, and $V_{ds} = -1.5$ meV, are coupled only very weakly (approximately 15% of the intensity of the main peak) and would therefore contribute very little to the overall conductance. However, the fourth excited state at $V_{ds} = -1.7$ meV is more strongly coupled. Since an excited state contributes to the conductance only when $4k_BT \gtrsim \Delta E$ (ΔE is the energy of the excited state), within our temperature range of 0.25 to 2.5 K only the ground state contributes significantly, and one expects a single power law behavior as indeed is observed in Fig. 3. It should be noted that, theoretically, g can also be written in terms of the charging energy U_c, and the level spacing ΔE, as $g \approx 1/\sqrt{1 + U_c/\Delta E}$ [12]. In our 1D island $U_c/\Delta E \approx 5$ and, hence, one expects $g \approx 0.4$. The large disagreement between the measured g and the expected one is not understood at this stage.

A different case is presented in Fig. 4b with a strongly coupled excited state at $V_{ds} = -0.6$ meV. Hence, we expect that at temperatures above 1.2 K this excited state would contribute to the conductance. Figure 5 shows the temperature dependence of the extracted Γ_i of this CB peak. Indeed above 1 K, Γ_i deviates from the low-temperature power law, indicating a contribution of an additional transport channel to the total conductance. At low temperatures though, only the ground state contributes to the conductance. Therefore, a fit of the low-temperature data to a power law enables us to extract a g value of 0.66 for this wire. Using this g value and the measured energy of the excited state (−0.6 meV from Fig. 4b), we use Furusaki's model to predict the dependence of Γ_i over the entire temperature range. The dashed curve in Fig. 5 is

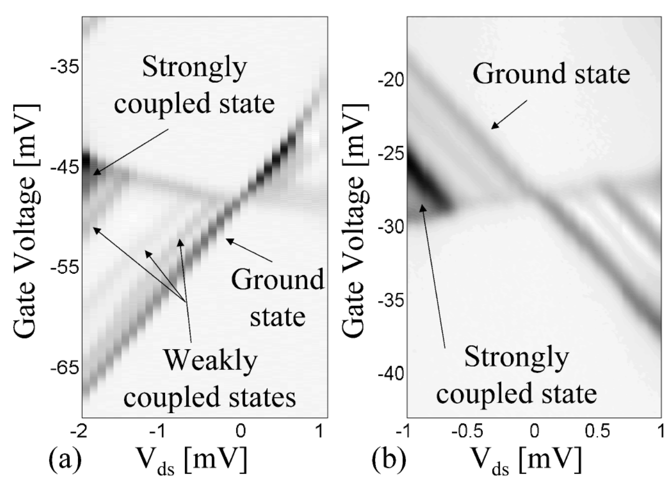

FIG. 4. Gray scale plots of the nonlinear differential conductance of two peaks. Darker color stands for higher differential conductance. The scale is nonlinear in order to enhance low features. (a) The peak marked as #1 in Fig. 1b (V_{ds} is stepped with 100 μV intervals). (b) A different resonance that has a strongly coupled state at $V_{ds} = -0.6$ meV (V_{ds} is stepped with 20 μV intervals).

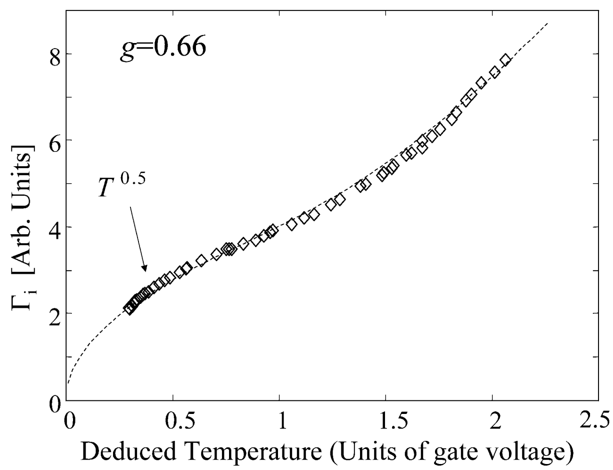

FIG. 5. The intrinsic linewidth of the resonance described in Fig. 4b vs temperature (in units of gate voltage). The dashed line is a fit to the data based on Furusaki's model. g is determined from the low-temperature behavior and the energy of the excited state is determined from Fig. 4b. The coupling strength to the excited state is the only adjustable parameter in the fit.

the result of such a calculation where only the coupling strength to the excited state has been adjusted. We see that the temperature dependence predicted by the model agrees quantitatively with the measured dependence, further supporting the fact that Luttinger-liquid behavior describes the transport properties of these resonances.

In conclusion, we have studied the temperature dependence of CB resonances of a 1D island embedded in an interacting 1D wire. The observed power law behavior of the intrinsic resonance width on temperature is direct proof of Luttinger-liquid behavior in this system. The measured g values range from 0.66 to 0.82 for the various resonances studied. The measured behavior agrees quantitatively with the model of Furusaki even when excited states of the 1D island are taken into account.

We would like to thank H. L. Stormer for the fruitful collaboration. We would also like to thank A. M. Finkel'stein and A. Stern for helpful discussions. This work is supported by the U.S.-Israel BSF.

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