Crossover from Fermi Liquid to Multichannel Luttinger Liquid in High-Mobility Quantum Wires

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We investigate the electrical conductance of long, high-mobility quantum wires formed by the split-gate technique, which allows for adjustment of the wire width and the number of one-dimensional electron subbands, n. In wires with $3 \leq n \leq 8$, a logarithmic temperature dependence of the conductance is observed for $1 < T < 10$ K, which reaches as much as 30% of the Drude conductance. In even narrower wires, the logarithmic dependence changes to a power-law variation. Our observations are shown to be in good agreement with recent theoretical studies, which attribute the logarithmic term to interaction effects in a weakly disordered quasi-one-dimensional conductor. This interaction correction is associated with the emergence of a crossover from a quasi-one-dimensional weakly disordered Fermi liquid to a multichannel Luttinger liquid.

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Since the beginning of the 1980s, the interplay of disorder and interaction in low-dimensional conductors has been the subject of intensive theoretical and experimental research [1–4]. Much of this attention has focused on the electrical properties of quasi-1D conductors. In the absence of disorder, interacting electrons in quasi-1D conductors are often described by the Luttinger-liquid model, which manifests itself as a power-law temperature dependence of the conductance [5,6]. In the diffusive limit, which corresponds to relatively strong disorder, $T\tau < 1$ (τ is the electron momentum relaxation rate), the Altshuler-Aronov correction to the Drude conductance has been widely studied in quasi-1D conductors [7]. While these two limiting cases have been intensively investigated and are well understood, much less is known about weakly disordered ($T\tau > 1$) quasi-1D conductors.

The corrections to the Drude conductance, σ_D, due to electron-electron interaction in a quasi-one-dimensional weakly disordered Fermi liquid have been calculated in Ref. [8], and may be presented as

$$\frac{\sigma(T)}{\sigma_D} = 1 + \frac{C}{n} \ln\left(\frac{2k_B T}{\epsilon_F}\right), \tag{1}$$

where n is the number of conducting channels (1D subbands), C is a constant that describes the electron-electron interaction in the singlet and triplet channels, and ϵ_F is the Fermi energy. The above result was obtained in a perturbative way and assumes that the log$T$ term is substantially smaller than 1. More recently, employing the interacting nonlinear sigma model, the authors of Ref. [9] accounted for the next orders in the interaction and presented strong arguments in favor of the exponentiation of Eq. (1). Considering Eq. (1) as an expansion of the exponential function in the log$T$ term [9], we obtain the Luttinger-liquid temperature-dependent conductance,

$$\frac{\sigma(T)}{\sigma_D} = \left(\frac{2k_B T}{\epsilon_F}\right)^{C/n}. \tag{2}$$

Note, while the above consideration was relevant to the long wires, the same power-law dependence was also obtained for weakly disordered multichannel Luttinger liquid in short constrictions [10–12]. To the best of our knowledge, the logarithmic interaction correction and the corresponding crossover from the Fermi liquid to the Luttinger-liquid behavior have not yet been experimentally investigated.

In this Letter, we present new data on the temperature dependence of the conductance in long quasi-1D weakly disordered quantum wires. We investigate the transport in high-mobility wires of submicron width that are formed by the split-gate technique in a two-dimensional electron gas (2DEG) [13,14]. This technique allows us to vary the width of the relatively long wire while maintaining high electron mobility within it, ensuring that the condition $T\tau > 1$ is fulfilled above 1 K. For wire widths ranging from 90 to 180 nm, we observe a clear logarithmic temperature dependence of the conductance in the range 1–10 K. The logarithmic term increases as the width of the wire decreases. For this range of parameters, the width of the wire, w, is smaller than $L_T = \hbar v_F / k_B T$, and, therefore, our submicron-width wires should be considered as one-dimensional with respect to the electron-electron interaction. Thus, these observations allow us to associate the observed log$T$-conductance variation with the interaction correction in the weakly disordered quasi-1D Fermi liquid [Eq. (1)]. Moreover, we find that the prelogarithmic factor is in good quantitative agreement with the theoretical prediction of Ref. [8]. On the other hand, the log$T$ term may also be considered as a precursor to the weakly disordered multichannel Luttinger liquid [Eq. (2)]. A transition from a logarithmic to a power-law dependence is expected when the log$T$ term becomes comparable with the temperature-independent Drude conductance [9]. Our measurements support this scenario. If the width of the wire decreases, the log$T$ term increases. Once the number of one-dimensional electron subbands in the wire decreases to 3, the log$T$ term at 10 K exceeds 30% of the Drude conductance. When the width further decreases, the logarithmic temperature dependence starts changing to a power-law dependence.

Our long, submicron-width, quantum wires with relatively high electron mobility were formed by employing the split-gate technique in AlGaAs/GaAs quantum wells. These heterostructures were grown by molecular beam epitaxy on undoped (100) GaAs substrates in the following order: 120 nm smoothing superlattice, 1000 nm GaAs buffer layer, 20 nm $Al_{.33}Ga_{.66}As$ spacer layer, Si-delta doping layer, 40 nm $Al_{.45}Ga_{.55}As$, and 5 nm capping layer. The 2DEG is located 65 nm below the surface. At 4.2 K, its electron mobility, density, and mean free path is $4.7 \times 10^5\ \mathrm{cm}^2/\mathrm{V\,s}$, $3.0 \times 10^{11}\ \mathrm{cm}^{-2}$, and 4.25 μm, respectively. A six-probe Hall bar was fabricated [Fig. 1(a)], and two Cr/Au Schottky contacts were deposited on top of this to form a split-gate electrode with a lithographic width and length of 0.5 μm $\pm$ 20 nm and 100 μm, respectively, [see Figs. 1(b) and 1(c)]. Low-temperature transport measurements were carried out using standard low-frequency four terminal lock-in techniques with appropriate low-pass filters in a dilution refrigerator with a base temperature of $\sim$25 mK. Voltage measurements to characterize the 2DEG and the quasi-1D wire were performed between two different sets of contacts labeled V_{ch} and V_{2DEG} respectively in Fig. 1(a). This allowed for a more accurate determination of the 2DEG parameters while excluding the influence of the gate electrodes. The measured resistance is composed of the wire's resistance and about one square of 2DEG resistance, which was negligible compared with the more than 200 squares which make up the submicron wide wire.

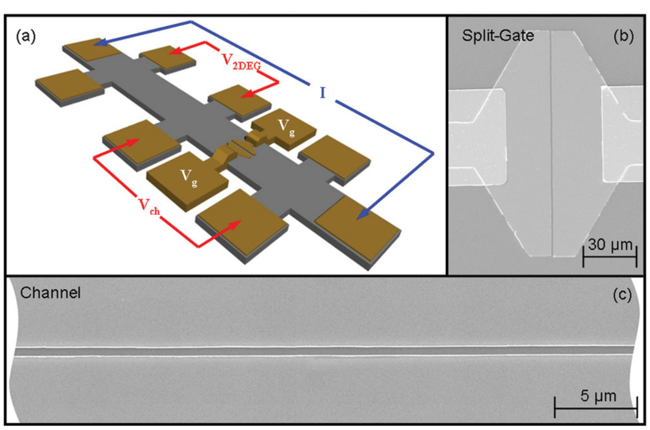

FIG. 1 (color). (a) Schematic diagram of the device's geometry. (b) SEM image of the split-gate structure. (c) Magnified image of the split-gate defined quantum wire.

The 2D electron concentration in the wire was determined from Shubnikov–de Haas oscillations (SdH) presented in Fig. 2. Measurements of the SdH oscillations throughout the entire experimental range of temperatures showed that the electron concentration does not depend on temperature, in both the wires and the 2DEG. The slope of the linear portion of the Landau-level plot at higher fields, where the cyclotron radius is smaller than the width, was used to determine the 2D electron concentration. The concentration as a function of gate voltage is shown in the inset (a) of Fig. 3. In the narrowest wires the concentration decreases to roughly one half of the 2DEG concentration which is reasonable for split-gate structures [14].

In the narrow quantum wires, the oscillation index N as a function of the inverse magnetic field B^{-1} starts to deviate from linearity when the cyclotron radius $r_c(B)$ becomes $\sim w/2$ [15]. For a harmonic confinement potential, the onset of this nonlinearity in $N(B^{-1})$ directly provides the number n of 1D subbands in the wire. The results of this analysis are presented in Fig. 3 by blue triangles. In our measurements, the method was limited by $n = 4$, because for smaller n, the linear dependence is not well defined.

We also determine the number of 1D subbands following the widely used empirical method suggested in Ref. [16]. This approach is based on the analysis of the low-field magnetoresistance peaks due to diffusive electron scattering at the edges of the wire. This electron-boundary scattering manifests itself as two small side-peaks, which are marked by red arrows in the inset of Fig. 2. The peaks move to higher fields with increasing negative gate bias.

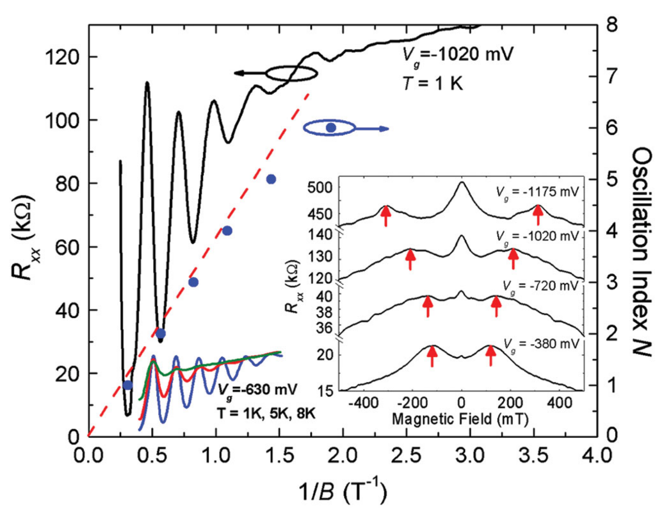

FIG. 2 (color). Resistance R_{xx} of the wire (left axis) and SdH oscillation indices N (right axis) as a function of B^{-1} at $V_g = -1020$ mV and -630 mV. As can be seen from the SdH oscillations at $V_g = -630$ mV for $T = 1$ K, 5 K, 8 K (blue, red, green) the electron concentration is independent of temperature. Dependence $N(B^{-1})$ starts to deviate from linear when cyclotron radius $r_c(B)$ is $\sim w/2$. Inset: Resistance of the wire R_{xx} vs B for various gate voltages at $T = 1$ K. Arrows mark local peaks which correspond to $r_c(B) \simeq w/2$.

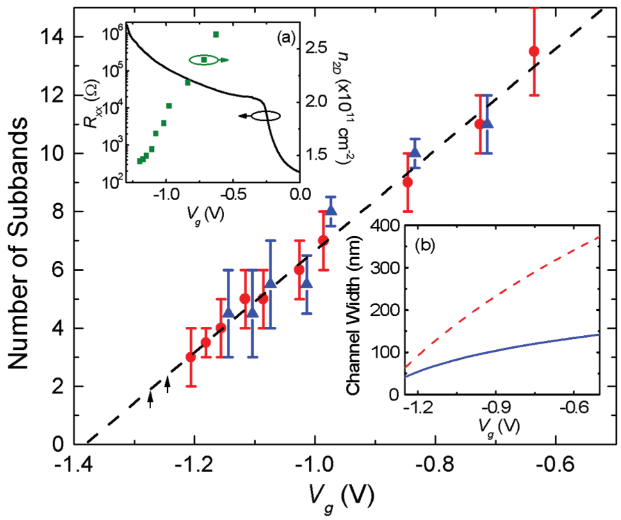

FIG. 3 (color). Number of subbands (channels) in the wire vs gate voltage V_g. Arrows indicate position of $V_g = -1245$ mV and $V_g = -1265$ mV. Inset (a): resistance of wire (left axis) and electron concentration (right axis) vs V_g. Inset (b): Channel width determined from $n(V_g)$ for both the parabolic (solid blue line) and square-well (dashed red line) model potentials vs V_g.

The number of 1D subbands can be evaluated via an empirical relation, $n = 0.55\hbar/(\pi e B_{\max})$ Ref. [16], which has subsequently been confirmed in numerous works. The results of this method are presented in Fig. 3 as the red circles. The error bars represent the uncertainty in the determination of $B_{\max}$ from the magnetoresistance measurements. In our experiments, the method was limited to $n = 3$, because for more narrow wire widths, the peaks become difficult to identify. As can be seen in Fig. 3, the two methods used give consistent results for the number of subbands n as a function of the gate voltage. In what follows, we will compare our results with the theory [Eqs. (1) and (2)] in terms of the number of conducting channels, n. For illustrative purposes, in inset (b) of Fig. 3, we present the wire width, w, as a function of V_g. The dependence $w(V_g)$ was calculated from $n(V_g)$ employing two model potential shapes, the square-well and parabolic infinite confinement potentials. These two extreme models provide lower and upper boundaries for more realistic potentials, such as the parabolic potential with a flat bottom.

The magnetoresistance data also provide evidence of weak-localization effects (WL), which should contribute a positive logarithmic temperature-dependent correction to the conductance. The WL effects are evident as the sharp peak at zero field shown in the inset of Fig. 2. At magnetic fields above ~100 mT, the effects of WL are suppressed, and effects of the electron-electron interaction which do not depend on magnetic field can be observed.

The resistance of the wire as a function of gate voltage $R(V_g)$ at $T = 1.4$ K is shown in Fig. 3, inset (a). The depletion threshold of the 2DEG underneath the split-gates is identified by the rapid increase in the resistance at $V_g = -0.28$ V. This is consistent with the calculated voltage $V_g = -0.27$ V for which all electrons underneath the split gate are depleted and the wire is of the same width as the lithographic gap between the split gates. In our long wires with large resistances, the universal conductance fluctuations are small. Measurements of $R(V_g)$ over the entire range of temperatures $T = 25$ mK–10 K did not show any shift in the depletion threshold voltage. As can be seen in the inset (a) of Fig. 3, the resistance does not show a linear dependence on gate voltage, for voltages larger than threshold. From the above analysis of the magnetoresistance data, a linear dependence of the electron concentration was found [inset (a) in Fig. 3]. From the low-field residual resistance, we determined that the channel mobility decreases with the electron concentration to the power 3/2, which is expected from electron scattering dominated by ionized impurities [14,17].

The relative conductance, $[\sigma(T) - \sigma_D]/\sigma_D$, as a function of temperature for various gate voltages is shown in Fig. 4(a). The data were taken in the presence of a 100 mT perpendicular magnetic field to suppress the effects of WL. The data shows that the conductance has a logarithmic temperature dependence in the range $1\ \text{K} < T < 10$ K at $-1020\ \text{mV} < V_g < -1200$ mV, i.e., for $3 \leq n \leq 8$.

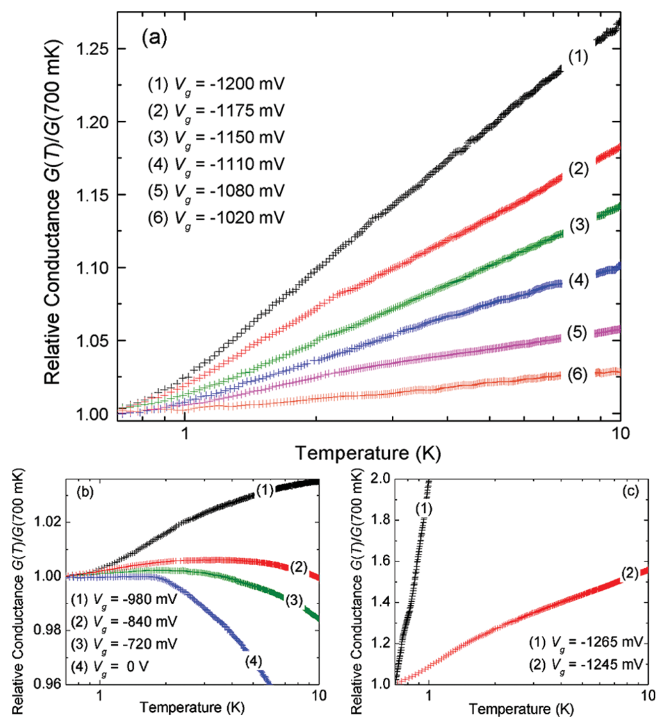

FIG. 4 (color). Temperature dependencies of the wire conductance $G(T)/G(700\ \text{mK})$ for various gate voltages V_g: (a) The logarithmic temperature dependence dominates at $-1020\ \text{mV} < V_g < -1200$ mV, i.e., $3 \leq n \leq 8$; (b) Conductance of wider wires, $V_g < -980$ mV, i.e., $n > 8$, shows significant negative contributions due to electron-phonon scattering; (c) Conductance of narrow wires, $V_g > -1245$ mV, i.e., $n < 2$, shows transition from log$T$ to power-law dependence.

Evaluating the momentum relaxation time, τ, from the electron mobility, we find that the condition of weak disorder, $T\tau > 1$, is satisfied at temperatures above 700 mK. Below 10 K, the samples studied may be considered as quasi-one-dimensional conductors with respect to the electron-electron interaction, if $w < L_T = \hbar v_F / k_B T \simeq$ 200 nm. According to the above analysis, the observed logarithmic dependence may be associated with the interaction correction in weakly disordered quasi-one-dimensional conductors [8]. In accordance with Eq. (1), this correction, normalized by the Drude conductance, is inversely proportional to the number of channels n. Therefore, the relative correction increases with a decrease in the width of the wire, as can be seen in Fig. 4(a). According to the evaluations above, at $V_g < -980$ mV, i.e., for $n > 8$, we expect a transition from the quasi-one-dimensional limit to the two-dimensional one. However, such transition is not observed directly, because the phonon contribution becomes comparable with the two-dimensional interaction correction. Figure 4(b) shows that in the transition area the upper temperature limit for the $\log T$ term decreases with an increase of n.

The logarithmic term increases with a decrease in the width. At $V_g = -1200$ mV, i.e., at $n \simeq 3$, the $\log T$ term at 10 K reaches 30% of the Drude conductance. Further decrease in the width of the wire results in a crossover from the logarithmic temperature dependence to a power-law dependence. As it is seen in Fig. 4(c), at $V_g = -1245$ mV, i.e., at $n \simeq 2$, the logarithmic temperature dependence becomes unobservable. The exponent in the power-law dependence increases with decreasing width. In the narrowest channel, at $V_g = -1265$ mV, we observe the quadratic temperature dependence, which was previously found in narrow GaAs channels in Ref. [18] and associated with a phonon-assisted hopping processes.

Finally, let us quantitatively compare our observations with the theory. Fitting the logarithmic dependencies in Fig. 4(a) by Eq. (1), we find the constant $C_{\rm exp}$ to be 0.19 ± 0.04. According to the theory, the constant C accounts for the contributions of the singlet and triplet channels in the electron-electron interaction, so $C_{\rm th} = C_s + C_{\rm tr}$. In the unitary limit, $C_s = 1/\pi$. The contribution of the triplet channel depends on the Fermi liquid constant F_0 [8]. It may be evaluated by using the value $F_0 = -0.15$, determined previously for similar AlGaAs/GaAs 2DEGs [19]. Then, using Eqs. 3.41 and 3.42 of Ref. [8], we obtain $C_{\rm tr} = -0.055$. Thus, the experimental value $C_{\rm exp}$ turns out to be very close to the theoretical prediction, $C_{\rm th} = 0.26$. Taking into account that the theory was developed for the simplest white-noise disorder, the above agreement seems to be very good.

In summary, we present new data on the temperature-dependent conductance in quasi-1D weakly disordered wires. The observed logarithmic temperature dependence is in good quantitative agreement with the theory [8], developed for the quasi-1D Fermi liquid in the first order in the dynamically screened electron-electron interaction. At the same time, the recent theory [9] identifies the $\log T$ term as the first term in the expansion of the Luttinger power-law dependence and predicts the transition from the logarithmic to the power-law dependence, when the $\log T$ term reaches 30–40% of the Drude conductivity [see Eqs. (1) and (2)]. Such a transition is observed in our experiments.

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[1] B.L. Altshuler and A.G. Aronov, in *Electron-Electron Interactions in Disordered Systems*, edited by A.L. Efros and M. Pollak (North-Holland, Amsterdam, 1985).
[2] G. Zala, B.N. Narozhny, and I.L. Aleiner, Phys. Rev. B **64**, 214204 (2001).
[3] V.M. Pudalov, M.E. Gershenson, H. Kojima, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett. **91**, 126403 (2003).
[4] W.R. Clarke, C.E. Yasin, A.R. Hamilton, A.P. Micolich, M.Y. Simmons, K. Muraki, Y. Hirayama, M. Pepper, and D.A. Ritchie, Nature Phys. **4**, 55 (2008).
[5] A.O. Gogolin, A.A. Nersesyan, and A.M. Tsvelik, *Bosonization and Strongly Correlated Systems* (Cambridge Uni. Press, Cambridge, UK, 1998).
[6] T. Giamarchi, *Quantum Physics in One Dimension* (Clarendon Press, Oxford, 2004).
[7] P.M. Echternach, M.E. Gershenson, H.M. Bozler, A.L. Bogdanov, and B. Nilsson, Phys. Rev. B **50**, 5748 (1994).
[8] A. Sergeev, M. Yu. Reizer, and V. Mitin, Phys. Rev. B **69**, 075310 (2004).
[9] Ch. Mora, R. Egger, and A. Altland, Phys. Rev. B **75**, 035310 (2007).
[10] D.L. Maslov, Phys. Rev. B **52**, R14368 (1995).
[11] N.P. Sandler and D.L. Maslov, Phys. Rev. B **55**, 13808 (1997).
[12] I.V. Gornyi, A.D. Mirlin, and D.G. Polyakov, Phys. Rev. B **75**, 085421 (2007).
[13] N. Romero Kalmanovitz, I. Hoxha, Y. Jin, S.A. Vitkalov, M.P. Sarachik, Ivan A. Larkin, and T.M. Klapwijk, Phys. Rev. B **77**, 035415 (2008).
[14] H.Z. Zheng, H.P. Wei, D.C. Tsui, and G. Weimann, Phys. Rev. B **34**, 5635 (1986).
[15] K.-F. Berggren, G. Roos, and H. van Houten, Phys. Rev. B **37**, 10118 (1988).
[16] T.J. Thornton, M.L. Roukes, A. Scherer, and B.P. Van de Gaag, Phys. Rev. Lett. **63**, 2128 (1989).
[17] A. Gold, Phys. Rev. B **38**, 10798 (1988).
[18] T.J. Thornton, M. Pepper, H. Ahmed, D. Andrews, and G.J. Davies, Phys. Rev. Lett. **56**, 1198 (1986).
[19] L. Li, Y.Y. Proskuryakov, A.K. Savchenko, E.H. Linfield, and D.A. Ritchie, Phys. Rev. Lett. **90**, 076802 (2003).