Density-Dependent Spin Polarization in Ultra-Low-Disorder Quantum Wires

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There is controversy as to whether a one-dimensional (1D) electron gas can spin polarize in the absence of a magnetic field. Together with a simple model, we present conductance measurements on ultra-low-disorder quantum wires supportive of a spin polarization at $B = 0$. A spin energy gap is indicated by the presence of a feature in the range $(0.5\text{–}0.7) \times 2e^2/h$ in conductance data. Importantly, it appears that the spin gap is not constant but a function of the electron density. Data obtained using a bias spectroscopy technique are consistent with the spin gap widening further as the Fermi level is increased.

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In the presence of strong exchange coupling, electrons can spin polarize in the absence of an applied magnetic field. Such a scenario is predicted for a variety of different systems including one-dimensional (1D) ballistic quantum wires [1,2], the two dimensional (2D) electron gas [3], three dimensional (3D) metal nanowires [4], and circular quantum dots [5]. In the case of 1D, interactions become increasingly important at low densities and models such as the Tomanaga-Luttinger liquid theory [6] are required to describe them. Despite the large exchange energy present in low-density 1D systems there are strict theoretical arguments against magnetic ordering [7] and the notion of a 1D spin-polarized ground state remains the subject of wide debate, in particular since the important experimental results of Thomas *et al.* [8]. Here we present results taken on quantum wires in zero magnetic field that provide strong evidence in favor of a spin energy gap developing in the 1D region. This density-dependent energy gap between spin-up and spin-down electrons is revealed in conductance measurements as an anomalous feature in the range $(0.5\text{–}0.7) \times 2e^2/h$.

A feature near $0.7 \times 2e^2/h$ can be seen in some of the earliest transport measurements on quantum point contacts [9,10]. In 1996 Thomas *et al.* [8] revealed that the anomalous feature was related to spin by showing that it evolves smoothly into the Zeeman spin-split level at $0.5 \times 2e^2/h$ with an in-plane magnetic field. Since that time experimental studies have concentrated on the behavior of the anomaly as a function of temperature, source-drain bias, magnetic field, thermopower, wire length, and density [11–18]. Together with these investigations, numerous mechanisms to explain the origin of the conductance feature have been proposed [19–26]. Among the most compelling of these models is the notion of Fermi-level pinning in the presence of a fixed spin energy gap [24,25].

In this work we propose, and present supportive experimental data for, an alternative simple phenomenological model that appears to explain the characteristic details of the 0.7 feature by means of a *density dependent* spin gap arising in the region of the quantum wire. Key differences exist between this simple model and other explanations based on pinning. In contrast to the case of a *constant* spin polarization, the subbands remain spin degenerate until they are populated, after which the spin gap opens with increasing 1D density as depicted in Fig. 1. Consequently, this model also explains the absence of conductance plateaus at $0.25 \times 2e^2/h$ in the presence of a finite source-drain (SD) bias. This density dependence, suggestive of many-body interactions, is consistent with a spin polarization driven by exchange as predicted by Wang and Berggren [1]. In their calculations the polarization weakens as higher subbands are populated (see Fig. 1). The nonlinear dependence of Fermi energy E_F on density or gate voltage in Fig. 1 is a consequence of the singularity in the 1D density of states, $\rho \sim E^{-1/2}$ [23].

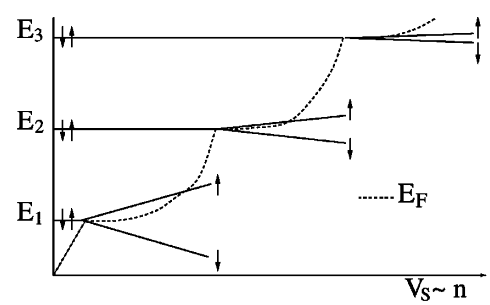

FIG. 1. Phenomenological picture of a density-dependent spin gap opening linearly with increasing density (n) or gate voltage (V_S). E_1, E_2, E_3 indicate the 1D subband edges. The Fermi level (dashed line) is nonlinear with density n due to the singularity in the 1D density of states.

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Our proposed model is consistent with data we have obtained on GaAs/AlGaAs quantum wires free from the disorder associated with modulation doping [12]. Although we illustrate our simple model with this data, the model is not limited to these samples but appears to be consistent with the key published results [8–18].

Turning now to the experimental data, we note that the presence and shape of conductance anomalies depend on how the spin gap opens with 1D density and are likely to be sample dependent. Figure 2 depicts the three main scenarios that may arise. Scenario (I) occurs if spin splitting takes place quickly with increasing density, so that an appreciable energy gap develops in comparison to the thermal energy kT. In this case we see a fully resolved spin-split plateau near $0.5 \times 2e^2/h$ in linear response conductance G and no feature near $0.7 \times 2e^2/h$. This is shown on the left of Fig. 2(I), for a quantum wire of length $l = 0.5\ \mu$m at $T = 50$ mK. The right side of the figure shows the dependence of the differential conductance (di/dv) with finite SD bias, where the thick lines represent conductance plateaus. Because of an averaging of the conductance at the chemical potential of the source S and drain D, half plateaus at (0.5 and 1.5) $\times 2e^2/h$ occur at finite bias when the two potentials differ by one subband [27,28]. The simultaneous application of a finite SD bias and large magnetic field lifts the spin degeneracy [9] so that additional quarter plateaus are produced at $(0.25, 0.75, 1.25, 1.75, \ldots) \times 2e^2/h$ [29]. However, in the case of a density-dependent spin gap at $B = 0$, the plateaus at 0.25 and $1.25 \times 2e^2/h$ will be absent, since the 1D density is not yet large enough to appreciably open the spin gap.

Scenario (II) considers the case where kT is comparable to the spin gap. In this case no feature near $0.5 \times 2e^2/h$ will be resolved as E_F crosses the band edges. Instead, as E_F approaches the upper spin-band edge, the spin gap continues to open so that the number of electrons which thermally populate the upper spin band remains approximately constant. A quasiplateau near $0.7 \times 2e^2/h$ therefore occurs due to the pinning of the Fermi level to the band edge and the simultaneous increase of both E_F and the upper spin-split subband (shown in the data for the same $l = 0.5\ \mu$m wire at $T = 4.2$ K). In this model the quasiplateau can occur in the range (0.5–1.0) $\times 2e^2/h$, as has been observed experimentally [14,18].

The right side of Fig. 2(II) illustrates the behavior of the differential conductance at elevated temperatures. In contrast to the low temperature case of scenario (I), the feature remains close to $0.75 \times 2e^2/h$ even when the SD bias is close to zero [Fig. 2(II), d and e].

Scenario (III) illustrates the case where the spin splitting is weak and grows slowly with increasing density. At low T there is no feature near $0.5 \times 2e^2/h$ if the spin gap remains small in comparison to kT. We illustrate this with data from a $l = 0$ quantum wire at $T = 50$ mK. Although there is no evidence for a gap at zero SD bias, the spin gap can still be observed as a feature near $0.75 \times 2e^2/h$

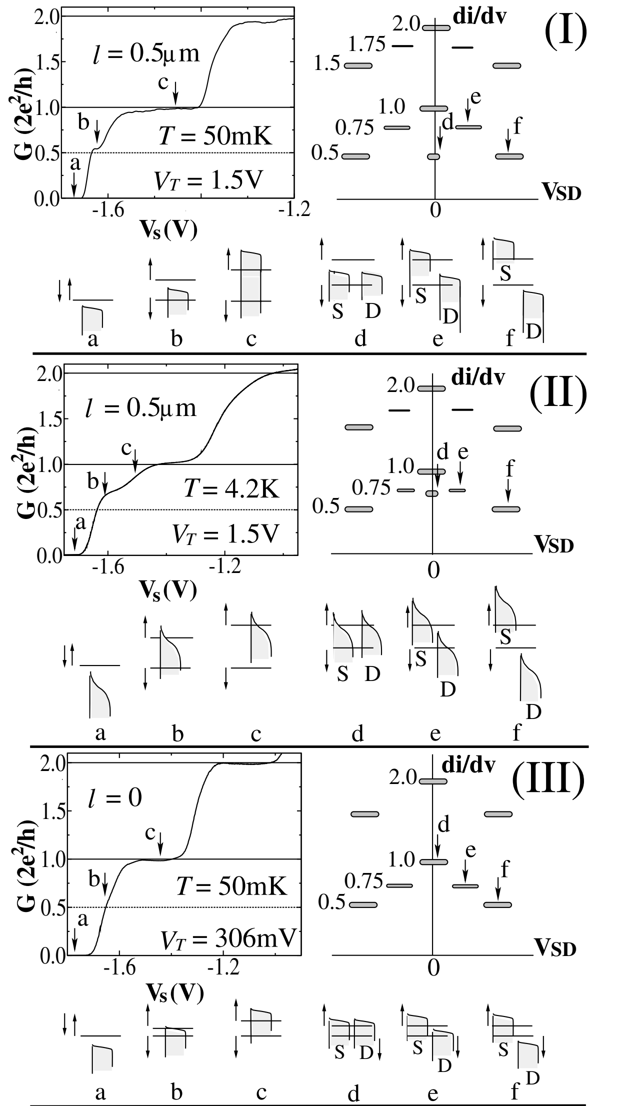

FIG. 2. Data and a schematic showing the three main scenarios that lead to features near $0.5 \times 2e^2/h$ and $0.7 \times 2e^2/h$ in the conductance. Linear response data are shown on the left, with a schematic depicting the main differential conductance features seen at finite SD bias (right). In the lower portion of each graph the horizontal lines indicate the subband edges and shaded regions represent the Fermi distributions. (I) The spin gap is large in comparison to kT; (II) high temperatures when kT is close to the spin gap; (III) weak spin splitting.

in di/dv as shown in the schematic on the right. This is because the splitting is too small to be resolved at low densities where $G < 2e^2/h$ at $V_{SD} = 0$. However, a moderate SD bias evolves the $1.0 \times 2e^2/h$ plateau into a feature near $0.75 \times 2e^2/h$ as the S and D potentials differ by one spin subband [Fig. 2(II), e]. Such behavior has been observed by Kristensen *et al.* [15,30].

We now present additional data taken on two different samples which support our model. The devices are fabricated from ultra-low-disorder GaAs/AlGaAs heterostructures with electron mobilities in the range (4–6) $\times 10^6$ cm^2 V^{-1} s^{-1}. The top layer of the heterostructure is sectioned into three separately controllable gates with the middle or top gate being biased positively (V_T) to control both the density in the 2D reservoirs [$n_{2D} = (1.5–7.5) \times 10^{11}$ cm^{-2}] and in the 1D channel [12]. The side gates are negatively biased (V_S) and simultaneously control the 1D density and the transverse potential. We find that the 0.7 feature tends towards $0.5 \times 2e^2/h$ with *increasing* top gate bias and length of the 1D region [18].

Figure 3(a) shows data taken on a quantum wire of length $l = 0.5$ μm at $T = 4.2$ K and $T = 50$ mK. The data taken at $T = 50$ mK show an evolution towards fully resolved spin splitting with the 0.7 feature moving closer to $0.5 \times 2e^2/h$ with increasing top gate bias (right to left). In the context of the model this evolution is consistent with the spin gap opening more rapidly with 1D density n, for larger V_T (2D reservoir density) [i.e., moving from scenario (III) to scenario (I) with increasing V_T]. In particular, the leftmost traces in Fig. 3(a) are consistent with scenario (I) at $T = 50$ mK and scenario (II) at $T = 4.2$ K, where the feature has risen from $(0.55 \text{ to } 0.7) \times 2e^2/h$.

At $T = 4.2$ K the position of the feature does not evolve with V_T (2D density) but remains close to $0.7 \times 2e^2/h$ at these higher temperatures, as both of the spin bands are populated [cf. Fig. 2(II)], and the position of the feature is insensitive to small changes in the spin gap.

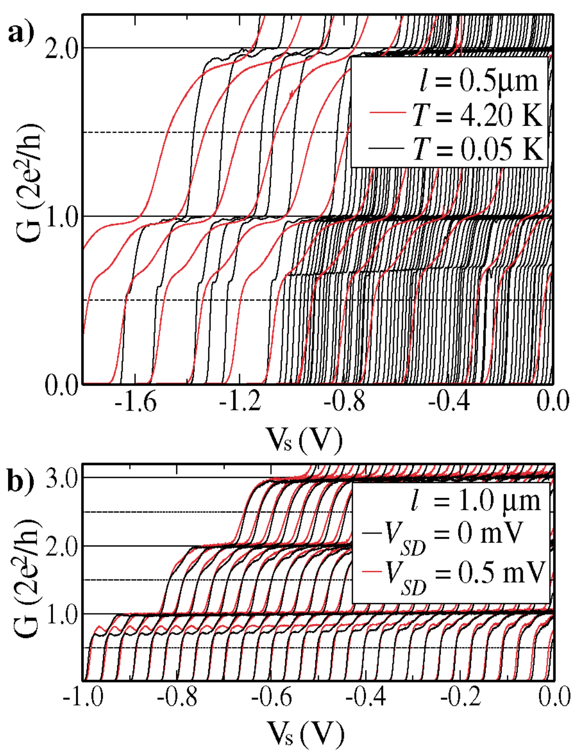

FIG. 3 (color). (a) Conductance of a $l = 0.5$ μm quantum wire as a function of side gate voltage V_S for top gate voltages in the range; $V_T = 420–1104$ mV (right to left). (b) Conductance of a $l = 1.0$ μm quantum wire as a function of V_S for V_T in the range; 270–800 mV (right to left). $T = 50$ mK.

The shape of the feature will depend on the slope of the Fermi function as it crosses the second spin-band edge: at high temperatures the broad Fermi function produces a broad quasiplateau. At low temperatures, depending on the size of the spin gap, the sharp Fermi function will either produce a small but sharp feature at $0.5 \times 2e^2/h$ [strong splitting, scenario (I)] or a weak inflection [weak splitting, scenario (III)] in the conductance.

Figure 3(b) explores the effect of a constant dc SD bias on both the shape and position of the feature. At $V_{SD} = 0$ (black curves) we observe evolution of the feature from 0.75 towards $0.5 \times 2e^2/h$ with increasing V_T, consistent with the $T = 50$ mK data for the $l = 0.5$ μm quantum wire shown in Fig. 3(a). The application of a dc offset bias $V_{SD} = 0.5$ mV causes the feature to remain close to $0.75 \times 2e^2/h$, with a much weaker dependence on V_T. This behavior mirrors that in Fig. 3(a) since increasing V_{SD} or increasing T will distribute electrons between both spin bands.

With the application of a dc SD bias the spin gap can be studied as a function of the 1D density, controlled by the side gate bias V_S. Figure 4 shows the differential conductance of a $l = 1.0$ μm quantum wire as a function of V_{SD} for different V_S at $T = 50$ mK. We compare the di/dv at two different 2D reservoir densities [$V_T = 385$ mV, $n_{2D} = 2.6 \times 10^{11}$ cm^{-2} in (a) and $V_T = 700$ mV, $n_{2D} = 5.4 \times 10^{11}$ cm^{-2} in (b)]. In these plots conductance plateaus appear as a grouping of individual curves, as can be seen in Fig. 4(b) where plateaus occur at 2, 1, and $0.75 \times 2e^2/h$ for $V_{SD} = 0$. In both Figs. 4(a) and 4(b) half plateaus at $(0.5 \text{ and } 1.5) \times 2e^2/h$ can be seen developing near $V_{SD} = \pm 1.5$ mV (the 0.5 half plateau on the right side of each graph is suppressed due to the asymmetric bias across the constriction near pinch-off [28]).

Most importantly there are no plateaus near 0.25 and $1.25 \times 2e^2/h$, despite the presence of strong features rising from $0.75 \times 2e^2/h$. This cannot be explained by a constant spin gap, but is a natural consequence of a density-dependent gap: at low 1D densities (small conductances) the spin gap has not yet developed, but at larger densities the gap opens up and features are observed at $\approx 0.75 \times 2e^2/h$.

Further evidence for the density dependence of the gap can be seen in the region close to zero bias where a characteristic "cusp" feature is seen below the $1 \times 2e^2/h$ plateau. Traces associated with this feature start at $0.5 \times 2e^2/h$ at zero SD bias [scenario (I)] and move towards $0.75 \times 2e^2/h$ as V_{SD} is increased. As the 1D density is increased (by altering V_S) the spin gap widens, and a larger V_{SD} must be applied before the conductance increases above $\approx 0.5 \times 2e^2/h$. The cusp feature is a result of many of these traces overlapping, and the strength and width of the feature is a measure of how large the spin gap is, and how rapidly it changes with 1D density. The increasing strength of the spin splitting with increasing V_T can be seen by comparing Figs. 4(a) to

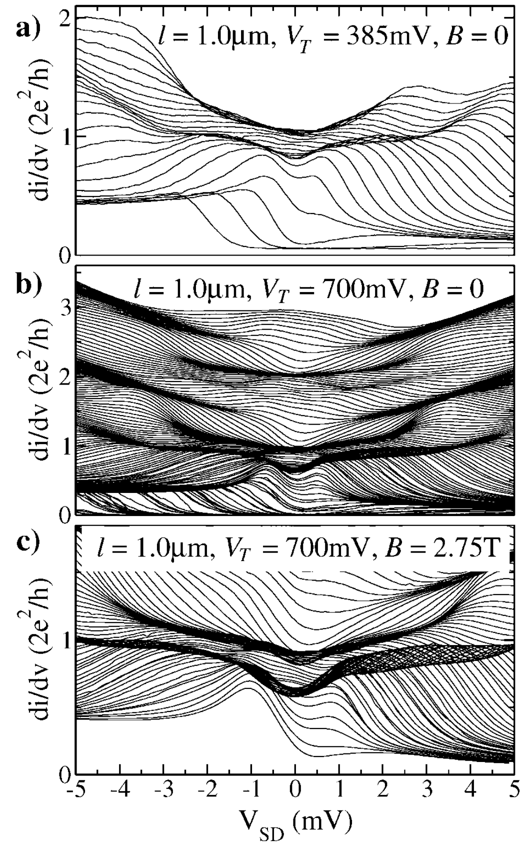

FIG. 4. Differential conductance of a $l = 1.0\ \mu$m quantum wire at 50 mK. (a) $V_S = 0$ to -1200 mV (top to bottom) in -5 mV steps. (b) $V_S = -850$ mV to -1400 mV in -0.5 mV steps. (c) $V_S = -900$ mV to -1400 mV in -1 mV steps.

4(b), where the cusp becomes deeper and more strongly resolved. With the application of an external parallel magnetic field the spin gap opens further and the cusp widens [Fig. 4(c)] [31].

In conclusion, we have presented a simple model to explain the $0.7 \times 2e^2/h$ conductance feature in terms of a density-dependent spin polarization arising in the 1D region. While our phenomenological model is consistent both with experimental data for ultra-low-disorder quantum wires presented here, and with other published data, a detailed microscopic explanation of the spin polarization is still lacking. In particular, how the spin splitting grows with 1D density is sample dependent and seems to depend on the length of the 1D region, the surface gate geometry, and the 2D reservoir density. A detailed understanding of the spin polarization will have implications for 1D transport in mesoscopic devices and may have important applications in the field of spintronics.

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Note added.—Recent work by Cronenwett *et al.* [32] (see also the review by Fitzgerald [33]) discusses a Kondo-like mechanism for the feature near $0.7 \times 2e^2/h$. This microscopic explanation is consistent with the phenomenological description presented here, where scenarios (I) and (III) discussed in Fig. 2 correspond to different Kondo temperatures T_K. We note that T_K is likely to depend on the 2D reservoir density, consistent with the data presented in Fig. 4.

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