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Spin-dependent transport in a clean one-dimensional channel

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A shoulderlike feature close to $(0.7\times 2e^2/h)$, ''the *0.7 structure*'' at zero magnetic field was observed in clean one-dimensional (1D) channels [K.J. Thomas *et al.*, Phys. Rev. Lett. **77**, 135 (1996)]. To provide further understanding of this structure, we have performed low-temperature measurements of a 1D channel with overlaying finger gates to study the 0.7 structure as a function of lateral confinement strength and potential profile. We found that the structure persists when the lateral confinement strength is changed by a factor of 2. We have also shown that the 0.7 structure present in two 1D channels in series behaves like a single 1D channel that shows the 0.7 structure, demonstrating that the 0.7 structure is not a transmission effect through a ballistic channel at zero in-plane magnetic field. [S0163-1829(99)07839-X]

Using the now well-established electrostatic squeezing split-gate technique,[1] it is possible to define a one-dimensional (1D) channel within a two-dimensional electron gas (2DEG). If the elastic-scattering length is longer than the 1D channel length, one may observe ballistic conductance plateaus quantized in units of $2e^2/h$ (Refs. 2,3) at zero magnetic field, where the factor of 2 arises from the electron spin degeneracy. When a large magnetic field is applied parallel to the 1D channel, such that the electron spin degeneracy is lifted, conductance plateaus quantized in units of e^2/h are observed.[4] Quantized conductance plateaus in units of $2e^2/h$ at zero magnetic field (e^2/h at high parallel fields) observed in a 1D channel can be well explained by cancellation of the Fermi velocity and 1D density of states within a single-particle picture.

In very clean 1D channels a clear plateaulike structure close to $(0.7\times 2e^2/h)$ has been observed at zero magnetic field[5] $B=0$. This *''0.7 structure''*, whose conductance value is placed between the spin-degenerate conductance plateau at $2e^2/h$ and the spin-split conductance plateau at e^2/h, cannot be explained within a single-particle picture. The fact that the 0.7 structure evolves into a $(0.5\times 2e^2/h)$ spin-split conductance plateau on the application of an in-plane magnetic field suggests the structure is related to spin. The 0.7 structure has also been observed in 1D channels with different sample designs,[5–7] establishing that it is a universal effect. In particular, Kristensen *et al.*[8] reported activated behavior of the 0.7 structure as a function of temperature with a density-dependent activation temperature around 2 K. Various theoretical models[9,10] involving partial transmission[11,12] and hybridization of different spin states[13] have been proposed to explain this undisputed result; however, its exact physical origin is still unknown. It is the purpose of this paper to report further experimental studies.

We have designed a 1D channel with three separate and independently contacted overlaying finger gates. It is well known that the potential profile of a ballistic 1D channel is often best described by a saddle-point potential[14] with both lateral and longitudinal confinement. By changing the applied voltages on the overlaying gate fingers above the 1D channel, we are able to vary both the lateral confinement strength and the potential profile within the channel. We find that the 0.7 structure is an intrinsic property of a clean 1D channel well over the range investigated. Moreover, we shall present experimental evidence that the 0.7 structure is not a transmission effect at zero in-plane magnetic field.

Figure 1(a) shows a schematic diagram of the device configuration. The device was defined by electron beam lithography on the surface of the sample T258, 157 nm above a 2DEG. There is a 30-nm-thick layer of polymethylmethacrylate (PMMA), which has been highly dosed by an electron beam, to act as a dielectric[15] between the split-gate and three gate fingers so that all gates can be independently controlled.[16] The carrier concentration of the 2DEG was 1.9×10^{15} m^{-2} with a mobility of 250 m^2/V s after brief illumination with a red light-emitting diode. The transport mean free path is 16.5 μm, much longer than the effective 1D channel length. Experiments were performed in a pumped ^{3}He cryostat and the two-terminal conductance $G=dI/dV$ was measured using an ac excitation voltage of 10 μV with standard phase-sensitive techniques. In all cases, a zero split-gate voltage series resistance ($\approx 900\ \Omega$) is subtracted from the raw data. The in-plane magnetic field $B_\parallel$ is applied parallel to the source-drain current. Three different samples on five different runs showed similar behavior, and the data that we present here are obtained from two devices A and B at three different cooldowns.

To demonstrate the high quality of our 1D channel, Fig. 1(b) shows the conductance measurements $G(V_{\mathrm{SG}})$ as a function of split-gate voltage V_{SG} when all finger-gate voltages V_{F1}, V_{F2}, and V_{F3} are zero at $T=300$ mK. We observe conductance plateaus at multiples of $2e^2/h$, with no resonant feature superimposed on top, demonstrating that we have a clean 1D channel in our system in which impurity scattering is negligible. In addition, we also observe the 0.7 structure.

We now describe the effects of applying a negative finger gate voltage V_{F2}. Figure 2(a) shows $G(V_{\mathrm{SG}})$ for various voltages on $F2$ while $F1$ and $F3$ are at 0 V. The results presented here are taken at a measurement temperature of 1.2 K since the 0.7 structure is known to be more pronounced at higher temperatures.[5] Increasing the negative voltage on $F2$ decreases the electron density underneath the finger gate. We use a technique developed by Patel *et al.*[17] to measure the energy separation of 1D subbands from the effects of an

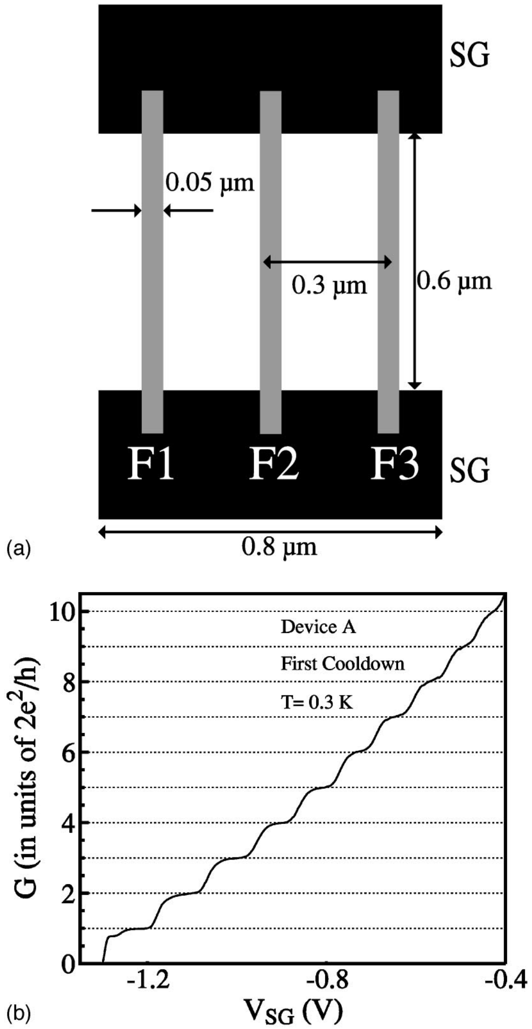

FIG. 1. (a) Schematic diagram showing the device configuration. The gray regions correspond to finger gates, labeled as $F1$, $F2$, and $F3$ lying above the split gate (labeled as SG), with an insulating layer of cross-linked PMMA in between. (b) $G(V_{\mathrm{SG}})$ for all finger gates at 0 V. The measurement temperature was 300 mK.

applied dc source-drain voltage V_{sd} at various V_{F2}. The results are presented in Fig. 2(b) and demonstrate a good linear fit $\Delta E_{1,2}=(0.915V_{F2}/\mathrm{V}+2.71)$ (meV). It can be seen that as V_{F2} is made more negative the energy spacing between the first and the second 1D subbands $\Delta E_{1,2}(V_{\mathrm{SG}})$ decreases, giving rise to the reduction in flatness of the conductance plateaus presented in Fig. 2(a). Using the saddle-point model,[14] we estimate the value ω_y/ω_x to decrease from 1.1 to 0.6 over the measurement range $-0.3\ \mathrm{V}\geqslant V_{F2}\geqslant -1.8$ V. While the 1D ballistic conductance plateaus are no longer observable, the shoulderlike structure close at $G=(0.7\times 2e^2/h)$ persist despite this change in the lateral confinement strength. The data shown in Fig. 2(a) provide compelling evidence that the 0.7 structure is intrinsic to a clean 1D channel and persists over a wide range of lateral confinement strengths.

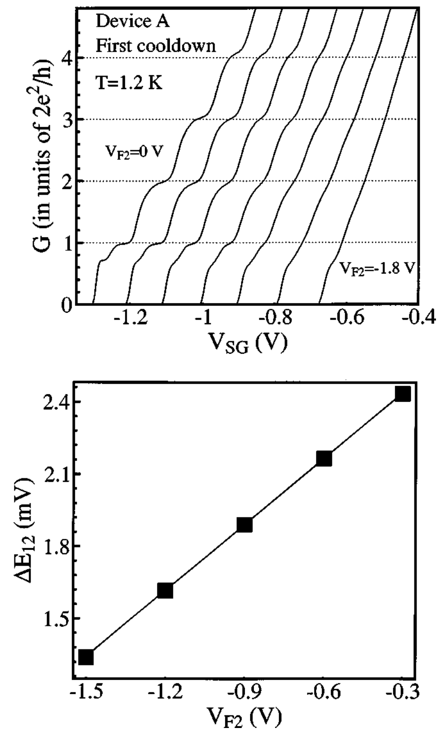

FIG. 2. (a) $G(V_{\mathrm{SG}})$ for $V_{F2}=0$ to -1.8 V in 0.3 V steps when $V_{F1}=V_{F3}=0$ V. The measurement temperature was 1.2 K. (b) $\Delta E_{1,2}(V_{\mathrm{SG}})$ (marked by squares) determined by the source-drain bias technique. The linear fit is discussed in the text.

To demonstrate the observed shoulderlike structure close to $(0.7\times 2e^2/h)$ when the conductance steps are not well quantized and pronounced but has the same physical origin as those observed that coexist with well-quantized conductance steps,[5] we have measured $G(V_{\mathrm{SG}})$ at various $B_{\parallel}$. As the applied $B_{\parallel}$ is increased, the shoulderlike feature indeed evolves into a spin-split $(0.5\times 2e^2/h)$ conductance plateau, as clearly shown in Fig. 3, in agreement with early studies of Thomas *et al.*[5] The fact that the structure at $(0.7\times 2e^2/h)$ is not replicated at $0.7\times e^2/h$ when the spin degeneracy is removed at high $B_{\parallel}$, previously reported by Thomas *et al.*[5] and also shown here, is evidence that the 0.7 structure is not a transmission effect.

Finally, we present clear experimental evidence that the 0.7 structure is not a transmission effect in zero in-plane magnetic field. The solid line in Fig. 4 shows $G(V_{\mathrm{SG}})$ when $V_{F1}=-0.22$ V, $V_{F2}=0$ V, and $V_{F3}=0$, and the dotted line

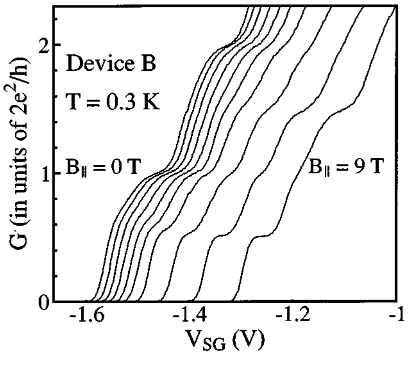

FIG. 3. $G(V_{\mathrm{SG}})$ at various applied in-plane magnetic fields $B_{\parallel}$ for $V_{F2}=-1.4$ V and $V_{F1}=V_{F3}=0$ V. From left to right: $B_{\parallel}=0$ to 9 T in 1 T steps. Successive traces have been horizontally offset by 3 mV for clarity. The measurement temperature was 300 mK.

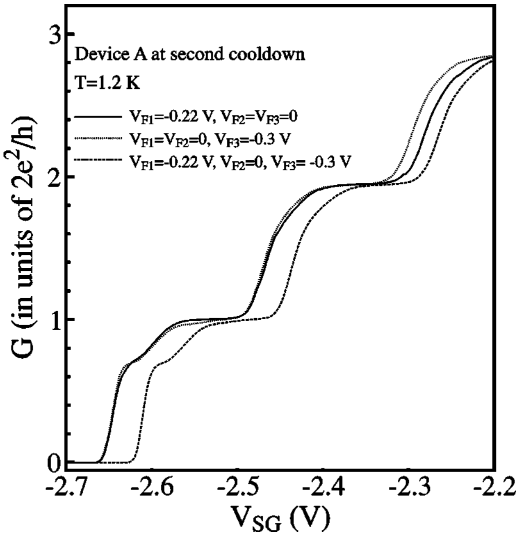

FIG. 4. The solid line shows $G(V_{\mathrm{SG}})$ when $V_{F1}=-0.22$ V, $V_{F2}=0$ V, and $V_{F3}=0$, and the dotted line shows $G(V_{\mathrm{SG}})$ when $V_{F1}=0$ V, $V_{F2}=0$, and $V_{F3}=-0.3$ V. The dashed line shows $G(V_{\mathrm{SG}})$ when $V_{F1}=-0.22$ V, $V_{F2}=0$ V, and $V_{F3}=-0.3$ V, so that we have *0.7* structure present in two 1D channels in series. The measurement temperature was 1.2 K.

shows $G(V_{\mathrm{SG}})$ when $V_{F1}=0$ V, $V_{F2}=0$ V and $V_{F3}=-0.3$ V. In both cases, we observe the 0.7 structure at the same V_{SG} so that the two barriers underneath gate fingers are of the same height. If we now set $V_{F1}=-0.22$ V, $V_{F2}=0$, and $V_{F3}=-0.3$ V, we obtain the dashed line in Fig. 4. From the data for $V_{F1}=V_{F2}=V_{F3}=0$, we know that for $V_{\mathrm{SG}}=-2.67$ V there are two 1D subbands present in the ballistic channel defined by SG. As illustrated in Fig. 4, the 1D channel pinches off at $V_{\mathrm{SG}}=-2.67$ V for both cases when $V_{F1}=-0.22$ V and $V_{F3}=0$, and $V_{F1}=0$ and $V_{F3}=-0.3$ V. The distance between $F1$ and $F3$ is twice as much as the distance between $F1$ ($F3$) and the underlying 2DEG. Also the presence of the grounded $F2$ varies the flow of the electric field lines emitted from $F1$ and $F3$, which makes the 2DEG regions underneath $F2$ less affected by the fringing fields from $F1$ and $F3$. All these results demonstrate that for $V_{F1}=-0.22$ V, $V_{F2}=0$, and $V_{F3}=-0.3$ V, we have two narrower 1D constrictions underneath $F1$ and $F3$ in series, present in the ballistic channel defined by SG, as illustrated in Fig. 5. Here we estimate the constriction width underneath $F1$ ($F3$). Assume that the lateral (the y component) confining potential in the 1D channel has a form

$$U(y)=U(0)+\frac{1}{2}m^*\omega_y^2y^2, \tag{1}$$

where $m^*=0.067m_e$ and m_e is the electron mass.

From the source-drain biased measurements, we know that $\Delta E_{1,2}=2.434\ \mathrm{meV}=\hbar\omega_y$. The difference between the first 1D subband and the conduction-band edge is simply $\frac{1}{2}\hbar\omega_y$ in a simple harmonic oscillator. Thus we calculate ω_y to be $3.698\times10^{12}\ \mathrm{s}^{-1}$ and $U(0)$ to be 5.78 meV. The 1D channel width can be estimated when the energy of the first 1D subband crosses the Fermi energy in the bulk 2DEG ($E_F=7$ meV). From this we calculate that the constriction width underneath $F1$ ($F3$) at the Fermi energy to be 43.3 nm. As shown in Fig. 4, we can see that the 0.7 structure is still observed when the two 1D constrictions are in series, but it occurs at a slightly less negative V_{SG}. This is to be expected since two gate fingers are being biased rather than one, and there is a small degree of cross talk between $F1$ and $F3$. The ratio of the reduction of pinch-off voltage to the initial pinch-off voltage is only 0.04/2.65=1.5%. If the 0.7 structure were a transmission effect, then when we have the 0.7 structure present in two 1D channels in series, a shoulderlike structure close to $0.7\times0.7=0.49(2e^2/h)$ should be observed. Instead, the 0.7 structure persists and behaves as if it is like two ballistic resistors in series as studied by Wharam *et al.*[18] and reproduced here. Thus our experimental results show that the 0.7 structure is *not* a transmission effect through a clean one-dimensional channel at zero in-plane magnetic field.

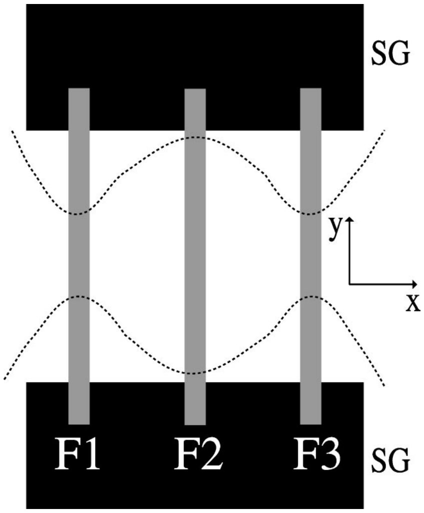

FIG. 5. A schematic diagram showing that applying negative voltages on $F1$ and $F3$ creates two narrower 1D constrictions in series. The dotted lines indicate the depletion regions.

In conclusion, we have shown further supporting evidence that the 0.7 structure is an intrinsic property of a clean one-dimensional channel, even when quantized ballistic plateaus are no longer observable for weak lateral confinement. Moreover, we have shown that the 0.7 structure is *not* a transmission effect at zero in-plane magnetic field.

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