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Suppression of impurity scattering in a one-dimensional wire

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We examined discrete time-dependent changes in the conductance of a one-dimensional (1D) wire, due to a change in the scattering potential of a single defect, as a function of the width of the wire. We discovered that the discrete time-dependent changes are suppressed whenever a 1D subband is fully occupied. Our observations explicitly demonstrate that defect scattering and excess noise can be suppressed in a 1D wire.

There has been much recent interest in electron transport through narrow, one-dimensional (1D) wires.[1] A primary motivation for this activity is the possibility that elastic impurity scattering or scattering from disorder[2] is suppressed in 1D.[3] The suppression is supposed to occur when the width of the wire becomes comparable to the Fermi wavelength (λ_F) of the electron. Due to confinement of the electron, the transverse momentum is quantized and so scattering is allowed only through certain discrete angles instead of a continuum. The suppression of scattering has startling ramifications: e.g., the elimination of excess noise,[3] and an increase in mobility[3] resulting, ultimately, in zero electrical resistance in a normal-metal wire. Yet, despite all the activity and the ramifications, the suppression of scattering in a 1D wire has not been demonstrated unequivocally.[4]

In this Rapid Communication, we demonstrate unambiguously that scattering and excess noise can be suppressed in a 1D wire through an examination of discrete time-dependent changes found in the conductance which resemble a random telegraph signal (RTS).[5-7] RTS is due to a change in the scattering potential of a single trap or defect in the wire and is supposed to be a constituent of the $(1/f)$ noise observed in large devices.[7] We show that the switching associated with RTS is inhibited whenever an integral number of 1D subbands are occupied, but reappears near each threshold for the occupation of a subband. We attribute the inhibition of RTS to the suppression of scattering in a 1D constriction.

We make a 1D wire using a split-gate electrode to laterally constrict a high-mobility two-dimensional electron gas (2D EG) in a modulation-doped $Al_xGa_{1-x}As/GaAs$ heterostructure. By applying a negative voltage to the split-gate electrode on top of the heterostructure, we deplete the 2D EG beneath the electrode and so laterally constrict the 2D EG to the region within the gap in the electrode. The heterostructure consists of a GaAs substrate, an $Al_xGa_{1-x}As$ ($x=0.3$) spacer layer (42 nm thick), a δ-doped Si layer (4×10^{16} m^{-2}), an Al-Ga-As buffer layer (24 nm thick), and a doped GaAs cap (7 nm thick). The mobility of the 2D EG is approximately $\mu=110$ m^2/Vs and the 2D electron density is $n=2.8\times10^{15}$ m^{-2}. The split gates are fabricated on top of the heterostructure using electron-beam lithography to prepare a mask for liftoff. A Ti/Au-Pd film approximately 7.5–50 nm thick is evaporated on the mask and lifted off to form the electrodes. The disposition of the electrodes on top of the heterostructure is shown in Fig. 1. The convention for labeling the constrictions and the electrodes is also given there. Associated with each of the gaps numbered 1–4 there is a contact to the 2D EG which is not shown.

Figure 2 shows the four-terminal resistance (conductance), $R_{12,43}$ ($G_{12,43}$), as a function of the applied gate voltage, V_g, that we found in the device of Fig. 1 when electrodes A and C are used to define a constriction. The notation $R_{kl,mn}$ denotes a resistance measurement in which there is a positive current from leads k to l, and a positive voltage is detected between leads m and n. The depletion of the 2D EG immediately beneath the gate electrodes in this device occurs at $V_g=V_A=V_C\approx-0.35$ V, and is not shown in Fig. 2. As the gate voltage decreases beyond $V_g=-0.35$ V, the constriction within the gap between the electrodes narrows; the carrier density within the constriction decreases; and plateaus are observed in the resistance.[8,9] The conductance obtained by inverting the resistance (i.e., $G_{12,43}\equiv1/R_{12,43}$) versus V_g is also shown in Fig. 2. $G_{12,43}$ is evidently quantized in steps of $2e^2/h$ with about 1–5% accuracy as V_g decreases. The conductance is well represented by $G_{12,43}=2e^2N/h$, with N an integer ranging from 1 to 7 depending on V_g. The

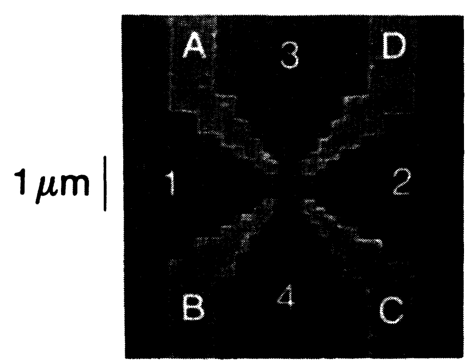

FIG. 1. An electron micrograph of the split-gate electrodes on the heterostructure. The split gates are each 200 nm long with a 300-nm gap between the electrodes. Each of the gate electrodes labeled A–D can be addressed independently. Associated with each gap, numbered 1–4, there is a contact to the 2D EG.

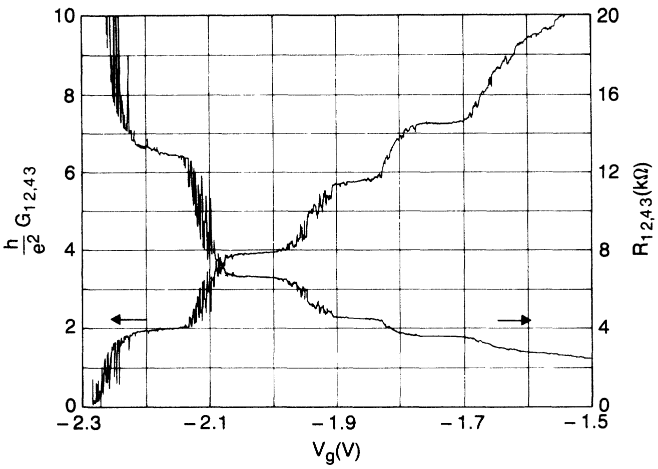

FIG. 2. The four-terminal resistance (conductance), $R_{12,43}$ ($G_{12,43}$), of a constriction in a 2D EG as a function of gate voltage, $V_g = V_A = V_C$, found at 280 mK. The resistance (conductance) fluctuates as a function of time at the threshold of a step which is indicative of RTS.

conductance of the constriction formed by every other pair of electrodes is quantized similarly.

When electrode pairs A-C or B-D are used to define a constriction, discrete time-dependent changes are observed in the conductance near the threshold for a step, which are indicative of RTS. Although the discrete changes are time dependent, the statistics associated with the fluctuations at a particular V_g are not.[6] As shown in Fig. 3, the conductance as a function of time, measured when $V_g = V_A = V_C = -2.250$, -2.103, and -1.950 V, fluctuates with an amplitude of $\Delta G_{12,43} \approx e^2/h$. The largest change found in conductance versus time is $1.2e^2/h$. The conductance generally fluctuates between three different values. The time spent at each value is supposed to correspond to a particular configuration of the defect,[7] and varies depending upon V_g.[6] The variation of the frequency of the switching with V_g has been attributed to a change in the Fermi energy in the wire relative to the energy of the defect.[6]

In stark contrast with the results obtained near the threshold for a step, RTS is completely inhibited at the center of the $N = 1$, 2, 3, and 4 plateaus in the conductance. As shown in Fig. 3 for the $N = 1$ and 2 plateaus, when $V_g = V_A = V_C = -2.163$ and -2.037 V, the value of $G_{12,43}$ is approximately $2e^2/h$ and $4e^2/h$ independent of time.

Each step found in the conductance as a function of V_g corresponds to the depopulation of one 1D subband due to a change in the width of the constriction, W, relative to λ_F. According to the Landauer,[10] the conductance of the constriction is $G = (2e^2/h)\sum_{j,k=1}^{N} t_{jk}$, where t_{jk} is the probability intensity for transmission from subband k into subband j, and N is the number of subbands in the constriction. If there is no scattering (i.e., $t_{jk} = \delta_{jk}$, where δ_{jk} is the Kronecker delta) and the 2D contracts are adiabatically tapered to the constriction,[11] then the low-temperature conductance of a constriction with N occupied subbands is exactly $G = (2e^2/h)N$. Thus, the ideal conductance of a constriction is a quantized function which

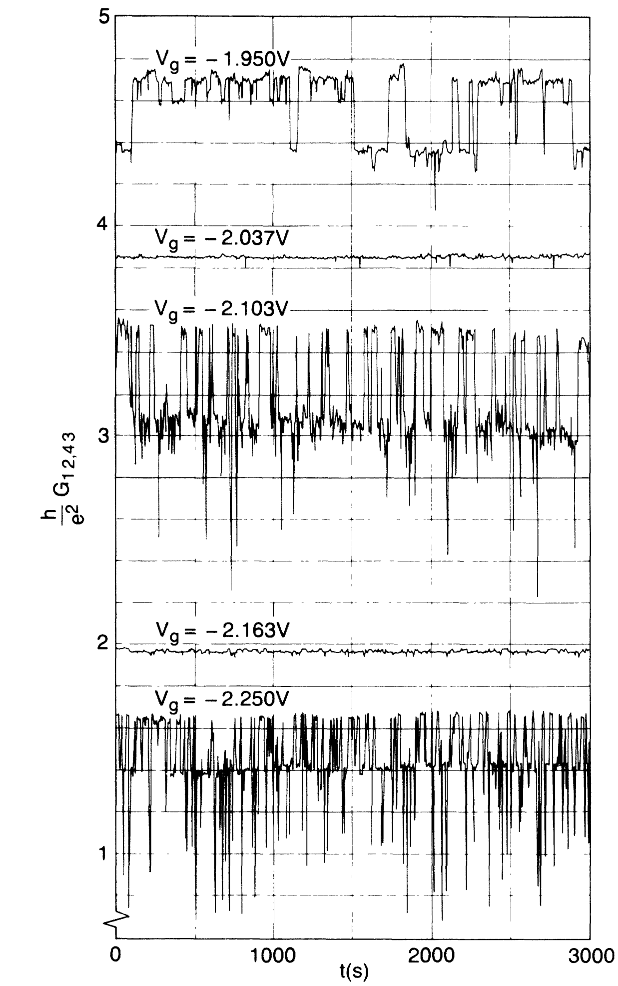

FIG. 3. Figure 3 shows the conductance, $G_{12,43}$, of a constriction in a 2D EG as a function of time measured at five different gate voltages, $V_g = V_A = V_C$, with $T = 280$ mK. For $V_g = -2.037$ and -2.163 V, RTS is suppressed because small-angle scattering is quenched when $N = 1$ and 2.

measures the number of occupied 1D subbands.

The inhibition of noise like RTS on a plateau in the conductance of a constriction was anticipated theoretically by Lesovik.[3] Lesovik showed that the low-frequency noise power measured in a 1D constriction with adiabatically tapered contacts is

$$S(\omega = 0) = (2e^2/h)V \sum_{j,k=1}^{N} t_{jk}(1 - t_{jk}),$$

where V denotes the applied voltage. Therefore, excess noise vanishes on a plateau in the conductance because $t_{jk} = \delta_{jk}$. The noise vanishes because there is no scattering.

If a defect in the constriction backscatters or reflects an electron from the constriction,[12] then the transmission probabilities t_{jj} becomes less than unity; the conductance is reduced from the quantized value; and RTS or noise can be observed. Figure 4 shows two elastic scattering events at the Fermi energy which are detrimental to the quantization of the conductance: (i) a large-angle back-

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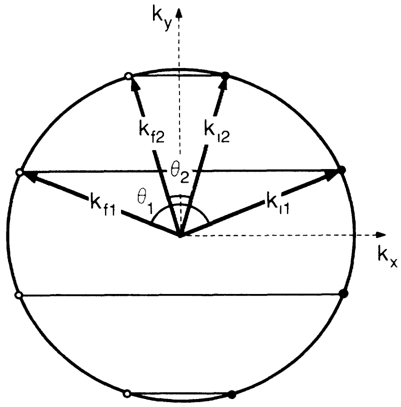

FIG. 4. The circle represents the Fermi surface of a 2D EG in reciprocal space; the intersection between the circle and the horizontal lines represents the allowed transverse wave vectors in the 1D constriction. Current is applied along the k_x direction. Two scattering events which cause the quantization to deteriorate are depicted.

scattering event away from threshold, and (ii) a small-angle backscattering event near threshold for the occupation of a subband.[13] The Fourier components at the $Al_xGa_{1-x}As/GaAs$ interface of the ion potentials in the δ-doped layer are exponentially small beyond $k_x > 1/z_0$, where z_0 is the spacer-layer thickness.[14] If an impurity in the δ-doped layer gives rise to a potential fluctuation at the $Al_xGa_{1-x}As/GaAs$ interface responsible for the RTS, then large-angle backscattering from the potential fluctuation is improbable because the fluctuation only has spatial frequencies less than $z_0^{-1} = \frac{1}{42}$ nm^{-1}. (This is also the reason μ of the 2D EG is so high.) However, small-angle backscattering from a potential fluctuation is not only possible, but likely in GaAs (Refs. 15 and 16) and could destroy the quantization near the threshold for occupation of the highest-index subband. If an electron is reflected through a small angle, the change in the conductance associated with the reflection is constrained by unitarity to be less than $2e^2/h$ because the transmission probability associated with the 1D subband will either be 0 or 1.[10] Thus, the amplitude of the RTS must be less than $2e^2/h$. Away from threshold, the spatial frequencies required to backscatter an electron in the highest subband are not available since the potential is too smooth. Consequently scattering is suppressed and RTS is inhibited.

From another perspective,[17] the transport through the constriction is nonadiabatic near threshold because the wavelength is long relative to the potential fluctuations. Consequently, the conductance is not quantized.[11] But when the subband is completely occupied, the wavelength becomes short relative to the potential fluctuations; the transport is adiabatic and the conductance is quantized.

We contend that the defect associated with the RTS is near the constriction, somewhere in the gap between the electrodes A-C and B-D, because it is observed when the pairs A-C or B-D are biased independently or all together. (RTS is not observed when the pairs A-B, B-C, C-D, or A-D are biased, but the V_g used is a factor of 2 smaller than that used to bias the A-C pair. No RTS is observed when A-C is biased at such low V_g.) Furthermore, we contend that a defect in the $Al_xGa_{1-x}As$, set back from the constriction, gives rise to the scattering since the RTS depends on V_g as shown in Fig. 2, and is suppressed when an integral number of 1D subbands are occupied independent of the lateral position of the constriction with the gap between A-C.

In an attempt to ascertain the position of the defect, we laterally changed the position of the constriction within the gap between A-C by independently biasing the split gates. Independent control of the electrodes provides the opportunity to laterally change the position of the constriction while maintaining the same number of 1D subbands.[18] For a split-gate configuration similar to Fig. 1, the maximal value of the potential due to the electrodes, measured from the center of the gap between A-C, corresponds to the position $y_0 = D\Delta V/2V^p$, where $\Delta V \equiv V_A - V_C$, $D = 425$ nm is the width of the gap between A-C,

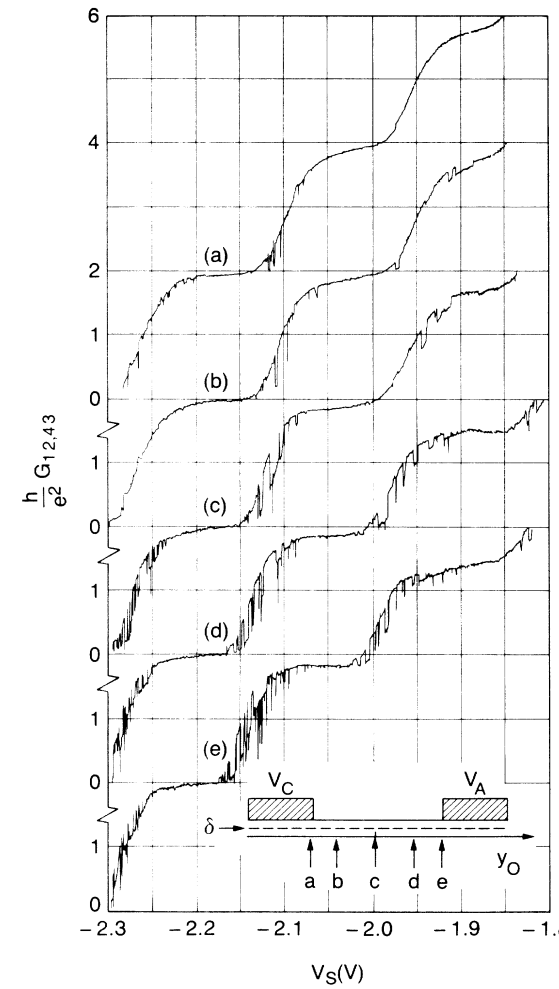

FIG. 5. The conductance, $G_{12,43}$, versus gate voltage, $V_s = \frac{1}{2}(V_A + V_C)$, for (a) $\Delta V = V_A - V_C = -0.425$ V, (b) -0.275 V, (c) 0 V, (d) 0.275 V, and (e) 0.425 V. The position of the 1D constriction within the gap between the electrodes of Fig. 1 is supposed to be linearly related to ΔV. The inset shows the relative positions of the center of the channel; the defect is supposed to be located in the δ-doped layer near gate A.

and $V^p \approx -0.35$ V is the pinchoff voltage.[18] Thus, the lateral position of the constriction within the gap depends linearly on ΔV. The changes in the threshold for each step in the conductance as a function of $V_s = \frac{1}{2}(V_A + V_C)$ depend on $(\Delta V/V^p)^2$ and are supposed to be small.[18]

In Fig. 5, $G_{12,43}$ is shown as a function of V_s for $\Delta V = -0.425$, -0.275, 0, 0.275, and 0.425 V, ideally corresponding to $y_0 = -260$, -170, 0, 170, and 260 nm. The quantization of the conductance is preserved when $\Delta V \neq 0$, and the thresholds are not very sensitive to changes in ΔV, as anticipated. We observe RTS at the threshold for occupation of a subband for each ΔV, but the magnitude and characteristic frequency of the switching noise change dramatically with the lateral position of the constriction. RTS is reduced when $\Delta V < 0$ compared to $\Delta V \geq 0$ which may indicate that the trap is in the $Al_xGa_{1-x}As$ near electrode A.

Our data are consistent with an impurity in the donor-layer switching. If the RTS found as a function of ΔV is all due to the same trap, that trap affects a region which is comparable to the size of the gap. This deduction is consistent with the long-range effect that a poorly screened impurity potential would have at the $Al_xGa_{1-x}As/GaAs$ interface.[14,19] Alternatively, if different traps are activated with each ΔV, the relevant trap must still be set back from the constriction into the $Al_xGa_{1-x}As$ because RTS is always suppressed whenever an integral number of subbands is occupied.

We can estimate the vertical separation between the defect and the constriction from the width of the transition between plateaus where RTS is observed. For example, at the threshold for occupation of the $N=2$ subband, where RTS is first observed ($V_g = -2.14$ V), the longitudinal component of the wave vector, k_x in Fig. 4, vanishes. The RTS vanishes on the $N=2$ plateau at $V_g = -2.06$ V, where the Fermi wave vector $k_F = 7.93 \times 10^7$ m^{-1}. (k_F is determined by the carrier density in the constriction, $n = 1 \times 10^{15}$ m^{-2}, which we deduced from the magnetoresistance measurements.) At the same gate voltage we deduce that $W \approx 100$ nm using a hard wall confinement potential. Thus, $k_x = [k_F^2 - (2\pi/W)^2]^{1/2} \approx 5 \times 10^7$ m^{-1} when RTS is suppressed at the $N=2$ conductance plateau. The absence of scattering for $-1.98 \text{ V} > V_g > -2.06$ V, where $k_x > 5 \times 10^7$ m^{-1}, implies a separation between defect and constriction of $z_0 \approx k_x^{-1} > 21$ nm, a distance comparable to the spacer-layer thickness.

In summary, we have discovered that RTS is inhibited in a wire when a 1D subband is fully occupied. We attribute the inhibition of RTS to the suppression of scattering and the resulting adiabatic transport.

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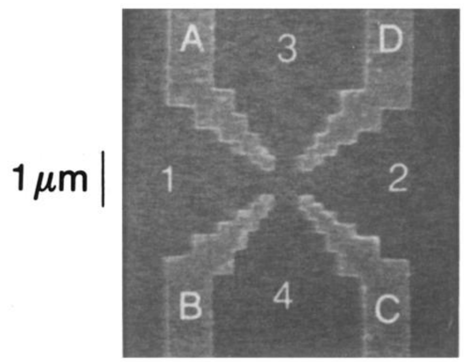

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