Shifting a Quantum Wire through a Disordered Crystal: Observation of Conductance Fluctuations in Real Space

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A quantum wire is spatially displaced by suitable electric fields with respect to the scatterers inside a semiconductor crystal. As a function of the wire position, the low-temperature resistance shows reproducible fluctuations. Their characteristic temperature scale is a few hundred millikelvin, indicating a phase-coherent effect. Each fluctuation corresponds to a single scatterer entering or leaving the wire. This way, scattering centers can be counted one by one.

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The mesoscopic regime in electronic transport is characterized by a sample size $L$ comparable to the phase coherence length $\ell_\phi$. In this regime, electronic waves get reflected at the elastic scatterers and interfere with each other. As a consequence, the sample conductance $g$ depends on $\ell_\phi$ as well as on the configuration of the elastic scatterers, in contrast to the macroscopic regime, $\ell_\phi \ll L$. Theoretically, this effect can be treated by changing the scatterer configuration and studying the corresponding change in the conductance $g$.

In the experiments, however, the conductance fluctuations (CF) are measured as a function of an externally controllable parameter, such as Fermi energy $E_F$ or magnetic field $B$. The CF reflect the parametric modification of the interference pattern. The experimental results are then connected to theory by using the ergodic hypothesis, which states that averaging over the disorder in many samples is the same as changing a parameter that modifies the electronic properties at the Fermi level. In completely phase coherent samples, the average CF amplitude is of the order of $e^2/h$ ($e$ is the elementary charge and $h$ is Planck’s constant), independent of material parameters. Therefore, they are also known as “universal conductance fluctuations” $g_\ell$, although true universality can be disturbed by various effects.

The average amplitude is reduced not only when $L$ gets larger than $\ell_\phi$, but also at non-zero temperature.

Here, we report the experimental observation of CF as a function of the scatterer distribution inside a quasi-one-dimensional wire, which can be shifted through the host crystal by gate electrodes. Pronounced fluctuations in $g$ as a function of the displacement $\delta z$ of the wire perpendicular to the transport direction are found, which is the central result of this letter. We show that the quasi-period of the CF essentially reflects the displacement needed to shift the wire into or out of a single scatterer.

The sample is a Ga[Al]As heterostructure with the two-dimensional electron gas (2DEG) residing 37 nm below the surface. A 10$\mu$m wide Hall bar was defined by optical lithography and wet chemical etching. Two oxide lines, written with an atomic force microscope in the heterostructure surface, define the wire of length $L = 40 \mu$m and lithographic width of 150 nm (inset in Fig. 1(a)). In a final fabrication step, the Hall bar was covered by a homogeneous Ti/Au top gate electrode. The sample was mounted in the mixing chamber of a $^3$He/$^4$He-dilution refrigerator with a base temperature of 30 mK. The sample chamber is carefully shielded from high frequency noise. We estimate the electronic temperature to be about $T = 90$ mK. Under these conditions and with the top gate grounded, the 2DEG has a sheet density of $4.3 \cdot 10^{15}$ m$^{-2}$ and a mobility of 102 m$^2$/Vs. The Drude and quantum scattering lengths are $\ell_D = 11.0 \mu$m, and $\ell_q = 0.46 \mu$m, respectively, while the thermal length is $\ell_T = 11.5 \mu$m.

A DC current of 2 nA was passed through the quantum wire, and the voltage drop was measured using a four-terminal setup. Magnetic fields up to $B = 8$ T were applied perpendicular to the plane of the sample surface. From the autocorrelation function of the CF as a function of $B$, we obtain $\ell_\phi \approx 7 \mu$m. The wire can be tuned by voltages $V_1$, applied to two planar gates $pg_1$ (i=1,2), as well as with a top gate voltage $V_{tg}$ (Fig. 1(a)). Assuming a parabolic confinement, we use the model by Berggren et al. to fit the positions of the Shubnikov-de Haas minima, from which we obtain the one-dimensional electron density $n_{1D}$ and the electronic wire width $w$.

In Fig. 1(a), the magnetoresistance of the wire is shown for different planar gate voltages ($V_1$, $V_2$) with the top gate grounded. By changing $V_1$ and/or $V_2$, $n_{1D}$ and $w$ can be tuned from $(n_{1D} = 5.5 \cdot 10^8$ m$^{-1}$, $w = 116$ nm) for $V_1 = V_2 = -80$ mV to $(n_{1D} = 6.7 \cdot 10^8$ m$^{-1}$, $w = 141$ nm) for $V_1 = V_2 = +80$ mV. Our scan range is limited to...
bands. Furthermore, \( R(B) \) and thus the fit parameters for \((V_1, V_2) = (-80 \text{ mV}, +80 \text{ mV})\) are identical to those for \((V_1, V_2) = (+80 \text{ mV}, -80 \text{ mV})\). Hence, by applying antisymmetric voltage changes to \(V_1\) and \(V_2\) (i.e. \(\delta V_1 = -\delta V_2\)), the wire can effectively be shifted through the semiconductor host while keeping \(w\) and \(n_{1D}\) constant. A similar technique has been used already in order to investigate the spatial location of noise-generating carrier traps in quasi-ballistic channels \([18]\), and to study the average distribution of elastic scatterers of parabolic quantum wells in growth direction \([19]\). The shift \(\delta z\) can be estimated by assuming that a voltage difference \(\delta V_i\) (i=1,2) on one planar gate moves the wire edge next to it by half the change in wire width achieved when both gate voltages are changed symmetrically by \(\delta V_i = -\delta V_i\). We find a lever arm of \(\delta z/|\delta V_i| \approx 70 \text{ nm/V}\). Fig. 1(b) shows the wire conductance in the plane spanned by the planar gate voltages. The recording time for such a measurement is 30 hours. Background charge rearrangements, which appear as sudden, small shifts in the conductance pattern, are observed on a time scale of \(\approx 1\) day. The diagonal axis running from \((V_1, V_2) = (-80 \text{ mV}, -80 \text{ mV})\) to \((80 \text{ mV}, 80 \text{ mV})\) corresponds to \(\delta z = 0\), while the axis from \((V_1, V_2) = (-80 \text{ mV}, +80 \text{ mV})\) to \((V_1, V_2) = (+80 \text{ mV}, -80 \text{ mV})\) corresponds to constant \(n_{1D}\) and \(w\). Both axes have been calibrated by measuring and fitting \(R(B)\) for the points \((V_1, V_2) = (-80 mV + m \cdot 20 mV, -80 mV + n \cdot 20 mV)\) (\(m, n = 0, \ldots 8\)). Reproducible fluctuations in the conductance are observed as a function of both \(n_{1D}\) and \(\delta z\). They are almost completely smeared out at \(T \approx 850 \text{ mK}\) [Fig. 1(c)], indicating a phase coherent origin. The overall conductance increases as \(T\) is increased, since the weak localization effect \([14]\) is reduced. The characteristic fluctuation period is \(\approx 5 \times 10^6 m^{-1}\) in \(n_{1D}\) and \(\approx 4 nm\) in \(\delta z\). The characteristic CF fluctuation amplitude in both directions is \(\delta g \approx 0.25 e^2/h\), in good agreement with the value expected from theory for \(\omega < \ell_F \approx \ell_T < L [20]\), i.e. \(\delta g \approx \sqrt{2\ell_F/\ell_T})^{1.5} \cdot [1 + (9/2\pi)(\ell_F/\ell_T)^2]^{-0.5} e^2/h\), which gives \(\delta g \approx 0.22e^2/h\) for our parameters.

In the following, we discuss the origin of CF as a function of the displacement of the wire. Cahay et al. \([3]\) have studied theoretically CF as a single scatterer is moved inside a quantum wire. In this case, the CF quasi-period was found to be of the order of the Fermi wave length \(\lambda_F\) of the lowest one-dimensional subband. In our sample, \(\lambda_F \approx 30 \text{ nm}\), which is about one order of magnitude larger than the observed quasi-period. Possibly, this theoretical model could be realized experimentally by using scanning probe microscopes to induce a scattering center in a quantum wire \([21]\). In our experiment, however, we do not scan individual scatterers with respect to the others inside the wire, but rather scan the conductive region through a rigid configuration of scatterers. Occasionally, a scatterer enters or exits the electronic wire. This changes the interference pattern.

FIG. 1. (a) Magnetoresistance for different planar gate voltages \((V_1, V_2)\), corresponding to the corners in Figs. b and c. Curves are vertically offset by 5 kΩ each. Left inset: schematic cross section through the sample. The 2DEG is separated into wire and planar gates pg1 and pg2 by the oxide lines. The surface is covered by a metallic top gate. Right inset: atomic force microscope picture showing the surface topography before evaporation of the top gate. The oxidized regions are 8 nm elevated above the heterostructure surface and appear as bright lines. (b): Conductance \(g\) at \(T = 90 \text{ mK}\) and for \(V_{pg} = 0, B = 0\) as a function of \((V_1, V_2)\). The data have been obtained by sweeping \(V_1\) and changing \(V_2\) in steps of 2 mV. The two diagonal axes correspond to the electronic wire width \(w\) (as well as to the electron density in the wire \(n_{1D}\), measured in units of \(10^9 m^{-1}\)) and to the wire displacement \(\delta z\) (see text). (c): The same measurement as in (b), taken at \(T = 850 \text{ mK}\).
of the electronic waves and influences the conductance. On average, the number of scatterers inside the wire changes by one if the wire is displaced by $\Delta z = d^2/2L$ ($d$ is the relevant scattering length). The factor of two takes into account that scatterers may enter the wire on one side as well as exit it on the other. We find $\Delta z = 2.7$ nm for $d = \ell_q$ and $\Delta z = 1.5$ $\mu$m for $d = \ell_D$. This suggests that the observed quasi-period in $\delta z$ is caused by individual small-angle scatterers that the wire passes on its way through the crystal. As we will argue below, the actual situation is more complicated, since the two-dimensional quantum scattering length is not a good quantity to characterize the scattering inside the quantum wire. Rather, additional scattering is produced by the wire boundaries. This interpretation of the data in Fig. 1 is supported not only by a simple argument based upon a numerical simulation, but also by further, density-dependent measurements.

We have modeled the wire conductance using the scattering-matrix approach of Ref. [3]. All scatterers are represented by identical delta-function potentials $\gamma \cdot \delta(x,z)$, located at random positions within an area of 400 nm $\cdot$ 40 $\mu$m. We choose their average distance equal to $\ell_q$ [Fig. 3(a)]. The wire parameters (i.e. $w$, $\omega_0$, and $n_{1D}$) are taken from the data in Fig. 1. Transport through the wire is assumed to be completely phase coherent. The conductance is obtained from the transmission part of the overall scattering matrix, which is composed of coherently combined propagation matrices and single-impurity scattering matrices. The conductance as a function of the position of the wire, $g(\delta z)$, is obtained by shifting the conducting region through the rigid configuration of scatterers. Fig. 3(b) shows $g(\delta z)$ of a wire with 8 occupied modes ($w = 130$ nm, $\omega_0 = 3.1 \cdot 10^{12}$ $s^{-1}$, $n_{up} = 4.7 \cdot 10^{12}$ m$^{-2}$) for 3 different values of $\gamma$. The calculated CF quasi-period is of the same order as $\lambda_F \approx 30$ nm for small $\gamma$. By increasing $\gamma$, however, it can be reduced to the quasi-period observed experimentally. Note that in this simulation, the amplitude is of order $e^2/h$, since transport through the wire is completely phase coherent in our model.

We have also simulated $g(\delta z)$ when the number of scatterers inside the wire is kept fixed (not shown). Here, the quasi-period is of the order $\lambda_F$, independent of $\gamma$. Furthermore, the quasi-period does not depend on the wire width at constant scatterer density. Our simulations thus indicate that only those scatterers that enter or exit the wire determine the observed quasi-period for large $\gamma$. As $\gamma$ is reduced, the quasi-period approaches $\lambda_F$. We are not aware of any theoretical consideration on how the observed quasi-period should depend upon $\ell_q$. Qualitatively, however, we expect it to increase as $\ell_q$ gets smaller, as this is the case for the CF in magnetic fields and in electron density [14]. Consequently, we can consider the value for $\gamma$ that simulates the experiment as a lower limit for the scattering strength. The experiment is simulated best for a value of $\gamma \approx 10^{-36}$ $\text{J} \cdot \text{m}^2$. Assuming a scattering cross section with a radius $r_{sc}$ of the screening length for a 2DEG in GaAs [22], i.e. $r_{sc} = (a_B^2/2 = 5$ nm ($a_B$ denotes the effective Bohr radius in GaAs), we find as a lower limit a characteristic height of the scatterers, given by $\gamma/(\pi r_{sc}^2) \approx 80$ meV. This corresponds to a strong scatterer. We conclude that in the wire region, scattering is enhanced. Presumably, the additional scattering comes from the roughness of the wire boundaries [11] [3] [8] [24]. In addition, in the depleted regions underneath the oxide lines, screening is strongly reduced.

In order to test this picture, we have changed $w$ by applying top gate voltages [Fig. 3]. As the wire is narrowed to $w \approx 100$ nm ($V_{tg} = -100$ mV, Fig. 3(a)), only 6 one-dimensional modes are occupied. The feature sizes in $\delta z$ increase almost above our scan range. The fluctuation amplitude is reduced. Note that the smearing of the CF as a function of $n_{1D}$, which is determined by the reduction of $\ell_{ph}$, is weaker. Compared to the measurements in Fig. 1, the edges of the wire are 15 nm further away from the oxide lines. Consequently, the boundary roughness is smoothed and the quasi-period increases, as seen qualitatively in Fig. 3(b). For positive top gate voltages ($V_{tg} = +100$ mV, Fig. 3(b)), $w$ increases only slightly, while $n_{1D}$ increases rapidly. Here, 12 one-dimensional modes are occupied. The quasi period is decreased to about 2nm, which reflects the fact that here the wire is pushed very hard into the oxidized region. Note that the observed dependence of the quasi-period on the top gate voltage is opposite to what is expected from density dependent screening, since increasing $n_{1D}$ im-

FIG. 2. (a) Distribution of delta-shaped scatterers around the wire. The shaded region shows the wire position. (b) Calculated conductance fluctuations $g(\delta z)$. With increasing scattering strength $\gamma$, $g$ decreases and the quasi-period drops from 15 nm to about 5 nm.

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proves the screening, which should result in larger quasi-periods. However, our interpretation does not take into account the density-dependence of $\ell_\phi$, which may play a role as well.

FIG. 3. Wire conductance at $T = 90$ mK in the $(V_1, V_2)$-plane for $V_{tg} = -100$ mV (a) and $+100$ mV (b). The diagonal axes are defined as in Fig. 1(b,c). At positive $V_{tg}$, the fluctuation quasi-period in $\Delta z$ decreases significantly. At $V_{tg} = 100$ mV, the break-down voltage of the planar gates decreases to $\pm 60$ mV, which reduces the scan range.

In conclusion, we have reported the measurement of conductance fluctuations in a quantum wire as a function of its position with respect to a rigid scatterer configuration. The fluctuation period decreases with increasing electron density. We have interpreted the period in real space in terms of individual scatterers entering or leaving the wire region, while its dependence on the width of the wire can be understood in terms of increased scattering at the wire boundaries. It will be particularly interesting to apply our technique to quasi-ballistic quantum point contacts as well as to single-mode quantum wires. We hope that our experiment will stimulate theoretical studies as well as new experiments, in order to get a better understanding of conductance fluctuations in real space. We have enjoyed fruitful discussions with S.E. Ulloa, D. Loss and T. Ihn. This work was supported by the Swiss National Science Foundation.

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