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Scanning gate measurements on a quantum wire

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Abstract

We have performed measurements on a semiconductor quantum wire in which we induce a local potential perturbation with the metallic tip of a scanning force microscope. Measurement of the sample resistance as a function of tip position results in an electrical map of the wire in real space. We find the fingerprint of potential fluctuations in the wire which appear as local resistance fluctuations in the images. In a local transconductance measurement we observe small oscillations on the scale of the Fermi-wavelength of electrons which may arise from interference of electron waves. © 2002 Elsevier Science B.V. All rights reserved.

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Electronic transport in mesoscopic semiconductor structures at low temperatures is non-local and phase coherent [1]. In a conventional transport experiment, in which the resistance or conductance of a sample is typically measured as a function of gate voltage or magnetic field, the measured conductance is given by the transmission probabilities between the leads connecting the system to the measurement circuit [2]. In general, it is not possible to reconstruct the scattering potential within the mesoscopic system from the knowledge of the transmission matrix. However, additional information about the quantum states within the device can be obtained from measurements which apply a local perturbation to the system [3–7]. While in Ref. [3] the local potential perturbation was fixed and the two-dimensional electron gas in a parabolic quantum well could be displaced, in Refs. [4–7] the local electrostatic potential induced by the tip of a scanning force microscope was utilized. In this paper, we adopt this approach for the investigation of the transport properties of a quantum wire.

The sample is based on a GaAs/AlGaAs heterostructure in which the heterointerface is buried 34 nm below the surface. A Hall-bar geometry, a part of which can be seen in Fig. 1, was patterned using photolithography. At the temperature $T = 1.7$ K the bulk electron density measured in this system is $n_S = 4.3 \times 10^{11}$ cm^{-2}, corresponding to a Fermi wavelength of 38 nm. The mobility at $T = 1.7$ K is $\mu = 10^6$ cm^2/V s corresponding to a mean free path of $l_e^{2D} = 10.8$ μm and a diffusion constant of $D = 1.52$ m^2/s. The quantum wire has been patterned by AFM-lithography [8] directly onto the Hall-bar structure (see Fig. 1). The white lines on the Hall bar are the AFM-written oxide lines which deplete the 2DEG below them and thereby form a long quantum

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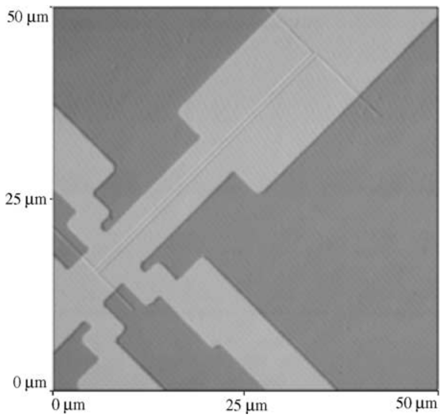

Fig. 1. SFM-image of the Hall-bar with the oxide lines defining the quantum wire.

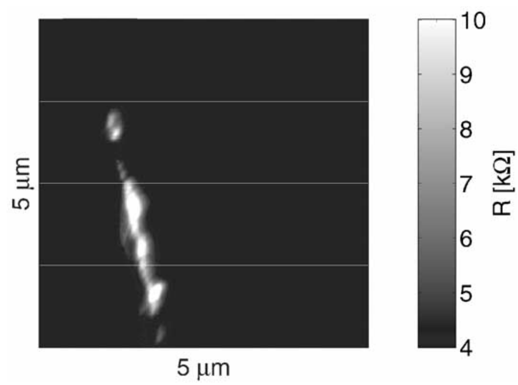

Fig. 2. Resistance image of the quantum wire measured at $T = 1.7$ K.

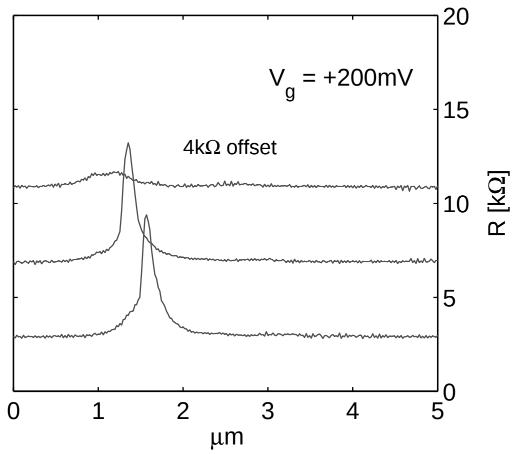

Fig. 3. Cross sections through the resistance image shown in Fig. 2.

wire flanked by two separately contacted regions of the 2DEG which we used as in-plane gates. The wire length is $L = 40$ μm and its lithographic width is $W = 400$ nm. The lateral depletion length is typically 15–20 nm such that the number of modes in the channel can be estimated to be $N = 20$. This number can be confirmed by Shubnikov de Haas-measurements which count the number of modes which become successively depopulated as the magnetic field is increased.

The sample was mounted in the sample holder of a low-temperature scanning force microscope (SFM) [9]. This microscope utilizes piezoelectric quartz tuning forks with a metallic tip attached to one prong as the force sensor. Operation characteristics at low temperatures and sensor calibration have been reported in Refs. [10,11]. The microscope was cooled to $T = 1.7$ K in the He gas flow of a variable temperature insert. The resistance of the wire was measured at an AC current of 20 nA in a 4-probe configuration. The measurement frequency was 421 Hz and a lock-in time constant of 10 ms was used in order to obtain a reasonably large output bandwidth. The tungsten tip of the SFM was kept grounded while it was oscillating with an amplitude of about 1 nm normal to the surface at the tuning fork resonance frequency of about 32 kHz. Resistance images of 256×256 points were taken at scan speeds of 500 nm/s.

Fig. 2 shows the resistance image of a 5×5 μm^2 area obtained with a voltage of $+200$ mV on one of the in-plane gates. The fact that the wire can be electronically imaged indicates that when the tip is above the wire the resistance is enhanced. This resistance contrast is due to the fact that tungsten and the heterostructure have a work function difference of the order of 100 mV which causes the tip to induce a local repulsive electrostatic potential in the 2DEG which is scanned along when the tip moves. The stripe of enhanced resistance is not visible in the topmost quarter of the image. From the simultaneously measured topography we know that the wire ends there.

Cross-sections through this image as indicated by three horizontal lines in Fig. 2 are shown in Fig. 3. As the tip moves across the wire the resistance goes from its base value of 3 kΩ through a pronounced peak of 9.4 kΩ. We estimate the number of modes which become locally depleted, ΔN, with a simple model which regards the repulsive tip potential as the cause of an additional resistance ΔR which adds to the background wire resistance R_0. In the simplest case ΔR can be modeled by a short piece of wire with transmission $T = 1$ which is not mode-matched to the rest of the wire. In this case $\Delta R = h/(2e^2)(1/(N_0 - \Delta N) - 1/N_0)$ with $N_0 = 20$ being the number of modes in the wire in the absence of the tip. This gives a substantial depletion of $\Delta N = 18$ Modes if the tip is centered above the wire.

From the width of the two lower peaks of about 400 nm which is close to the geometrical width of the wire we estimate that the tip induced potential perturbation cannot be much wider than that.

A very striking feature of the image in Fig. 2 is the variation of the resistance along the wire direction. In a perfect wire with no potential fluctuations and perfectly smooth boundaries no such variation would be expected irrespective of the exact geometrical shape of the tip-induced potential. From a comparison of the resistance variations with the surface topography we find no correlation between the two that could explain the former as the result of a varying tip-2DEG separation. We therefore conclude that the variations of the resistance along the wire direction reflect the roughness of the potential landscape in the electron gas.

There are two distinct effects in mesoscopic systems that could cause the observed resistance fluctuations as the perturbation is moved along the wire. The first is the ballistic chaotic motion of *classical* electrons in a spatially varying potential landscape. In order to develop a better understanding of how this mechanism would appear in our measurements we have calculated the classical transmission through wire structures with a given potential landscape as a function of the position of an additional external perturbation. The results which will be discussed elsewhere show that the complex electron dynamics does indeed lead to fluctuations in the resistance image.

The second effect which could produce resistance fluctuations along the wire is the *quantum interference* of phase coherent paths which leads to fluctuations in the transmission as a function of tip position. Theories exist that predict conductance fluctuations in a disordered sample when the position of a single impurity is moved [12]. Given our sample parameters and the measurement temperature the phase coherence length can be estimated to be $\ell_\varphi \approx 8$ μm but the observability of phase coherence effects is limited by energy averaging through the Fermi-distribution function, i.e. the thermal length $\ell_T = \sqrt{\hbar D/(kT)} \approx 2$ μm. Fluctuations will have the order of magnitude $\Delta R = R^2 \Delta G \approx R^2 e^2/h(\ell_T/\ell_\varphi)(\ell_\varphi/L)^{3/2} \approx 100\ \Omega$. The characteristic length scale for these fluctuations is the Fermi-wavelength of the electrons.

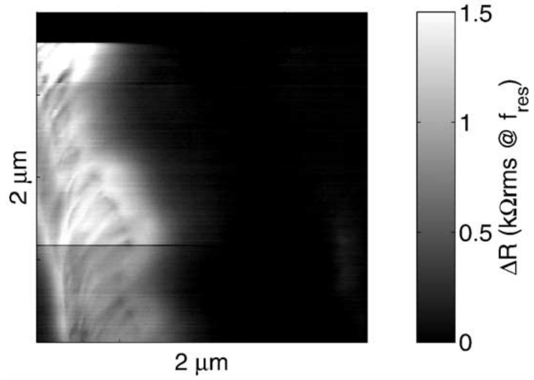

Fig. 4. Local transconductance image of the wire exhibiting resistance fluctuations on the scale of the Fermi wavelength.

Fig. 4 shows an image of the wire measured in a different measurement configuration, where a DC-current was applied and the wire resistance was measured at the resonance frequency of the oscillating tip effectively resulting in a local transconductance measurement. This image taken with increased spatial resolution exhibits amazingly regular stripe-like patterns on a length scale of less than 100 nm. Given the above considerations about phase coherence the tentative explanation in terms of interference effects seems reasonable. Clarifying experiments are in progress.

In conclusion, we have investigated the mesoscopic transport through a quantum wire as a function of a local SFM-tip-induced perturbation. The resistance image shows fluctuations along the wire which can be due to the classical ballistic motion of electrons or quantum interference effects.

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