Transport properties of a Si/SiGe quantum point contact in the presence of impurities

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The conductance of a quantum point contact, defined in a Si/SiGe heterostructure by a short split gate, shows Aharonov-Bohm oscillations between the quantized plateaus in the presence of magnetic fields above $B \approx 2$ T. Their period increases with decreasing gate bias, indicating that they arise from the point-contact geometry itself. A more detailed analysis demonstrates, however, that their origin is also associated with an impurity state close to or in the constriction. This interpretation is further supported by distinct conductance peaks which appear at gate voltages close to the channel "pinch-off" and which result from resonant tunneling through such impurity states.

Split-gate devices fabricated from semiconductor heterostructures containing high-mobility two-dimensional electron gases (2DEG's) are known to be ideally suited for the investigation of ballistic transport through quantum point contacts (QPC's).[1] The length of such devices is much smaller than the electronic mean free path, and their width can be tuned to become comparable to the Fermi wavelength via the applied gate bias. The conductance G of such a QPC was found to be quantized in units of $N \times 2e^2/h$ when the gate voltage is swept,[2,3] even in the absence of a magnetic field, where N is the number of occupied one-dimensional (1D) subbands contributing to the current. The application of a perpendicular magnetic field B shifts the quantized plateaus to more positive gate voltages as the 1D hybrid levels are depopulated.[4,5] The purely electrostatic quantization is thereby smoothly transformed into the quantum Hall effect. Information about the shape of the potential in the QPC can be obtained from such experiments by fitting the data to appropriate models.[6] Very recently, we have demonstrated both the conductance quantization at $B=0$ as well as magnetic depopulation of 1D subbands in a QPC defined in a Si/SiGe heterostructure.[7] In this paper we report on transport properties of this device which are associated with an impurity site in the vicinity of the constriction.

The modulation-doped $Si/Si_{0.7}Ge_{0.3}$ heterostructure was grown at Daimler-Benz on top of a relaxed, graded SiGe buffer layer. The 2DEG is thus confined to a Si layer under tensile strain located 66 nm beneath the surface. It possesses a carrier density $n_s = 4.45 \times 10^{11}$ cm^{-2} and an elastic mean free path of about 1.3 μm. To fabricate the QPC a standard Hall bar was first defined by optical lithography and wet chemical etching, and its sidewalls were coated with Si_3N_4. Ohmic contacts made of Sb and Au were then deposited and alloyed. Finally a Pd split gate was positioned between the Hall voltage probes by means of electron-beam lithography. The constriction defined by this split gate was lithographically 500 nm wide and 240 nm long.

As reported in Ref. 7, a 1D channel is formed in this device at $V_{gate} \approx -0.1$ V and "pinch-off" occurs at $V_{gate} \approx -1.6$ V. Five conductance plateaus are observed at $B=0$ and $T=25$ mK in units of $N \times 4e^2/h$, reflecting the additional valley degeneracy $g_v = 2$ in this material system. Both the spin and valley degeneracies can be lifted by applying a perpendicular magnetic field. The magnetic depopulation of the 1D subbands can be adequately described assuming a square-well potential of width W and an energy barrier E_c at the entrance to the constriction. This model was found to be valid as long as one is not too close to pinchoff. In the voltage range between -0.7 and -1.3 V a linear dependence of the fitting parameters on V_{gate} is observed: W decreases from 157 to 95 nm while E_c is enhanced from 0.78 to 1.83 meV. Extrapolation of the data for the channel width and energy barrier to zero bias is also consistent with other experiments.

Since the sample was maintained at temperatures well below 1 K throughout the entire series of measurements, one can assume that the actual shape of the QPC remains unchanged, and that hence the depopulation model de-

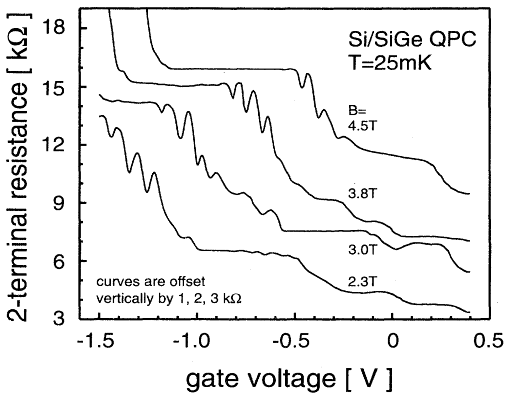

FIG. 1. Two-terminal resistances of the QPC at $T=25$ mK for magnetic fields corresponding roughly to filling factors $\nu=8$, 6, 5, and 4 in the 2D leads. The curves are offset vertically for clarity.

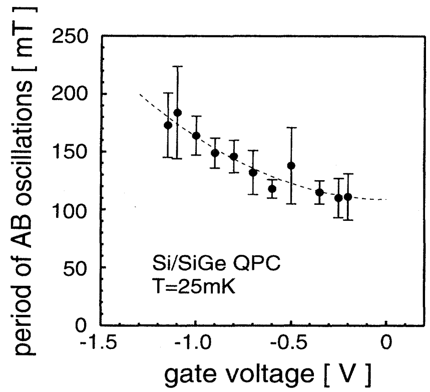

FIG. 2. Period of the Aharonov-Bohm oscillations as a function of the applied gate voltage. The dashed line is a guide to the eye.

scribed above can be applied for the evaluation of further features. Figure 1 shows the two-terminal resistances of the device at $T=25$ mK for magnetic fields $B=2.3$, 3.0, 3.8, and 4.5 T. These fields correspond roughly to filling factors $\nu=8$, 6, 5, and 4 in the 2D leads. The curves are offset vertically by 1 kΩ with respect to each other for clarity. The data were determined from four-terminal measurements after correcting for the series resistances and the anomalous magnetoresistance.[8] The conductance plateaus are rather broad since the quantization is very much of magnetic nature, and the spin degeneracy is clearly resolved for all traces. The shift of the plateaus to more positive gate voltages illustrates the magnetic depopulation of 1D subbands. Interestingly, though, oscillations are observed with amplitudes of several kΩ before the onset of the plateau at $h/2e^2$. A similar structure can also be seen, though not as pronounced, for all other magnetic fields above $B\approx 2$ T and between—but never on—different conductance plateaus. Since these features do not appear for vanishing or small magnetic fields they cannot stem from transmission resonances, as postulated theoretically by Szafer and Stone for an abrupt constriction.[9]

A similar oscillatory structure has been observed in QPC's by van Loosdrecht *et al.*[10] and Wharam *et al.*,[11] and has been interpreted to arise from Aharonov-Bohm (AB) oscillations.[12] However, there has been some difference in the interpretation of the precise origin of this interference effect in singly connected geometries. While van Loosdrecht *et al.* attributed the effect to a tunneling process between edge states at the entrance and exit of the constriction, Wharam *et al.* pointed out the possible influence of impurities in or close to the QPC. It is also interesting to note that the AB period obtained from sweeps of the magnetic field was found to be independent of the gate voltage in Ref. 10, whereas a monotonic shift to higher periods for more negative biases was reported in Ref. 11. The latter observation is more reasonable if one assumes that the area enclosed by the two interfering electron waves is identical or closely related to that of the QPC.

This presumed AB effect is hard to interpret from measurements as shown in Fig. 1, i.e., for constant magnetic field and varying gate voltage, because the size and shape of the QPC changes continuously. We therefore also performed magnetotransport measurements at fixed gate voltages and thus analyzed the AB oscillations while the width and length of the constriction were kept constant to first order. The extension of the edge states and thus the area they define within the QPC are of course changed slightly by the magnetic field even if the gate bias is kept constant. The AB periods thus obtained are plotted in Fig. 2 as a function of the applied gate voltage. The dashed line is merely a guide to the eye. The large relative errors arise mostly from the four-terminal geometry used since the AB oscillations often appear at magnetic fields at which the Shubnikov–de Haas (SdH) oscillations from the 2D leads possess comparable or even larger amplitudes. Nevertheless, an increase of the AB period with decreasing gate bias is clearly observable in Fig. 2 as the general tendency. Our findings are thus in agreement with those of Ref. 11.

The product of the AB period ΔB and the area A enclosed by the two interfering waves is equal to the fundamental magnetic flux quantum $\Phi_0=h/e$. From the data of Fig. 2 one finds that the enclosed area changes from about 2.1×10^{-10} to 3.8×10^{-10} cm^2 as the gate voltage is decreased. By dividing the area A thus obtained by the width W extracted from the depopulation model for each gate voltage, one can calculate an effective length L of the QPC. Both L and W are plotted as full and open circles, respectively, versus the gate voltage in Fig. 3. As expected, the effective length of the constriction increases when the width is reduced by lateral depletion. Interestingly, though, the length deduced in this manner is slightly smaller than the lithographically defined length of 240 nm for all gate voltages.

The sum $L+W$ is also shown as full squares in the upper part of Fig. 3. It was pointed out by Wharam *et al.* that the sum of $L=L_0+2d$ and $W=W_0-2d$ in a rectangular channel should be approximately constant with L_0 and W_0 being the length and width of the QPC at zero bias, and d the depletion length induced by the applied voltage.[11] It is obvious from Fig. 3, however, that in our data $L+W$ is not constant even within the limits

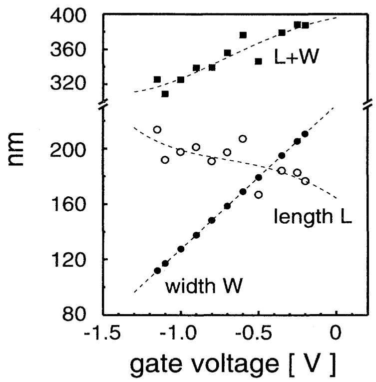

FIG. 3. Width W (●), length L (○), and their sum $L+W$ (■) of the QPC as functions of the gate voltage. The width is calculated from the depopulation model of Ref. 7, whereas the length is derived by dividing the area A obtained from the Aharonov-Bohm period by W. The dashed lines are guides to the eye.

of the experimental error, but decreases with more negative gate voltages.

A simple explanation for the smaller effective length as compared to the lithographically defined one would be rounding of the gate-finger tips by imperfect fabrication. However, the sum of width and length should nevertheless remain constant. We therefore conclude that the oscillations do not stem from interference of waves from a common source and reflected at different ends of the 1D channel alone. The average number of impurities in the enclosed area A derived from Fig. 2 is of the order of 1–10 assuming a background impurity level of about $10^{14}-10^{15}$ cm^{-3}.[13,14] It is thus much more reasonable to assume that an impurity in or close to the constriction is involved in the occurrence of these AB oscillations acting as a reflector. The measured AB area is thus defined by the relative position of the impurity as well as by the boundaries of the QPC. This conclusion agrees well with the fact that a nominally identical QPC showed no indication of such a structure.

Further supporting evidence for the existence of such an impurity site in our device is given in Fig. 4, where the conductance close to "pinch-off" for the several magnetic fields is shown. The curves have been offset vertically for clarity. These experiments were performed in a two-terminal geometry on the same Hall bar. A voltage of 4 μV was applied to the drain contact, and the current was measured. However, the data thus obtained also contain contributions from the metallic contacts and from the unpatterned regions of the 2DEG, both of which are dependent on the magnetic field. We therefore calibrated the conductance of the QPC in this regime by matching the data to the results obtained from the four-terminal measurements. Due to the large oscillatory series contributions, this calibration is not totally reliable for all magnetic fields. The vertical axis of Fig. 4 is thus a more qualitative nature, and we estimate the conductance determined to be accurate to within 20–30 %.

The traces of Fig. 4 display several distinct conductance peaks, all of which are clearly smaller than $4e^2/h$, i.e., than the contribution of a 1D subband to the conductance in this material system. At these magnetic fields, spin splitting should not be very pronounced. As the magnetic field is increased the maxima shift monotonically to more positive gate voltages. The position of the peak closest to zero conductance is plotted versus the applied magnetic field as full symbols in Fig. 5. Its width, as fitted to a Lorentzian, is also displayed (open circles). A general tendency of the width to decrease from about 17 to 12 mV can be observed. At higher magnetic fields the curves are difficult to fit because of the monotonically rising background.

We suggest therefore that these conductance peaks in the vicinity of the pinchoff arise from resonant tunneling through an impurity site in or close to the constriction. Kopley, McEuen, and Wheeler[15] as well as McEuen *et al.*,[16] have reported upon similar observations in Si metal-oxide-semiconductor field-effect transistors (MOSFET's) containing a small gap in the gate and in a split-gate device made from a GaAs/Al_xGa_{1-x}As heterostructure, respectively. Comparable peak shifts were observed under the influence of an applied magnetic field. The transmission coefficient of a lateral resonant tunneling process through the quasibound state of an impurity with energy E_0 is well described by a Breit-Wigner for-

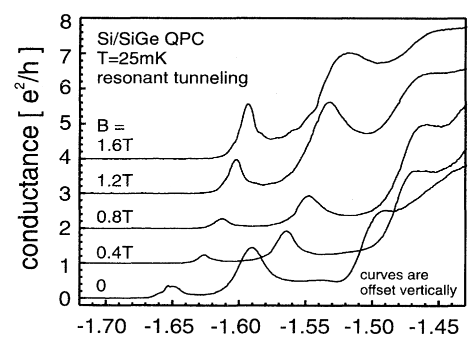

FIG. 4. Conductance of the QPC close to "pinch-off" for the several magnetic fields. The peaks are interpreted to arise from resonant tunneling of electrons through impurity states. The curves have been offset vertically for clarity.

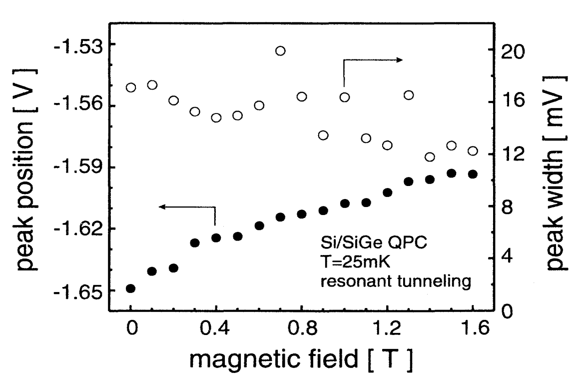

FIG. 5. Position (●) and Lorentzian width (○) of the resonant tunneling peak closest to zero conductance in Fig. 4 as function of the applied magnetic field.

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$$T(E)=\frac{\Gamma_L\Gamma_R}{(E-E_0)^2+(\Gamma_L/2+\Gamma_R/2)^2} . \quad (1)$$

The overall width $\Gamma_L+\Gamma_R$ is therefore determined by the leakage rates to the left and right sides of the impurity. For $\Gamma_L \approx \Gamma_R$ one expects the absolute height of the tunneling peak to be independent of the applied magnetic field, and its width to decrease monotonically, while the amplitude should be reduced with increasing magnetic field for $\Gamma_L \gg \Gamma_R$. Kopley, McEuen, and Wheeler found examples for both situations in their structures.[15] In the device used by McEuen *et al.* the expected number of impurities was about an order of magnitude smaller, and they only observed a single resonant tunneling peak accompanied by a scattering resonance.[16]

It is not possible to compare the absolute amplitudes of the maxima reliably in our data because of the uncertainties in the calibration mentioned above. However, the shift of their positions with magnetic field and the slight decrease of the Lorentzian width qualitatively supports the interpretation of resonant tunneling through an impurity state. The second prominent feature in Fig. 4 may then be interpreted as a scattering resonance. A fully satisfying interpretation, including smaller structures such as the shallow maximum at $V_{\text{gate}}=-1.54$ V and $B=0$, would require a more quantitative analysis.

In conclusion, we have observed both AB oscillations at magnetic fields above $B \approx 2$ T and resonant tunneling peaks in the conductance close to pinchoff in the same split-gate device fabricated from a Si/SiGe heterostructures. The analysis of the AB period as a function of the gate voltage as well as of the peak positions and widths when a magnetic field is applied leads to the conclusion that an impurity site (or sites) in or close to the QPC is the origin of both phenomena. The quality of the material system used for these investigations is high enough to be able to observe ballistic transport at low temperatures, and at the same time there is still a sufficient degree of disorder to study interference and resonant tunneling effects in mesoscopic devices.

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