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# Quantum ballistic transport in constrictions of *n*-PbTe

G. Grabecki, J. Wróbel, and T. Dietl
*Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, PL-02-668 Warszawa, Poland*

K. Byczuk
*Institute of Theoretical Physics, Warsaw University, PL-00-681 Warszawa, Poland*

E. Papis, E. Kamińska, and A. Piotrowska
*Institute of Electron Technology, PL-02-668 Warszawa, Poland*

G. Springholz, M. Pinczolits, and G. Bauer
*Institut für Halbleiterphysik, Johannes Kepler Universität Linz, A-4040 Linz, Austria*

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Conductance of submicron constrictions of PbTe:Bi was studied up to 8 T and between 4.2 K and 50 mK. The structures were fabricated by electron beam lithography and chemical etching of high-electron mobility films grown by molecular beam epitaxy on $BaF_2$. In the moderately strong magnetic fields perpendicular to the current, $B \geqslant 1$ T, the conductance shows accurate quantization in the units of $1e^2/h$ as a function of the side-gate voltage. In the absence of the field, a temperature-independent step structure, with an average step height of $\approx e^2/h$, is observed. It is suggested that such a quantization may reflect the lifting of the Kramers degeneracy by the exchange interaction among the electrons, effective despite a large dielectric constant of bulk PbTe. [S0163-1829(99)50532-8]

Recent studies on point contacts and wires of high mobility $GaAs/Al_xGa_{1-x}As$ heterostructures suggest that conductance quantization deviates from the simple behavior expected for electron ballistic transport in one-dimensional (1D) systems. In particular, Thomas *et al.*[1] have detected a conductance step at $\sim 1.4e^2/h$, which evolves in a strong in-plane magnetic field into the spin-split plateau at $e^2/h$. Spin-orbit coupling,[1] spontaneous spin splitting driven by the exchange interaction within the electron liquid,[1–3] or scattering by plasmons,[4] have been considered as possible mechanisms accounting for the observation. Similar findings have been reported for structures characterized by somewhat lower values of electron mobilities.[5,6] In longer wires, as shown by Tarucha *et al.*[7] and Yacoby *et al.*,[8] the conductance steps assume the quantized values $n2e^2/h$ at high temperatures, $T \sim 1$ K, but on lowering temperature their magnitude gradually decreases, $G = rn2e^2/h$, where $r < 1$. A combined influence of disorder, Luttinger-liquid effects, and coupling to the Fermi-liquid reservoirs is thought[8–10] to result in such behavior of the conductance.

Owing to the high-electron mobility $\mu$ at low temperatures, *n*-PbTe constitutes a promising material for studies of 1D systems by means of ballistic transport. The large magnitudes of $\mu$, $10^5 - 10^6$ $cm^2/Vs$, achieved with no modulation doping, result from the low values of the effective masses ($m_\perp^*/m_o \approx 0.02, m_\parallel^*/m_o \approx 0.2$), and the high value of the static dielectric constant, $\epsilon_L \approx 10^3$. The latter stems from the fact that PbTe is at the border line to a ferroelectric phase transition due to a cubic-rhombohedral distortion.[11] The large value of $\epsilon_L$ significantly reduces the magnitude of backward scattering by the Coulomb potentials. We suggest that this is the main reason for the unusual aspects of ballistic transport in *n*-PbTe reported in the present paper. In particular, the destructive effect of electron scattering upon quantization of the density of states is much weaker, for a given value of $\mu$, in the case of IV-VI compounds than for standard semiconductors.[12–14] Indeed, in the latter, the lifetime $\tau_q$ of quantum states is much shorter than the momentum relaxation time $\tau$ calculated from the mobility.[15] By contrast, since in IV-VI compounds the Coulomb potentials are screened, electron scattering is dominated by a short range part of defect potentials, for which $\tau_q \approx \tau$.

We have grown, by molecular beam epitaxy (MBE), 0.7-$\mu$m-thick epilayers of PbTe:Bi onto {111}-oriented $BaF_2$ substrates. Because of the difference between thermal expansion coefficients of $BaF_2$ and PbTe, the epilayers are under tensile strain at low temperatures. As a result, the fourfold valley degeneracy at the *L* point of the Brillouin zone is lifted and the valley with its main axis oriented along $\langle 111 \rangle$ is shifted downwards in energy as compared to the three obliquely oriented valleys.[16,17] Furthermore, the interface defects, brought about by both mismatch of the lattice constants and the thermal stresses, limit the electron mobility and deplete the vicinity of the interface from the carriers.[18] From the magnitudes of the Hall resistance and electron concentration $n = 2 \times 10^{17}$ $cm^{-3}$, resulting from the period of the Shubnikov–de Haas oscillations, we evaluate the width of the depletion region to be between 0.4 and 0.5 $\mu$m in our layers. The value of *n*, together with the Hall mobility $\mu_H = 2 \times 10^5$ $cm^2/V\,s$, lead to the mean free path $l = 1.6$ $\mu$m at 4.2 K.

Submicron constrictions with side gates have been fabricated of the epilayers employing single-level electron-beam lithography followed by wet chemical etching. This process produces a semicircular constriction of geometrical radius of about 0.5 $\mu$m in the most etched region, as shown in Fig. 1.

 

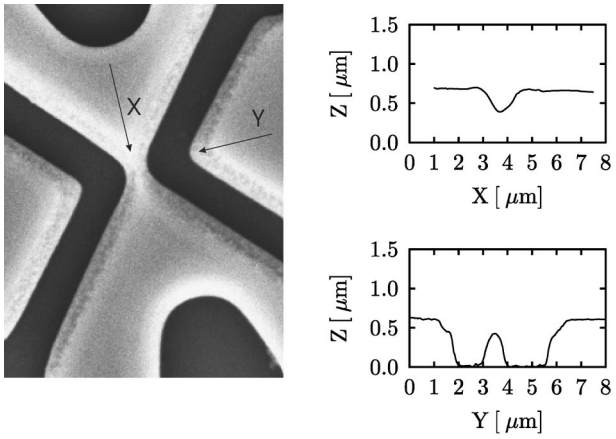


FIG. 1. Scanning electron microscopy (SEM) picture of a constriction made of PbTe:Bi (white regions). Atomic force microscopy (AFM) depth profiles along (*X*) and across (*Y*); the constrictions are shown in the right panels. The horizontal scales correspond exactly to the magnification of the SEM picture.

This is comparable to the width of the depletion layer implying that the carriers occupy only a narrow channel located near the top of the constriction. Further reduction of the channel width can be achieved by means of the two side PbTe gates. Since the dielectric constant of $BaF_2$ is about 8, the capacitive coupling between the gates and the channel proceeds mainly via the substrate. Accordingly, the electrons are pushed towards the top of the constriction for the negative gate voltages. We have noted that the pinch-off voltage, $V_{th}$, slowly evolves with time, even at low temperatures, as well as becoming more negative after subsequent cooling cycles. These effects are presumably caused by slow and incomplete strain relaxation at the interface. We have checked that there is no gate leakage current up to the gate voltage $V_g = \pm 200$ V, which implies that the dielectric strength of $BaF_2$ is $E_s \approx 150$ V/$\mu$m. For the conductance measurements, low-frequency ac currents of magnitudes not greater than 2 nA and phase sensitive detection have been employed.

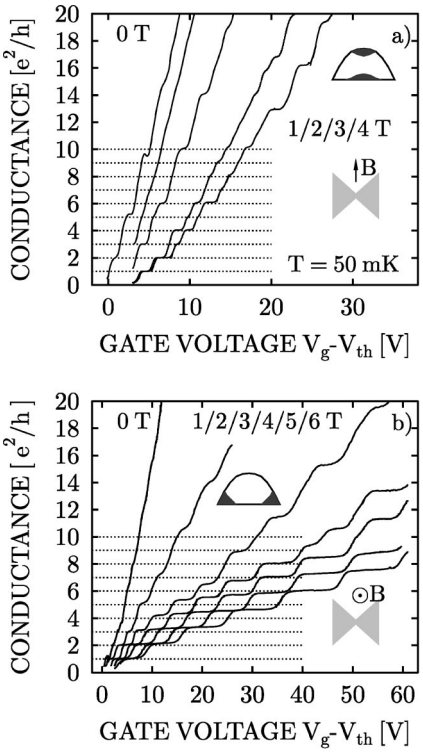


FIG. 2. Conductance as a function of the gate voltage in PbTe constriction for two configurations of the magnetic field perpendicular to the current. (a) $\mathbf{B} \perp \langle 111 \rangle$, (b) $\mathbf{B} \| \langle 111 \rangle$. Numbers denote subsequent values of the magnetic field. Cross sections of the constrictions together with positions of the edge currents (shaded area) are shown schematically.

Figure 2 presents the conductance $G = 1/R$ as a function of gate voltage in units of $e^2/h$ at various values of the magnetic field **B** for its two directions in the plane perpendicular to the current. Several conclusions emerge from those findings. First, when depleting the electrons in the constriction by $V_g$, a sequence of conductance steps is observed, whose width increases strongly with *B*, an observation confirming the strong suppression of backscattering and the depopulation of 1D subbands by the magnetic field.[19] Second, while the steps are accurately quantized for the in-plane magnetic field, the plateau values are systematically greater than multiples of $e^2/h$ in the case of **B** along the growth axis. This is consistent with the fact that for our four-probe arrangement shown in Fig. 1, the influence of series resistances is negligible, whereas the Hall effect of the wide regions gives a contribution to *R*.[19] Actually, as shown in Fig. 3, the deviations of *R* from the quantized values are linear in *B*, and correspond to the value of the apparent Hall constant, which is greater than that measured prior to the nanofabrication by a factor of about 2. Finally, the rate of change of the filling factor, $d\nu/dV_g$ is about two times larger if **B** is in the plane of the epilayer, compared to the case of **B** along the growth

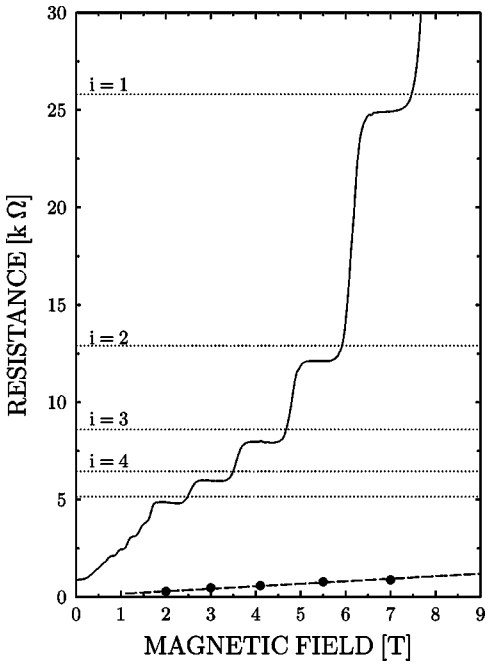


FIG. 3. Resistance of the PbTe constriction as a function of the magnetic field at 50 mK. The difference between the measured (solid curve) and quantized values (dotted lines) is given by solid dots. The dashed line corresponds to the resulting Hall resistance of the wide regions.

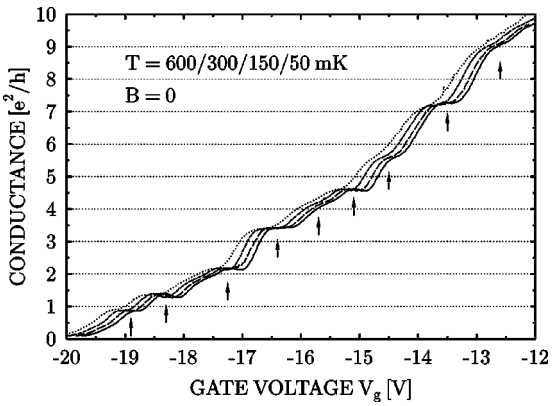


FIG. 4. Conductance of a PbTe constriction at various temperatures as a function of the gate voltage.

direction. This means that the ratio of an effective width $w$ of the constriction to its height $d$ is about 2.

As already mentioned, we presume that the gate voltage-induced change of the charge in the construction is primarily associated with a change in the width of the depletion region. In order to evaluate the constriction cross-section $S \approx 2d^2$ at given $V_g$, we employ the modified Sharvin relation,[20] generalized to the case of the ellipsoidal Fermi surface,

$$G(d) = \frac{e^2}{h} \frac{(3\pi^2 n)^{2/3}}{2\pi} \left( \frac{m_{\parallel}^*}{m_{\perp}^*} \right)^{1/6} (2d^2) \left( 1 - \frac{1}{\sqrt{2}(3\pi^2 n)^{1/3} d} \right)^2 . \tag{1}$$

In this way we estimate $d \approx 15$ nm for $n = 2 \times 10^{17}$ cm$^{-3}$ and $G = e^2/h$. This value of $d$, together with the effective mass $m^* = 0.02 m_o$, leads to an energy distance between the ground-state and excited electric subbands of about 19 meV.[21] It is worth noting that despite a substantial increase in the density of the electric subbands with $d$, and thus with $V_g - V_{th}$, no corresponding degradation of conductance quantization is observed. This follows presumably from a reduction of scattering when the electrons becomes less squeezed near the top surface.

Of particular relevance are experimental results in the absence of the magnetic field, presented in an expanded scale in Fig. 4. Distinct and temperature-independent steplike structure, superimposed on a smoothly increasing background, is visible. The lack of temperature-dependent resonances or fluctuations suggest that the constriction is both adiabatic and nondiffusive. However, many plateaus do not occur at the quantized values, and the conductance difference between them corresponds rather to $e^2/h$, not to $2e^2/h$. While there are clearly visible changes in the dependence of the conductance on the gate voltage after subsequent cooling cycles, the above conclusion appears to remain valid.

The most natural explanation of these results would be the assumption that the structure corresponds to a *quasi*ballistic regime, $L \approx l$, in which impurity scattering may reduce the width and height of the steps.[22] At the same time we note that the spin-orbit coupling, although rather strong in PbTe, is not expected to lift the twofold degeneracy according to the Kramers theorem. It might appear also that the large dielectric constant of PbTe makes effects of electron-electron interactions totally unimportant.

We have, however, decided to develop a Hartree-Fock theory of the electron-electron interaction for a quantum wire with the dielectric constant $\epsilon_1$ embedded in an environment with the dielectric constant $\epsilon_2$.[23] The wire is modeled by an infinitely long cylinder of radius $a$. An electrostatic potential between two electrons is determined by solving the Poisson equation with the appropriate boundary conditions at the cylinder boundary. We have obtained the matrix element $V(q)$ of the interaction potential in the one-particle basis of states corresponding to the ground-state subband. While for $qa \gg 1$ $V(q) \sim 1/\epsilon_1 q^2$, in the opposite limit $V(q) = -2e^2 \ln(aq/2)/\epsilon_2$; so it diverges logarithmically. This behavior, independent of the exact shape of the subband wave function, is characteristic for a 1D Fourier transform of the Coulomb interaction $e^2/r$ (with $a$ as a short-distance cutoff).[2] Moreover, it turns out that $V(q)$ for $aq \to 0$ is entirely determined by the interaction with the image charges, as it does not depend on the dielectric constant $\epsilon_1$ of the wire but only on $\epsilon_2$. This means that in the structures under consideration, for which a substantial part of the image charge resides in either vacuum or $BaF_2$, the exchange energy $E_{ex}$ is rather large since it is determined by $V(q)$ for $q \to 0$.

Within the above model, we have computed a critical density $n_c$, below which the Hartree-Fock ground state of the 1D electron liquid is ferromagnetic. By taking $\epsilon_1 = 1350$, $\epsilon_2 = 1$, $m^* = 0.02 m_o$, and $a = d/\sqrt{2} = 8.5$ nm, we obtain $n_c = 0.64 \times 10^5$ cm$^{-1}$. On the other hand, the concentration of the spin-polarized electrons filling up the ground-state subband till the bottom of the first excited subband is $n_{1d} = \sqrt{2m^* E_1}/h = 1.6 \times 10^5$ cm$^{-1}$, as $E_1 \approx 19$ meV. Those estimates suggest, therefore, that over a significant range of the gate voltage, the concentration of the electrons in particular subbands is small enough for the spin polarization to be sustained. The tendency toward a ferromagnetic ordering can be enhanced even further in the case of chaotic level distribution in low-dimensional systems.[24]

In conclusion, we have fabricated submicron constrictions of PbTe coupled to 3D reservoirs. Magnetoconductance measurements show accurately quantized steps for any direction of the magnetic field perpendicular to the current. At the same time, our findings suggest that the spin degeneracy is removed in the absence of the magnetic field. While the Hartree-Fock model is not expected to provide the accurate value of the instability point, and the actual ground state can be more complex than a simple ferromagnetic phase, our results demonstrate that despite the large dielectric constant, electron-electron interaction may account for the observed behavior of the ballistic conductance.

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