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PbTe constrictions for spin filtering

G. GRABECKI*

Institute of Physics, Polish Academy of Sciences, 02-668 Warsaw, Poland
and ERATO Semiconductor Spintronics Project, Japan Science and Technology Agency

The present article is a review of our experimental work performed on PbTe nanostructures. The uniqueness of lead telluride lies in a combination of excellent semiconducting properties, such as high electron mobility and tuneable carrier concentration, and parelectric behaviour leading to a huge dielectric constant at low temperatures. For nanostructured constrictions of PbTe, we have observed 1-dimensional quantization of electron motion at much more impure conditions than in any other system studied so far. This is possibly due to the dielectric screening of Coulomb potential fluctuations produced by various defects usually existing in the solid-state environment. In an external magnetic field, this quantization exhibits a very pronounced spin splitting, already discernible at several kilogauss. This indicates that PbTe nanostructures are very promising as local spin-filtering devices.

Key words: *PbTe; nanostructures; quantum ballistic transport; spin filter*

1. Introduction

Recent progress in semiconductor technology allowed the reduction of sample dimensions both below the electron mean free path l_e and Fermi wavelength λ_F. This is the so-called quantum ballistic regime, where electronic quantum states can be tuned at will. Currently, these studies attract much attention, because quantum ballistic devices are regarded as the basis of future applications of sensing, information processing, and quantum computation [1]. One-dimensional (1D) conductance quantization in narrow constrictions is a canonical example of these effects [2]. A necessary condition for its observation is the reduction of random potential fluctuations arising from charged defects that exist in the device surroundings [3]. In most constrictions studied so far, such as those patterned from two-dimensional electron gas (2DEG) adjacent to a AlGaAs/GaAs hererostructure, spatial separation of charged donors from mobile carriers has been achieved by modulation doping. Remote charges, however, still produce small potential fluctuations in the 2DEG plane. They cause low-angle scattering

*E-mail: grabec@ifpan.edu.pl

of electron waves, precluding 1D quantization in devices larger than 0.5 μm [4, 5]. Since then, the future development of quantum ballistic devices relies heavily on the further minimization of the influence of background defect potentials. This is continuously realized by improving material purity and refined fabrication procedures.

In the present work, we propose an entirely new way of reducing long-range Coulomb potentials in quantum ballistic devices, namely by using a background material with a huge dielectric constant. We have examined such a possibility experimentally, developing fabrication methods and performing transport measurements in nanostructures of PbTe. This paper is an update for two previously published works [6, 7]. In the following sections, we review the basic properties of PbTe, nanostructure fabrication methods, experimental results of conductance quantization, and finally the application of PbTe constrictions as spin-filters.

2. Basic properties of PbTe

PbTe is a narrow gap semiconductor crystallizing in the rock-salt structure [8]. It has an inversion symmetry and the conduction band is formed of four ellipsoids of revolution with energy minima at the L points of the Brillouin zone. Since this material is at the borderline of the ferroelectric phase transition due to a cubic-rhombohedral distortion, it is characterized by strong parelectric behaviour [9]. The static electric permittivity ε increases with increasing temperature and reaches the value as high as 1350 at 4.2 K. It has already been noted more than 30 years ago [10] that in bulk PbTe electron mobilities exceed 10^6 $cm^2/(V\cdot s)$ at low temperatures. Indeed, this observation was interpreted in terms of the suppression of the Coulomb potentials of ionised defects by dielectric screening. For the purpose of nanofabrication, however, material in form of thin layers or quantum wells (QW) is necessary. Unfortunately, in such cases various misfits usually reduce carrier mobility by about one order of magnitude. Worse still, the best available QWs of PbTe are grown on barium fluoride, BaF_2, and this material combination is characterized by a large thermal misfit arising at cryogenic temperatures. This causes a tensile strain of about 0.0016, giving rise to dislocations [7, 11]. Obviously, in any usual semiconductor such prerequisites would preclude any possibility of observing quantum ballistic effects. Nevertheless, as we will show below, they are still possible in the case of PbTe.

3. Preparation of PbTe nanostructures

As the initial material we have used 50 nm thick PbTe n-type quantum wells (QW) placed between 100 nm Bi-doped $Pb_{1-x}Eu_xTe$ barriers ($x = 0.08$). They were grown by MBE on a (111)-oriented BaF_2 substrate through a 2.5 μm thick buffer layer of $Pb_{1-x}Eu_xTe$, with the same x. Typical values of electron concentration and Hall mobility in the QW are 4×10^{12} cm^{-2} and 0.9×10^{5} $cm^2/(V\cdot s)$, respectively. Because of relatively large thickness, there are up to 7 partially occupied electric subbands in the unperturbed QW, so it can be regarded as 3-dimensional. We have estimated that l_e at helium temperatures is about 2 μm. This value was also confirmed by observations of magneto-size effects on Hall bridges of various widths [7]. It should be noted that the fourfold valley degeneracy in PbTe QWs is lifted due to quantum confinement. The conduction band minimum is formed by a single valley with its long axis parallel to the growth direction, whereas three obliquely oriented valleys are shifted upward with respect to it [12]. This fact significantly simplifies the complex band structure of the material, since for sufficiently low carrier concentrations only one valley contributes to the conductance.

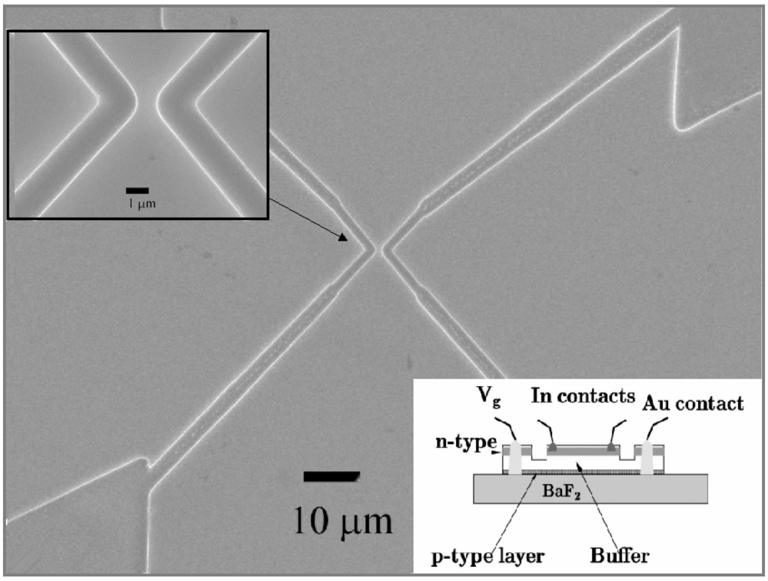

Fig. 1. Scanning electron microscopy profile of a 1 μm wide constriction made of PbTe/PbEuTe. Inset: schematic view of the device cross-section, illustrating the gate in contact with the interfacial p-type layer

To fabricate narrow constrictions (Fig. 1), we have employed single-level electron-beam lithography followed by wet chemical etching. The trenches defining the nanostructures were about 0.7 μm deep. Since they do not reach BaF_2, the thermal stress is quite uniform and does not impair the device quality too much, even after multiple coolings down to helium temperatures [7]. To make the gate electrode necessary for tuning the device, we employ a p-n junction between the n-type PbTe QW and p-type interface layer existing at the BaF_2 substrate [13]. In such an arrangement, the gate electrode extends under the entire structure, including the macroscopic contact pads. When the negative gate voltage V_g is applied, however, the narrow constrictions are depleted first due to the large contribution of edge effects to the constriction capacitance [14]. Due to a huge dielectric constant, the values of V_g necessary for fully depleting the constriction are quite small, of the order of a hundred millivolts. Electric contacts to the p-type gate have been made using gold chloride brown liquid. For the n-type QW, pure indium spots are soldered (Fig. 1 inset). At helium temperature, the gate resistance reaches the values above 10^9 Ω for near-zero bias and for larger biases it exhibits diode type *I-V* characteristics.

4. Conductance quantization in PbTe nanostructures

When a negative V_g was applied to the constriction, the conductance was gradually reduced, showing a sequence of steps as represented in Fig. 2. The presence of steps indicates the 1D quantization of the electron gas in the channel, squeezed by the electric field applied to the gate. Interestingly, we are able to resolve only steps ($G = i\,(2e^2/h)$) corresponding to $i = 1, 3, 6, ...$, for other intermediate values of i the steps are absent. This

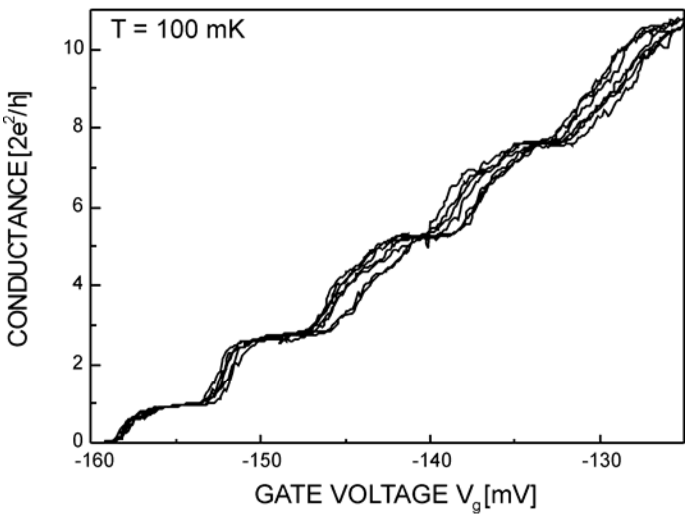

Fig. 2. Zero field conductance quantization in one of the PbTe quantum point contacts. Multiple traces were taken during long-time subsequent sweeps of V_g. The quantised values at the steps are slightly reduced due to the contribution of serial resistance from contact regions

demonstrates the presence of an additional orbital degeneracy of the 1D subbands. Such degeneracy stems from the oval shape of the constriction cross-section, whose two transverse directions contribute equally to the quantum confinement [15]. This is a consequence of the large thickness of the initial QW. The multiple curves presented in Fig. 2 were obtained by many slow sweeps of V_g performed during a period of 12 hours. The positions of the conductance steps are always the same despite some changes visible in the intermediate regions. They probably reflect the temporal evolution of the potential near the constriction, however the quantization remains almost unaltered. This is a result of smoothing out the potential relief due to the huge ε and its constant value over the whole constriction volume. Any changes in the potential caused by some defect redistribution or their re-charging simply add to V_g and do not affect the electron transmission through the constriction.

It should also be reminded that the concentration of background defects in PbTe is not smaller than 10^{17} cm^{-3} due to material non-stoichiometry [16]. Therefore, for a constriction diameter equal to the initial QW width, i.e. 50 nm, one still expects about 100 defects inside the conducting channel. For comparison, in AlGaAs/GaAs constrictions even a single defect would destroy the conductance quantization [3]. In contrast to this, in a PbTe device the transmission coefficient for step i = 1 (Fig. 2) exceeds 90%. This is also the effect of the huge ε, which converts the defects within the channel into short-range centres. According to recent theoretical predictions [17], in such a case the quantization will not be destroyed.

5. Spin-splitting in PbTe nanostructures

There has been a great deal of interest in the concept of spintronics, according to which the control and manipulation of electron spins in solids provides the basis for novel quantum technology. As a first step towards the practical realization of such ideas, the efficient generation of spin-polarized currents, preferably by electrical means and at a small spatial scales, should be mastered [18]. It is well known that narrow constrictions in a magnetic field act as spin dependent barriers for electrons and can be used for constructing local spin filters [6, 19]. In standard semiconductors such as GaAs, however, the electronic Landé factor is rather small and, thus, a high magnetic field must be employed to operate the device. One possible solution circumventing this problem is to exploit materials with a large g-factor. This is the case of narrow-gap semiconductors, in which Zeeman splitting can compete with the separation between 1D energy levels. PbTe constrictions seem to be an ideal candidate for this purpose.

The effect of the magnetic field B on the conductance quantization is illustrated in Fig. 3. Here, we show the conductance quantization for a device of "quantum dot" geometry (see inset). In fact, this can be regarded as two quantum point contacts connected in series [20]. For such a system, the resistances are not additive and we observe conductance quantization as for a single constriction. The visible reduction in step height may be explained by some backscattering from the boundaries in the central "dot" region. In a perpendicular magnetic field, already well below 1 T the half integer step, i=1/2, is resolved, indicating the development of spin splitting in the 1D subbands. Surprisingly, however, the *plateau* i = 1 disappears at the same field range. Instead, a step with i = 3/2 becomes resolved. In order to visualize the energy spectrum, we present in Fig. 4 a contour plot of the transconductance dG/dV_g as a function of V_g and B. The black shadow stripes indicate the occupation thresholds of the subsequent 1D subbands. One can see that the disappearance of the step at $i = 1$ is the result of a crossing between two spin sublevels, which belong to two different 1D

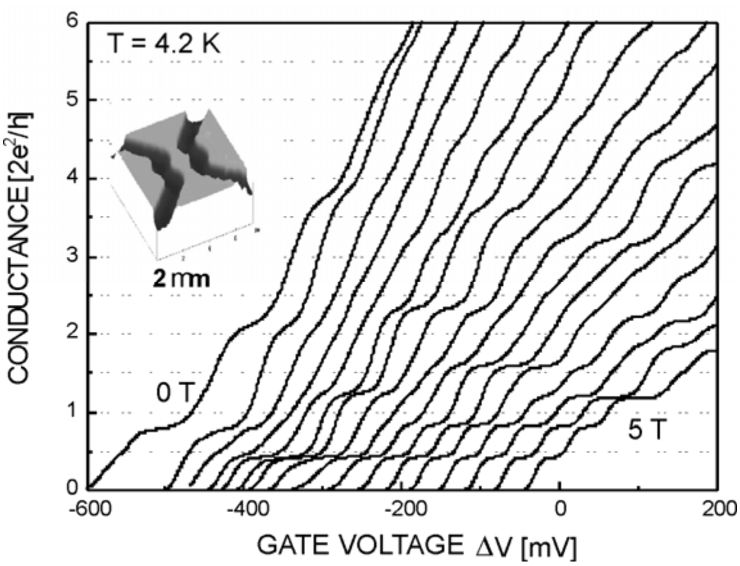

Fig. 3. Evolution of conductance quantization induced by a magnetic field in two serially connected PbTe quantum point contacts. The magnetic field varies from 0 to 5 T with 0.25 T increments. The curves were shifted horizontally to prevent overlap. Inset: atomic-force microscopy image of the device

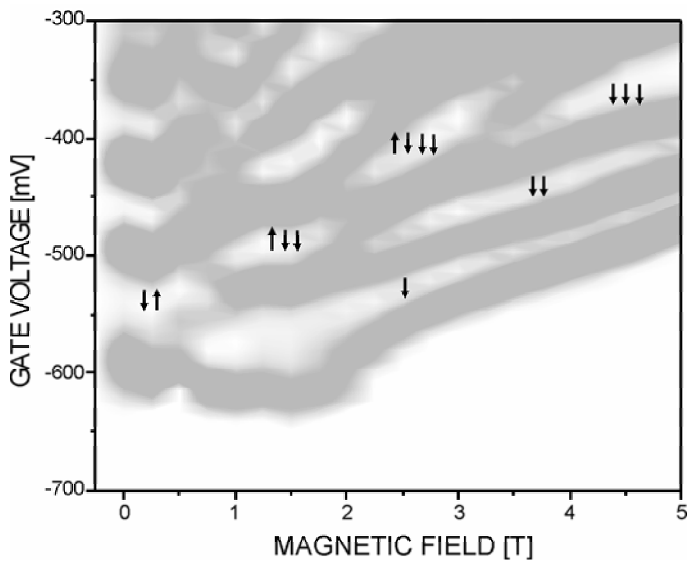

Fig. 4. Shadow contour plot of transconductance dG/dV_g for the data presented in Fig. 3, as a function of gate voltage and the perpendicular magnetic field. Dark stripes represent thresholds of subsequently occupied 1D subbands, and arrows indicate their number and spin polarization

subbands: the "spin up" sublevel of the ground subband and the "spin down" sublevel of the first excited subband. The crossing takes place slightly above $B = 1$ T, indicating that already at this field Zeeman splitting is equal to the energy separation between the lowest 1D subbands.

For larger fields, the step at $i = 1$ appears again, but corresponds to the occupation of two 1D subbands with the same 'spin down' orientation. Furthermore, at about 2.5 T the ground "spin up" subband crosses the second excited "spin down" subband, and the spin polarized current is carried by three 1D subbands. In this way, we have a unique situation where the totally spin polarized current is carried by many 1D subbands.

6. Conclusions

We have fabricated nanostructures of PbTe and demonstrated the effect of conductance quantization. It is possible, even though our system contained background charged defects up to a level as high as 10^{17} cm^{-3} and a significant amount of strain-induced dislocations. The origin of such an unusual situation is the huge static dielectric constant suppressing the Coulomb potentials of the defects. Our observations prove that PbTe should be considered as a serious candidate for fabricating future quantum devices. In our opinion, this may be an interesting alternative for the most explored system of AlGaAs/GaAs. An additional advantage of PbTe is a large g^*-factor and spin-filtering capability. Since spin splitting in moderately strong magnetic fields is larger than the 1D level quantization energy, we can obtain a totally spin polarized 1D gas with several partially occupied subbands. Finally, it has to be stressed that since the initial substrate layers used in this work were not optimised (for example, the initial mobility was much lower than the records of bulk PbTe), there is still much room for improving the devices.

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References

[1] BURKARD G., LOSS D., DIVINCENZO D.P., Phys. Rev. B, 59 (1998), 2070.

[2] VAN WEES B.J., VAN HOUTEN H., BEENAKKER C.W.J., WILLIAMSON J.G., KOUVENHOVEN L.P., VAN DER MAREL D., FOXTON C.T., Phys. Rev. Lett., 60 (1988), 848; WHARAM D.A., THORNTON T.J., NEWBURY R., PEPPER M., AHMED H., FROST J.E.F., HASKO D.G., PEACOCK D.C., RITCHIE D.A., JONES G.A.C., J. Phys C, 21 (1988), L209.

[3] NIXON J.A., DAVIES J.H., BARANGER H.U., Phys. Rev. B, 43 (1991), 12638.

[4] TIMP G., [in:] *Semiconductors and Semimetals* Vol. 13, Chapt. 3, R.K. Willardson, A.C. Beer, E.R. Weber (Eds.), Academic Press, San Diego, 1992.

[5] GLAZMAN L.I., JONSON M., Phys. Rev. B, 44 (1991), 3810.

[6] GRABECKI G., WROBEL J., DIETL T., PAPIS E., KAMINSKA E., PIOTROWSKA A., SPRINGHOLTZ G., BAUER G., Physica E, 13 (2002), 649.
[7] GRABECKI G., WROBEL J., DIETL T., PAPIS E., KAMINSKA E., PIOTROWSKA A., RATUSZNA A., SPRINGHOLTZ G., BAUER G., Physica E, 20 (2004), 236.
[8] for properties of PbTe, see e.g., *Lead Chalcogenides, Physics and Applications*, D. Khokhlov (Ed.), Taylor and Francis Books, New York, 2003.
[9] BATE R.T., CARTER D.L., WROBEL J.S., Phys. Rev. Lett., 25 (1970), 159.
[10] RAVICH J.I., EFIMOVA B.A., SMIRNOV I.A., *Semiconducting Lead Compounds*, Plenum, New York, 1968.
[11] ZOGG H., BLUNIER S., FACH A., MAISSEN C., MUELLER P., TEODOROPOL S., MEYER V., KOSTORZ G., DOMMANN A., RICHMOND T., Phys. Rev. B, 50 (1994), 10801.
[12] ABRAMOF E., ANDRADA E SILVA E.A., FERREIRA S.O., MOTISUKE P., RAPPL P.H.O., UETA A.Y., Phys. Rev. B, 63 (2001), 085304.
[13] TRANTA B., CLEMENS H., *Lecture Notes in Physics*, Vol. 301, G. Ferenzi, F. Beleznay (Eds.), Springer-Verlag, Berlin.
[14] DE VRIES D.K., STELMASZYK P., WIECK A.D., J. Appl. Phys., 79 (1996), 8087.
[15] SCHERBAKOV A.G., BOGACHEK E.N., LANDMAN U., Phys. Rev B, 53 (1996), 4054.
[16] SPRINGHOLZ G., [in:] *Lead Chalcogenides, Physics and Applications*, Chapt. 3, D. Khokhlov (Ed.), Taylor and Francis Books, New York, 2003.
[17] VARGIAMIDIS V., POLATOGLOU H.M., Phys. Rev B, 71 (2005), 075301.
[18] GILBERT M.J., BIRD J.P., Appl. Phys. Lett., 77 (2000), 1050.
[19] WROBEL J., DIETL T., ŁUSAKOWSKI A., GRABECKI G., FRONC K., HEY R., PLOOG K.H., SHTRIKMAN H., Phys. Rev. Lett., 93 (2004), 246601.
[20] WHARAM D.A., PEPPER M., AHMED H., FROST J.E.F., HASKO D.G., PEACOCK D.C., RITCHIE D.A., JONES G.A.C., J. Phys. C, 21 (1988), L887.

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