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Quantum nanostructures of paraelectric PbTe

G. Grabecki[a,*], J. Wróbel[a], P. Zagrajek[a], K. Fronc[a], M. Aleszkiewicz[a], T. Dietl[a,b,c], E. Papis[d], E. Kamińska[d], A. Piotrowska[d], G. Springholz[e], G. Bauer[e]

[a]*Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, PL-02-668 Warszawa, Poland*
[b]*Institute of Theoretical Physics, Warsaw University, Warszawa, Poland*
[c]*ERATO Semiconductor Spintronics Project, Japan Science and Technology Agency, Japan*
[d]*Institute of Electron Technology, al. Lotników 32/46, PL-02-668 Warszawa, Poland*
[e]*Institut für Halbleiterphysik, Johannes Kepler Universität Linz, A-4040 Linz, Austria*

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Abstract

This article provides a review of our results on nanostructurization of lead telluride, PbTe. This IV–VI group narrow-gap semiconductor exhibits paraelectric behaviour leading to a huge dielectric constant $\varepsilon > 1000$ at helium temperatures. Because the Coulomb potential fluctuations produced by charged defects are strongly suppressed in PbTe nanostructures, one can reach the quantum ballistic regime at significantly relaxed conditions in comparison with other systems. In particular, we observe precise zero-field conductance quantization in the wires made of modulation doped PbTe/PbEuTe quantum wells where the heavily doped layer is separated from the conducting channel only by a 2 nm thick spacer layer. The second important property is the very large Zeeman splitting. It reaches 4 meV/T. Accordingly, significant spin splitting of the conductance plateaux is observed already at fields below 1 T. Therefore, the system is attractive for the construction of local spin filters. We show that the presence of metal layers does not impair the quantum ballistic properties. Furthermore, we have developed a new method of tuning the PbTe nanostructures, using laterally placed metallic electrodes. We have found that this method is more effective than previous schemes using used p–n junctions and it provides better stability of the nanostructures.

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1. Introduction

Present state-of-the-art epitaxial growth and processing techniques enable one to fabricate semiconductor nanostructures whose dimensions are comparable to the de Broglie wavelength of band carriers. Typical examples are narrow point contacts whose conductance becomes quantized in $2e^2/h$ units [1], as well as quantum dots revealing discrete energy levels, in close analogy to atomic levels [2]. Recently, much research effort has been devoted to quantum nanostructures in which controllable quantum states necessary for the hardware basis of quantum information and communication technologies are formed [3,4]. In the present work we review our works on lead telluride-based nanostructuctures, PbTe. This IV–VI group compound is a narrow gap semiconductor with the rock-salt structure. It has a multivalley band structure with anisotropic conduction band valleys at the L point of the Brillouin zone. It possesses excellent semiconducting properties [5], namely high carrier mobility and controllability of the electron concentration. We will show that this material also offers several unique features which may be very useful from the point of view of quantum nanostructures [6–9].

The first and most important property of PbTe is its paraelectric character leading to a huge dielectric constant, $\varepsilon = 1350$ at 4.2 K [10]. It is well known that one of the fundamental limits for nanostructuring is the discrete character of the electric charge. One of its consequences

*Corresponding author. Tel.: +48 22 843 53 24; fax: +48 22 843 09 26.
E-mail address: grabec@ifpan.edu.pl (G. Grabecki).

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is the distortion of the nanostructure potentials by random potential fluctuations produced either by unintentional defects introduced during the processing or heteroepitaxial growth or by artificially incorporated doping impurities. The latter cannot be completely avoided as they provide the free carriers necessary for the device operation. Modulation doping, in which the doped region is spatially separated from the free carriers, has been utilized as a means to reduce the problem; however, even in this case, one still observes distinct effects caused by the potential fluctuations produced by the long-range tails of Coulomb potentials of the remote ionized dopants [11]. We have demonstrated [9] that in PbTe nanostructures the fluctuation amplitude is strongly suppressed, even in the presence of a significant concentration of charged impurities in the close vicinity of the device. In particular, we observe pronounced one-dimensional (1D) quantization in a modulation doped PbTe wire separated from the heavily doped layer by only 2 nm. This is possible because the huge dielectric constant strongly diminishes contributions from single charged centres to the total potential, which as a result is smoothened. In other words, in PbTe the limits of nanostructuring imposed by granularity of the electric charge are significantly relaxed.

The second property is the very small Coulomb charging energy. In particular, we have not observed any indications of Coulomb blockade in PbTe quantum dots [8]. Potentially, PbTe would offer the possibility of tuning the Coulomb charging energy independently of the device size. Such property is necessary for realization of the quantum entanglement in the quantum dots [12].

The third property results from the narrow-gap character of PbTe. For appropriate crystallographic orientations, PbTe is characterized by a very large magnitude of the Landé factor of electrons, $g^* \approx 60$. Accordingly, the quantized conductance shows pronounced spin splitting of the plateaux already in magnetic fields below 1 T [7]. It is well known that if the Fermi energy is adjusted to the spin gap of the lowest 1D subband, the quantum point contact becomes a spin-dependent barrier. Therefore, it can be exploited to develop devices generating spin polarized current at a small spatial scale [13]. Importantly, in the case of PbTe, the necessary magnetic field is so low that it could be generated locally, e.g. by means of deposited micromagnets [14].

The fourth property of PbTe may also be useful for spin electronics. Namely, PbTe forms only very small barriers if connected with various metals. In particular, one expects that junctions between PbTe and superconductors would be of high transparency, enabling observations of Andreev reflection mediated transport [15]. It is well known that Andreev reflection is very sensitive to the spin polarization [16]. Placing the superconducting nanoelectrodes near the spin filter would allow for measurements of the spin polarization degree of the emitted current. Another interesting possibility is the fabrication of an electrically controlled source of entangled electron pairs as proposed in Ref. [17].

However, one disadvantage of the small metal–semiconductor barriers is that it is not possible to use the "split-gate" technique [1]. Instead, we have used etched trenches for the definition nanostructures and naturally occurring interface p–n junction as a gate electrode for tuning their properties [8]. However, such a gate does not provide good stability because of a large number of dislocations in the interface region [9]. Therefore, in the present work we demonstrate another gating method using an in-plane metallic gate electrode.

In the following sections, we review the fabrication methods and show several experimental results illustrating these unique properties of PbTe nanostructures.

2. Initial multilayer fabrication and properties

The multilayers used for fabrication of the nanostructures were grown by molecular beam epitaxy (MBE) onto (1 1 1) BaF_2 substrates by using the protocols described in detail in Ref. [18]. As shown schematically in Fig. 1, in the structures, a PbTe quantum well resides between $Pb_{0.92}Eu_{0.08}Te$ barriers. We have studied quantum wells with widths 12, 25 and 50 nm. For an Eu composition of 8%, the barrier is as high as 235 meV. Due to the (1 1 1) growth direction, the fourfold L-valley degeneracy of the conduction band in PbTe is lifted, so that the ground-state 2D subband is formed in a single valley with the long axis parallel to the [1 1 1] growth direction. Due to this orientation, the 2D electrons occupying the ground state are characterized by a very small effective mass, $= 0.021m_0$ [19].

In order to introduce electrons into the quantum well, modulation doping with Bi ($N_D \approx 3 \times 10^{18}\,cm^{-3}$) was used with an undoped 2 nm wide $Pb_{0.92}Eu_{0.08}Te$ spacer layer separating the quantum well and the doping layer. Standard transport measurements reveal total electron densities n_{2D} from $1-10^{12}$ to $1 \times 10^{13}\,cm^{-2}$ and mobilities not exceeding $10^5\,cm^2/V\,s$ in the PbTe quantum wells at $T = 4.2$ K. This corresponds to the electron mean free paths $l_e \leqslant 3\,\mu m$.

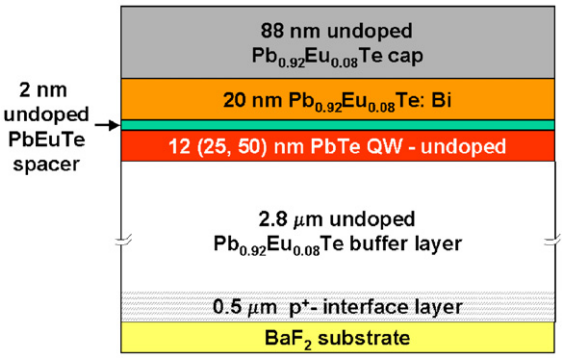

Fig. 1. Schematic view of the initial multilayer used for nanostructurization of PbTe.