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# Fabrication and Electrical Characterization of PbS–EuS Ferromagnetic Semiconductor Microstructures

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Current–voltage characteristics and temperature dependence of differential conductance were studied in lithographically patterned (lateral dimensions from $10 \times 10$ $\mu$m$^2$ to $100 \times 100$ $\mu$m$^2$) ferromagnetic EuS–PbS–EuS microstructures. Below the ferromagnetic transition temperature a 4% decrease in the structure conductance was observed for mutual antiferromagnetic orientation of magnetization vectors of ferromagnetic EuS layers.

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## 1. Introduction

PbS–EuS heterostructures owing to the nearly perfect lattice matching and a large difference in the energy gap offer a unique semiconductor tunneling system, in which ferromagnetic electron barriers of EuS separate diamagnetic PbS quantum wells. Due to a large spin splitting of the conduction band of ferromagnetic EuS, which amounts to about 0.36 eV, the EuS barrier height is spin-dependent below its Curie temperature. It results in distinctively different tunneling probabilities for electrons with opposite spin orientations, suggesting its prospective application for spin filtering.

Bulk EuS is a ferromagnetic semiconductor with an energy gap of 1.6 eV and the Curie temperature $T_C = 16.6$ K (cf. [1] and references therein). Magnetic properties of PbS–EuS multilayers, grown on PbS substrates, depend on the thickness of EuS layers as well as on the thickness of non-magnetic PbS layers separating the EuS ones. The Curie temperature of the structures decreases with a decrease in EuS layer thickness from its bulk value to 15 K for 3 nm thick layers [2]. In addition, the structures with sufficiently thin (below 2 nm) non-magnetic PbS spacers reveal an antiferromagnetic interlayer coupling between the EuS layers [3].

In our recent papers we investigated vertical electron transport through PbS–EuS heterostructures containing either a single EuS barrier [4], or two EuS barriers separated by a thin PbS quantum well [5], embedded into a PbS matrix. The investigated samples in the form of rectangular pillars with the side dimensions ranging from 200 to 500 $\mu$m were prepared by a direct cleavage of the heterostructures. They revealed a pronounced nonlinearity in the current–voltage ($I-V$) characteristics, typical of the tunnel current, but most of the samples exhibited rather low resistance and strongly reduced effective barrier height [4]. The most interesting result obtained for several samples with double EuS barrier was the appearance of a range of negative differential resistance in their $I-V$ characteristics, which is the feature characteristic of resonant tunneling [5]. In the present paper we report on a manufacturing of mesa-type microstructures of lateral dimensions below 100 $\mu$m, suitable for vertical electron transport measurements, and their electrical characterization.

## 2. Fabrication of microstructures

The investigated heterostructures were epitaxially grown on (100)-oriented $n$-PbS monocrystalline substrates by high-vacuum thermal evaporation of PbS and electron-beam evaporation of EuS [1]. They consisted of two EuS barriers, 2 to 10 nm thick, separated by a thin PbS well, embedded into a PbS matrix. Some of the structures contained a $LaB_6$ cap layer evaporated in the process of multilayer growth, which served as an ohmic contact to $n$-type PbS. Figure 1 presents a cross-sectional view of one of the heterostructures revealed by transmission electron microscopy (TEM). The samples for TEM analysis were prepared by means of mechanical polishing followed by low-angle and low-energy ion milling to a thickness of electron transparency, which was rather difficult for the PbS–EuS structures because of their high brittleness and the content of heavy elements.

The mesa-type structures of square cross-sections with the side dimensions ranging from 10 to 100 $\mu$m were patterned with the help of either standard photolithography or electron-beam lithography and chemically etched in the multilayer structures using either 0.5% aqueous solution of $Br_2$:HBr (1:24) or 0.05% $Br_2$ solution in ethylene glycol ($C_2H_6O_2$). We determined the etching rate of about 5 nm/s

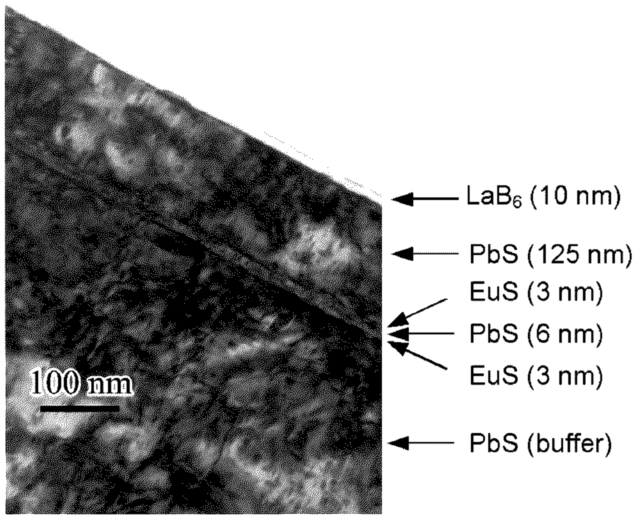


Fig. 1. Bright field TEM micrograph of a cross-section of PbS–EuS double-barrier heterostructure.

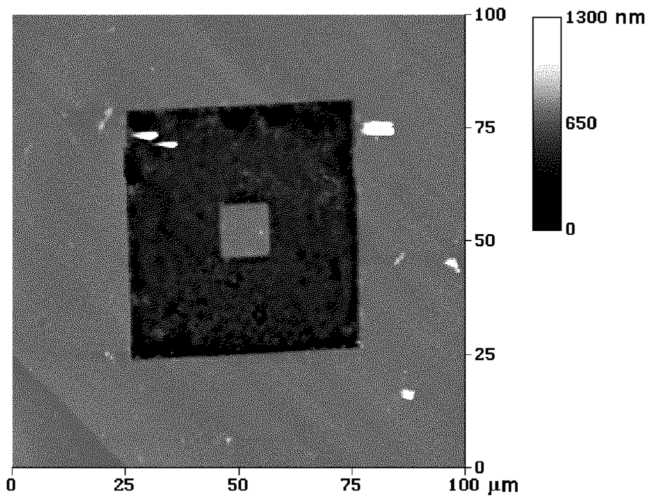


Fig. 2. AFM image of a microstructure of $10 \times 10$ $\mu m^2$ fabricated from PbS–EuS double-barrier heterostructure.

for the first etchant and 2 nm/s for the second one. Dimensions of the mesas and the depth of etching were controlled by means of atomic force microscopy (AFM) (Fig. 2). Ohmic contacts to the microstructures were made by gold evaporation through lithographically patterned small windows on the top of mesas.

### 3. Vertical transport measurements and discussion

We measured the *dc* current, $I$, passing through the microstructures and, simultaneously, the differential conductance, $G = \mathrm{d}I/\mathrm{d}V$, as a function of the applied voltage, $V$, in the temperature range down to the liquid helium temperature. All measured structures revealed nonlinear $I-V$ characteristics, typical of the tunnel current. Predominantly, larger mesas exhibited lower resistance characteristic of strongly reduced effective barrier height (Fig. 3). Similarly as in the case of the structures with a single EuS barrier [4] we consider here the vertical current transport in the investigated structures to proceed via pinhole microbridges, which give rise to shunting electrically the EuS barriers, as proposed by Rabson et al. [6].

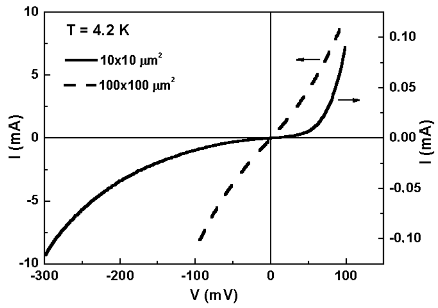


Fig. 3. $I-V$ characteristics of two microstructures with different lateral dimensions fabricated from the same heterostructure consisting of a 2.5 nm PbS quantum well sandwiched between two EuS barriers of 3 and 4.5 nm thickness, measured at 4.2 K.

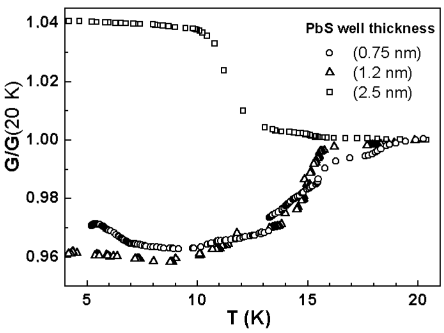


Fig. 4. Conductance (normalized to its value at 20 K) of three PbS–EuS microstructures of different PbS well thickness (written in the inset) vs. temperature.

Interesting result obtained for several structures was the appearance of a distinct change in the structure conductance while lowering its temperature below $T_C$ of the EuS barriers (Fig. 4). The structures with very thin, below 2 nm, PbS wells separating the EuS barriers exhibited a decrease in the conductance below 15 K. On the other hand, the differential conductance of the structures with thicker PbS wells increased below 15 K. We interpret these results as an evidence of the tunneling of spin-polarized electrons through the EuS barriers below $T_C$, taking into account antiferromagnetic coupling of the EuS layers separated by a thin PbS spacer and random arrangement of their magnetization in the case of thicker spacers. In fact, recent analysis of magnetic properties of the same series of EuS–PbS–EuS trilayers on PbS substrates showed the antiferromagnetic interlayer coupling for PbS spacers of 0.75 nm and 1.2 nm whereas the coupling was not found for 2 nm thick spacers [7]. However, the observed by us changes in the structure conductance of about 5% (Fig. 4) are much smaller than expected. Likely, mentioned above shunting of the tunnel current by pinholes can account for the reduced spin filtering of the investigated microstructures.

Much effort has been done by us to reveal an effect of destroying the antiferromagnetic coupling of the EuS layers by applying of external magnetic field, up to 600 Oe, parallel to the layer plane. Surprisingly, no noticeable effect of this magnetic field on the structure conductance was so far observed.

In conclusion, the electrical characteristics of lithographically patterned $10 \times 10$ $\mu$m$^2$ ferromagnetic EuS–PbS–EuS mesa structures reveal the contribution of tunneling mechanism of charge transport that is sensitive to the ferromagnetic transition temperature and mutual orientation of magnetization vectors of neighboring EuS layers. Although we observe a significant improvement of the tunneling $I-V$ characteristics of PbS–EuS microstructures upon reduction of their lateral dimensions from 100 $\mu$m to 10 $\mu$m, these characteristics are still strongly influenced by pinhole microbridges or other defects shunting electrically the EuS barriers.

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