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Search for Spin Filtering by Electron Tunneling through Ferromagnetic EuS Barriers in PbS

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Perpendicular transport through single- and double-barrier heterostructures made up of ferromagnetic EuS layers embedded into a PbS matrix was investigated. Both resonant tunneling and probably spin filtering through EuS barrier were observed.

KEY WORDS: spin; tunneling; EuS; PbS.

1. INTRODUCTION

PbS–EuS is a potential system, which can couple semiconductor optoelectronics with magnetism. EuS is a semiconductor with an energy gap of 1.6 eV that becomes ferromagnetic below the temperature of 16.7 K. On the other hand, PbS is a diamagnetic degenerate semiconductor with a gap of 0.3 eV, which enables emitting light in the mid-infrared range. The same rocksalt structure of PbS and EuS crystals with nearly perfect lattice matching and a large difference in the energy gap offer a possibility of using these materials for effective tunnel injection of spin-polarized electrons.

Because of 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. And because of the exponential dependence of tunnel current on barrier height, electrons with opposite spin orientations have distinctively different tunneling probabilities. In fact, spin polarized tunneling through EuS barriers in various configurations has been already demonstrated by several authors [1–4].

2. OBJECTS OF INVESTIGATIONS

Our study has been basically aimed at the investigation of layer structures consisting of an *n*-PbS matrix, containing two EuS barriers, a few lattice constants thick, separated by a thin PbS layer. It has been predicted theoretically and confirmed by neutron diffraction and magnetization measurements that mutual orientation of the directions of spontaneous magnetization in each ferromagnetic EuS barrier could be antiparallel for the distance between the barriers up to a few monolayers [5,6].

The second EuS barrier has been incorporated into the sample to act as an analyzer of spin polarization of electrons that have passed through the first barrier. If the coupling between spins in the two barriers was antiferromagnetic, one could switch the system from low to high electron transmission by applying an external magnetic field aligning magnetization in both barriers. In reality, the spin flip processes occurring in the PbS well, sandwiched between the EuS barriers, or at the interfaces could substantially reduce the expected magnetoresistance of the system.

We also investigated samples with a single EuS barrier separating two parts of the PbS crystal. Above the Curie temperature T_C, where EuS is paramagnetic, the barrier height is identical for both spin orientations. However, after cooling the sample below T_C the barrier height decreases for spin up electrons but increases for electrons with spin down. Thus, because of the exponential dependence of tunnel current on

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barrier height, electrons with opposite spin orientations will have different tunneling probabilities, eventually giving rise to an increase in the net tunnel current.

Multilayers that form the basic structure of the investigated samples were epitaxially grown on (100) n-PbS monocrystalline substrates by high-vacuum thermal evaporation of PbS, and electron-beam evaportion of EuS. PbS substrate crystals used in this study were grown by physical vapor transport. Details of the growth technology have been described elsewhere [7].

Samples in the form of mesas were chemically etched in the multilayer structures. Mesas were patterned with the help of electron-beam lithography and had square cross sections of the side dimensions ranging from 10 to 100 μm. Also, larger samples in the form of pillars with the side dimensions ranging from 300 to 500 μm were prepared by a direct cleavage of the structure. Ohmic contacts to n-type PbS were made either by chemical deposition or evaporation of gold, and also by evaporation of LaB_6 cap layer in the process of multilayer growth. Detailed parameters of some of the investigated samples are specified in the figure captions.

3. EXPERIMENTAL RESULTS

We measured the dc current and differential conductance of the samples, using the pseudo-four-probe method, as a function of the temperature and magnetic field strength. In contrast with a monocrystalline PbS reference sample, all multilayer samples exhibited a pronounced nonlinearity in the current–voltage (I–V) characteristics, typical for the tunnel current.

The most striking result obtained for several samples with double EuS barrier was the appearance of a range of negative differential resistance in the I–V characteristics, which was the more pronounced the lower temperature was (Fig. 1). This feature is typical for resonant tunneling and has already been reported for similar structures [8]. However, its appearance in our samples is somewhat surprising since it would mean that the interfaces between the layers are very flat: over an area as large as 0.1 mm^2 the deviation from perfect flatness would correspond to only a small fraction of the Fermi wavelength in PbS, which is about 20 nm in our structures (c.f. ref. [9]). Moreover, in contrary to our expectations, no noticeable effect of a magnetic field on these characteristics was observed. The reason for that is not understood at present.

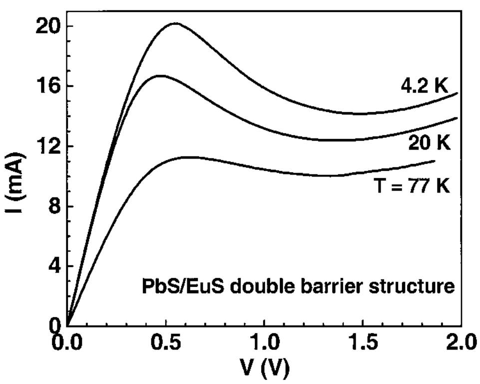

Fig. 1. Current–voltage characteristics at three different temperatures for the cleft sample with a cross section of 300 × 350 μm^2 containing two EuS barriers of 4.5 nm in width each, separated by a 7 nm wide PbS layer. Resonance peak in the current appears when the Fermi level in the emitter of the heterostructure equates with the bottom of a subband in the quantum well.

Much effort has been done by us to reveal a change in the electron transmission through the EuS barrier while crossing T_C. It was made more difficult because of the drawback effects discussed in Section 4. We have succeeded in finding the searched effect in samples with a single EuS barrier. We observed a distinct step-like increase in the conductance when the investigated samples were cooled down and its temperature passed through a temperature close to T_C of bulk EuS crystal, Fig. 2. It might be evidence for a spin filtering of this system, although, we should expect rather a more gradual change of the conductivity that would reproduce a change in the magnetization of EuS. However, if we account for instability of the PbS layers against small changes in applied voltage and temperature, the observed behaviour could be acceptable.

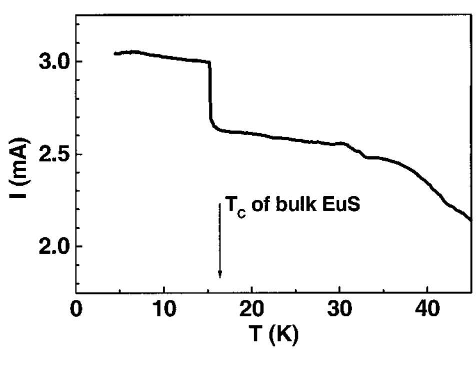

Fig. 2. Current as a function of temperature for the cleft sample with a cross section of 500 × 500 μm^2 containing a single barrier of the width 5 nm, measured at the bias voltage of 150 mV.

4. COMMENTS AND CONCLUSIONS

The main drawback of the investigated samples was the instability of their electrical characteristics against changes in the applied voltage and temperature, which causes that electrical characteristics are poorly repeatable. The reason for that is not understood at present. Most probably the blame lies on PbS layers, which were not sufficiently perfect in structures investigated so far. It should be added that many samples behaved as if their barriers were pinholed, which gave rise to a shunting of the tunnel current. It is a puzzling problem how to reconcile the resonant tunneling observed in some double-barrier heterostructures, testifying to their perfect interfaces, with otherwise very poor electrical behaviour of the structures. Maybe, the key to solution to this problem lies in the influence of treading dislocations whose density in the investigated samples was rather high.

In conclusion, our results show that the PbS–EuS structures might be a promising system for applications in some special spin-injection devices after identification and elimination of their electrical instability.

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