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Observation of Negative Differential Resistance in a Double Barrier Tunnel Structure Based on PbS (Semiconductor) – EuS (Magnetic Semiconductor) System

V.N.Lutskii[1], V.A.Petrov[1], A.S.Rylik[1]
E.V.Galkina[2], A.Yu.Sipatov[2], A.I.Fedorenko[2], and A.G.Fedorov[2]

[1] *Institute of Radioengineering and Electronics,*
Russian Academy of Sciences,
Mokhovaya 11, Moscow, 103907, Russia

[2] *Kharkov Politechnical Institute, Frunze St.61, Kharkov, Ukraine*

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We have investigated double-barrier tunnel structures on the basis of the PbS (semiconductor) - EuS (magnetic semiconductor) system. Regions of negative differential resistance were first observed in current - voltage characteristics of such structures at $T = 77K$. The shape of these characteristics allows us to connect the observed peculiarities in these characteristics with the resonant electron tunneling through the structure.

1. Introduction.

Quantum structures based on semiconductor (S) – magnetic semiconductor (MS) systems (S-MS systems) where the MS layers can act as either barriers or quantum wells (QW) have recently attracted increased interest [1-3]. The reason is that by varying the magnetic field B and temperature T one can substantially change the quasiparticle energy spectrum in MS and thus the physical properties of the overall structure.

It is known that when a MS is magnetized by a magnetic field and (or) by cooling below the Curie point T_c, the exchange interaction between free electrons and the magnetic subsystem results in large spin splitting of the valence band and the conductance band of MS. As a consequence, in S-MS structures, where MS forms potential barriers, this spin splitting of the spectrum results in substantially different heights of the potential barriers for electrons (holes) with different spin directions inside the nonmagnetic semiconductor. This fact, in turn, changes dramatically optical and kinetic properties of the structure.

Currently the quantum structures based on diluted MS CdMnTe and ZnMnSe are most extensively investigated. These materials with a wide band gap (E_g more than 2 eV) containing magnetic ions of Mn play the role of barriers separating the quantum wells of either CdTe or ZnCdSe, respectively.

In this work the subject of our study is another new so far poorly investigated structure based on the PbS (semiconductor) – EuS (MS) system. Note that the conduction band spin splitting in magnetically ordered EuS is anomalously large (about 0.4 eV). PbS is a narrow-band semiconductor ($E_g = 0.41eV$ at $T = 300K$) allowing to study the EuS barrier magnetization effects on the optical properties of PbS in the infrared range.

In Ref.[4], where a number of new effects in quantum S-MS structures were studied theoretically, the effect of the MS barrier magnetization on resonant tunneling of electrons in double barrier structures was analyzed. It was shown that in the resonant tunneling systems the barrier magnetization can qualitatively change the current–voltage (I–V) characteristics of the structures (appearance of new N-shaped regions, switching of the resonant tunneling on or off).

Planning future investigations of the influence of EuS barrier magnetization at $T < T_c$ on resonant electron tunneling in the structures based on PbS–EuS we at first have investigated tunnel properties of these structures at room temperature and at $T = 77K$. The results obtained are presented in this paper. Note that similar effects in structures PbS–EuS were not investigated before.

2. Sample preparation and experimental details.

The samples were grown by thermal evaporation of PbS from a tungsten boat and electron-beam evaporation of EuS in an oilfree vacuum of $10^{-4} - 10^{-5}$ Pa and their sequential condensation on polished (001) PbTe substrates at $250 - 300°C$. The substrates were annealed before condensation at 450°C (10–15 minutes) for reevaporation of the defect surface layer. Film thickness and condensation rate were monitored with a calibrated quartz resonator. The obtained PbS films possessed the n-type conductivity.

The film structure was investigated by electron microscopy and X-ray diffraction technique. X-ray diffraction pattern was obtained with a double crystal spectrometer using Cu-K radiation. (400) reflection from Si monochromator and (200) reflection from the samples in the $(2n, -n)$ arrangement were used.

Preliminary study of epitaxial growth of EuS on PbS showed that films grew in the layer-by-layer fashion (by the Frank-van-der Merwe mechanism) with a high quality monocrystalline structure. X-ray rocking curve linewidths are 0.1°

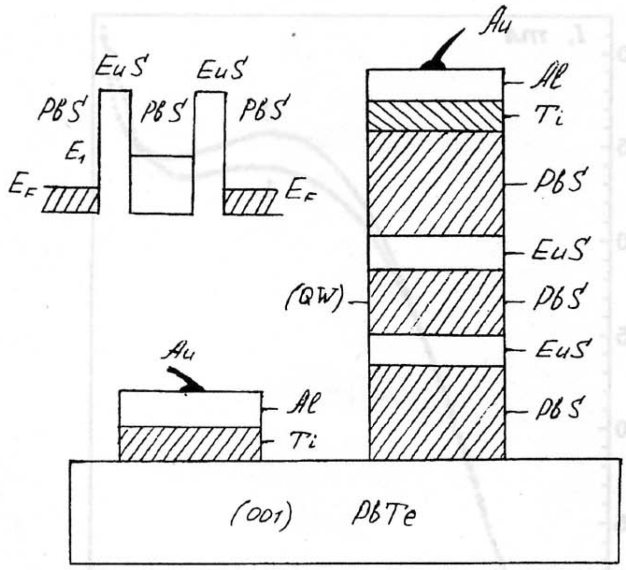

Figure 1. Schematics of the investigated structures. The energy diagram of a resonant tunneling diode is shown in the inset, E_1 is the resonant level in the PbS quantum well, E_F is the electron Fermi level.

for the substrate and epitaxial layers. The small value of EuS and PbS lattice misfit ($f = 0.5$ %) results in the pseudomorphic state of the multilayer structure: the interfaces have no misfit dislocations which was verified by electron microscopy. The series of five-layer films with buffer PbS layers (3000 Å), barrier EuS layers (20–50 Å) and middle PbS layer - quantum well(50–150 Å) were grown.

In order to investigate the transverse transport and tunnel effects in a double barrier PbS–EuS structure, a double layer Al–Ti film with the thickness of 1 μm which served as an upper contact was condensed upon the specimen surface. Then the mesostructures - square columns with the 50×50, 100×100, and $200 \times 200\mu$m cross-section - were photolithographically etched. The PbTe substrate was used as a lower contact. The schematic sketch of the structure is presented in Fig.1. Structures of different widths of EuS barriers and PbS quantum wells between EuS layers were investigated.

We measured the I-V characteristics for four series of samples with the following parameters of the central three-layer part (EuS–PbS–EuS) of the structure:

35 Å– 70 Å– 35 Å; 30 Å– 90 Å– 30 Å
40 Å– 120 Å–40 Å; 50 Å– 130 Å– 50 Å.

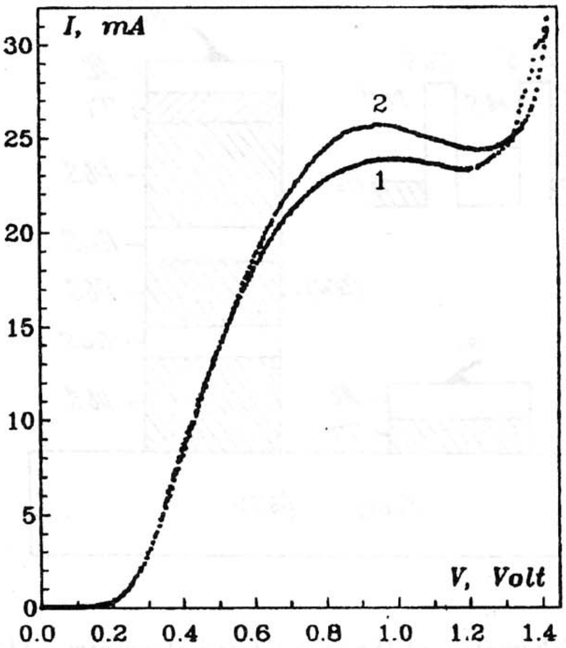

Figure 2. The current – voltage characteristics of the PbS (900 Å) – EuS (30 Å) – PbS (70 Å – QW) – EuS (30 Å) – PbS (1500 Å) structure measured for increasing (1) and decreasing (2) voltage at $T = 77$ K.

The measurements were carried out at room temperature and at $T = 77$ K. In each series there were samples demonstrating at $T = 77$ K the I-V characteristics with regions of negative differential resistance (NDR) (N-shaped regions). For all such samples an I–V region was observed where voltage increase from zero led to only slight increase in the current through the structure. When the voltage was further increased, an abrupt rise of the current was observed. The typical I–V characteristics measured in the increasing (1) and decreasing (2) voltage modes at $T = 77K$ for the sample with layer parameters PbS (900 Å) – EuS(30 Å) – PbS (70Å– QW) – EuS (30Å) – PbS (1500Å) are presented in Fig.2. As one can see, the NDR region takes place on the both curves. Current change in the NDR regions was about 2 μA. At T=300 K the N-shaped regions of the I–V characteristics disappeared and instead the regions with inverse inflexion points were observed. At the same time the low-current region the beginning of the I–V curves remained practically unaltered. As it is known [5], a low-current region at the beginning of the I–V characteristics followed by a sharp current increase and NDR part are the typical features of the resonant tunnel diodes. That is why the presence of all these peculiarities in measured I–V characteristics allows us to suppose that the origin of the peculiarities of the investigated structures are connected with the effects of resonant electron tunneling.

Of course, quantitative comparison of obtained results with the calculated I–V characteristics for a structure with particular parameters requires further studies. In future we also plan to investigate the influence of the magnetization of EuS barriers arising at temperatures $T < T_c$ on the observed N-shaped I–V characteristics.

3. Conclusion

In this work we have presented the results of experimental investigations of the I–V characteristics of double barrier structures based on the PbS (semiconductor) – EuS (magnetic semiconductor) system at $T = 300$ K and $T = 77$ K. The regions of negative differential resistance on the I–V characteristics at $T = 77K$ of such structures were first observed. The features on the measured I–V characteristics typical of the resonant tunnel diodes allows us to connect the observed peculiarities with the effects of resonant electron tunneling.

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