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Magnetization of EuS–PbS Multilayers with Antiferromagnetic Interlayer Coupling

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SQUID magnetometry is applied to study the temperature and magnetic field dependence of magnetization $M(T, H)$ of semiconductor EuS–PbS ferromagnetic multilayers grown on insulating KCl(100) and conducting *n*-PbS(100) monocrystalline substrates. For low external magnetic fields (of the order of 10 Oe) and PbS spacer layers thinner than about 2 nm, we observe in EuS–PbS–EuS trilayers the strongly nonmonotonic temperature dependence of magnetization with almost zero total magnetic moment below the Curie temperature. The application of the magnetic field of the order of 100 Oe restores the regular monotonic increase of magnetization with decreasing temperature. To explain this $M(T, H)$ dependence we present a model that considers the competition of three (temperature dependent) contributions to the total magnetic energy of the trilayer: the antiferromagnetic interlayer interaction energy, the Zeeman energy, and the energy of in-plane magnetocrystalline anisotropy.

KEY WORDS: magnetic semiconductors; interlayer exchange; magnetic multilayers; IV–VI semiconductors.

1. INTRODUCTION

In EuS–PbS semiconductor multilayers the ferromagnetic insulating layers of EuS are separated by thin nonmagnetic PbS spacer layers [1]. Both EuS and PbS crystallize in the same rock salt crystal structure and their lattice parameters differ only by 0.5%. Because of the large exchange splitting of the conduction band states in EuS below its ferromagnetic transition temperature ($T_C = 16.6$ K), the EuS–PbS multilayers form an intriguing spintronic system with spin-dependent electron barriers serving, e.g., as a very efficient spin filter [2]. Magnetic properties of these structures depend on the thickness of magnetic layers, the strain present in these structures as well as on the interlayer exchange interaction that couples magnetic moments of neighboring EuS layers [1,3]. In this work, we examine experimentally and model theoretically the pronounced influence of the antiferromagnetic interlayer coupling on the temperature and magnetic field dependence of the magnetization $M(H, T)$ of EuS–PbS multilayers grown along (100) crystal direction, either on insulating KCl or conducting *n*-PbS monocrystalline substrates. Although our experimental observations are very similar for the case of EuS–PbS structures grown on PbS and KCl substrates, we concentrate in this work on structures grown on conducting *n*-PbS due to their importance for the realization of the vertical spin current transport through ferromagnetic insulating barriers.

2. EXPERIMENTAL

We studied epitaxial EuS–PbS multilayers deposited in high vacuum on monocrystalline (100)-oriented insulating KCl and conducting *n*-PbS

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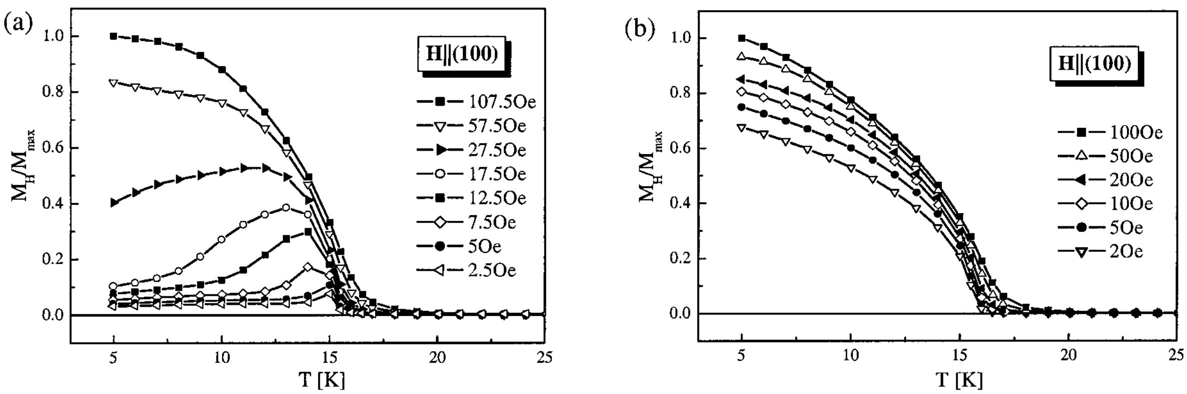

Fig. 1. The temperature dependence of magnetization of two PbS = 50 nm/EuS = 3 nm/PbS–d/EuS = 3 nm structures on PbS(100) substrate with thin (Fig. 1a, $d = 0.75$ nm) and thick (Fig. 1b, $d = 5$ nm) PbS spacer.

substrates employing an electron gun and standard resistive heating for the evaporation of EuS and PbS, respectively. Both superlattices and trilayers with the thickness of EuS layer of 3–7 nm and the thickness of PbS spacer varying in the range 0.75–10 nm were studied. A SQUID magnetometer was used to study the temperature and magnetic field dependence of the magnetization $M(T, H)$ of EuS–PbS multilayers. The external magnetic field was applied in the plane of the multilayer both along the (in plane) easy (110) and hard (001) axis of magnetization. Figure 1 shows the temperature dependence of the magnetization of two EuS–PbS–EuS trilayers with 3 nm layers of EuS and varying PbS spacer: very thin (0.75 nm, Fig. 1a) and much thicker (5 nm, Fig. 1b). For EuS–PbS–EuS trilayer with 5-nm spacer we find, for any applied external magnetic field, a regular monotonic increase of magnetization upon decreasing temperature. For the analogous structures but with much thinner spacer we find that, at low external magnetic fields, the magnetization displays the nonmonotonic behavior upon decreasing temperature (see Fig. 1a), revealing almost zero total magnetic moment at low temperature. It strongly suggest that the magnetization vectors of the two EuS layers are aligned antiferromagnetically. The application of a stronger magnetic field of the order of 50–100 Oe fully restores the monotonic $M(T)$ dependence. The antiferromagnetic mutual orientation of the magnetization vectors of EuS layers in the trilayer is also reflected in the shape of magnetic hysteresis loops of EuS–PbS–EuS trilayers. For the structures with thick PbS spacers the hysteresis loops have a regular character with a large magnetic remanence and coercive fields of the order of 20 Oe. On the contrary, hysteresis loops of EuS–PbS–EuS structures with PbS spacer layers thinner than about 2 nm reveal nearly zero magnetic remanence and a characteristic plateau in the $M(H)$ dependence. The experimental observation reported in this work for structures grown on PbS(100) substrates were also recently observed by us in EuS–PbS structures grown on other (100)-oriented KCl substrates [3,4].

3. DISCUSSION AND CONCLUSIONS

The $M(T,H)$ dependence observed in EuS–PbS multilayers can be described by a simple model that takes into account three (temperature dependent) contributions to the total magnetic energy of the multilayer: the antiferromagnetic interlayer interaction energy, the Zeeman energy of ferromagnetic layers in an external magnetic field, and the in-plane magnetocrystalline anisotropy. The geometry of the problem is illustrated in Fig. 2a. As in EuS–PbS multilayers the volume (shape) contribution to the magnetic anisotropy dominates over the surface one even for the thinest EuS layers [1], the magnetization vectors of EuS layers are assumed to be in the plane of the multilayer.

The mutual orientation of magnetization vectors of the magnetic layers was determined from the condition of minimal total magnetic energy for two antiferromagnetically coupled magnetic moments applying Weiss mean-field theory to calculate the temperature and magnetic field dependence of the modulus of magnetization vectors of each of the layers. For negligible magnetic anisotropy the energy minimum corresponds to two solutions: $\theta = 0$ (at $T \leq T_C$) or $\cos\theta = -MHt/2J$ (at $T \ll T_C$), where t is the thickness of magnetic layers. For the general case with in-plane anisotropy one has to solve simple third

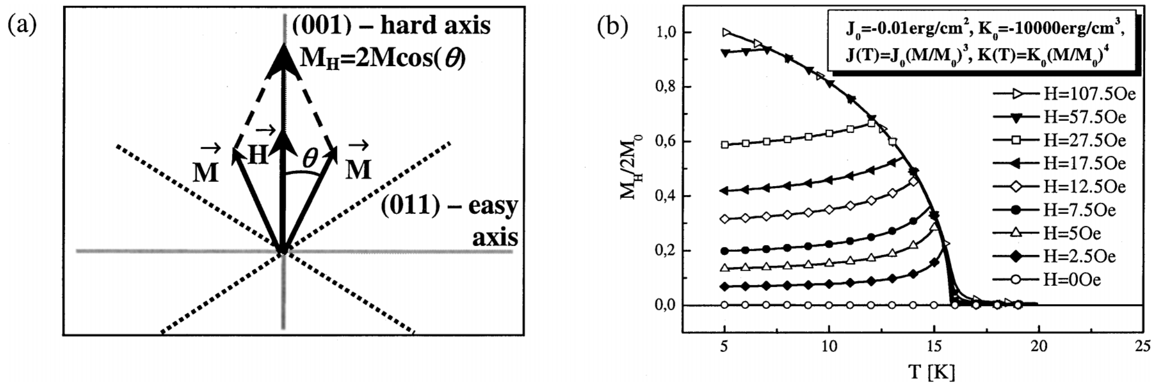

Fig. 2. (a) A scheme of the in-plane magnetization vectors in EuS–PbS–EuS trilayers. As both EuS layers are of equal thickness we discuss a case of symmetric arrangement of magnetization vectors with respect to the direction of magnetic field; (b) The result of model calculations of the temperature dependence of the magnetization. The inset gives the assumed values of interlayer exchange integral J_0 and the in-plane magnetocrystalline anisotropy constant K_0, as well as their temperature dependence.

order algebraic equation. The results of these calculations of $M(T, H)$ dependence are presented in Fig. 2b. The model successfully explains the characteristic features of the temperature dependence of the magnetization of our structures and allows for the quantitative estimate of the interlayer coupling energy as indicated in Fig. 2b.

In conclusion, our experimental investigations as well as modeling of the temperature and magnetic field dependence of magnetization of EuS–PbS–EuS multilayers grown either on PbS(100) or on KCl(100) substrates gives a clear evidence for the presence of antiferromagnetic interlayer coupling between EuS layers via ultrathin nonmagnetic PbS spacer. The switch between antiferromagnetic and ferromagnetic alignment of the magnetization vectors of EuS layers can be achieved by the application of small external magnetic fields of 100 Oe. A simple model calculation is able to qualitatively reproduce the temperature dependence of the magnetization.

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