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MAGNETIC ANISOTROPY IN EuS–PbS MULTILAYERS

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We present the results of ferromagnetic resonance studies of the thickness dependence of magnetic anisotropy in 2 series of EuS–PbS multilayers grown on (111) BaF_2 and (100) KCl substrates with the EuS thickness varying in the range $d = 6-70$ Å. The anisotropy constant K was found to follow the dependence $K(d) = K_V + 2K_S/d$, with the surface term K_S larger for layers grown on BaF_2 as compared to KCl. This difference is discussed in terms of different thermal stress-induced distortions of cubic crystal lattice of EuS. We found that the thickness of EuS layer required for the perpendicular (to the layer) magnetization is $d \leq 2-3$ Å, i.e., it is below 1 monolayer.

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1. Introduction

EuS–PbS multilayers are ferromagnet–diamagnet structures composed entirely of semiconducting compounds. EuS is the well-known model Heisenberg magnetic system with short-range exchange interactions. Bulk crystals of EuS order ferromagnetically at $T_C = 16.6$ K [1, 2]. PbS is a diamagnetic material belonging to the family of narrow-gap IV–VI compound semiconductors. Both materials grow in cubic rock salt crystal structure. The lattice parameters of EuS and PbS match very well: $\Delta a/a \approx 0.5\%$. It allows to grow pseudomorphic EuS–PbS multilayers with the overall thickness of the structure exceeding 1000 Å.

Recently, the ferromagnetic transition in EuS–PbS multilayers has been studied by magnetization and ac magnetic susceptibility measurements [3, 4]. The well-defined ferromagnetic transition was observed in the structures with EuS thickness d down to 2 monolayers (ML). In EuS, 1 ML $\approx$ 3.0 Å for layers grown along (100) direction, whereas 1 ML $\approx$ 3.5 Å for layers with the

(111) growth axis. For EuS thicknesses smaller than about 10 ML, the Curie temperature decreases with decreasing EuS thickness according to the simple relation $T_C(n) = T_C^{\infty}(1 - c/n)$. Here n is the number of monolayers of EuS, c is a numerical parameter depending on the direction of the growth axis of the multilayer and the composition profile of the EuS–PbS interface, and T_C^{∞} is the reference Curie temperature of the thick semibulk layer grown on the same substrate. There is a considerable difference between T_C^{∞} parameters for layers grown on KCl ($T_C^{\infty} = 17.3$ K) and on BaF_2 ($T_C^{\infty} = 13.6$ K). This effect is understood as a result of the action of thermal stress caused by the difference between thermal expansion coefficient of the substrate and the layer [4].

In this work, we examine experimentally the dependence of the magnetic anisotropy constant K of EuS–PbS multilayers on the thickness of the EuS layer, and discuss the influence of thermal stress on the magnetic anisotropy in these multilayers.

2. Experimental results

We studied two series of EuS–PbS multilayers grown on KCl (100) and BaF_2 (111) substrates. The thickness of the EuS layers (d) covered the range d = 6–70 Å. The thickness of the non-magnetic PbS layers was kept constant and relatively large (about 200 Å) to assure the lack of interlayer coupling between the EuS layers. Each structure consists of 5 repetitions of EuS and PbS layers. The EuS–PbS multilayers were grown by thermal evaporation of PbS from tungsten boat and electron gun evaporation of EuS, and their sequential condensation on monocrystalline substrate at temperature $T_s = 250°$C under high vacuum conditions. The layer thickness was monitored by quartz resonator. The quality of the multilayers was checked by X-ray diffraction: the typical width of the rocking curve is 300 arcsec whereas the diffraction pattern shows the superlattice satellite peaks of the 1st and 2nd order. The same set of samples was previously studied by magnetization, magnetic susceptibility, and photoluminescence measurements.

To determine the magnetic anisotropy constant we applied the well known method of ferromagnetic resonance (FMR) [5]. The ferromagnetic resonance in EuS–PbS multilayers was studied using Bruker X-band spectrometer operating at frequency $f = 9.45$ GHz in the temperature range $3.5 \leq T \leq 300$ K and in the magnetic field range $B \leq 2$ T. We studied the temperature dependence of the position of the FMR line both in the configuration with magnetic field in the plane of the layer ($B_{\parallel}$) and in the configuration with magnetic field normal to the plane of the layer ($B_{\perp}$). At temperatures $T \ll T_C$, we also examined the complete angle dependence of the resonance line position. The FMR spectrum in the configuration $B_{\parallel}$ consists of a single line with the peak-to-peak width of about 300 Gs for layers grown on KCl and about 500 Gs for layers grown on BaF_2. In the configuration $B_{\perp}$ we usually observed the spectrum consisting of the strong line at high magnetic fields (the so-called, uniform FMR mode) followed (at lower magnetic fields) by spin wave resonances.

From the analysis of the temperature dependence of both the $H_{\parallel}$ and $H_{\perp}$ we determined the ferromagnetic transition temperature T_C, which was found

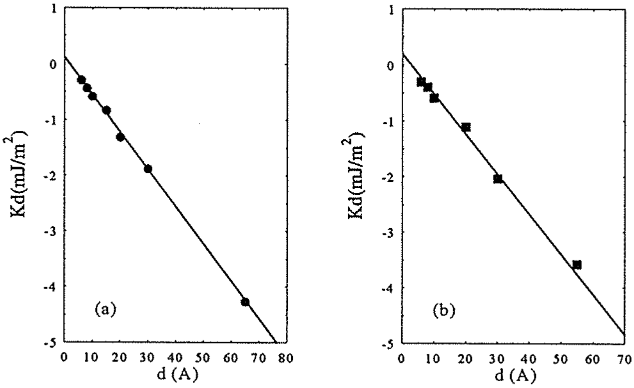

Fig. 1. The dependence of the magnetic anisotropy constant K in EuS–PbS multilayers on the thickness of the EuS layer d: (a) structures grown on KCl (100), and (b) structures grown on BaF_2 (111) substrates.

to follow the thickness dependence determined from our magnetization measurements [3, 4]. From the analysis of the angle dependence of the FMR resonance field we determined the effective magnetization and the magnetic anisotropy constant K of EuS layers [5]. The reduction of the effective magnetization of the thin layer from the value observed in bulk crystals is attributed to the magnetic surface anisotropy.

The thickness dependence of the magnetic anisotropy constant K in EuS–PbS multilayers studied by us is presented in Fig. 1 in the form of Kd vs. d plot frequently used to extract the volume (K_V) and surface (K_S) contributions to the magnetic anisotropy [6]. The experimental data are well described by the relation $K(d) = K_V + 2K_S/d$. For EuS–PbS structures on KCl substrate the anisotropy constants are: $K_V = -0.67(\pm 0.01)$ MJ/m^3 and $K_S = 0.06(\pm 0.02)$ mJ/m^2, while for the BaF_2 case: $K_V = -0.72(\pm 0.02)$ MJ/m^3 and $K_S = 0.10(\pm 0.03)$ mJ/m^2. One can notice that for EuS–PbS layers the surface term becomes dominant only for extremely thin layers of EuS with $d \leq d_\perp$. The parameter $d_\perp = 2K_S/K_V$ equals: $d_\perp \approx 2$ Å for layers grown on KCl and $d_\perp \approx 3$ Å for layers grown on BaF_2.

3. Discussion and conclusions

Our experimental results clearly indicate that the dominant contribution to the magnetic anisotropy in EuS–PbS multilayers is the volume dipolar (shape) anisotropy. It requires that the magnetization vector is located in the plane of the structure. The characteristic thickness $d_\perp$ below which the surface anisotropy outweighs the volume part leading to the perpendicular magnetization is in our structures below 1 ML. Therefore, this effect cannot be observed even in ultrathin EuS–PbS multilayers.

The magnetic anisotropy contribution $K_S \propto 1/d$ (surface anisotropy) is likely to arise from the Néel mechanism, i.e., from the lowering of the symmetry of the magnetic layers at the EuS–PbS interface. We also expect the contribution from the effect of the biaxial thermal stress which leads to the small distortion of the cubic unit cell of EuS to lower symmetry: tetragonal for layers grown on KCl (100) substrates and even lower (trigonal) for layers grown on BaF_2 (111) substrates [4]. This effect is likely to account for the marked increase in both the (positive) surface and the (negative) volume anisotropy constants in EuS–PbS multilayers grown on BaF_2 as compared to layers grown on KCl substrates.

Since in our structures the dominant source of stress is expected to be the thermal stress due to the difference between the thermal expansion coefficients, we do not expect the $1/d$ contribution due to magnetoelastic effects observed in some metallic multilayers [6]. The magnetoelastic anisotropy is likely to contribute to EuS volume anisotropy constant and might partially explain the small difference of volume anisotropy contributions observed for layers grown on different substrates.

In conclusion, we determined experimentally (by ferromagnetic resonance measurements) the magnetic anisotropy constant K in EuS–PbS multilayers grown on KCl (100) and BaF_2 (111) substrates. We found that the dependence of the anisotropy constant on the thickness of the EuS layer can be described by the relation $K = K_V + 2K_S/d$ with the dominant role of the volume K_V term (shape anisotropy). Our results show that the thickness of the EuS layer required for the perpendicular (to the layer) magnetization of the structure is about 1 ML. We discussed the effect of thermal stress as a likely mechanism explaining experimentally observed larger magnetic anisotropy in the EuS–PbS layers grown on BaF_2 as compared to the layers grown on KCl substrates.

Acknowledgments

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