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MAGNETIC PROPERTIES OF EuS/PbS SEMICONDUCTING STRUCTURES

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We report results of magnetization study of EuS/PbS superstructures with different thicknesses of magnetic and nonmagnetic layers. Reduction of ferromagnetic phase transition temperature was found with decreasing EuS thickness. Reasonable description of this effect is obtained within the model based on the mean field approximation.

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The superstructures built of magnetic epilayers intercalated with nonmagnetic material have recently attracted considerable interest. They offer attractive possibilities to study dimensional effects (3D to 2D crossover) as well as coupling between magnetic layers via nonmagnetic medium. The structures of EuS/PbS can be regarded as a model Heisenberg-type ferromagnet/semiconductor superstructure. The collective magnetic behavior of bulk EuS is governed by ferromagnetic (F) nearest neighbors (NN) interaction ($J_1 = +0.22$) and antiferromagnetic (AF) next nearest neighbors coupling ($J_2 = -0.11$) [1]. In effect EuS orders ferromagnetically at $T_c = 16.6$ K [1]. Electronically EuS is a semi-insulator [1] and PbS a degenerated semiconductor [2]. Moreover EuS and PbS both occur in the rock salt structure with nearly perfect lattices matching ($\Delta a/a = 0.6\%$) [3]. These features make EuS/PbS especially attractive for studying their magnetic properties as a function of layer thickness and electronic properties of nonmagnetic PbS.

The epitaxial layers of EuS/PbS were grown from vapor phase on monocrystalline BaF_2 (111) or KCl (001) substrates, with PbS buffer layer. EuS was evaporated using the electron gun. The obtained structures were checked by X-ray diffraction in order to determine the superlattice period. We studied a set of structures with EuS thicknesses ranging from 6 Å to 700 Å and PbS from 20 Å to 600 Å. Magnetization of the structures was measured using a SQUID magnetometer in the temperature range of 2–100 K and magnetic field up to 6 T. The magnetic field was in the plane of the epilayers.

The temperature dependence of low field (0.001 T) magnetization clearly shows a paramagnetic–ferromagnetic phase transition. The representative result is displayed in Fig. 1a. Since magnetization obeys mean field (MFA) prediction $M \approx (T_c - T)^{1/2}$, this formula was used to evaluate phase transition temperature (Fig. 1b). Alternatively transition temperature was determined from the magnetization $M(T)$ inflection point. Both methods produced very similar results. The determined ferromagnetic Curie temperature strongly depends on magnetic EuS and nonmagnetic PbS epilayers thickness. In Fig. 2 we show magnetic layer thickness dependence for EuS–PbS/BaF$_2$ structures, for which EuS layer thicknesses varied from 2 to 23 monolayers (MLs), while PbS layers were kept nearly constant (150–175 Å). It is clear that for EuS thicker than roughly 10 ML T_c is nearly the same, but appreciably lower than for bulk EuS: 13.6 K versus 16.6 K. We ascribe this lowering of the critical temperature to the residual strain present in our structures. Whether it results from EuS/PbS or superstructure/substrate mismatch is not entirely clear at the moment.

For the structures with EuS layers thinner than roughly 10 ML T_c decreases with decreasing EuS layer thickness (Fig. 2). We attribute this effect primarily to the reduction of the number of magnetic neighbors at the superstructures. Even for sharp EuS/PbS interface spins in the two outermost MLs have only 9 NN (less on average if the number of MLs is less than 2), instead of 12 NN for bulk. For EuS/PbS interfaces with finite widths, the intermixing of EuS with PbS reduces the average number of magnetic neighbors even further.

We considered this effect using the so-called "bond-loss model" [4], which assumes that the phase transition temperature for a superstructure T_c' scales by the average number of magnetic neighbors: $T_c' = T_c^{\mathrm{bulk}}(z_1 J_1 + z_2 J_2)/(12 J_1 + 6 J_2)$, where z_1 and z_2 are the average numbers of NN (coupled by J_1) and NNN (coupled by J_2), respectively. In Fig. 2 we show prediction of this approach for a sharp interface, as well as for sample with a non-sharp interface. In the latter case 2 ML interface with linear profile was assumed. For both sharp and non-sharp interfaces $T_c^{\mathrm{bulk}} = 13.6$ K was adopted, as resulting from thick EuS layers samples. As may be noticed a reasonable description of the data may be obtained for rather a sharp interface, extending for about 1 ML. This finding is in agreement with X-ray experiments, which suggest the sharp EuS/PbS interface, of the order of 1 ML.

We note that the above approach ignores the strain effects (except reduction of T_c^{bulk}), which may be important. The substrate/superstructure mismatch influences strongly T_c^{bulk} (= 13.6 K for BaF$_2$ substrate and 17.3 K for KCl). Also EuS/PbS misfit, although relatively small, may influence T_c substantially. These effects will be discussed elsewhere.

Finally we note a strong effect of the nonmagnetic PbS layer thickness on the paramagnetic–ferromagnetic transition. Generally speaking the thinner PbS layer the lower critical temperature, as low as about 8 K for 40 Å EuS/25 Å PbS on

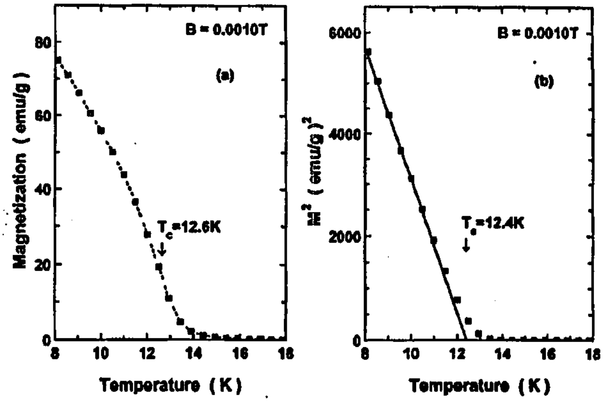

Fig. 1. (a) Magnetization at $B = 0.001$ T of EuS(55 Å)–PbS(175 Å) grown on (111) BaF_2 substrate as a function of temperature. The line is to guide the eye only. (b) The same data plotted as squared magnetization versus temperature. The straight line corresponds to the mean field prediction for a ferromagnet $M \approx (T_c - T)^{1/2}$. The extrapolated critical temperature is in this case $T_c = 12.4$ K.

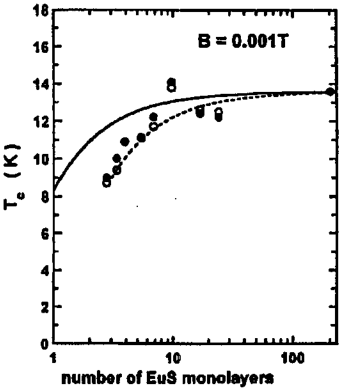

Fig. 2. Critical temperature T_c of EuS–PbS/BaF_2 as a function of EuS layer thickness, expressed in EuS monolayers. The thickness of PbS layers is nearly constant (44–52 ML). Full points denote T_c obtained from MFA extrapolation, while empty symbols show T_c resulting from the magnetization $M(T)$ function inflection point. The lines represent the results of the model described in the text. Solid line: sharp EuS–PbS interface, broken line: interface extending for 2 monolayers, with linear profile. $T_c^{\rm bulk} = 13.6$ K was assumed.

KCl. The observed behavior may reflect the magnetic interlayer coupling. Further studies are necessary to clarify the actual situation.

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