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Spectral dependence of magnetooptical Kerr effect in EuS-based ferromagnetic semiconductor multilayers

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The magnetooptical Kerr effect (MOKE) magnetometry was used to study the magnetic hysteresis loops of EuS–PbS and EuS–SrS semiconductor epitaxial multilayers composed of ferromagnetic layers of EuS and nonmagnetic ultrathin spacer layers of PbS or SrS. The spectral dependence of the MOKE in EuS-based semiconductor multilayers was studied in the photon energy range covering the fundamental interband electronic transitions in EuS. The measurements of the longitudinal MOKE established two maxima on the spectral dependence of the Kerr rotation for the photon energy $h\nu$ of 1.65 eV and 2.1 eV. This experimental finding has been explained based on the model of the electronic band structure of EuS. The observed maxima of the Kerr rotation correspond to the electronic transitions from the localized 4f levels of Eu^{2+} ions and from 3p valence band to the 5d6s conduction band of EuS.

Key words: *magnetooptical Kerr effect; ferromagnetic semiconductors; Eu chalcogenides*

1. Introduction

Ferromagnetic EuS-based multilayers with PbS or SrS spacers form all-semiconductor ferromagnetic/nonmagnetic model spintronic heterostructures. Europium sulfide (EuS) belongs to the family of europium chalcogenides and is a well known Heisenberg (nonmetallic) ferromagnet with the energy gap of 1.65 eV [1, 2]. Lead sulfide (PbS, energy gap 0.3 eV, IV–VI semiconductor family) and strontium sulfide (SrS, energy gap about 7 eV, alkaline earth chalcogenide) are nonmagnetic spacer layer materials in the investigated structures. EuS, PbS, and SrS crystallize in the cubic (NaCl-type) crystal structure with very similar lattice parameters (the lattice mismatch of only 0.5%). This feature permits the epitaxial growth of pseudomorphic heterostructures of good crystal and magnetic quality [3–5].

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The magnetic properties of EuS–PbS ferromagnetic multilayers were mostly studied by the SQUID magnetometry, neutron reflectivity and ferromagnetic resonance techniques. These experimental investigations revealed, in particular, a dependence of the Curie temperature on the thickness of ferromagnetic EuS layer and an increase of the Curie temperature in EuS layers grown on KCl substrates due to strong compressing in-plane strain [3, 4]. In EuS–PbS multilayers with ultrathin (about 1 nm) PbS spacer layers, the antiferromagnetic interlayer exchange coupling was experimentally found [5, 6]. The magnetic properties of EuS–SrS multilayers have not been studied so far. Recently, the magnetooptical Kerr effect (MOKE) magnetometry was applied to study the antiferromagnetic interlayer exchange coupling in EuS–PbS wedge-like structures grown on KCl (001) substrates [7]. The MOKE magnetometer is particularly useful for such a study because it combines the spatial resolution (given by the laser spot area) and high magnetic sensitivity. The aim of this work is to experimentally study the spectral dependence of the magnetooptical Kerr effect in EuS-based structures. It is expected that such measurements will permit establishing optimal conditions (wavelength of incident light) for the MOKE measurements and will provide experimental information about the electronic structure of these heterostructures.

2. Experimental

We experimentally examined the magnetooptical properties of a variety of EuS –PbS and EuS–SrS multilayers deposited on KCl (001) monocrystaline substrates. The multilayers were grown by high vacuum deposition on freshly cleaved substrates with 50 nm thick PbS buffer layer using electron gun (EuS and SrS sources) and resistively heated tungsten boats (PbS source). The thicknesses of ferromagnetic EuS layers were in the range 3–8 nm while the thicknesses of PbS and SrS spacers covered the range 0.8–10 nm. In the case of EuS–PbS structures, only the multilayers terminated with the top EuS layer were investigated because of the fundamental absorption in PbS layers which is in the near infrared range. The spectral dependence of the MOKE in EuS-based semiconductor multilayers was studied in the photon energy range E_{phot} between 1.5 eV and 2.5 eV covering the fundamental interband electronic transitions in EuS. The halogen lamp and He–Ne laser (photon energy $h\nu = 1.93$ eV) were employed as light sources. The angle of incidence of light on the sample was about 30°. The standard lock-in technique with photo-elastic modulator ($f_{\mathrm{mod}} = 50$ kHz) and a Si diode detector was used. The longitudinal MOKE measurements were carried out in the temperature range 4–35 K with an external magnetic field up to 300 Oe applied in the plane of the multilayer along (100) crystal direction.

An example of magnetic hysteresis loops obtained for EuS (5 nm)–SrS (0.5 nm) –EuS(5 nm) trilayer by the MOKE magnetometer is shown in Fig. 1. The ferromagnetic transition for this structure takes place at the Curie temperature $T_C \approx 17$ K. The magnetization switching effect found at low magnetic field is due to the interlayer

exchange coupling observed in EuS–PbS and EuS–SrS heterostructures with ultrathin spacer layers. The spectral dependence of the MOKE obtained for EuS–PbS multilayer structure at 4 K in an external magnetic field of 150 Oe is shown in Fig. 2.

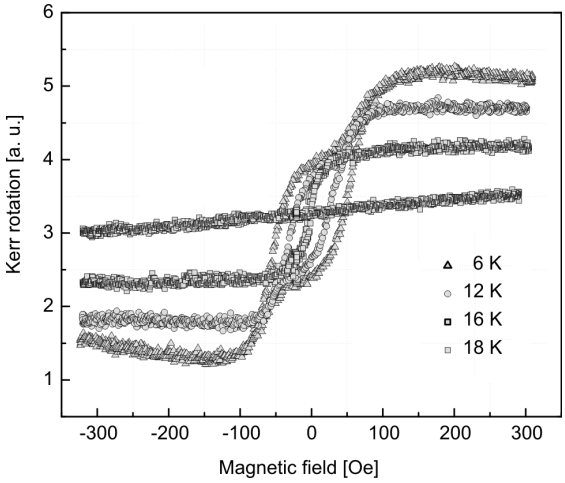

Fig. 1. Hysteresis loops of EuS (5 nm)–SrS (0.5 nm)/KCl trilayer at various temperatures; He–Ne laser, photon energy 1.93 eV

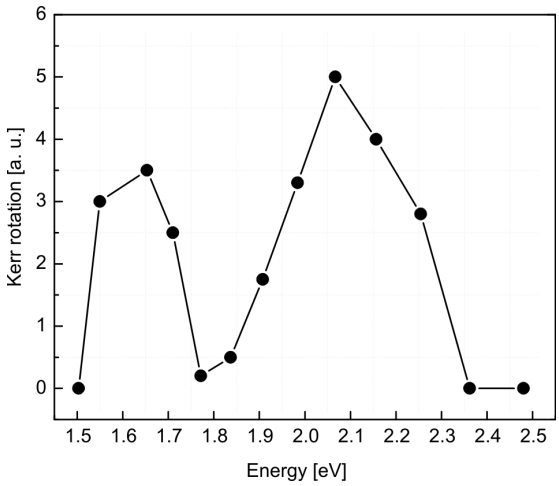

Fig. 2. Kerr rotation vs. light energy for EuS–PbS/KCl multilayer at 4.2 K

3. Discussion and conclusions

Two maxima of the Kerr rotation are clearly visible at photon energies of 1.65 eV and 2.1 eV on the spectral dependence presented in Fig. 2, with the second maximum

being about twice broader and stronger than the first one. This experimental finding can be qualitatively explained taking into account the model of the electronic structure developed for bulk EuS crystals [1, 2, 8] with the valence band (at the Γ point of the Brillouin zone) composed essentially of $3p^6$ states of sulfur and the conduction band (at the X point) built of 5d and 6s states of Eu (Fig. 3).

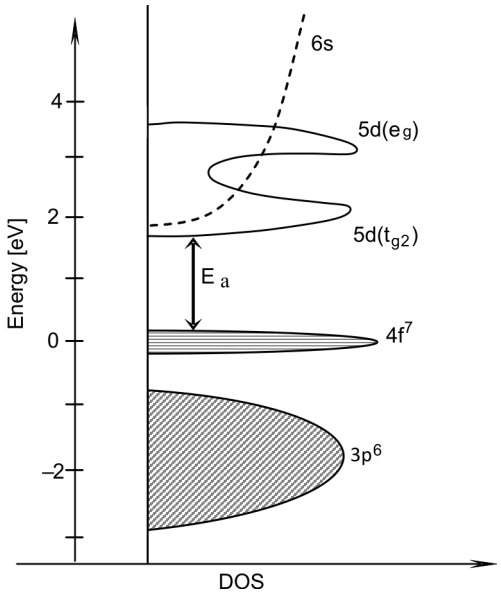

Fig. 3. Density of states of EuS in a paramagnetic state. The absorption edge at E_a = 1.65 eV is due to 4f→5d electronic transitions [8]

The localized $4f^7$ (spin-up) states of Eu are located about 0.5 eV above the top of the valence band. The 5d conduction band is known to split due to crystal field into t_{2g} and e_g subbands. The conduction band states in EuS undergo, below the Curie temperature, the exchange splitting due to the 5d–4f exchange interaction. The energy gap between $4f^7$ states and the conduction band minimum at 300 K is 1.65 eV. Thus, the first maximum of the MOKE in EuS–PbS multilayers can be interpreted as originating from the $4f^7 \rightarrow 4f^6 5d(t_{2g})$ transitions, what corresponds to the absorption edge in EuS. We note that in Fig. 2 the MOKE signal below 1.65 eV is also visible. It is likely that it reflects the red shift of the absorption edge of EuS due to the exchange splitting of the conduction band states (estimated to be about 0.18 eV [1]). For the explanation of the origin of the second maximum of the MOKE found in EuS–PbS at $h\nu$ = 2.1 eV two scenarios should be envisioned. We interpret this maximum as brought about by the transition between $3p^6$ states of the valence band and the bottom of conduction band. This interpretation is supported by much higher amplitude and half-width of the second maximum as well as by the vanishingly small MOKE signal between both maxima. However, the energy separation between the $3p^6$ valence band and the $4f^7$ states as well as the conduction band is not exactly known.

On the other hand, if spin-orbit interaction in the $4f^6$ electron configuration of Eu ions is taken into account, an another interpretation of this maximum is possible.

Namely, the spin-orbit interaction results in formation of two multiplets, for which two kinds of transitions, with spin inversion or conservation, are possible. The transitions with spin inversion correspond to energy beyond the considered range but transitions with spin conservation approximately match the second MOKE maximum [9]. Thus, in order to unambigously establish the microscopic origin of this maximum, a more complete set of optical investigations is still needed.

In conclusion, our investigations of the spectral dependence of the magneto-optical Kerr effect in EuS-based multilayers revealed two characteristic maxima, which can be interpreted taking into account only the specific features of the EuS electronic band structure. This finding suggests that, in the examined energy region of light absorption, the influence of optical properties of ultrathin narrow gap PbS spacers can be neglected in the analysis of MOKE measurements. Our experimental study of the spectral dependence of the MOKE in EuS-based multilayers confirmed that He–Ne laser with $E_{\mathrm{phot}} = 1.93$ eV (corresponding to the second spectral maximum of the Kerr rotation) is well suitable for the magnetooptical investigations of hysteresis loops of EuS-based ferromagnetic heterostructures.

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