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Photoluminescence in EuS–PbS–EuS semiconductor structures with a double ferromagnetic barrier

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The temperature, magnetic field, and laser excitation power dependences of photoluminescence (PL) were studied in 5×(EuS (5.5 nm)–PbS (17.5 nm)) semiconductor ferromagnetic multilayers grown epitaxially by high vacuum deposition on a BaF_2 (111) substrate. In EuS–PbS heterostructures, ferromagnetic layers of EuS form electron barriers for both electrons and holes in nonmagnetic quantum wells of PbS. PL was observed in the near infrared due to electronic transitions in PbS quantum wells with narrow energy gaps. Measurements carried out at 4.2 and 77 K (i.e., below and above the Curie temperature of EuS layers, which is about 14 K) showed characteristic PL spectra consisting of one or two lines with a strongly non-linear response upon increasing the YAG laser excitation power. Below the Curie temperature, the application of a weak magnetic field of 200 Oe results in a change of the PL intensity as well as a small red shift in the PL energy of about 1 meV. These observations are discussed in terms of the model taking into account the magnetization-dependent height of the EuS potential barrier for electrons in a PbS quantum well.

Key words: *spintronics; magnetic semiconductor; europium chalcogenide; IV–VI semiconductor*

1. Introduction

EuS–PbS multilayers are ferromagnetic–nonmagnetic heterostructures built only of semiconductor materials. EuS is a well-known ferromagnetic semiconductor with the Curie temperature of bulk crystals T_c = 16.5 K [1]. It is considered to be a model example of a Heisenberg ferromagnet. PbS is a diamagnetic material from the IV–VI group of semiconductor compounds [2]. Both materials crystallize in a rock salt lattice and have very well matching lattice parameters, $\Delta a/a$ = 0.5%. Employing high vacuum deposition techniques permits epitaxial growth of high-quality multilayer structures [3, 4]. A ferromagnetic transition in EuS–PbS multilayers is observed even for structures with ultrathin EuS layers of only 0.6 nm, i.e. just about two monolayers [3, 4]. In EuS–PbS multilayers grown along the

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[001] crystal direction with ultrathin (about 1 nm) PbS nonmagnetic spacer layers, the effect of antiferromagnetic interlayer coupling is observed [5, 6]. In EuS–PbS multilayers, wide-energy-gap ($E_g = 1.65$ eV) ferromagnetic layers of EuS form electron barriers, whereas narrow-energy-gap ($E_g = 0.3$ eV) nonmagnetic layers of PbS constitute quantum wells for both electrons and holes (Fig. 1) [4, 7–9]. These semiconductor heterostructures exhibit good luminescence properties in the near infrared, related to the direct-gap electronic band structure of PbS (also exploited in PbS bulk crystals and thin films near infrared lasers and detectors) [2].

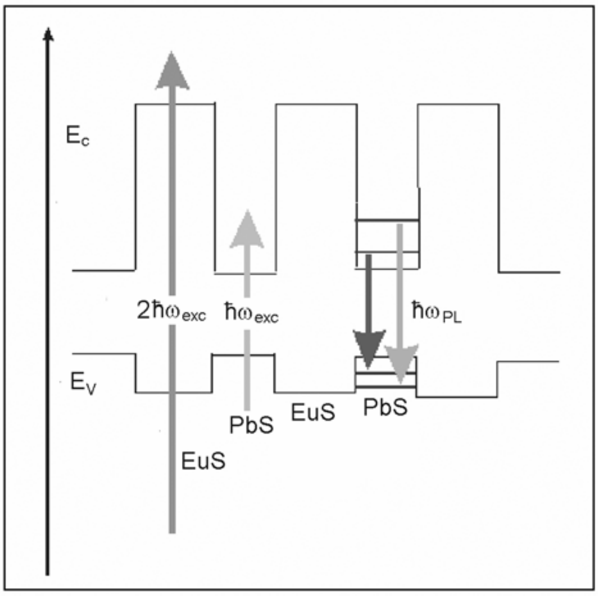

Fig. 1. The energy scheme of a EuS–PbS multilayer with PbS nonmagnetic quantum wells and EuS ferromagnetic barriers. The arrows labelled $2\hbar\omega_{\text{exc}}$ and $\hbar\omega_{\text{exc}}$ depict two optical excitation modes employed. The arrows labelled $\hbar\omega_{\text{PL}}$ show photoluminescence radiation due to electronic transitions between the conduction and valence band states in the PbS well

Due to the ferromagnetic character of EuS barriers which exhibit strong exchange splitting of conduction band states below the Curie temperature, the height of the potential barrier for electrons in a PbS well depends on the magnetization of the EuS layers. This effect is particularly strong in EuS with a total exchange splitting (corresponding to full magnetic saturation) of 0.36 eV as compared to the average (observed in the paramagnetic state) height of the potential barrier of about 1.2 eV. Such a change in the potential barrier influences the energies of size-quantised electronic states in a PbS well. An additional control mechanism may also be related to the influence of the mutual orientation of the magnetization vectors of two EuS barriers, as modelled theoretically in Ref. [9]. Therefore, EuS–PbS multilayers form a new spin optoelectronic semiconductor system, in which the electronic states and optical processes can be controlled by low external magnetic fields needed to magnetically saturate EuS barriers. In this work, we experimentally examine a new spin optoelectronic idea of controlling the wavelength and other characteristics of PL emission in a semiconductor magnetic heterostructure of EuS–PbS multilayers by changing the height of the ferromagnetic barriers induced by low magnetic fields.

2. Experimental results and discussion

Photoluminescence (PL) was studied in a 5×(EuS (5.5 nm)–PbS (17.5 nm)) multilayer grown by high-vacuum deposition on a BaF_2 (111) substrate. EuS was evaporated using an electron gun, whereas for PbS a standard thermal source (tungsten boat) was used.

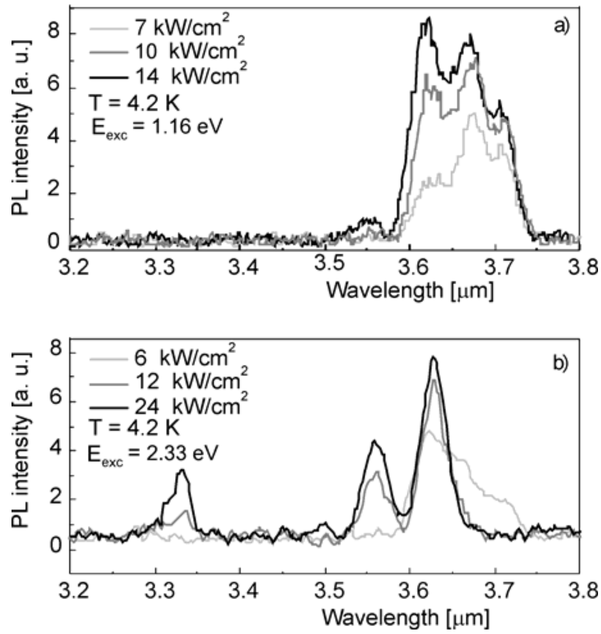

Fig. 2. Dependence of the photoluminescence spectra of a 5×(EuS (5.5 nm)–PbS (17.5 nm))/BaF_2 (111) multilayer on laser excitation power as indicated in the Figure. The experimentally observed minimum at a wavelength of about 3.6 μm is due to the absorption of the atmosphere. The spectra were detected in the backscattering optical geometry of the experiment

The analysis of the crystalline structure as well as the magnetic and optical properties of this multilayer showed its high crystal and excellent optical quality. This multiple quantum well showed a very strong, relatively well resolved PL spectrum which is a necessary pre-condition for our experiment. We did not observe such a strong PL in EuS–PbS multilayers with narrower PbS wells. The ferromagnetic transition temperature of the multilayer, T_c = 14 K, was determined from the analysis of the temperature dependence of magnetization. The PL was excited by YAG:Nd laser pulses with 1.16 eV photon energy (absorbed only in PbS wells) or pulses with 2.33 eV photon energy (absorbed in both the quantum wells and barriers, as shown in Fig. 1). The measurements were carried out at 4.2 and 77 K (i.e., below and above the Curie temperature of EuS layers). The pulse duration was 6 ns, which is much longer than the recombination time of the material, hence the excitation was quasi-steady. Both backscattering and edge emission optical experimental geometries were employed, with the PL emission collected along the normal to the layer or from the side of the layer, respectively. A weak external magnetic field was applied in the plane of the layer.

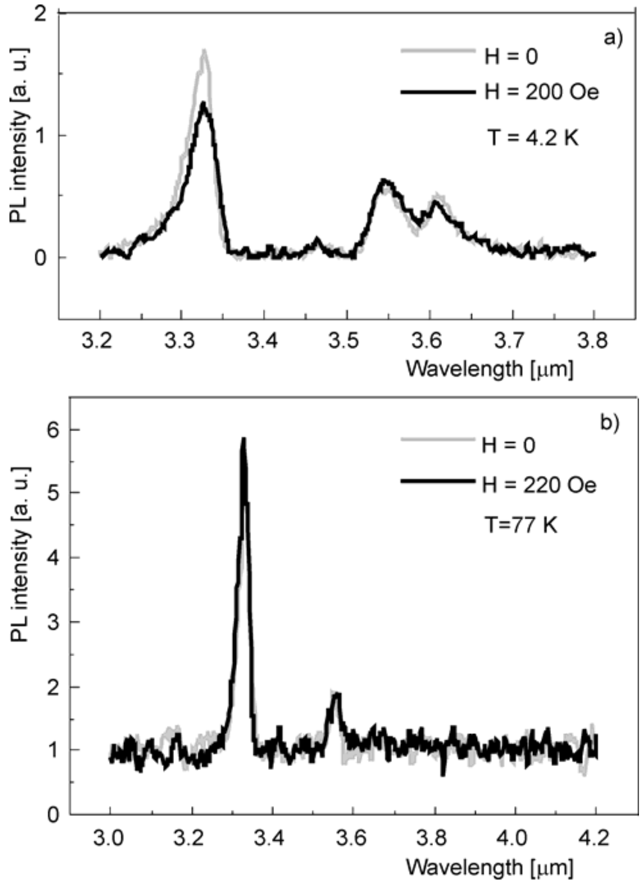

Fig. 3. The effect of a weak magnetic field on the photoluminescence of a 5×(EuS (5.5 nm)–PbS (17.5 nm)]/BaF_2 (111) multilayer below (a) and above (b) its Curie temperature (T_c = 14 K). The spectra were detected in the edge emission geometry, with a 2.33 eV laser excitation and pumping power of 6 kW/cm^2

The PL spectra of the PbS-EuS multilayer are presented in Fig. 2. The spectra are attributed to the allowed optical transitions between PbS well states of the first and the second size-quantization sub-bands (see Fig. 1). The PL spectra presented in

Fig. 2 were recorded as a function of an increasing power density of the laser excitation. For pumping by laser pulses with 1.16 eV photon energy we observed only PL radiation related to the first size-quantised sub-band (Fig. 2a), while for PL excitation by laser pulses with 2.33 eV photon energy radiation related to both the first and the second sub-bands was observed for high density power pumping (Fig. 2b). One can notice a strongly non-linear dependence of the intensity of the PL line related to the second sub-band with increasing laser pumping power density. This indicates the importance of the transfer of photo-excited electrons between ferromagnetic EuS barriers and nonmagnetic PbS wells. Figure 3a presents the effect of a weak external magnetic field on the PL spectra of the PbS-EuS multilayer at 4.2 K. A red shift (of about 1 meV) of the higher energy line is observed in a field of 200 Oe. Above the Curie temperature of the EuS–PbS multilayer, no shift of the PL lines is experimentally found (Fig. 3b). The application of a weak external field also substantially reduces the intensity of the PL line below the Curie temperature, with practically no effect above the Curie temperature.

The estimated Zeeman splitting of electron states in the nonmagnetic PbS well induced by an external field of 200 Oe is about 0.02 meV and can be neglected. This conclusion is supported by PL spectra measurements in the paramagnetic region ($T = 77$ K, Fig. 3b). Therefore, it is likely that the mechanism responsible for the experimental observations discussed above is related to magnetization-dependent changes in the EuS potential barrier. As a consequence of a rather wide PbS well used in our multilayers (optical limit of the experiment), however, the expected red shift is barely resolved experimentally. We believe that the other effect (the change of PL intensity) is also related to the same mechanism. No theoretical model for this effect, however, is known yet.

3. Summary

In conclusion, we have experimentally studied the photoluminescence excited by a YAG laser in EuS–PbS ferromagnetic semiconductor heterostructures. The PL spectra were studied both above and below the Curie temperature of EuS, applying low magnetic fields and using two laser excitation energies. The PL spectra observed in the near infrared range were attributed to electronic transitions between size-quantised electronic states in the conduction and valence bands of the PbS well. In the ferromagnetic state, an external field of 200 Oe (magnetically saturating EuS layers) substantially influenced the intensity of the PL as well as produced a small red shift in the position of the higher energy PL line. This effect can be understood in terms of the influence of magnetization-dependent ferromagnetic EuS potential barriers on the electronic states in PbS wells.

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