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Antiferromagnetic interlayer coupling in EuS/YbSe superlattices

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Abstract

Semi-insulating EuS/YbSe superlattices were fabricated and studied both experimentally and theoretically. Antiferromagnetic correlations between ferromagnetic EuS layers were observed in neutron reflectivity spectra for samples with thin spacer layers (up to 20 Å). This is explained by a model in which the interlayer exchange coupling is dependent upon the electronic band structure of the superlattice. The calculated strength and the range of the coupling are in qualitative agreement with the experimental findings.

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Keywords: Superlattices; Neutron reflectivity; Magnetic semiconductors

The interlayer coupling (IC) between ferromagnetic (FM) metallic layers, discovered in Fe/Cr system [1], continues to be a subject of intense research. Investigation of IC across nonmetallic spacer layers has been pioneered by Toscano et al. [2], who studied hybrid Fe/Si structures. Recently, AFM IC was also observed between semi-insulating FM EuS layers separated by PbS, a narrow-gap semiconductor [3]. Here, we report the observation of IC in EuS/YbSe superlattices (SLs), in which both, the magnetic and nonmagnetic, materials are semi-insulators with the energy gaps 1.5 and 1.6 eV, respectively. Such structures could offer a possibility of controlling their magnetic properties by temperature, electrical field or light.

Neutron reflectivity measurements were carried out at the NG-1 reflectometer at NIST Center for Neutron Research using an unpolarized neutron beam. In Fig. 1, the spectra measured below and above the EuS Curie temperature ($T_C = 18.0 \pm 0.5$ K) in the SL with a relatively thin (20 Å) YbSe spacer are presented, as an example. A purely magnetic peak corresponding to the AFM arrangement of magnetization vectors in the adjacent EuS layers is clearly seen. A scan in the saturating external magnetic field of 150 G, which aligns all EuS layer magnetizations parallel to the field, is also shown. The AFM peak has disappeared and the increased intensity of the structural peak, resulting from the FM layer alignment, is visible. For YbSe layers thicker than 40 Å no traces of interlayer spin correlations were observed—only structural SL peaks are present in the reflectivity spectra.

The strength of the IC can be directly obtained from the value of the saturating magnetic field. This is, however, possible only when the coupling is much stronger than the in-plane anisotropy forces, i.e., when the AFM peak, which vanishes in the saturating magnetic field, is fully restored, when the field is decreased back to zero (see, e.g., Ref. [3]). In contrast, when the IC is comparable or weaker than the anisotropy forces, a hysteresis-like behavior makes the

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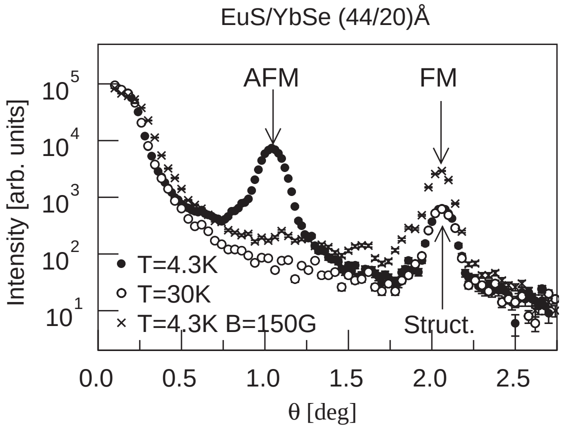

Fig. 1. Neutron reflectivity spectra for EuS/YbSe (44/20) Å SL below and above T_C in zero magnetic field. A scan in the saturating field of 150 G, measured below T_C, is also shown.

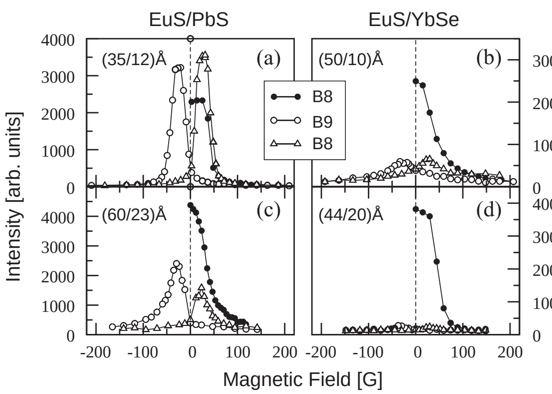

Fig. 2. The intensity of AFM superlattice peak vs. applied magnetic field for several EuS/PbS and EuS/YbSe SLs.

determination of the coupling strength very difficult. In Fig. 2 the dependences of the AFM peak intensity on the external magnetic field for EuS/PbS and EuS/YbSe SLs are compared. In Fig. 2(a) the results for EuS/PbS with a 12 Å PbS spacer show a complete restoration of the AFM peak when the direction of the applied magnetic field is reversed. For EuS/PbS with a 23 Å PbS spacer, the AFM configuration is restored only partially due to the weaker IC for the thicker nonmagnetic spacer. In the case of EuS/YbSe SLs with comparable spacer thicknesses (10 and 20 Å), the restored AFM peak intensities after the field reversal are considerably lower than for EuS/PbS SLs. This comparison leads to a qualitative conclusion that the IC strength in EuS/YbSe SLs is significantly weaker than in EuS/PbS SLs with the same spacer thickness.

To explain the interlayer spin correlations observed in nonmetallic EuS/PbS SLs, a model in which the exchange interactions are mediated by valence band electrons has been proposed in Ref. [4] .We use the same

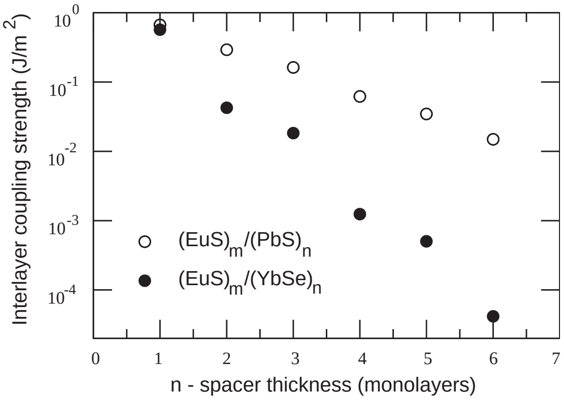

Fig. 3. IC constant as a function of the spacer thickness in EuS/YbSe and EuS/PbS SLs.

model to calculate the coupling in the case of (EuS)$_m$/(YbSe)$_n$ SLs. In this model one has to calculate the spin-dependent part of the total electronic energy of the system, i.e., to describe the band structure of the SL. To determine the tight binding parameters for the SL, knowledge of the energy structure of its constituent materials is needed. The EuS band structure is taken from Ref. [5], but there is no information in the literature about the structure of YbSe. Therefore, to simulate the band structure of YbSe we took the known structure of EuSe [5], put the spin splitting to zero, and rescaled the parameters according to Harrison's rules.

In agreement with the experiment, an AFM IC was obtained. The calculated strength of the coupling decreases with the nonmagnetic layer width n and depends only marginally on the magnetic layer thickness m. In Fig. 3 the calculated IC exchange constants (strength) for the EuS/YbSe and EuS/PbS systems are presented. The theoretically obtained smaller strength and shorter range of the AFM coupling between EuS layers, when separated by YbSe instead of PbS, agree with the qualitative experimental result deduced from Fig. 2.

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