Available online at www.sciencedirect.com

ScienceDirect

Journal of Magnetism and Magnetic Materials 310 (2007) 2280–2282

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Neutron reflectivity investigations of EuS/PbS superlattices grown on (1 1 1) BaF_2 substrate

H. Kępa[a,b,*], C.F. Majkrzak[c], A.Yu. Sipatov[d], Z.Q. Wiren[b], T.M. Giebultowicz[b]

[a]*Institute of Experimental Physics, Warsaw University, ul. Hoża 69, 00-681 Warszawa, Poland*
[b]*Physics Department, Oregon State University, 301 Weniger Hall, Corvallis, OR 97331, USA*
[c]*NIST Center for Neutron Research, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*
[d]*Kharkov State Polytechnic University, 21 Frunze St., Kharkov 310002, Ukraine*

Abstract

The existence of the pronounced ferromagnetic interlayer correlations in EuS/PbS superlattices grown in the [1 1 1] direction on BaF_2 substrate has been revealed by unpolarized neutron reflectivity measurements. This is in a stark contrast with the previous findings of antiferromagnetic interlayer coupling in a similar EuS/PbS superlattices grown in the [0 0 1] direction on KCl substrate. In order to confirm that the observed FM correlations result from interlayer exchange coupling, rather than from spurious layer magnetization alignment, the in-plane magnetic domain orientation distribution has been investigated with neutron polarization analysis.

PACS: 75.25.+z; 75.50.Pp; 68.65.Cd; 61.12.Ha; 61.12.Ld

Keywords: Magnetic semiconductor; Superlattices; Polarized neutron reflectivity

---

With the advent of "spintronics", ferromagnetic semiconductor superlattices (SLs), and the magnetic interlayer exchange interactions (IEC) within them, have played a crucial role both from a practical and fundamental research point of view. In the all-semiconductor EuS/PbS superlattices grown on (0 0 1) KCl substrates, a pronounced antiferromagnetic (AFM) IEC has been observed by SQUID magnetometry [1] and neutron scattering [2]. The AFM alignment of the magnetization vectors in the adjacent EuS layers was clearly seen in neutron reflectometry experiments even for a very thick (up to 400 Å) PbS spacer.

Here, we report the results of neutron reflectivity measurements carried out on EuS/PbS superlattices grown on the (1 1 1) plane of BaF_2 single crystal substrate. In Fig. 1 a typical neutron reflectivity pattern taken with unpolarized neutron beam is presented for the EuS/PbS superlattice with 150 Å thick PbS spacer. The measurements performed above and below T_C (18.5 K) show a considerable increase of the intensity of the first and second order structural SL Bragg peak with decrease of the temperature. This clearly demonstrates the formation of the ferromagnetic (FM) interlayer correlations in the investigated SL. At the same time no intensity increase can be detected at the AFM (half order) peak positions (see the AFM arrows in Fig. 1). Thus, there are no AFM interlayer correlations in this superlattice. In other samples studied, with 40 and 65 Å PbS spacer, strong magnetic contributions to the structural superlattice Bragg peaks have also been observed, indicative of a parallel i.e., FM alignment of the magnetization vectors of the EuS layers and no, even the slightest, traces of any AFM correlations have been seen.

The existing theoretical model explaining the AFM IEC in EuS/PbS SLs grown on (0 0 1) KCl substrate [3] does not predict the FM IEC in SLs grown on (1 1 1) BaF_2. Thus, the most important question concerns the origin of the FM

---

[*] Corresponding author. Institute of Experimental Physics,Warsaw University, ul. Hoża 69, 00-681 Warszawa, Poland.
Tel.: +48 22 5532197; fax: +48 22 6294229.
E-mail address: Henryk.Kepa@fuw.edu.pl (H. Kępa).

0304-8853/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2006.10.748

alignment of the EuS layers in SLs grown on BaF_2. One cannot exclude that it might be caused by other than the IEC factors, in particular, cooling the sample through T_C in a small magnetic field (e.g., earth field or other field present at the neutron reflectometer) might induce a parallel alignment of the magnetic domains along the field direction and mimic the effect of the ferromagnetic IEC.

In order to determine the in-plane magnetic domain orientation distribution, additional polarized neutron reflectivity measurements have been performed. In neutron polarization analysis experiments four intensities are measured corresponding to the different neutron spin orientations before and after scattering, i.e., I^{++}, I^{--}, I^{+-}, and I^{-+}. The + and − signs describe neutron spins 'up' and 'down' respectively. In the first two processes the spin state of the neutron does not change (non-spin-flip or NSF processes) whereas in the last two the neutron spin is reversed (spin-flip or SF processes). Vertical (i.e., along the neutron polarization direction) and horizontal in-plane magnetization components give rise to the NSF and the SF scattering, respectively. By rotating the SL sample about the horizontal [1 1 1] axis, normal to the reflecting surface, one can change these components which in turn affects the measured spin-dependent intensities (see Fig. 2). During the measurements, the sample was kept in a small (1.7 G) guide field to preserve the neutron polarization. This field was too weak to affect the domain structure of the sample.

In Fig. 3(a)–(d) the obtained ratios of I^{++}/I^{--}, I^{++}/I^{sf}, I^{--}/I^{sf} and $(I^{++} - I^{--})/I^{sf}$ vs. angular position (rotation) of the SL sample are presented together with the fit of the model of the magnetic domains distribution. The I^{sf} is the average value of I^{-+} and I^{+-}.

A model of the in-plane magnetic domain distribution has been developed in which the domains are oriented along the six, symmetry allowed, in-plane ⟨0 1 1⟩-type directions as presented in Fig. 4. The calculated, from the model, flipping ratios were fitted to the experimentally determined ones. The fraction of all the domains aligned along the given direction was one of the fitting parameters. The obtained values are shown in the Fig. 4. The details of the fitting procedure will be published elsewhere.

The domain direction distribution obtained, although not equal for the all symmetry-allowed directions, is definitely not uniaxial. Thus, spurious magnetization line-up by an external field has to be excluded. FM IEC between EuS layers is then the most probable cause of the observed FM interlayer correlation. A similar non-uniform domain distribution has also been observed in the AFM coupled EuS/PbS SLs on (0 0 1) KCl [2].

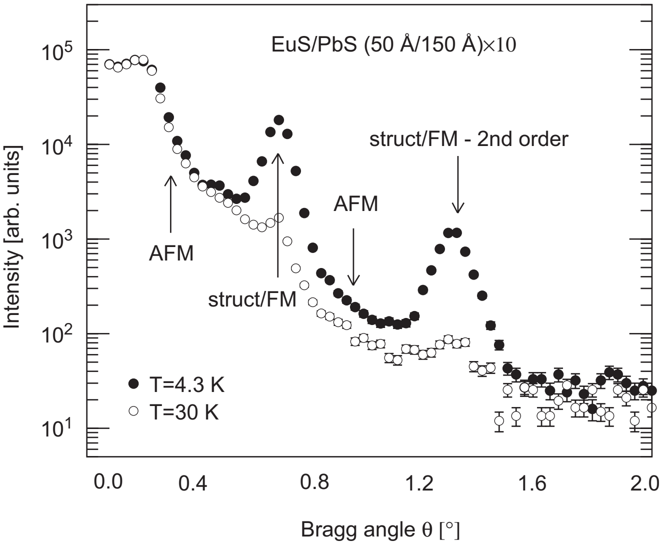

Fig. 1. Neutron reflectivity spectra for EuS/PbS (50 Å/150 Å) × 10 SL, measured below and above T_C (18.5 K).

Work supported by NSF DMR-0509478 Grant.

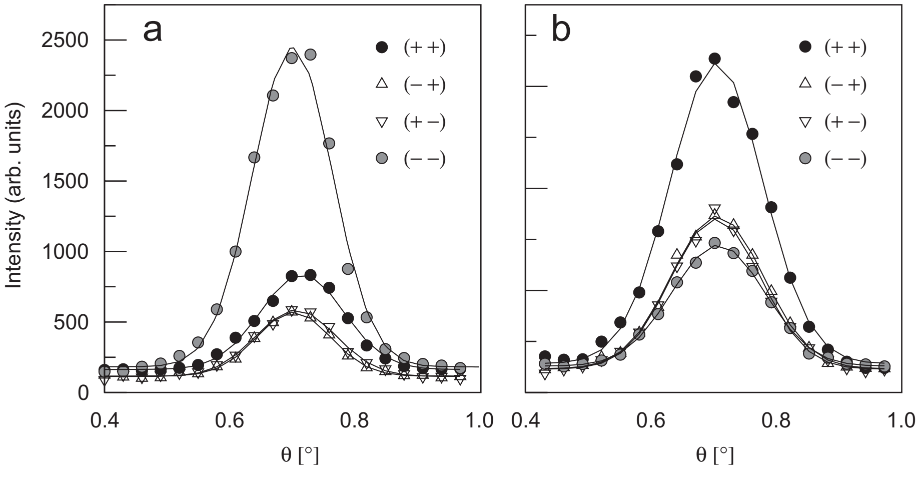

Fig. 2. Neutron polarization analysis of the first order SL Bragg peak for two angles of rotation of the EuS/PbS (50 Å/150 Å) × 10 SL; (a) and (b) the sample rotated by 60° and 150° from the starting position, respectively.

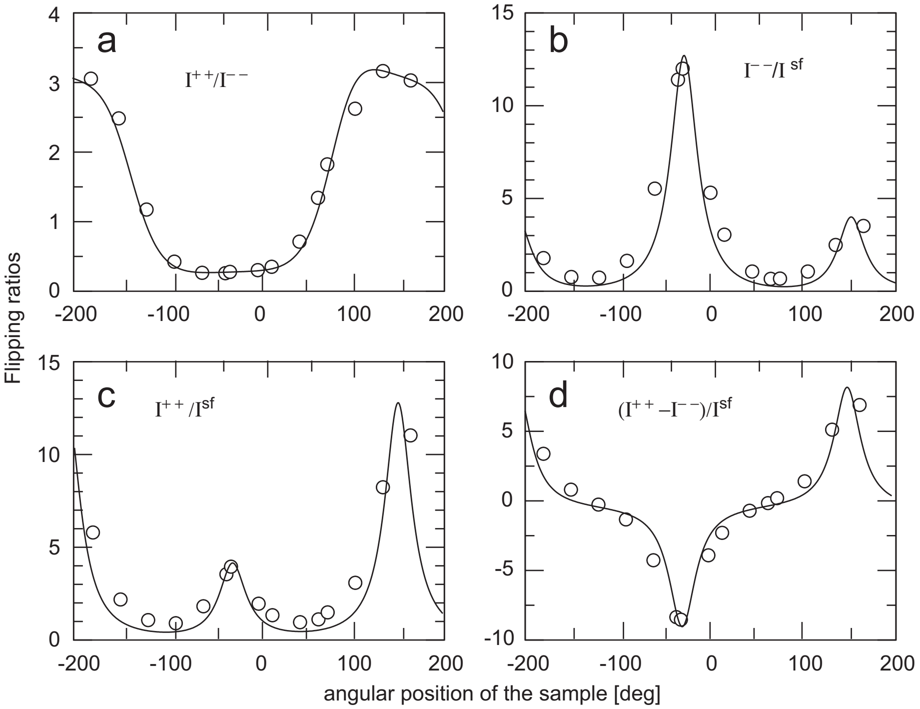

Fig. 3. The flipping ratios vs. angle of rotation for EuS/PbS (50 Å/150 Å) × 10 superlattice. The fit of a model domain orientation distribution is shown by a solid line.

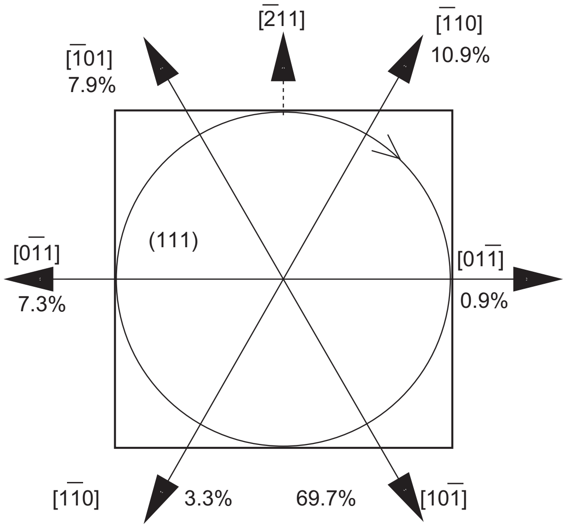

Fig. 4. The (1 1 1) plane of the superlattice with the six symmetry allowed ⟨0 1 1⟩ directions. At the each ⟨0 1 1⟩ direction the percentage of the magnetic domains oriented along this direction is given, The "zero-angle", starting, sample position was with the [$\bar{2}$ 1 1]-direction vertical. The sample was rotated about the normal to the surface, horizontal [1 1 1] direction.

References

[1] C.J.P. Smits, et al., Phys. Rev. B 69 (2004) 224410.
[2] H. Kepa, et al., J. Alloys Compd. 401 (2005) 238.
[3] J. Blinowski, P. Kacman, Phys. Rev. B 64 (2001) 045302.