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Neutron reflectivity investigations of EuS/PbS superlattices grown on (1 1 1) BaF₂ substrate

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Abstract

The existence of the pronounced ferromagnetic interlayer correlations in EuS/PbS superlattices grown in the [1 1 1] direction on BaF₂ 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.

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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 BaF₂ 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) BaF₂. Thus,

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1 the most important question concerns the origin of the FM
 2 alignment of the EuS layers in SLs grown on BaF₂. One
 3 cannot exclude that it might be caused by other than the
 4 IEC factors, in particular, cooling the sample through T_C
 5 in a small magnetic field (e.g., earth field or other field
 6 present at the neutron reflectometer) might induce a
 7 parallel alignment of the magnetic domains along the field
 8 direction and mimic the effect of the ferromagnetic IEC.

9 In order to determine the in-plane magnetic domain
 10 orientation distribution, additional polarized neutron
 11 reflectivity measurements have been performed. In neutron
 12 polarization analysis experiments four intensities are
 13 measured corresponding to the different neutron spin
 14 orientations before and after scattering, i.e., I^{++} , I^{--} ,
 15 I^{+-} , and I^{-+} . The + and - signs describe neutron spins
 16 'up' and 'down' respectively. In the first two processes the
 17

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.

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

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

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

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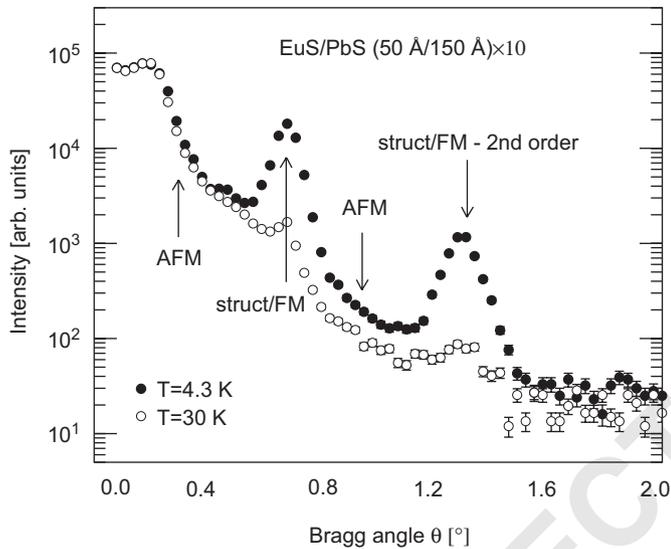


Fig. 1. Neutron reflectivity spectra for EuS/PbS (50 Å/150 Å) × 10 SL, measured below and above T_C (18.5 K).

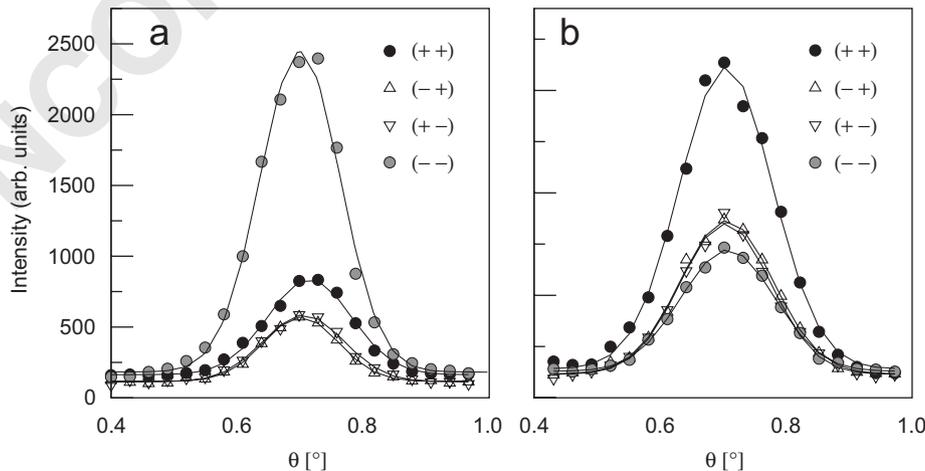


Fig. 2. Neutron polarization analysis of the first order SL Bragg peak for two angles of rotation of the EuS/PbS (50 Å/150 Å) × 10 SL; (a) and (b) the sample rotated by 60° and 150° from the starting position, respectively.

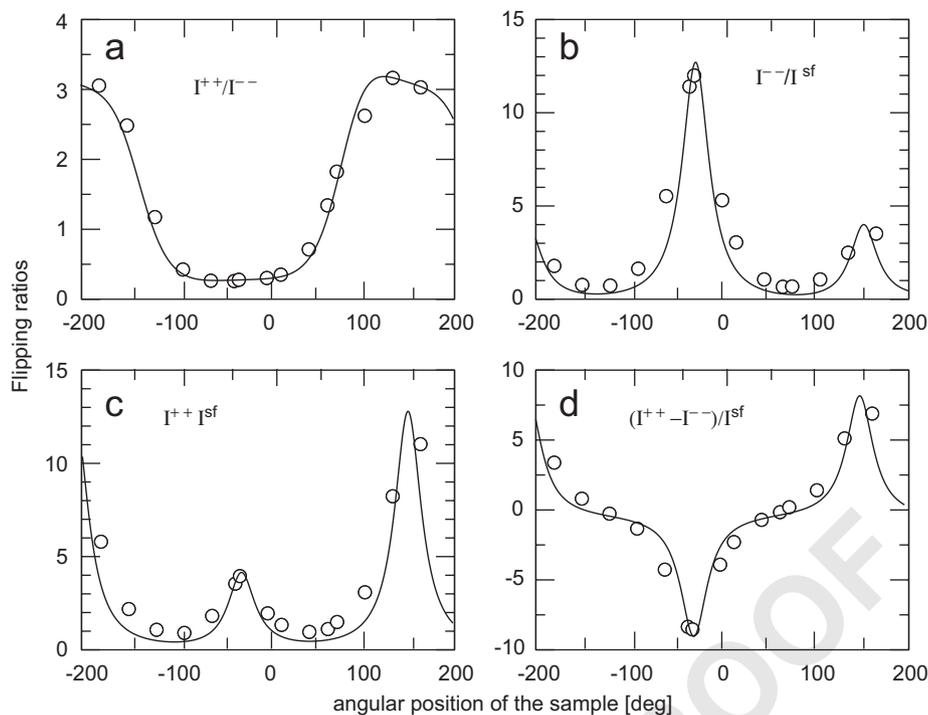


Fig. 3. The flipping ratios vs. angle of rotation for EuS/PbS ($50 \text{ \AA}/150 \text{ \AA}$) $\times 10$ superlattice. The fit of a model domain orientation distribution is shown by a solid line.

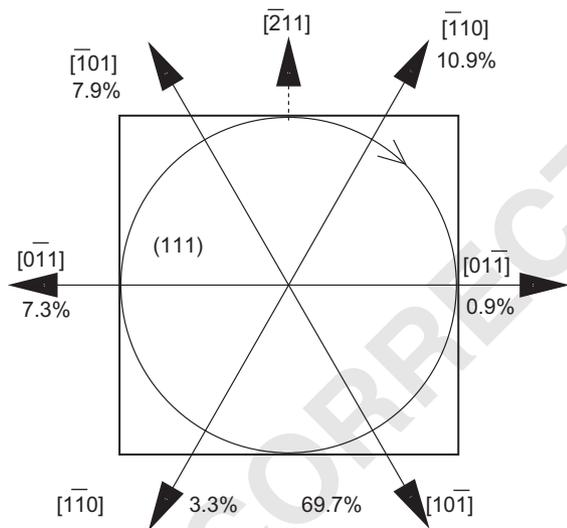


Fig. 4. The (111) plane of the superlattice with the six symmetry allowed (011) directions. At the each (011) direction the percentage of the magnetic domains oriented along this direction is given. The “zero-angle”, starting, sample position was with the $[\bar{2}11]$ -direction vertical. The sample was rotated about the normal to the surface, horizontal $[111]$ direction.

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