# Domain structure of EuS/PbS and EuS/YbSe superlattices studied by polarized neutron reflectometry

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**Abstract**

Polarized neutron reflectivity experiments have been carried out on a number of specimens of ferromagnetic (FM) semiconductor superlattices EuS/PbS and EuS/YbSe with (001) growth plane in order to determine the distribution of magnetization direction in the in-plane FM domains. A preferred magnetic domain orientation along an unique direction within the growth plane was found in all the samples investigated.

*Key words:* neutron reflectivity, superlattices, magnetic semiconductors, domain structure, magnetic anisotropy
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## 1. Introduction

The all-semiconductor superlattice (SLs) systems EuS/PbS and EuS/YbSe exhibit a range of intriguing magnetic properties. Neutron reflectivity data from these structures show the existence of pronounced antiferromagnetic (AFM) exchange coupling between the ferromagnetic EuS layers across the nonmagnetic, and virtually nonconducting PbS and YbSe spacers [1,2]. In this paper, we present polarized neutron reflectometry results that reveal interesting facts about the in-plane domain structure and in-plane magnetic anisotropy in the EuS layers.

Typical reflectivity spectra from the systems are displayed in Fig. 1. The structural SL Bragg maximum (purely nuclear) is seen only in the non-spin-flip (NSF) modes showing no splitting between (++) and (−−) cross-sections. A purely magnetic "half-order" maximum, arising from AFM interlayer coupling, shows a pronounced asymmetry in the NSF and spin-flip (SF) intensities. This clearly indicates that the in-plane domain states allowed by the fourfold crystallographic symmetry of the (001)EuS epitaxial layers are not uniformly populated.

## 2. Experimental

The first data set presented was obtained from a EuS/PbS SL sample with a 4.5 Å PbS spacer. This sample was found to exhibit the strongest interlayer coupling ever observed in any EuS/PbS SLs [1]. In Fig. 2 the polarization analysis of the first "half-order" SL maximum is shown for three different sample orientations. Figs. 2(*a*) and (*b*) show, respectively, the data from measurements in which the [110] and [100] high-symmetry in-plane axes were aligned vertically. In both cases there is quite a large difference in the NSF and SF reflected intensities. In principle, this can stem either from nonuniform magnetic domains distribution in the growth plane, or from the fact that there is only a *single* preferred orientation axis, making some an-

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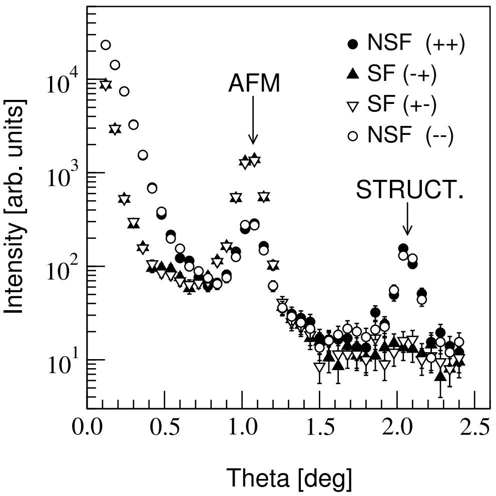

Fig. 1. Polarized neutron reflectivity profiles for a EuS/YbSe (46 Å/20 Å)×15 SL sample mounted with the in-plane [110] axis horizontal. The structural SL Bragg peak is of purely nuclear origin (no SF scattering and no splitting in (++) and (−−) NSF scattering). The presence of purely magnetic 'half-order' AFM SL Bragg maximum is a proof of antiparallel alignment of magnetizations vectors in consecutive EuS layers. A large difference in SF and NSF intensities indicates a non-uniform magnetic domains distribution in the growth plane.

gle with the neutron polarization axis. In the latter case, by rotating the sample about the normal to its surface, one would be able to find a "special" alignments of the magnetization direction in respect to the polarization axis (vertical in our experiments) that would allow an unambiguous determination of that direction. Essentially, there might be three such "special" orientations, with the unique direction vertical, horizontal or at 45°. In the first case all the scattering should be NSF, in the second — only SF, and in the third the NSF and SF intensities should be equal. The latter situation is shown in Fig. 2(*c*). Here the sample was rotated 19° from the [100]-vertical position. In this new alignment it is the [210] axis that makes a 45° angle with the vertical direction. One can thus conclude that the easy in-plane axis in this sample coincides with the [210] direction and that the magnetic domain structure is stripe-like with the domains magnetization in the [210] and $[\overline{2}\overline{1}0]$ directions. This uniaxial behavior is quite surprising, considering the fourfold symmetry of the cubic (001)EuS layer.

Reflectivity data obtained from a EuS/YbSe system are shown in Figs. 1 and 3. As can be seen in Fig. 1, the AFM SL peak is mostly spin-flip, with the SF/NSF intensity ratio being about 5:1. Guided by the results obtained for the EuS/PbS system we expected that here also the easy direction would be [210]. By rotating the sample about the normal to the reflecting surface by ∼ ±20° one would put the [210] axis close to horizontal position, and the scattering should be SF only (no vertical magnetization component). The data obtained for the sample rotated by 0, ±10°, and ±20° is presented in Fig. 3. Surprisingly, however, sample rotation by an angle as large as 40° hardly produced any change in the NSF and SF intensities. One likely explanation of these results is that in this sample there exist *two* domain families, with magnetization directions along the [210] and [120] axes. Both these axes make the angles ±18.43° with the [110] direction.

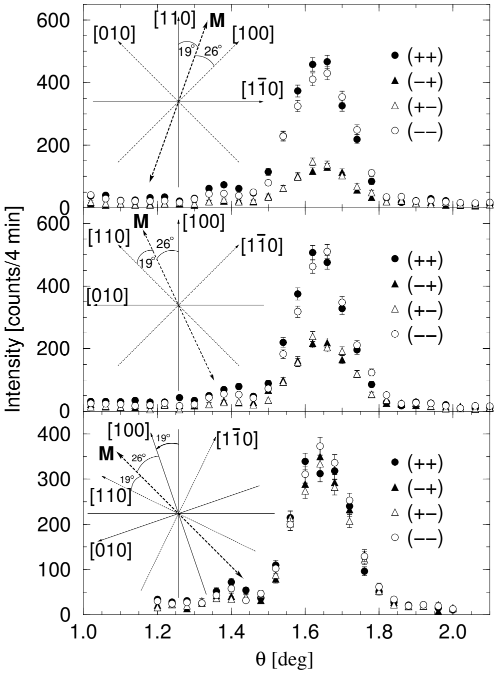

Fig. 2. Polarization analysis of the AFM SL Bragg peak for a strongly coupled EuS/PbS (30 Å/4 Å)×15 superlattice. The sample orientation is shown in each panel: (*a*) the in-plane [110] axis vertical, (*b*) the in plane [100] axis vertical, and (*c*) the [100] axis rotated 19° counterclockwise. The magnetic domains directions are along the line marked **M**. In (*c*) the all four cross-sections (++), (+−), (−+), and (−−) are equal, proving that the magnetization vectors in all domains make a 45° angle with the vertical direction.

A schematic diagram explaining polarized neutron reflection from a sample containing two sets of domains arranged in a "scissors-like" fashion is presented in Fig. 4. For the symmetric positions of the magnetization vectors, making angles ±0.5 rad with the horizontal direction, one obtains the SF and NSF intensities that roughly resembles the experimental situation depicted in the two lower panels of the Fig. 3. When the both magnetization directions are rotated by, for example, 0.2 rad the horizontal component of one of them increases and

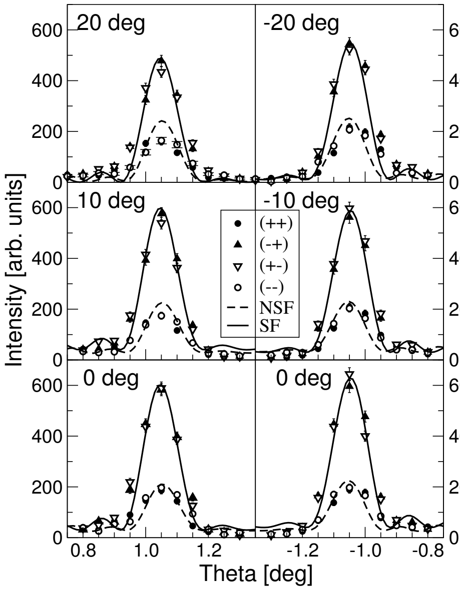

Fig. 3. Polarization analysis of the AFM SL peak for a EuS/YbSe (46 Å/20 Å)×15 sample for different in-plane orientations. The angle 0° corresponds to horizontal alignment of [110] axis.

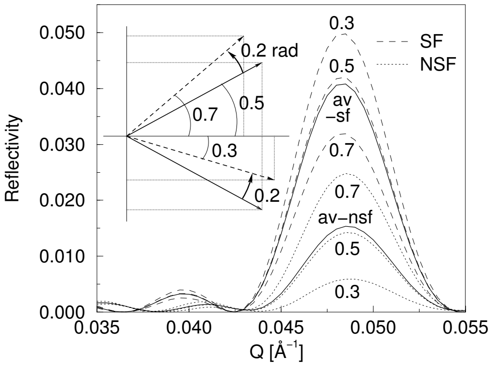

Fig. 4. Calculated NSF and SF intensities of the AFM SL Bragg peak for the sample with two coexisting easy directions, the angle between them being 1 radian as shown in the inset. The NSF and SF peaks shown are for the symmetric (with respect to the horizontal direction) as well as for the "scissors" rotated by 0.2 rad. For the latter case all the contributions from individual magnetizations and the average intensity are shown.

vertical component decreases. The other magnetization vector undergoes changes in the opposite direction, its horizontal component decreases and vertical one increases (see inset in Fig. 4). Consequently, corresponding SF and NSF intensities follow the changes in the horizontal and vertical magnetization components in the same way. However, if the domains are large enough, larger than lateral coherence length of the incoming radiation, the calculated intensities for the two sets of domains should be averaged. As can be seen in Fig. 4, the averaged NSF and SF intensities for the sample rotated and not rotated are almost identical.

Several EuS/YbSe superlattices with different SL periods were investigated, all of them showing the same behavior as the described above one.

## 3. Summary

In bulk EuS the easy axes lie along [111]-type directions, whereas in the layered structures, due to the shape anisotropy, the magnetization directions are confined to the (001) growth plane of the layers. Due to the fourfold symmetry one can expect analogous symmetry in the distribution of domain magnetization directions. It was found, however, that the domain magnetization vectors in EuS/PbS superlattices were aligned along [210] direction and that only one such direction makes an easy axis. In contrast, the other symmetry-equivalent direction, $[1\bar{2}0]$, makes a hard axis. In all analyzed EuS/YbSe samples two easy directions have been found, making an angle of about ±20° with only one of the in-plane [110] axes, whereas analogous directions adjacent to the symmetry-equivalent $[1\bar{1}0]$ axis were again found to be hard axes. The crystallographic axes closest to the observed easy directions are the [210] and [120] axes, making an angle of about 18 degrees with the [110] axis. These axes may be thus considered as the easy directions. Our results demonstrate that in magnetic semiconductor superlattices the symmetry of the in-plane anisotropy axes may be broken. The effect may have important practical implications – especially, if one finds a way of controlling it. However, the exact physical mechanism underlying the observed symmetry breaking is not yet clear, and further studies are still needed. One conceivable explanation is that the effect is associated with the existence of steps on the cleaved KCl surfaces on which the superlattice structures are grown.

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