Step-induced canting of magnetization in Fe/Ag superlattices

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We have investigated the reorientation of the easy axis of magnetization in (0 0 1) Fe/Ag superlattices using vibrating sample magnetometry, Mössbauer spectroscopy and nuclear resonance scattering of synchrotron radiation. Clear evidence is found that the Fe-layer magnetization can be oriented considerably out of the plane of the sample at room temperature, even for Fe-layer thicker than 6 ML at which the spin-reorientation transition usually occurs in Fe/Ag. The spin canting is attributed to frustration and a strong contribution of a step-induced anisotropy.

Recently, the breaking of the symmetry on a stepped Ag surface has been shown to lead first to an in-plane uniaxial anisotropy with the Fe easy axis parallel to the step edges and secondly to a slight increase of the critical thickness for the spin-reorientation transition by an increasing step density [1]. Here we investigated the influence of Ag steps, which have more than one orientation, on the magnetization of Fe and we discovered some new effects. We report the observation of a considerable canting out of the film plane of the magnetization of an Fe film with a thickness much larger than the critical thickness of 6 ML at which the spin-reorientation transition usually occurs in the system Fe/Ag. Moreover, the canting is shown to persist even at room temperature. A phenomenological explanation of the canting can be given by considering the competing contributions to the anisotropy energy of the thin film: the shape anisotropy, the effective volume anisotropy and a step induced anisotropy. A systematic study of the morphology of the deposited films during the superlattice growth allowed us to discover a unique correlation between the occurrence of the spin canting effect and the density and orientation of the Ag steps. Lowering the step density decreases the temperature at which the switching occurs. Fe/Ag superlattices were prepared by molecular beam epitaxy on MgO(0 0 1) substrates. The magnetic properties were measured using a vibrating sample magnetometer equipped with a continuous flow cryostat from 10 to 290 K. With decreasing temperature the magneti-

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zation loop of an [^{57}Fe(15 ML)/Ag(4 ML)]$_{16}$ superlattice changes from a square loop to a loop with the ratio between the remnant magnetization to the saturation magnetization smaller than 1 (not shown) and saturates at field values much larger than usually observed in a thin Fe film. Several physical pictures are consistent with such behavior. First exchange coupling between the Fe layers through the Ag spacer layer might be present and this can lead to an antiferromagnetic or biquadratic arrangement of the consecutive Fe layers. To clarify this hypothesis we have carried out ^{57}Fe nuclear resonant scattering experiments using 14.41 keV synchrotron radiation. Grazing incidence prompt and delayed time integral $\vartheta/2\vartheta$ – scans were recorded at 25 K in various external fields perpendicular to the scattering plane at the ID18 Nuclear Resonance beam line of the ESRF [2]. In the delayed nuclear scattering (not shown), there is a clear absence of an antiferromagnetic Bragg peak which strongly suggests that there is no long range antiferromagnetic ordering present in this [^{57}Fe(15 ML)/Ag(4 ML)]$_{16}$ superlattice. For the SL with a 4 ML thick Ag spacer layer the remnant magnetization varies from 0.68 M_s at ambient and saturates to about 0.45 M_s below liquid nitrogen temperatures. The decrease of the remnant magnetization with temperature can alternatively be explained by the occurrence of a canting of the magnetization out of the film plane. The canting angle seems to increase slightly more out of plane with decreasing temperature, without reaching the fully perpendicularly magnetized state at the lowest temperature. Clear evidence for a partial perpendicular arrangement or alternatively a canted alignment of the Fe spins is given in figure 1 where the CEMS spectrum of the [^{57}Fe(15 ML)/Ag(4 ML)]$_{16}$ superlattice at room temperature is shown.

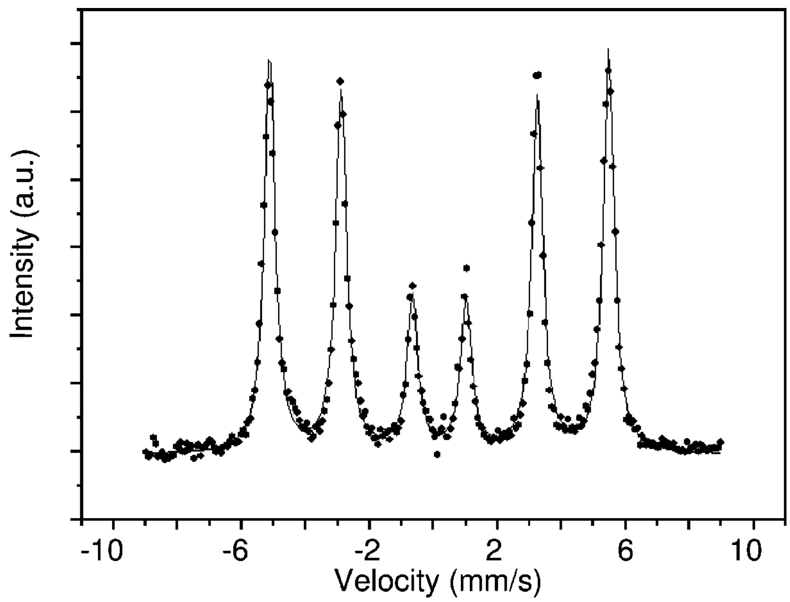

Figure 1. Conversion electron Mössbauer spectrum at 300 K on a [^{57}Fe(15 ML)/Ag(4 ML)]$_{16}$ superlattice. From the relative intensity of the lines the canting angle θ between the incident γ-radiation and the spins of the Fe is determined to be 62°.

The orientation of the spins is obtained from the ratio of the line intensities which is given by $3 : x : 1 : 1 : x : 3$ with $x = 4\sin^2\theta/(1+\cos^2\theta)$, where θ is the angle between the incident γ-ray and the direction of the hyperfine field. The measurement was performed directly after the MBE growth in a connecting UHV-CEMS set-up. The γ-rays are incident perpendicular to the sample surface. For the SL with 4 ML Ag spacer thickness the angle θ is calculated to be 62°. It is striking that a slight increase of the Ag spacer thickness brings the ratio of the line intensities to 3 : 4 : 1 which is exactly what should be observed when the Fe moments lie in the plane of the film (not shown). A continuous rotation of the magnetization out of the film plane has been observed previously, e.g., for Ni on Cu [3] and was attributed to the presence of strain which increases the importance of higher order anisotropy constants. In an attempt to better understand the origin of the observed canting of the magnetization, we have carried out scanning tunneling microscopy measurements of the growth of Ag on Fe during the SL growth (see figure 2). In the left and right hand panel of figure 2 is the STM image of 4 and 6 ML of Ag, respectively. By depositing the Ag on the Fe at room temperature, monoatomic steps with a preferred orientation along the [1 1 0] and [−1 1 0] in-plane Ag directions are observed. The average distance between the steps varies from 5 nm for the 4 ML Ag layer to 9 nm for the 6 ML Ag. It is precisely by increasing the Ag thickness in the Fe/Ag SL that the magnetization changes from a partially out of plane direction to the usual in-plane orientation. Thus the rotation out of the plane of the Fe spins is strongly influenced by the presence and the density of the Ag steps. Interestingly, Kawakami et al. have observed the in-plane orientation for a 20 ML thick Fe layer on a vicinal Ag surface with 5 nm step separation using magneto-optical Kerr effect measurements [1]. Thus, the presence of steps with various orientations is a necessity to observe the canting effect.

In summary, the present study provides evidence of the importance of the breaking of the symmetry of the surface by atomic steps for the occurrence of a partially out of plane or canted orientation of the Fe spins in Fe/Ag superlattices. The orientation

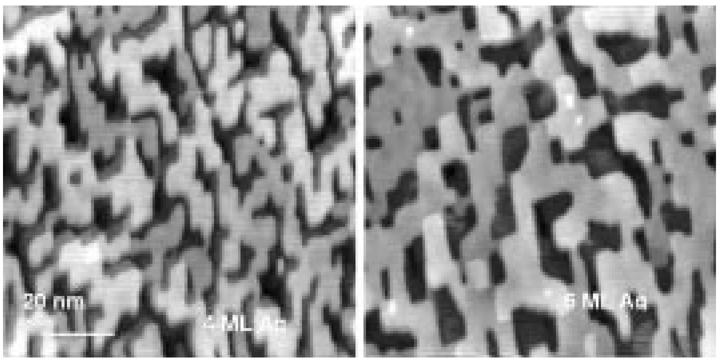

Figure 2. STM topography image of 4 ML Ag (left panel) and 6 ML Ag (right panel) deposited on 15 ML Fe during the growth of the SL. The density of the monoatomic Ag steps is drastically decreasing with the Ag layer thickness.

of the Fe magnetization can be altered from a canted to an in-plane orientation by increasing the Ag layer thickness. This is attributed to the strong dependence of the Ag layer step density on its thickness.

Acknowledgements

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