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Magnetic spiral structures in La/Fe multilayers

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Abstract

The magnetic properties of La/Fe multilayers were tested by magneto-optical Kerr effect and polarized neutron reflectometry. The experiments indicated that above a layer thickness $t_{La} = 25 \text{ \AA}$ the magnetic state of the virgin sample is represented by a spiral-like arrangement of magnetizations of subsequent Fe layers, whereas each Fe layer itself is ferromagnetic. Polarized neutron reflectometry shows that the helix has predominantly one chirality over the entire surface area of several cm^2 . The magnetic spiral structure is imprinted during the growth process by rotating the sample in a small residual magnetic field. External magnetic field of 90 Oe are sufficient to erase the magnetic structure irreversibly.

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Many recent studies have been dealing with magnetic structures arising in artificial multilayers. We have started investigating multilayers combining Fe and La which at the beginning seemed to exhibit special magnetic properties. Remarkably, it turned out that by controlling growth we are able to tailor the magnetic structure of the succeeding Fe layers on a mesoscopic length scale.

The samples were prepared by ion-beam sputtering with argon in an UHV chamber (base pressure $< 5 \cdot 10^{-12}$) at room temperature and have a nominal composition of $[\text{La } t_{\text{La}} \text{Å} / \text{Fe } t_{\text{Fe}} \text{Å}] \times N$ ($t_{\text{La}} = 26\text{-}35 \text{Å}$, $t_{\text{Fe}} = 20\text{-}35 \text{Å}$). Si (100) wafers covered with a 40Å Cr buffer served as substrates and a 100Å Pd cap layer prevents oxidation. During the preparation the samples were turned to provide a homogeneous layer thickness of several cm^2 which was needed for neutron reflection experiments. The structure of the samples was characterized by x-ray reflectometry [1]. Both sublayers were found to be crystalline and textured in the growth direction: Fe with bcc (111) and La in hcp (100) and fcc (111). The interface roughness was limited to one atomic plane.

The magnetic properties of the multilayers were investigated by magneto-optical Kerr effect (MOKE) in the longitudinal configuration using a modulated polarized laser beam ($\lambda = 6328 \text{Å}$). The magnetic response depends strongly on the Fe-layer thickness. Up to 30Å Fe the saturation field and the coercive field are small ($H_s < 100 \text{ Oe}$, $H_c < 10 \text{ Oe}$) whereas beyond this thickness a jump-like increase to $H_s \approx 500 \text{ Oe}$ and $H_c \approx 30 \text{ Oe}$ occurs (see Fig. 1). However, for all samples in the virgin state no net magnetization is observed. Indeed, the magnetic structure of the samples is complex as shown by neutron reflectometry in the virgin state as taken at the Hahn-Meitner-Institut Berlin and Argonne Laboratory [2]. Fig. 2 displays the polarized neutron spectrum of $[\text{La } 32 \text{Å} / \text{Fe } 30 \text{Å}] \times 32$ prior to a first magnetization. Beside the main peak (labeled with I_n) due to the chemical periodicity, magnetic

satellites (0^+_m , 1^+_m , 1^-_m) occur in the small-angle spectrum. In the kinematical theory their positions are given by

$$q = 2\pi \left[\left(\frac{n}{d} \right) \pm \left(\frac{1}{\Lambda} \right) \right] \quad (1)$$

where n refers to the order of the structural peak from the chemical periodicity at which the satellites occur. d and Λ are the chemical and magnetic periodicity, respectively. In this sample the magnetic moments of succeeding Fe layers are arranged in a spiral like structure with $\Lambda = 3.3$ bilayers whereas the Fe sublayers themselves are ferromagnetic. The periodicities observed in other samples with different La layer thickness were found to lie between 3 and 8.6 bilayers. Neutron polarization was used to better characterize the magnetic state of the sample. The polarization axis of the neutrons was chosen perpendicular to the layer plane, that means the scattering vector q the propagation vector Λ of the spiral are collinear. The direction of Λ indicates the chirality of the helix, for a left-handed screw Λ points out of the plane whereas for a right-handed screw it is directed in the opposite direction. In this geometry all magnetic scattering causes the neutrons to flip their spin, and for the intensities Γ^+ and Γ^- of the satellites right and left from the main peak the following selection rule is valid [3]:

$$\Gamma^+ \div 1 \pm (Pq)(q\Lambda) \quad (2)$$

Applied to the actual geometry in the experiment and supposed a positive polarization ($P = +1$), left handed spirals give only rise for the Γ^- satellites whereas for right handed screws solely the Γ^+ satellites appear. The opposite is true if the neutron spin points in the other direction ($P = -1$). From neutron reflectometry it turns out that in the La / Fe multilayer only a single chirality is observed over the entire surface area. In naturally occurring magnetic spiral structures (for instance in several magnetic rare earths) the domains of

opposite chirality are almost equally populated, and all efforts to change their balance has come to nought [4]. For La / Fe multilayers the helix and its single chirality are created by the method of preparation. During growth the substrate is turned in a small residual field (3 Oe) due to the ion guns. Subsequent experiments [2] showed that the spiral pitch and its turn chirality are determined by the velocity and the sense of the rotation. As a further test of this mechanism a sample with similar bilayer thickness [La 32Å/ Fe 30Å] was grown in the following way: at the beginning of Fe layer deposition the substrate was rotated by exactly 180°. Indeed, neutron reflectometry confirmed the antiparallel configuration of magnetization vectors of subsequent Fe layers. The magnetic structures (the spiral as well as the antiparallel arrangement) were irreversibly destroyed in an external field of ~90 Oe.

The above experiments prove that we are able to create artificial magnetic structures in La /Fe multilayers. As shown in Fig 1 for small layer thickness. Fe exhibits very soft magnetic properties in combination with La. Obviously during preparation the small field of 3 Oe is sufficient to orient the magnetization of the growing layer, but it is weak enough to not disturb the layers already built. By this mechanism arbitrary magnetic structures may be created on a mesoscopic length scale. The imprinted structures seem to stable in time. Among the possible applications we envision a new neutron polarizer based on the strict selection rules valid for the scattering on magnetic spiral structures with single chirality.

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Figures

Fig. 1: Saturation field H_s and coercive field H_c of the samples $[\text{La } 32\text{\AA} / \text{Fe } t_{\text{Fe}}\text{\AA}]$ measured by MOKE. At the Fe thickness $t_{\text{Fe}} = 28\text{\AA}$ the saturation field and the coercive field exhibit a jump like increase. The straight lines are guides to the eye only.

Fig. 2: Polarized neutron reflectivity of $[\text{La } 32\text{\AA} / \text{Fe } 30\text{\AA}] \times 32$. The solid and open symbols show the R^- and R^+ reflectivity, respectively. The magnetic satellites Γ_m occur solely in the R^+ intensity whereas the Γ_m satellites show up only for the neutron beam polarized in the opposite direction. As discussed in the text this indicates that the magnetic structure of the entire sample is a magnetic spiral with right handed chirality.