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Magnetic properties of laterally structured Fe/Cr multilayers

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Abstract

The surface layer of an epitaxial Fe/Cr multilayer system has been structured lithographically into stripes with 1 μm period. Polarized neutron reflectometry and diffuse scattering under grazing incidence measurements show strongly enhanced domain formation compared to the unstructured sample. The domains are correlated throughout the layers. The lateral domain size is partly the period of the stripe pattern of the surface layer, and partly the double.

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Keywords: Magnetic thin films; Magnetoelectronics; Polarized neutron reflectometry

Epitaxially grown Fe/Cr/Fe layered structures are known to exhibit the giant magnetoresistance effect, which has attracted great interest due to its applications, e.g. magnetic field sensors or read heads in computer hard disk drives [1]. Today, much effort is undertaken for the development of a magnetic random access memory [2]. Due to the necessary miniaturization of such a device, the magnetic interaction between the neighbouring cells is becoming a more and more important parameter that has to be controlled.

Here, we report on studies aiming at the determination of induced lateral magnetic modulations in a laterally structured Fe/Cr multilayer.

The model system under investigation is shown in Fig. 1. It is basically an epitaxial Fe/Cr (0 0 1) multilayer structure with 11 periods prepared on 150 nm Ag buffer on a GaAs (0 0 1) single crystal. The thickness of the Fe layers is 15, and 1.1 nm of the Cr layers, yielding antiferromagnetic coupling between the neighbouring Fe layers [3].

After deposition of the multilayer structure, the top Fe layer was patterned into stripes of 1 μm period using electron beam lithography and ion beam etching. The stripes are oriented parallel to the (1 0 0) easy magnetization axis of the Fe layers.

Fig. 2 shows a picture of the structure obtained with scanning electron microscopy (SEM). The sample was inclined by 60°, so the period of the structure appears to have half of the real size. The three-dimensional impression of the SEM picture is misleading, subsequent characterization of the structure with X-ray scattering under grazing incidence showed that the broader features are the hills and the narrower features are the valleys of the stripe structure. The depth of the valleys, as

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determined by X-ray scattering, matches well the thickness of the top Fe layer.

Magnetization measurements with the magnetooptical Kerr effect show a variety of phases. When the magnetic field is oriented parallel to the stripes, the structure is saturated magnetically above $\mu_0 H = 35\,\mathrm{mT}$. Between 35 and 17 mT, a region is identified, where the magnetizations of adjacent layers are oriented almost perpendicular to each other. This behaviour results from the competition between antiferromagnetic coupling, crystalline anisotropy and Zeeman energy. It is observed in the same way with the unstructured sample.

Between 17 and 6 mT, a complex phase is observed, that is being discussed below. This complex phase does not appear in the unstructured sample.

Below 6 mT, a state without remanent magnetization is observed. As seen from polarized neutron reflectometry and diffuse scattering, the magnetic layered structure is completely split into columnar domains. In each single domain, the magnetization of the neighbouring layers is oriented antiparallel to each other. No preferred orientation against the remaining external field and therefore no net magnetization is observed.

Reflectivity and diffuse scattering under grazing incidence of polarized neutrons with polarization

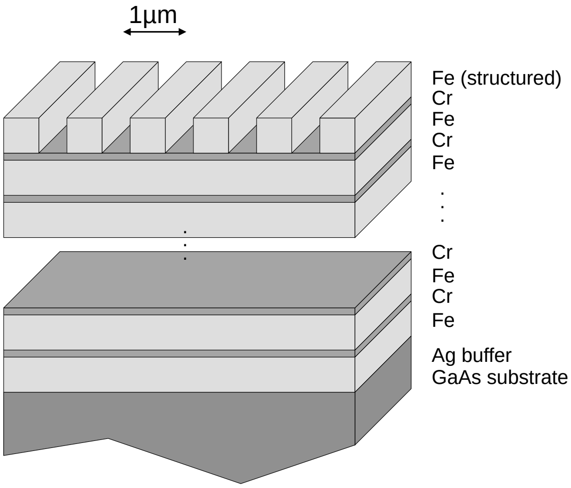

Fig. 1. Schematic sample configuration.

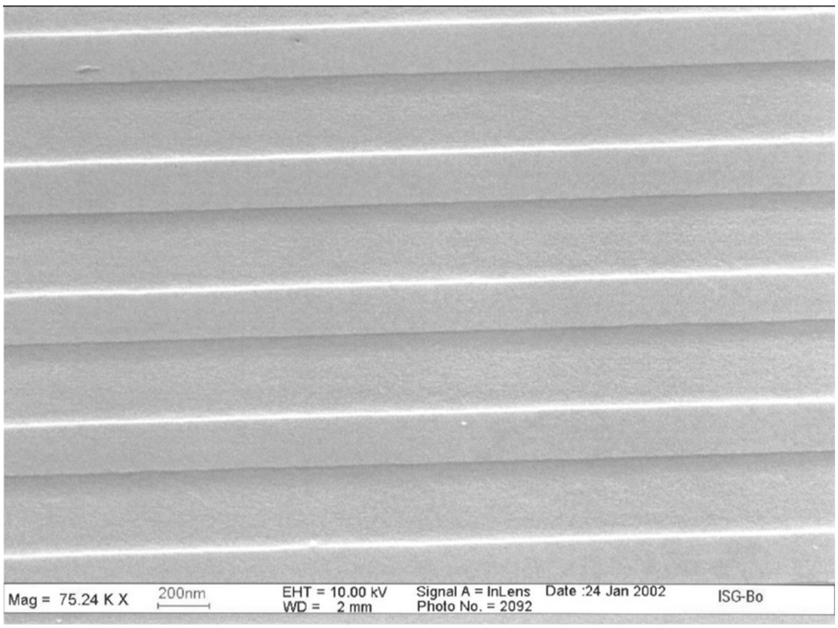

Fig. 2. SEM picture of the structured sample surface. The sample has been inclined by 60° around the horizontal axis of the picture, therefore the vertical distances are reduced to half.

analysis have been measured at the HADAS reflectometer in the neutron guide hall at the Jülich research reactor FRJ-2 (DIDO) [4]. Fig. 3 shows the four different polarization channels, measured at $\mu_0 H = 9.5\,\mathrm{mT}$ with the magnetic field oriented parallel to the stripes, i.e. in the intermediate, complex magnetization state.

On the diagonal of each picture, the specular reflectivity ($\alpha_i = \alpha_f$) is displayed. Beginning at small angles, one can see the total reflection plateau (only in the non-spin-flip channels), a half-order peak (representing the double of the period of the multilayer structure, not resolved from the plateau in $R{+}{+}$), the first-order multilayer peak at about $\alpha_i = 16\,\mathrm{mrad}$, and the peaks with the orders $\frac{3}{2}$, 2, and $\frac{5}{2}$.

The appearance of the half-order peaks is a clear indication of antiferromagnetic orientation of neighbouring Fe layers. But it is clearly visible, that the $\frac{3}{2}$ order and $\frac{5}{2}$ order peak are only sharp in the spin-flip channels, but not in the non-spin-flip channels.

A lot of diffuse scattering is seen that indicates domain formation within the sample. Compared to the unstructured sample, the amount of diffuse scattering is enhanced by a factor 3, and the extension of the diffuse scattering away from the specular line is much longer, indicating a smaller domain size. The diffuse scattering is mainly located in Bragg sheets around the antiferromagnetic reflections. The concentration of the diffuse scattering in these Bragg sheets indicates a strong antiferromagnetic vertical correlation between the domain pattern in adjacent layers. So we observe columnar alternating domains throughout the complete multilayer stack.

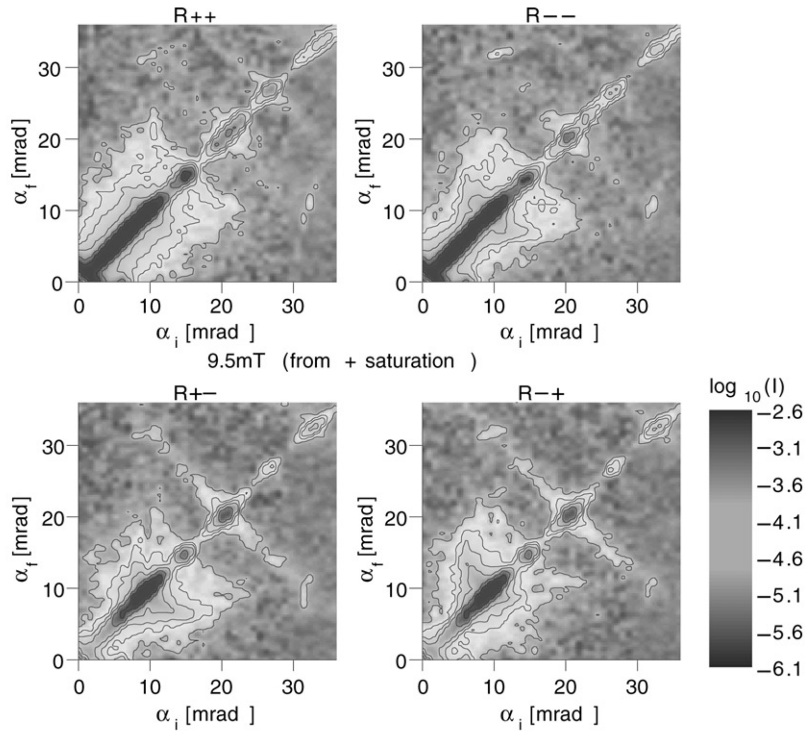

Fig. 3. Reflectivity and diffuse scattering under grazing incidence. The scattered intensity (logarithmic colour scale) is plotted against incident angle and outgoing angle of the neutrons. The polarization channels are $R++$ non-spin-flip with the neutron spin along the guiding field direction, $R--$ non-spin-flip with the neutron spin opposite to the guiding field, $R+-$ and $R-+$ spin-flip with the incident neutron spin parallel or antiparallel to the guiding field, respectively.

At the Bragg sheet across the $\frac{3}{2}$ peak, in all four polarization channels the first-order lateral Bragg can clearly be seen (at about 32 mrad in α_i and 10 mrad in α_f and symmetrically). In contrast to that, at saturation field, the Bragg reflection from the lateral grating can only be observed in the $R++$ measurement. This shows, that there is a tendency for the magnetic domains to order according to the pattern of the top layer. In the two spin-flip pictures, also a half-order lateral Bragg is observed, indicating that the domains in some part of the sample have twice the period of the patterned surface.

Until now, we have not yet found a suitable model to describe quantitatively the complete diffuse scattering that was observed. Nevertheless, we have found a description of the specular reflectivity with the different peak width in non-spin-flip and spin-flip for the half-order peaks. They can be described assuming a structure, in that the component of the magnetization perpendicular to the stripes is alternating regularly, while the magnetization component parallel to the stripes shows one phase shift between the third and fourth layer (counted from the top). With that structure, a net magnetization along the field is achieved, without breaking too much the antiferromagnetic coupling.

The next goal will be the complete description of the diffuse scattering, from the unstructured as well as from the structured sample, to be able to compare quantitatively the domain formation in the structured and in the unstructured sample, and to be able to describe the anisotropy created by the stripes inside the unstructured buried layers.

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