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Magnetic order in Co/Cu multilayers studied by polarized soft X-rays and neutrons

M. Hecker[a,*], C.M. Schneider[b], H.-Ch. Mertins[c], U. Rücker[b], E. Kentzinger[b]

[a]*Leibniz-Institut für Festkörper- und Werkstoffforschung, Helmholtzstraße 20, D-01069 Dresden, Germany*
[b]*Institut für Festkörperforschung, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[c]*FH Münster, University of Applied Sciences, Stegerwaldstr. 39, D-48565 Steinfurt, Germany*

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Abstract

The magnetic coupling in Co/Cu multilayers with individual layer thicknesses tuned to the 2nd maximum of the giant magnetoresistance (GMR) is investigated by soft X-ray magnetic scattering. A series of half-integer order magnetic peaks appears in the specularly scattered intensity especially with the higher orders being strongly sensitive to magnetic effects. Diffuse magnetic scattering, performed with polarized neutrons, indicates long-range magnetic correlation in the remanent multilayer state and a corresponding magnetic domain structure sensitive to the magnetic field applied before.

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Keywords: Multilayers; X-ray diffraction; Reflectometry; Magnetic structure

The utilization of polarized X-rays and neutrons for the investigation of magnetic effects in thin films has attracted wide interest in recent years. In particular, scattering techniques not only give high signals with regard to the magnetic state of films and multilayers but also yield a unique access to their layer structure. Whereas magnetic multilayers are well investigated with respect to transport properties related e.g. to the phenomenon of the giant magnetoresistance (GMR), the correlation between their magnetic and structural properties e.g. at the interfaces is still discussed contradictorily. It is the goal of the present paper to investigate the antiferromagnetic (afm) order in Co/Cu multilayers tuned to the 2nd coupling maximum of the GMR, and their corresponding domain structure, by magnetic scattering techniques. Applying soft X-ray reflectivity, the afm alignment in Co/Cu multilayers was proved by the appearance of a half-integer order Bragg peak

*Corresponding author. Tel.: +49 351 4659 246; fax: +49 351 4659 452.
E-mail address: m.hecker@ifw-dresden.de (M. Hecker).

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[1–3]. As will be shown below, due to the high intensity of the undulator radiation of a synchrotron, in a strongly coupled sample with smooth interfaces, peaks up to the 3rd order are resolved, allowing a detailed analysis of the structural and magnetic multilayer properties. By X-ray scattering, the measurement of element-selective hysteresis loops is also feasible (e.g. [3]). However, polarization analysis of the scattered radiation is more easily available for neutron scattering, directly allowing to separate structural and magnetic scattering contributions and yielding additional orientation characteristics of the magnetic order [4,5]. This is utilized below for the diffuse scattering related to the magnetic domain structure.

The synchrotron scattering experiments were performed at the BESSY II UE56 beamline with circularly polarized light ($p_{\mathrm{circ}} = 0.9$), using the polarimeter setup described in Ref. [6]. For the polarized neutrons scattering experiments, the HADAS reflectometer at Juelich research reactor FRJ-2 [7] was utilized. This instrument enabled separate evaluation of the four scattering channels R++, R−−, R+−, and R−+ (spin-flip), allowing the separation of intensities resulting from structural properties, magnetizations parallel to the applied field and magnetizations perpendicular to it. A special analyzer setup, covering the whole surface of a 2D detector, permits simultaneous polarization analysis of the specular and the diffuse scattering.

Multilayers consisting of 40 bilayers Co (0.9 nm)/Cu (2 nm) corresponding to the 2nd maximum of the afm coupling were deposited by DC magnetron sputtering onto thermally oxidized (1 0 0)-Si. According to the bilayer unit (2.9 nm) and the thickness of the whole metallic stack (117 nm), two significant Bragg peaks and a series of higher frequency Kiessig fringes appear in the specular reflectometry curve measured with hard X-rays, respectively (Fig. 1). For the Co/Cu interfaces, an r.m.s. roughness of 0.5 nm results from fitting the curve [8]. At photon energies close to the Co-L_3 edge, intensive Bragg peaks arise up to the 3rd order due to the enhanced resonant contrast. Most striking are the half-integer order peaks, which appear only close to the Co-$L_{2,3}$ edges and indicate a modulation wavelength twice that of the chemical one. As has been proven for the $\frac{1}{2}$ order peak [2] and shown by the neutron data hereafter, these peaks are of pure magnetic origin and correspond to the afm alignment of adjacent Co layers. However, the small Bragg angle of the $\frac{1}{2}$ order peak makes it sensitive to scattering at the surface and to the properties of the upper layer which is partially oxidized, whereas the higher orders should be more sensitive to the intrinsic multilayer properties. This is reflected e.g. by the particular shape of hysteresis loops measured at the $\frac{1}{2}$ order peak [3].

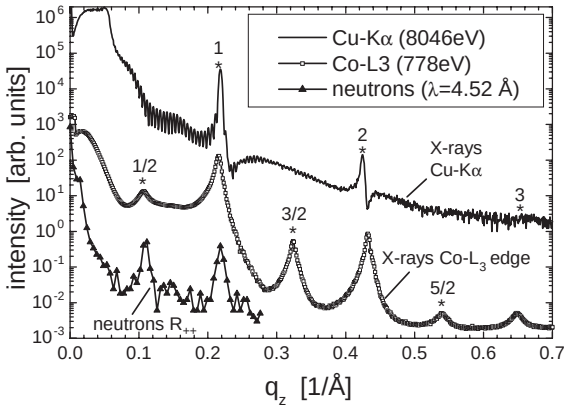

Fig. 1. Reflectometry curves measured with photons of Cu-Kα energy, with photons at the Co-L_3 absorption edge, and with polarized neutrons (nsf R++ channel), respectively. Numbers denote the order of the bilayer Bragg peak. Curves are shifted vertically for clarity.

The $\frac{1}{2}$ order peak can be furthermore enhanced by polarized neutron reflectivity (PNR), which is represented in the lower curve in Fig. 1 for the non spin-flip (nsf) intensity R++ measured in a demagnetized state of the multilayer. The intensive magnetic peak clearly reflects the strong coupling and high degree of periodicity in the multilayer (GMR ratio 27%). In all four scattering channels, this peak exhibits nearly equal intensity. Since, for the used geometry, the nsf and spin-flip (sf) intensity is sensitive to magnetization components parallel and perpendicular to the applied magnetic field, respectively, the equal $\frac{1}{2}$ order peak intensities correspond to randomly distributed orientations

of the magnetic domain structure within the film plane in the demagnetized state.

At an applied saturation field of 130 mT oriented perpendicular to the scattering plane, the magnetic $\frac{1}{2}$ order peaks were completely suppressed in both the nsf and sf channels, corresponding to the break-up of the afm coupling (cf. Fig. 2) $2\theta \approx 4.5^\circ$. The structural 1st order peak ($2\theta \approx 9^\circ$) is also suppressed in the R++ channel, whereas it is enhanced in the R−− channel. As the scattering length density of Cu and the sum of the nuclear and magnetic scattering length densities for Co are almost equal, the vanishing contrast in the R++ channel reflects the parallel alignment of the Co moments along the applied field. On removal of the external field, the Co moments rotate back, thus increasing again the contrast between Co and Cu in the R++ channel, as indicated by the first order peak. However, in this state the magnetic peak intensity is not furthermore distributed uniformly over all scattering channels, but concentrated to the sf intensity only. Correspondingly, in the direction of the former applied field, there is only weak afm alignment, whereas the domains with magnetic orientation perpendicular to the applied field are reestablished,

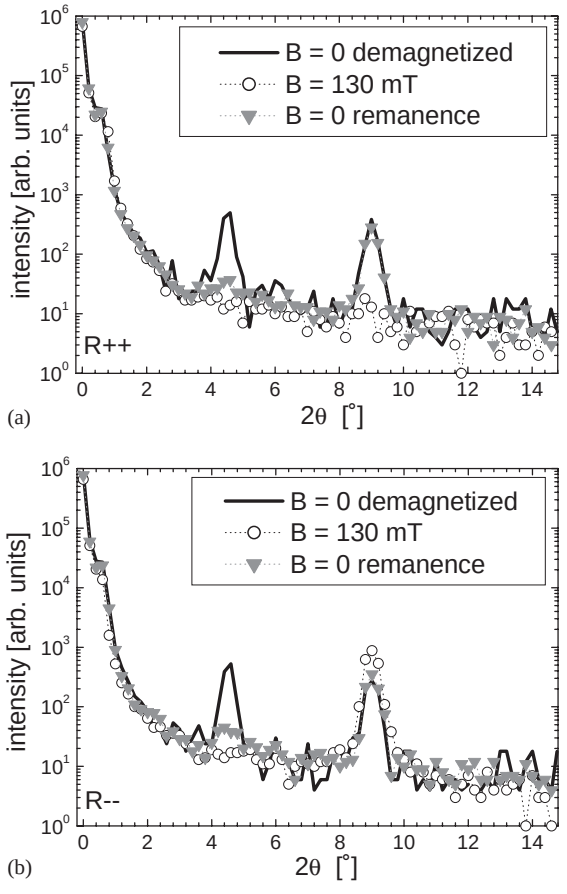

Fig. 2. Reflectometry curve measured with polarized neutrons in the demagnetized sample state, with external magnetic field of 130 mT, and without external field in remanence, in the nsf R++ (a) and R−− (b) channels. Apart from the external magnetic field, a small guide field for the neutrons is applied in all cases not significantly affecting the sample magnetization.

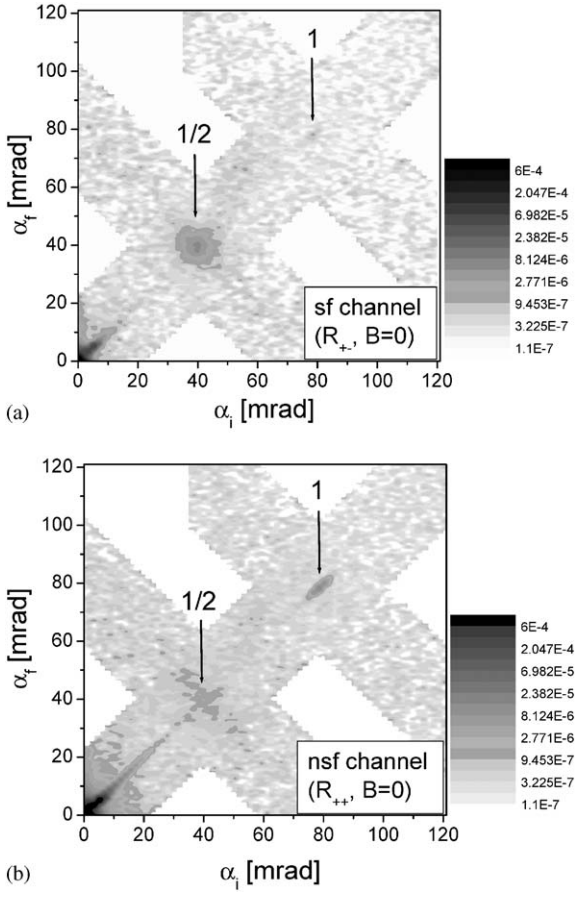

Fig. 3. Specular and diffuse scattering of polarized neutrons in the sf R+− channel (a) and in the nsf R++ channel (b), measured without external field in remanence. The incidence and exit angle of the beam is denoted by α_i and α_f, respectively. The complete transverse scans were measured only through the $\frac{1}{2}$ and 1st order peaks.

as indicated by the sf signal (cf. Fig. 3). This behavior could be related to the presence of both bilinear and biquadratic components for the layer coupling in the sample (cf. [2]).

Fig. 3 shows the intensity distribution in the specular and diffuse scattering without applied magnetic field in remanence. The diffuse scattering was measured in two extended angular ranges transverse to the positions of the two Bragg peaks, the vertical extension of each stripe corresponding to the window-length of the position-sensitive detector.

The sf $\frac{1}{2}$ order peak (Fig. 3a) being as intensive as in the demagnetized state, is strongly broadened in the diffuse scattering compared to the 1st order peak (Fig. 3b), thus giving evidence for magnetic domains with moments aligned perpendicular to the direction of the applied field. In the transverse cross-section, the magnetic peak exhibits a Lorentzian shape, allowing to estimate the domain size from the inverse of the peak half width [9] to an average value of 1.3 μm. A long-range lateral magnetic correlation length of 980 nm was also derived from soft X-ray scattering for the Co/Cu multilayer in the first afm coupling maximum [10].

The traced changes in the magnetic configuration indicate that magnetic fields influence not only the size, but also the preferred orientation of magnetic domains in strongly coupled GMR multilayers. The preferred domain orientation in the remanent state as derived from the polarized neutron-scattering experiments suggests an influence of the magnetic history on the domain structure, which may be related to observed irreversible changes in the magnetoresistance of magnetically stressed GMR systems [11].

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