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Hard and Soft X-Ray Reflectivity Studies of $(NiFe/Au/Co/Au)_{10}$ Magnetic Multilayers

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We report on hard and soft X-ray reflectivity investigations of $(Ni_{80}Fe_{20}$(2.2 nm)/Au(2.3 nm)/Co(0.8 nm)/Au(2.3 nm)$)_{10}$ multilayers. Specular reflectivity curves were measured with Cu K_α radiation and circularly polarized synchrotron radiation tuned to Co L_3 and Ni L_3 absorption edges. Structural properties of the multilayers were determined from the hard X-ray reflectivity curve. Comparison of reflectivity curves taken at different photon energies shows: (i) small difference in peak positions in dependence of reflectivity versus scattering vector q, (ii) different shapes of satellite Bragg peaks, (iii) different ranges of q for appearance of the Kiessig fringes. Analysis of soft X-ray reflectivity curves taken as a function of magnetic field allows to determine magnetic properties of Co and NiFe layer specifically.

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1. Introduction

Magnetic $(NiFe/Au/Co/Au)_{10}$ multilayers (MLs) with noncollinear magnetizations in neighboring magnetic layers in remanence are interesting for electronics applications, for instance as magnetic field sensors [1, 2] and spin-transfer oscillators [3]. We have previously shown that in some range of the magnetic field Co and NiFe layers are strongly magnetostatically coupled [4]. This coupling is related to the appearance of stripe domain structure in the Co layers with perpendicular anisotropy. Stray fields of Co domains influence the magnetic configuration of NiFe layers with in-plane anisotropy. Previously, we investigated magnetization reversal of the MLs by analyzing magnetic hysteresis loops and magnetoresistance curves (taken in different configurations of applied magnetic field). This analysis gives global information on the system. To determine the magnetization reversal of Co and NiFe layers separately, we employed soft X-ray resonant magnetic scattering (SXRMS), which combines the element specificity of magnetic circular dichroism and X-ray resonant scattering.

2. Experimental details

The $(Ni_{80}F_{20}$(2.2 nm)/Au(2.3 nm)/Co(0.8 nm)/Au(2.3 nm)$)_{10}$ ML was deposited onto naturally oxidized Si(100) wafer using UHV magnetron sputtering. Structural properties of the ML were studied using a Seifert XRD 3003 diffractometer with standard Cu K_α radiation (photon energy 8040 eV). Specular reflectivity curves were taken in the Bragg–Brentano ($\theta/2\theta$) geometry. Soft X-ray reflectivity curves were measured with the ALICE diffractometer [5] at the undulator beamline UE56/2-PGM2 at Bessy II (Berlin, Germany) in the same geometry. Circularly polarized radiation was tuned to the absorption edges of Co L_3 (778 eV) or Ni L_3 (853 eV). A magnetic field of up to 2.7 kOe was applied in the scattering plane either parallel or antiparallel to the photon helicity. The energies of soft X-ray radiation were taken near absorption edges to maximize the magnetic circular dichroism. Additionally, the magnetization reversal process (vibrating sample magnetometer) of the ML was measured for the magnetic field applied parallel to the sample plane.

3. Results and discussion

Reflectometric profiles A, B, C taken at different energies of incident radiation are shown in Fig. 1. For easy comparison measured intensities are presented as a function of scattering vector $q = 4\pi\sin(\theta)/\lambda$, λ being the wavelength of the incident X-rays. Generally, both structural Bragg peaks and Kiessig fringes between them are clearly seen in all profiles. These features

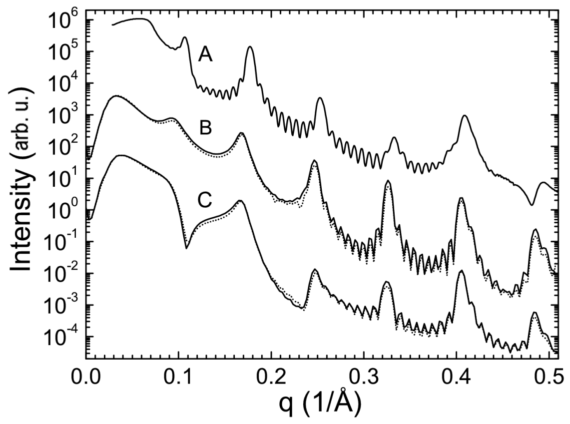

Fig. 1. Reflectivity profiles taken for the ML at different energies of incident radiation: A — at Cu K_α, B — at Co L_3 absorption edge, C — at Ni L_3 absorption edge. For B and C two curves were measured I_+ and I_- with $H = +2.7$ kOe (solid line) and $H = -2.7$ kOe (dotted line), respectively, to reveal magnetic scattering.

which are mainly related to charge (chemical) contrast in the MLs confirm the good quality of the samples. For soft X-ray profiles B and C, an average intensity $(I_+ + I_-)/2$ where I_+ and I_- denote the scattered intensity for magnetic fields +2.7 kOe and −2.7 kOe, respectively, reflects pure charge scattering. On the basis of the hard X-ray profile A, using numerical simulation, we determined averaged structural parameters of the ML: period $\Lambda = 7.6$ nm, thickness of individual sublayers: $t_{\mathrm{Ni}} = 2.2$ nm, $t_{\mathrm{Au}} = 2.3$ nm, $t_{\mathrm{Co}} = 0.8$ nm, and their roughness $\sigma_{\mathrm{Ni}} = 0.3$ nm, $\sigma_{\mathrm{Au}} = 0.45$ nm, $\sigma_{\mathrm{Co}} = 0.4$ nm. Comparison of profiles A, B and C clearly shows that shape and intensity of the Bragg peaks are different. The most pronounced difference is noticed for profiles C as compared to the other, especially for small q. Some shifts of the Bragg peaks position in soft X-ray profiles relative to the positions for hard X-ray are also observed. This is related to strong changes of dispersion corrections $\delta(E)$ at the Co and Ni absorption edges — δ is the period averaged real part of the refractive index $n = 1 - \delta - \mathrm{i}\beta$ [6]. Additionally, the ranges of q where the Kiessig fringes appear, are different for hard (A) and soft (B, C) X-ray reflectivity curves. They are shifted to q larger than about 0.2 Å^{-1} for the latter. Profiles B and C are also disturbed in the small q range. This is due to the strong absorption of the soft X-ray in MLs. For q smaller than about 0.2 Å^{-1}, soft X-rays do not penetrate the whole sample and information is mostly taken from its upper part. It should be also noted that in soft X-ray profiles of individual Co (Ni) layer taken at the absorption edge Co L_3 (Ni L_3), a critical angle is not observed as the refraction index n of Co (Ni) is larger than 1 [7]. Analyzing reflectivity profiles it is easy to notice that the number of the fringes between two neighboring Bragg peaks is equal to 8 for profiles A and B (as expected for 10 repetitions), whereas it equals 7 for profile C. This fact is quite surprising and suggests, in our opinion, a strong structural modification of the first NiFe layer next to the substrate which is most probably connected with its deposition on Si with native oxide.

The magnetic contribution to the reflectivity profiles is usually revealed by plotting the asymmetry ratio $\mathrm{AR} = (I_+ - I_-)/(I_+ + I_-)$. For our ML, AR, determined from profiles B and C are presented in Figs. 2a and b, respectively. It is easy to see that AR varies relatively strongly with q in the ranges where the Kiessig fringes are present. The maximal values of AR are achieved near the Bragg peaks nevertheless they are strongly q dependent. Therefore we decided to perform measurements of $\mathrm{AR}(H)$ dependences at the incidence angle of 8.5° (dashed line in Figs. 2a and b). At this angle both $\mathrm{AR}_{\mathrm{Co}}$ and $\mathrm{AR}_{\mathrm{NiFe}}$ are quite large, have the same sign, and weakly depend on q. The chosen angle of incidence is an optimal one as it allows eliminating geometrical effects.

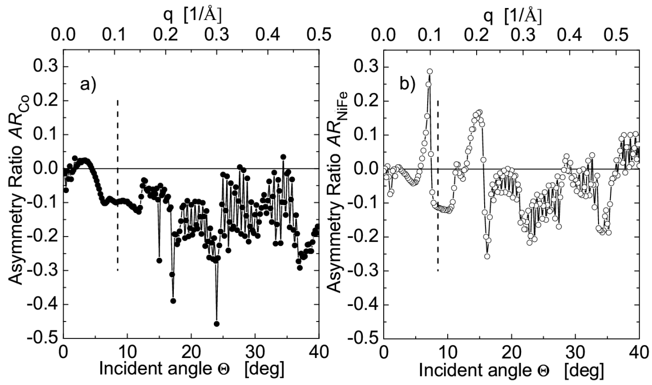

Fig. 2. The asymmetry ratio $\mathrm{AR}_{\mathrm{Co}}$ and $\mathrm{AR}_{\mathrm{NiFe}}$ versus incident angle Θ revealed from profiles I_+ and I_- taken at: (a) Co L_3 and (b) Ni L_3 edges, respectively.

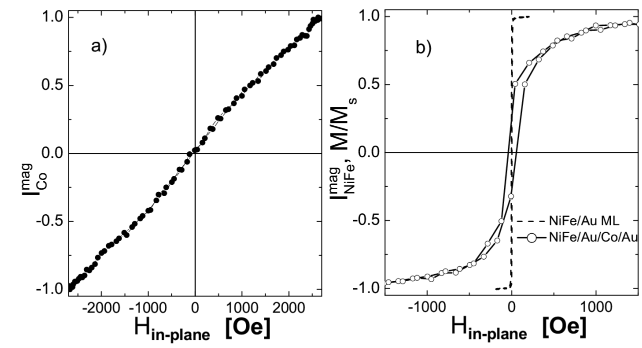

Fig. 3. Normalized magnetic signals I^{mag} as a function of applied magnetic field, determined from curves measured at: (a) Co L_3 edge and (b) Ni L_3 edge.

In our experiment the geometry corresponding to the classical longitudinal magneto-optic Kerr effect (LMOKE) was realized. Namely, the magnetic field was applied in the scattering plane parallel to the sample surface. In this configuration only the changes of the magnetization component parallel to the sample surface and the scattering plane are detected [5]. Normalized intensities $I^{\text{mag}} = [2I(H) - (I_+ - I_-)]/(I_+ - I_-)$, where $I(H)$ denotes the scattered intensity for magnetic field H, are shown in Fig. 3. The field dependence of the normalized intensities taken at different radiation energies can be treated as element specific hysteresis loops. Therefore, as it was shown in [8, 9], one can directly compare an $I^{\text{mag}}(H)$ dependence with a conventional vibrating sample magnetometer (VSM) hysteresis loop. This comparison clearly shows that, as expected, the NiFe and Co layers have in-plane and out-of-plane anisotropies, respectively. Ultrathin Co layer with thickness of 0.8 nm sandwiched between Au (Au/Co/Au system) have strong perpendicular anisotropy and hence easy axis perpendicular to the surface. Almost linear dependence of $I^{\text{mag}}_{\text{Co}}$ (Fig. 3a) agrees with the above assertion. The available maximal field of 2.7 kOe is not sufficient to saturate the Co layer (when applied parallel to layer surface). On the other hand, NiFe layer have in-plane anisotropy and should be saturated in a small field. VSM measurements performed for structurally very similar [NiFe (2 nm)/ Au (5 nm)]$_{10}$ MLs demonstrate that they are saturated in a field of about 150 Oe (Fig. 3b). We would observe analogous situation in our MLs if there were not the magnetostatic coupling between NiFe and Co layers. However, the $I^{\text{mag}}_{\text{NiFe}}$ dependence (Fig. 3b) proves that NiFe layers are not saturated in a field up to about 1.2 kOe, suggesting some additional out of plane anisotropy. This may serve as a direct evidence that, due to magnetostatic interaction resulting from stripe domain in the Co layers, a noncollinear magnetization configuration is induced in NiFe layers. Other magnetic couplings, like orange peel or oscillatory exchange coupling, are negligible in the studied MLs [4].

4. Conclusions

The structural and magnetic properties of $(\text{Ni}_{80}\text{F}_{20}$(2.2 nm)/Au(2.3 nm)/Co(0.8 nm)/Au(2.3 nm)$)_{10}$ multilayers were investigated using hard and soft X-ray reflectivity. The structural characterization was performed with hard X-ray which gives more precise information due to shorter wavelength of the radiation. It was shown that soft X-ray reflectivity profiles, taken in specular geometry, allow choosing the optimal incident angle of the X-ray beam for revealing magnetic signal (hysteresis). This allows direct, reliable measurements of magnetic reversal of Co and NiFe layers, separately. However, it should be noted that the present magnetic hysteresis measurements performed at the optimal angle (8.5°) reveal mainly information from the upper and probably the central part of sample due to the limited penetration depth in the direction perpendicular to the sample surface at small glancing angles. To obtain information from layers near the substrate, measurements at larger angle of incidence are needed.

Acknowledgments

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