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Domains Stimulated Magnetostatic Coupling in NiFe/Au/Co/Au Multilayers Investigated by Complementary Methods

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The magnetic structure of $Ni_{80}Fe_{20}$/Au/Co/Au multilayers characterized by easy-plane and easy-axis perpendicular to the sample plane anisotropies for NiFe and Co, respectively, is strongly modified by magnetostatic coupling resulting from stray fields of stripe domains in the Co layers. Using complementary methods it will be shown that the magnetostatic coupling increases with decreasing Au spacer thickness, with the weakening of the easy plane anisotropy of the NiFe layers and with increasing thickness of the Co layers.

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1. Introduction

$(\mathrm{NiFe/Au/Co/Au})_N$ (N — repetition number) multilayers (MLs) represent a new class of magnetic layered films which are characterized by easy-plane (NiFe = $Ni_{80}Fe_{20}$) and out-of-plane (Co) anisotropy of successive ferromagnetic layers. As we have demonstrated in our previous papers [1–3] such films are promising candidates for applications in spintronics and information technology. One of the particularly important parameters of magnetic MLs is the coupling between the different ferromagnetic layers. The origin of the coupling can be different: (i) direct coupling through pinholes, (ii) Ruderman–Kittel–Kasuya–Yosida-like (RKKY-like) exchange coupling, (iii) magnetostatic coupling caused by interface roughness, (iv) magnetostatic coupling through domain stray fields. In contrast to most of the other investigated MLs with in-plane anisotropy, in MLs with perpendicular anisotropy [4, 5] and in our samples [1, 6, 7] the last type of interaction plays a crucial role. This is caused by strong stray fields originating from dense stripe domains. In this contribution the influence of the sample parameters like film thicknesses on the magnetostatic coupling, studied with different complementary methods, will be discussed.

2. Experimental

The samples were deposited on naturally oxidized Si(100) wafers using UHV magnetron sputtering [1]. The magnetic properties were characterized at room temperature by measurements of hysteresis loops (with vibrating sample magnetometer, VSM) and magnetoresistance (current in-plane geometry) in a magnetic field applied in-plane ($H_{\parallel}$) and perpendicular ($H_{\perp}$) to the sample plane. The element specific measurements of hysteresis loops for $|H| \leq 2.7$ kOe were performed using soft X-ray resonant magnetic scattering (SXRMS) at BESSY II. For the geometry used in our SXRMS experiment, only the changes of the magnetization component parallel to the sample surface and the scattering plane are detected (longitudinal magneto-optical Kerr effect configuration) [7, 8]. For details related to the Mössbauer measurements see Ref. [6].

3. Results and discussion

First the modifications of the magnetic properties with changing t_{Au} will be discussed. To separate the coupling caused by the domains stray fields from other couplings we briefly mention results concerning a sandwich film of Au/NiFe/Au/Co/Au with only one repetition ($N = 1$) [1]. For such films the rectangular hysteresis loop for the magnetization reversal of Co layer in $H_{\perp}$ has been observed reflecting large-areal domain pattern formation. Therefore, the influence of domains stimulated interaction can be neglected for such types of samples [4]. Results obtained for a NiFe/Au-wedge/Co/Au sandwich sample can be summarized as follows: (i) for

$t_{\mathrm{Au}} \le 0.6$ nm NiFe and Co layers are strongly ferromagnetically coupled and show in-plane anisotropy, (ii) for $0.6 \le t_{\mathrm{Au}} \le 1$ nm the magnetization reversal of Co and NiFe layers can be separated, however, the strong increase in H_{C} with t_{Au} suggest a distinct decrease in ferromagnetic coupling (pinholes and/or orange peel coupling), (iii) for $t_{\mathrm{Au}} \ge 1$ nm the changes in magnetic properties of the sample are very small indicating a negligible role of the RKKY-like coupling [1]. Due to the existence of stripe domain structure (with a period in the submicrometer range) in (NiFe/Au/Co/Au)$_N$ MLs ($N > 3$) the dipolar coupling is created [1, 6, 7]. Consequently, the description of the magnetic structure is quite complicated. Nevertheless, magnetoresistance characteristics give more insight into magnetization configuration. In particular, from $R(H)$ dependences we can determine the following parameters: (i) the saturation fields of NiFe, $H_{\mathrm{S}}^{\mathrm{NiFe}}$ and Co, $H_{\mathrm{S}}^{\mathrm{Co}}$ layers reversed along the hard axis (i.e., in $H_\perp$ and $H_\parallel$ for NiFe and Co, respectively), (ii) the fields of nucleation (H_{N}) and annihilation (H_{A}) of domains, (iii) the effective angle between magnetization of NiFe (M^{NiFe}) and Co (M^{Co}) layers, $\Theta = \arccos\{[R_{90} - R(H)]/(R_{90} - R_0)\}$ (R_{90} and R_0 are the resistances corresponding to $\Theta = 90°$ and $\Theta = 0°$, respectively), (iv) the effective magnetic stray field H_Z created by domains and acting on NiFe layers at remanence. It should be noted that such parameters as: $H_{\mathrm{S}}^{\mathrm{NiFe}}$, $H_{\mathrm{S}}^{\mathrm{Co}}$, H_{N} and H_{A} can be determined both from $M(H)$ and $R(H)$ dependences. Similarly as for the sandwich sample discussed before, three ranges of t_{Au} can be distinguished for the investigated (NiFe-2 nm/Au-t_{Au}/Co-0.6 nm/Au-t_{Au})$_{15}$ MLs. The main characteristics of $R(H)$ and $M(H)$ curves (Fig. 1a, c) are preserved for all MLs with $t_{\mathrm{Au}} \ge 1.25$ nm. The linear $R(H_\perp)$ dependence for H_{N}, $H_{\mathrm{A}} \le |H_\perp| \le H_{\mathrm{S}}^{\mathrm{NiFe}}$ is related to coherent rotation of M^{NiFe} (M^{Co} is aligned along the field direction) and indicates a negligible interaction between NiFe and Co layers. However, for $|H_\perp| \le H_{\mathrm{N}}$, H_{A}, the resistance is reduced due to the modification of M^{NiFe} distribution caused by stray fields originating from stripe domains in the Co layers. The changes of parameters characterizing the dipolar coupling indicate that both the range of the field in which this coupling exists and the strengths of the interactions decrease with t_{Au} (Fig. 1e). It should be emphasized that without dipolar coupling $\Theta_{\mathrm{REM}} = \Theta$ at $H = 0$ should be 90°. The field corresponding to the creation of domains is not well defined in the magnetization reversal with $H_\parallel$. The transition from a weak to a strong coupling for decreasing $H_\parallel$ is stretched over a broad field range as a consequence of the continuous rotation of M^{Co} in the domains. For thinner spacer ($0.75 \le t_{\mathrm{Au}} \le 1$ nm), in contrast to the above discussed t_{Au} range, the coupling caused by domains is enhanced by coupling caused by pinholes and/or interface roughness. Moreover, the $H_\perp$ range corresponding to rotation of M^{NiFe} (H_{N}, $H_{\mathrm{A}} \le H_\perp \le H_{\mathrm{S}}^{\mathrm{NiFe}}$) is reduced due to a strong increase in H_{N}. As a consequence, the magnetization reversal of NiFe and Co layers in $H_\perp$ takes place simultaneously and is characteristic of the layers with perpendicular anisotropy and stripe domain structure (Fig. 1d). The residual magnetoresistance effect (Fig. 1b) is reduced to two small components, the first (observed for $|H_\perp| \le H_{\mathrm{N}}$, H_{A}) is related to scattering at superparamagnetic precipitations (this component is similar for all samples) and the second characteristic of MLs in which stripe domains are replicated in all ferromagnetic layers. For such a configuration a part of electrons traversing the structure in the vicinity of domain walls interacts with antiparallel oriented domains. The magnetoresistance effect for $H_\parallel$ indicates small changes in the mutual magnetization configurations of the NiFe and Co layers. This is caused by successive increase in domain stray fields for decreasing $|H_\parallel|$. For $t_{\mathrm{Au}} \le 0.5$ nm, similarly as for the sandwich sample, magnetic measurements indicate a lack of perpendicular anisotropy in Co layers and strong ferromagnetic coupling between NiFe and Co layers. Most probably this is a consequence of a non-continuous structure of the Au spacer layer.

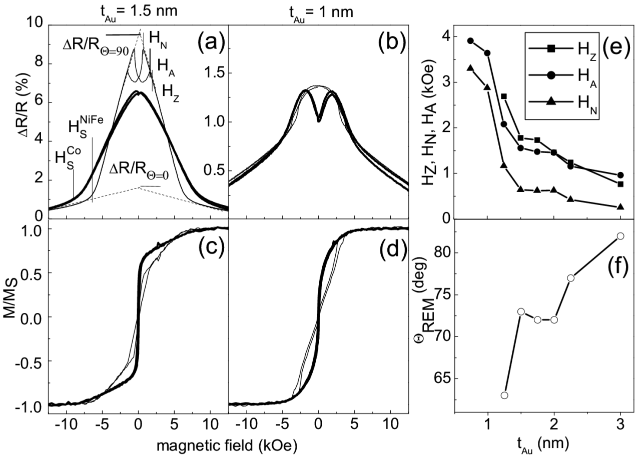

Fig. 1. Normalized resistance (a, b) ($\Delta R/R = [R(H) - R(20\ \mathrm{kOe})]/R(20\ \mathrm{kOe})$) and magnetization (c, d) ($M/M_{\mathrm{S}} = M(H)/M(H = 20\ \mathrm{kOe})$) of (NiFe-2 nm/Au-$t_{\mathrm{Au}}$/Co-0.6 nm/Au-$t_{\mathrm{Au}}$)$_{15}$ multilayers ($t_{\mathrm{Au}} = 1.5$ nm and 1 nm for parts (a, c) and (b, d), respectively) measured in a magnetic field applied perpendicular (thin line) or parallel to the sample plane (thick line). Spacer layer thickness dependence of parameters characterizing the coupling created by domains (e, f) (the description of parameters is given in the main text).

The coupling resulting from the stripe domains depends not only on the spacer thickness but also on the properties of the ferromagnetic layers. In (NiFe/Au/Co/Au)$_N$ MLs particularly important is the thickness of Co layers (t_{Co}) and the easy-plane anisotropy of NiFe layers. Dipolar interactions between Co and NiFe layers in (NiFe-2 nm/Au-2.4 nm/Co-t_{Co}/Au-2.4 nm)$_{10}$ are described in our previous papers [6, 7]. The results of magnetization reversal and magnetoresistance measurements are supplemented by element specific measurements. In particular, Mössbauer spectroscopy was used to deter-

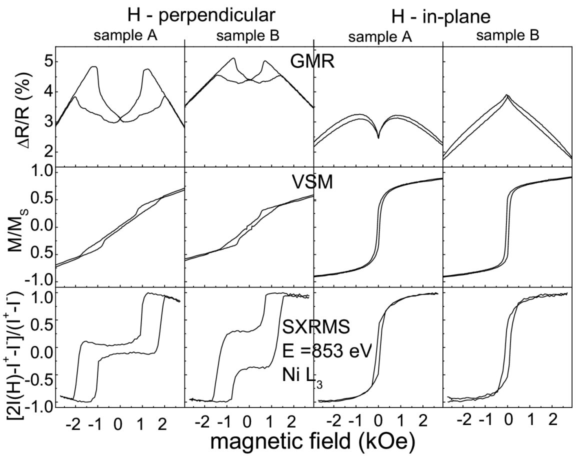

Fig. 2. Central part of field dependences of: magnetoresistance ($\Delta R/R$), normalized magnetic moment measured with VSM, and normalized scattered intensity ($[2I(H)-I^{+}-I^{-}]/(I^{+}-I^{-})), I(H), I^{+}, I^{-}$ denote the scattered intensity for magnetic field H, $+2.7$ kOe, and -2.7 kOe) for $E = 853$ eV (Ni L_3) and angle between the sample plane and incident X-ray 8.5 deg.

mine the remanent inclination of M^{NiFe} from the in-plane configuration [6] and SXRMS technique to define the magnetization reversal of permalloy layers [7]. The results concerning two samples: (A) (Co-0.6 nm/NiFe-2.6 nm/Au-2.4 nm/Co-0.8 nm/Au-2.4 nm)$_{10}$ and (B) (NiFe-2.6 nm/Co-0.6 nm/Au-2.4 nm/Co-0.8 nm/Au-2.4 nm)$_{10}$ deposited on Si substrates covered by NiFe-3.2 nm/Au-2.4 nm/Co-0.8 nm/Au-2.4 nm buffer layer are presented in Fig. 2. The difference between the samples is only related to the structure of the ferromagnetic layers with in-plane anisotropy. As we have demonstrated previously [9], the introduction of thin Co layers at NiFe/Au and/or Au/NiFe interfaces reduces the easy-plane anisotropy field ($H_{\mathrm{S}}^{\mathrm{NiFe}}$). This effect is stronger for Co layers located at the bottom interfaces of the permalloy layers [9]. For samples (A) and (B) the $H_{\mathrm{S}}^{\mathrm{NiFe}}$ are 5 and 7 kOe, respectively. Due to the difference in $H_{\mathrm{S}}^{\mathrm{NiFe}}$ the influence of stray fields caused by domains is stronger for sample (A) with weaker anisotropy (Fig. 2). In particular, this is manifested by the following features: (i) larger $H_{\perp}$ range corresponding to the existence of domains, (ii) stronger reduction of resistance, related to modification of Θ (Θ_{REM} are 56 and 75 deg for samples (A) and (B), respectively), (iii) stronger influence on the magnetization reversal of NiFe layers recorded by SXRMS measurements with energy of X-ray adjusted to the absorption edge of Ni L_3 (853 eV). The coupling effects listed above are visible both for $H_{\perp}$ and $H_{\|}$. However, as was discussed before, for samples with different t_{Au}, the transition from a weak to a strong ferromagnetic coupling is abrupt for $H_{\perp}$ and stretches over a broad field range for $H_{\|}$. Finally, it should be noted that remanent inclination of M^{NiFe} from in-plane position determined by the Mössbauer measurements is roughly equal to $90 - \Theta$. This indicates that M^{Co} is oriented along the surface normal [6].

4. Conclusion

Domain stimulated magnetostatic coupling in NiFe/Au/Co/Au multilayers increases with decreasing spacer thickness, increasing Co thickness and weakening of easy plane anisotropy of NiFe layers. The specific changes in the magnetic structure caused by the coupling has been suggested based on magnetometry and magnetoresistance investigations and has been confirmed by element specific measurements (Mössbauer spectroscopy and SXRMS).

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