Interfacial Magnetization in Exchange-Coupled Fe/Cr/Fe Structures

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Magnetic interlayer coupling is a crucial ingredient in building complex magnetic structures. Depending on the coupling strength, the magnetic properties of the participating layers, and the applied magnetic field, a wide variety of magnetic configurations may arise. We addressed this issue by means of magnetic optical second harmonic generation (MSHG) in the model system Fe/Cr/Fe. We clearly observe the field-induced transformations of the magnetic state at the interfaces in the trilayer in the SHG signal. The strong variations of the SHG signal with light polarization, experimental geometry (longitudinal or transversal), and in-plane orientation of the magnetic field H can be understood on the basis of a model accounting for nonmagnetic and magnetic contributions to SHG from the interfaces, as well as for changes of the interfacial magnetization orientation.

The interaction between the magnetizations $\mathbf{M_1}$ and $\mathbf{M_2}$ in magnetic films separated by a thin paramagnetic or diamagnetic metallic layer is characterized by the presence of bilinear ($E_{bl} = -J_1\hat{\mathbf{M}}_\mathbf{1}\hat{\mathbf{M}}_\mathbf{2}$, where $\hat{\mathbf{M}}_\mathbf{i}$ is a unit vector along the magnetization direction of layer i) or biquadratic ($E_{bq} = -J_2(\hat{\mathbf{M}}_\mathbf{1}\hat{\mathbf{M}}_\mathbf{2})^2$) interlayer exchange coupling [1]. Depending on the interlayer thickness bilinear coupling might lead to ferromagnetic ($\mathbf{M_1} \uparrow\uparrow \mathbf{M_2}, J_1 > 0$) or antiferromagnetic ($\mathbf{M_1} \uparrow\downarrow \mathbf{M_2}, J_1 < 0$) magnetzation orientations. The biquadratic exchange coupling stimulates an orthogonal orientation of the magnetizations ($\mathbf{M_1} \perp \mathbf{M_2}, J_2 < 0$). To date the magnetic properties of such coupled structures have been mainly addressed by such methods as ferromagnetic resonance, Brillouin light scattering, magnetoresistance, and magnetooptical Kerr effect [1]. All of these methods reflect the behavior of the volume-averaged magnetization $\mathbf{M_1}$ and $\mathbf{M_2}$ in the coupled layers. At the same time the interfacial magnetizations play important role in bilinear and biquadratic coupling formation. Therefore, investigations of the interfacial magnetization by specific interface-sensitive techniques are of particular interest.

For this purpose, we studied the interfacial magnetization in exchange coupled heterostructures Fe/Cr/Fe by magnetic-field-induced second harmonic generation (MSHG). The method is proved to be a highly sensitive tool to probe surface and interfacial magnetic properties of thin films and multilayers [2]. Epitaxial heterostructures Fe(50 Å)/Cr(10 Å)/Fe(100 Å)/Ag(1500 Å)/Fe(10 Å)/GaAs(100) grown by MBE served as model systems. To prevent the structure from the oxidation it was covered by a 20 Å Cr cap layer. The thickness (d=10 Å) of the Cr spacer layer corresponds to the first antiferromagnetic maximum of the $J_1(d)$ dependence [3]. Thus, in the absence of a magnetic field the system assumes a ferrimagnetic structure ($\mathbf{M_1} \uparrow\downarrow \mathbf{M_2}, \mathbf{M_1} > \mathbf{M_2}$). The structure displays biaxial in-plane magnetic anisotropy, with the easy and hard axes in the Fe layers pointing along [100] and [110]-type directions, correspondingly. The second harmonic generation was excited by short (~ 200 fs) light pulses from a Ti:Sapphire laser at $E_{ph} = 1.55$ eV. The measurements have been performed in reflection at the incidence angle of 5°. The magnetic field variations of SHG have been studied at room temperature in pp, ss, ps, and sp combinations of the light polarizations with magnetic field applied along the easy or hard axis in longitudinal (magnetic field is applied parallel to light incident plane) or transversal (magnetic field is applied perpendicular to light incident plane) geometries. The linear magneto-optical Kerr effect (MOKE) has also been measured in longitudinal geometry at light incidence angle of $35°$.

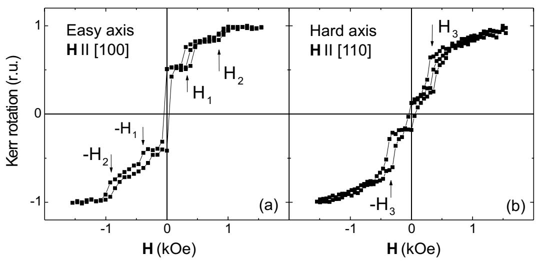

FIG. 1: Field variations of the normalized longitudinal magneto-optical Kerr effect measured in a Fe/Cr/Fe structure with the magnetic field along easy (a) and hard (b) axes.

In Fig. 1(a,b) and Fig. 2(a-d) field dependencies of the MOKE and MSHG are presented. The MOKE curves are odd functions in $\mathbf{M}$. The jump-like features appearing at certain values of the applied field ($\pm H_1, \pm H_2$ and $\pm H_3$) may be associated with magnetic switching events involving different mutual orientations of the layer magnetizations shown in Fig. 3(a,b). For example, when $\mathbf{H}$ is applied along the easy axis (comp. Fig. 1(a) and Fig. 3(a)) at $H \approx 0$ the inversion of the magnetization directions in the layers takes place, while at H_1 and H_2 the transitions into the orthogonal ($\mathbf{M_1} \perp \mathbf{M_2}$) and saturated states ($\mathbf{M_1}\|\mathbf{M_2}\|\mathbf{H}$) take place.

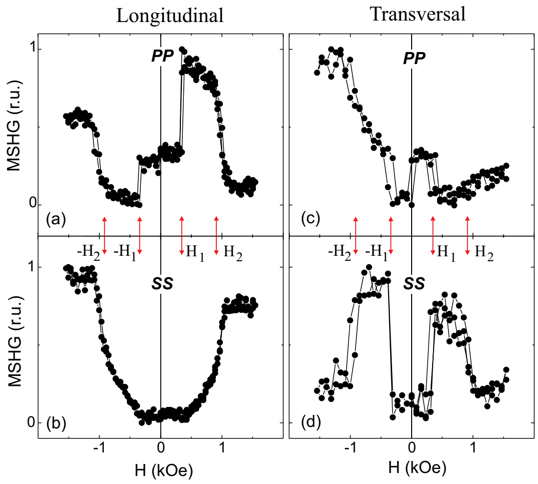

FIG. 2: Field variations of the normalized MSHG signal measured on a Fe/Cr/Fe structure at magnetic field along the easy axis in longitudinal (a,b) and transversal geometries (c,d) for different combinations of light polarizations, as indicated.

The field-induced variations of MSHG signal Fig. 2(a-d) principally differ from those in MOKE. In particular, in longitudinal pp (a) and ss (b), as well as in transversal ss (d) combinations of the polarizations the jump near $H = 0$ is absent. In the ss configurations the MSHG signals are even functions of the magnetic field, while in the pp configurations they have no defined parity. The difference in the field variations of MOKE and MSHG is due to the fact that MOKE probes mainly the bulk response, whereas MSHG originates from the interfacial magnetizations.
The linear on $\mathbf{M}$ contribution to SHG arises from an interference of light waves at frequency 2ω caused by magnetic field-dependent and independent components in the nonlinear optical susceptibility tensor χ [4]. To describe the MSHG response we employed the effective susceptibility model accounting for the surface and the Cr/Fe(1), Fe(1)/Cr and Cr/Fe(2) interfaces as possible sources of SHG. The validity of the model is based on the assumption that all interfaces have the same C_{4v} point symmetry, rendering the structure of χ the same for different interfaces. The model assumes the field-induced changes of the magnetic states at the interfaces to take place analogously to that in the bulk of the films (see Fig. 3) and the magnetic properties of the interfaces formed by the first and second iron layers to be identical. The intensity of the SHG signal accounting for a mutual orientation of interfacial magnetizations can be written:

$$I^{2\omega}_{\alpha\beta} = A|r^1_{\alpha\beta\gamma}m_{1\gamma} + r^2_{\alpha\beta\gamma}m_{2\gamma} + r_{\alpha\beta}|^2, \qquad (1)$$

where A is a parameter depending on the intensity of the fundamental light, $\mathbf{m_1}$ and $\mathbf{m_2}$ are interfacial magnetizations of the first and second iron layer, α and β are indices meaning s or p depending on the light polarization, and $\gamma = x, y, z$. The coefficients $r_{\alpha\beta}$, $r^1_{\alpha\beta\gamma}$ and $r^2_{\alpha\beta\gamma}$ are effective nonlinear susceptibilities.

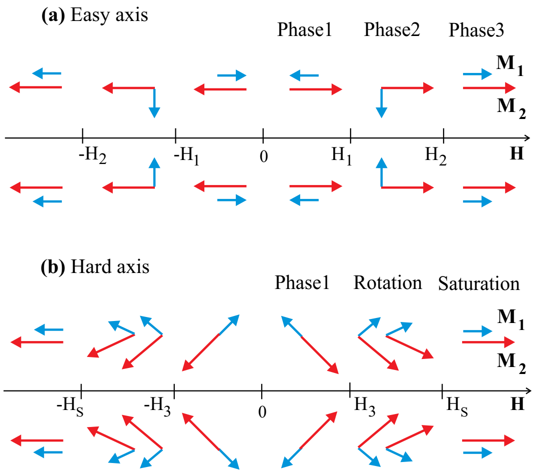

FIG. 3: Magnetic configurations arising during magnetization reversal with the field applied along easy (a) and hard (b) axis, respectively. The energetically equivalent states are shown above and below field axis.

Such an approach describes the salient features of the MSHG experiment. The comparison of the experimental and modelled field variations shows that using different combinations of input and output light polarizations and directions of the magnetic field (longitudinal or transversal) gives a possibility to independently investigate the magnetization components of $\mathbf{m_1}$ and $\mathbf{m_2}$ at the interfaces. We also find that the magnetization rotation processes appear much more pronounced in MSHG than in MOKE, and MSHG is able to clearly resolve magnetic switching events in the trilayer, which are not seen by linear Kerr effect [5].

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