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Laser-induced magnetization dynamics in Co/IrMn exchange coupled bilayers

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The response of a ferromagnet/antiferromagnet exchange coupled bilayer to femtosecond laser heating is studied by means of pump-probe time-resolved magneto-optical Kerr effect (TR-MOKE) in the polar geometry on a Co (10 nm)/IrMn (0–15 nm wedge) sample. When an external field is applied in the film plane, perpendicular to the exchange bias direction, a damped precessional motion of the ferromagnetic spins can be triggered by laser excitation. We observe that the exchange bias field $H_{EB,dyn}$, extracted from the TR data, systematically differs from the value $H_{EB,st}$, obtained by static MOKE loop measurements, for thin (<7 nm) IrMn. © *2008 American Institute of Physics.*
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The exchange interaction between a ferromagnetic and an antiferromagnetic thin film deposited on top of each other leads to a unidirectional anisotropy in the ferromagnet, called exchange bias (EB). As a consequence the hysteresis loop of such bilayers is shifted along the field axis by a quantity H_{EB}, the exchange bias field.[1] The phenomenon received a renewed attention in the past decade due to its importance in the development of devices based on magnetoresistive elements. Despite the remarkable amount of studies devoted to the subject, a unified microscopic picture of the effect has not emerged yet.[2]

In order to shed new light on the subject it is important to develop innovative tools of investigation. One of the most outstanding approaches that have been proposed is to bring the coupled bilayer out of equilibrium and study its relaxation. Toward this direction, in this paper we study the nonequilibrium dynamics of exchange interaction in a ferromagnet/antiferromagnet (FM/AFM) Co (10 nm)/IrMn (0–15 nm wedge) exchange coupled bilayer by means of pump-probe time-resolved magneto-optical Kerr effect (TR-MOKE).

In recent years, similar studies have been performed on different materials.[3–5] In their pioneering experiments Ju *et al.*[3] have shown that laser excitation can induce subpicosecond changes in the hysteresis loop of a NiFe/NiO bilayer, and in some cases, depending on the exact geometry of the experiment, trigger a precession of the FM spins. The authors suggested that laser heating induces an instantaneous decrease of the exchange interaction, followed by an exponential recovery. Simulations based on the Landau-Lifshitz-Gilbert (LLG) equation assuming such a temporal profile showed a qualitative agreement with the experimental precessional transients, indicating that the recovery takes place on the time scale of ~100 ps. Similar results were reported later on by Weber *et al.*[4] on NiFe/FeMn bilayers. The authors studied the quenching and recovering of exchange interaction by measuring the evolution of H_{EB}, the shift of the hysteresis loop, as a function of time after laser excitation. Although their results seem to confirm the temporal profile proposed by Ju *et al.*, doubts have been risen whether extracting the dynamics from the loop shift is a valid approach when the bilayer is brought out of equilibrium.

In this work we aim at gaining new insight in the out of equilibrium dynamics of exchange interaction by analyzing the frequency and amplitude of the precessional transients as a function of applied field and AFM thickness d_{AFM}.

The pump-probe TR experiments are carried out using ~100 fs pulses from a Ti:sapphire oscillator, with a pump fluence of ~2 mJ/cm² and a pump-probe power ratio of 20:1. The pulses hit the sample at almost perpendicular incidence and the purely polar MOKE signal is detected. The sample under investigation is a (polycrystalline) bilayer of ferromagnetic Co (10 nm) and antiferromagnetic IrMn (0–15 nm wedge), sputtered on top of Cu (10 nm) and capped with Ta (3 nm) to prevent oxidation; a Ta (5 nm) buffer layer optimizes the growth of the stack on the silicon substrate. A schematic representation of the wedge is shown in Fig. 1 (inset). The geometry of the TR experiments is depicted in Fig. 2 (inset). The sample lies in the *x-y* plane, the EB field acts along the positive *x* direction, and the external field H_{ext} is applied along the *y* axis. The equilibrium direction for the FM magnetization (indicated by point 1 in the figure) is determined by the vectorial sum of H_{EB} and H_{ext}. When H_{EB} is partially quenched by laser heating (block arrow along the negative *x* direction) the equilibrium position moves to point 2, forming an angle ϕ with the original equilibrium, a torque acts on the magnetization, and the precession is triggered. Notice that, since the initial displacement of H_{eff} is always in the *x-y* plane, the initial torque always pulls the magnetization along the *z* direction (vertical block arrow), thereby a *purely* polar signal is expected at the beginning of the precession.

The static magnetic properties of the sample are derived by measuring hysteresis MOKE loops throughout the wedge.

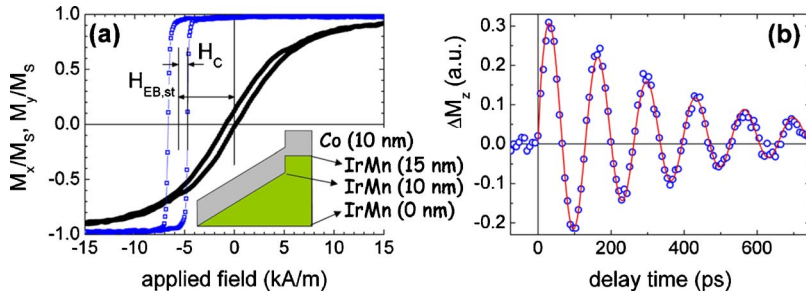a)Electronic mail: f.dalla.longa@tue.nl.

FIG. 1. (Color online) (a) Hysteresis easy axis (M_x, open squares) and hard axis (M_y, full circles) loops measured by static MOKE, and calculation of $H_{EB,st}$ and H_C. (b) Oscillations of the polar TR-MOKE signal for $d_{AFM}=15$ nm and $H_{ext}\sim 30$ kA/m, indicating a magnetization precession; the data (open circles) can be fitted with a damped sine. Inset: Sketch of the Co layer sputtered on top of the IrMn wedge.

In Fig. 1(a) a typical loop measured at $d_{AFM}=15$ nm is shown: The loop is shifted along the field axis by a quantity $H_{EB,st}=5.6$ kA/m, revealing the presence of exchange bias. By performing TR measurements throughout the wedge for different applied fields, the dynamic properties of the samples are derived. In Fig. 1(b) a typical precessional transient is shown for $d_{AFM}=15$ nm and $H_{ext}\sim 30$ kA/m. The data can be fitted with a damped sine function, as described in Ref. 5; the precessional amplitude, frequency, and damping can be extracted from the fit.

In Fig. 2(a) the precessional frequency is plotted as a function of the applied field for $d_{AFM}=15$ nm. The data can be fitted with the Kittel equation[6] $2\pi f=\gamma\mu_0\sqrt{H_{eff}(H_{eff}+M_S)}$, where γ is the gyromagnetic ratio, μ_0 the Bohr magneton ($\gamma\mu_0=0.23$ GHz(kA/m)$^{-1}$), and the effective field H_{eff} is given by the vectorial sum of the exchange bias field and the applied field. From the fit, the value of the exchange bias field, $H_{EB,dyn}$, can be extracted.

The precessional amplitude displays an interesting behavior as a function of the applied field: it grows monotonically from zero reaching a maximum for $H_{ext}\gtrsim H_{EB,st}$ and then it decays, as shown in Fig. 2(b) for $d_{AFM}=15$ nm. It is easy to qualitatively understand this behavior: For $H_{ext}=0$, $H_{eff}=H_{EB,st}$ and thereby a quenching of the exchange bias only affects the magnitude of the effective field leaving its direction unchanged; therefore no torque acts on the magnetization vector and no precession is expected. For $H_{ext}=\infty$ the magnetization is fully aligned with the external field and, again, quenching of EB will not give rise to any precession. In between, a precession is always observed and thereby the amplitude must go through a maximum. A simple model can be developed to get a deeper understanding of these data. Approximating the temporal profile of EB quenching with a step function (i.e., instantaneous decrease and infinitely long recovery), the precessional amplitude normalized by the length of the magnetization vector is given by the sine of the initial displacement angle ϕ multiplied by the ellipticity of the precession ϵ:

$$A = \epsilon M_S \sin(\phi) \approx \frac{m M_S H_{ext} H_{EB}}{(H_{ext}^2 + H_{EB}^2)\sqrt{1+\frac{M_S}{\sqrt{H_{ext}^2+H_{EB}^2}}}}, \quad (1)$$

where $\epsilon=(\sqrt{1+M_S/H_{eff}})^{-1}$ is found by solving the LLG equation in the case of small oscillations, and we introduced the parameter m to quantify the initial EB quenching: $H_{EB}[t=0]=(1-m)H_{EB}[t<0]$. The last part of Eq. (1) is a linearization in the case $m\ll 1$, which is expected to hold for the fluence used in our experiments. Despite the crude ap-

proximations, Eq. (1) can fit the amplitude versus field data quite well. The fit yields a third estimate of the exchange bias field, $H_{EB,A}$. We remark that the fact that the oversimplified model of Eq. (1) can fit the amplitude versus field data is an indication that the approximations used are not too far from reality. Therefore our results are compatible with the temporal profile $H_{EB}[t]$ originally proposed by Ju *et al.*[3] (almost) instantaneous decrease and slower recovery.

Let us now discuss how the static and dynamics properties vary as a function of AFM thickness. As shown in Fig. 3 $H_{EB,st}$ starts to deviate from zero at $d_{AFM}\sim 2$ nm; after a small negative dip, it rapidly grows reaching a maximum at $d_{AFM}\sim 5.5$ nm, and then it slowly decreases as the AFM becomes thicker. The appearance of a loop shift is accompanied by an increase of the coercivity H_C; the latter reaches its maximum at $d_{AFM}\sim 3$ nm and then monotonically decreases. While a thorough discussion of the details of the d_{AFM} dependence of $H_{EB,st}$ is beyond the scope of this article, it is worthwhile to notice that similar results for polycrystalline layers have been reported in the past.[2,7–9]

By measuring the precessional frequency as a function of applied field throughout the AFM wedge, the AFM thickness dependence of $H_{EB,dyn}$ can be traced. While the values of $H_{EB,dyn}$ are in good agreement with the corresponding val-

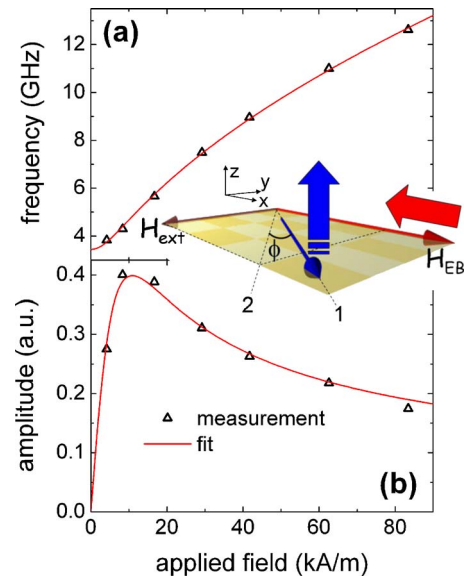FIG. 2. (Color online) Precessional frequency (a) and amplitude (b) vs applied field H_{ext} for $d_{AFM}=15$ nm. The open triangles are the experimental data obtained by fitting the precessional transients [such as the one in Fig. 1(b)] for different applied fields; the solid lines are fits according to the Kittel equation (a) and Eq. (1) (b). Inset: Sketch of the experiment geometry, as described in the text.
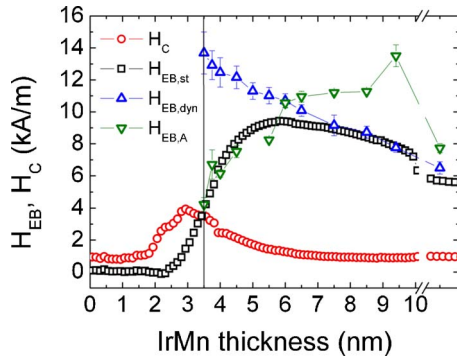
FIG. 3. (Color online) IrMn thickness dependence of the coercivity H_C and the various estimates of H_{EB} described in the text.

ues $H_{EB,st}$ for $d_{AFM} > 7$ nm, a strong deviation is observed as the AFM gets thinner, as shown in Fig. 3. The difference can be explained as follows: The (small angle) precessional frequency, and thereby the fitting parameter $H_{EB,dyn}$, is determined solely by the local value of the FM/AFM exchange coupling J_E. The hysteresis loop shift $H_{EB,st}$ is determined by the energy barrier that one needs to overcome in order to reverse the FM spins; the latter depends not only on the interfacial exchange coupling but also on the effective AFM anisotropy $K_{AFM}d_{AFM}$, which diminishes with decreasing thickness (notice that K_{AFM} itself is thickness dependent). For "thin" AFM, $J_E > K_{AFM}d_{AFM}$ and thus the interfacial AFM spins will reverse with the FM spins, resulting in a smaller $H_{EB,st}$. This result shows that in a fast dynamic experiment the (equilibrium) relation between the shift of the hysteresis loop and the exchange interaction might fail. It is interesting to notice that similar differences between static and dynamic measurements of H_{EB} were reported recently;[7,10–16] while in those works mainly ferromagnetic resonance and Brillouin light scattering measurements are compared with static results, the present paper extends the comparison to all-optical (out of equilibrium) dynamic measurements as well.

As it can be seen in Fig. 3, we observe a decrease of $H_{EB,dyn}$ as a function of d_{AFM}. Although we do not have a direct proof, we conjecture that this feature is related to the changing grain size of the polycrystalline IrMn. In the framework of the random field model,[17] the increase in grain size with d_{AFM} would cause a decrease in the number of uncompensated interface spins and thereby a lower exchange coupling.

By measuring the precessional amplitude as a function of applied field throughout the AFM wedge, the AFM thickness dependence of $H_{EB,A}$ can be traced. From Eq. (1) and the simple arguments reported above one can expect that, for a fixed value of m, the precessional amplitude is determined by the initial ratio between H_{ext} and H_{EB}. Since the initial value of H_{EB} is determined by the shift of the hysteresis loop,

the fit is expected to yield values $H_{EB,A}$ close to $H_{EB,st}$. As it can be seen in Fig. 3, these values are indeed qualitatively in agreement with the $H_{EB,st}$ measurements. We further observed that the amplitude of the precessional transients decreases as the AFM gets thinner, finally becoming of the order of the measurement noise. This is in agreement with Eq. (1), which predicts zero amplitude for $H_{EB,st}=0$. Interestingly, the minimum AFM thickness where a precession could be induced coincided with the point where H_C and $H_{EB,st}$ cross each other in Fig. 3.

In conclusion we studied the frequency and amplitude of the FM magnetization precession that can be induced by femtosecond laser excitation in exchange coupled Co/IrMn FM/AFM bilayers as a function of the applied field and the AFM thickness. Differences in the values of the exchange bias field $H_{EB,dyn}$, extracted from the TR data, and the values $H_{EB,st}$, obtained by static MOKE loop measurements, are observed for thin (<7 nm) IrMn. These are explained by the effect of the (thickness dependent) effective AFM anisotropy which alters $H_{EB,st}$, while leaving $H_{EB,dyn}$ unaffected. Our analysis of the precessional amplitude suggests, for the temporal profile of the exchange interaction after laser excitation, an (almost) instantaneous decrease and slower recovery, in agreement with previous works.[3,4] However, resolving the details of $H_{EB}[t]$ on a (sub)picosecond time scale by analyzing the precession of FM spins still remains a challenging open issue.

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