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Tuning the remanent spin structure of exchange coupled magnetic films

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Abstract. We have investigated the remanent coupling between a soft-magnetic and a hard-magnetic film separated by a nonmagnetic spacer layer. It turned out that the remanent coupling angle of the soft-magnetic layer relative to the hard-magnetic layer can be adjusted by temporarily applied external fields. The underlying mechanism is the competition between the exchange field and the soft layer coercive field. This could be applied in modern magnetic recording techniques like MRAMs to realize multiple or even continuous states per memory cell, thus constituting a re-emergence of analogue recording technology with the potential of much higher information density.

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The information density of magnetic storage devices is not only limited by the spatial extension of the magnetic memory cells, but also by the number of distinguishable magnetic states that can be realized in each cell. Conventional magnetic storage devices rely on the realization of two magnetic states for encoding information. One could expect a significant increase of the storage density for digital data, if multiple states per memory cell could be generated.

In the limit of encoding information in a continuous variable, a re-emergence of analogue recording technology in modern magnetic recording techniques is conceivable. If such a concept could be realized on sub-micrometre length scales, a tremendous increase in storage density could be expected. Therefore, it is appealing to reconsider the application of analogue technology in the field of magnetic recording technology. A potential route towards these goals is the controlled adjustment of different coupling angles between two exchange coupled magnetic films, as will be described in this paper.

A generic phenomenon that is observed if two layers of different magnetic materials are coupled to each other is the exchange-bias effect. This effect was first observed by Meiklejohn and Bean as an '*...interaction between an antiferromagnetic material and a ferromagnetic material.*' [1], where the essential features are: (i) a shifted hysteresis loop and (ii) an enhanced coercive field of the ferromagnetic material. These phenomena are not restricted to coupled ferromagnetic/antiferromagnetic layers but can also be observed for exchange-coupled magnetic layers with different magnitudes of their coercive fields, e.g. as in the case of soft magnetic and hard magnetic materials. Such layer systems are often referred to as exchange-spring magnets [2, 3] where the minor loops (i.e. the hysteresis loops where the field is cycled within limits below the switching field of the hard magnetic layer) exhibit the above mentioned exchange-bias phenomenology. Typically magnetic properties of the interfaces as described in detail in [4, 5] are responsible for different magnetic reversal and remanent coupling properties in magnetic heterostructures. For example, recent experiments on exchange coupled hard/soft magnetic films [6, 7] have shown how the bilinear coupling can be manipulated to result in a non-collinear coupling of both magnetization vectors. Both studies revealed that a modification of the micromagnetic structure in the hard-magnetic film by external fields changes the remanent coupling properties.

In this work, we identify the relevant parameters of an exchange coupled hard/soft magnetic layer that allow for an exact adjustment of the coupling properties. We show that the remanent magnetization direction of the soft magnetic layer can be controlled by temporally applied external magnetic fields due to the competition between the exchange bias field and soft layer coercive field.

The sample was a polycrystalline trilayer consisting of Fe(10 nm)/Cu(0.6...6.4 nm)/FePt (30 nm), deposited by rf-magnetron sputtering in an Ar atmosphere of $p = 1 \times 10^{-2}$ mbar on a superpolished Si substrate with an amorphous Ta seed layer ($d_{\mathrm{Ta}} = 10$ nm). For protection against oxidation the layer system was finally capped by 3 nm of Ta_2O_5. To achieve a continuous variation of the bilinear coupling across the samples, the Cu spacer layer was wedge shaped with a slope of $S = 3.3\,\mathrm{nm\,cm^{-1}}$. The surface quality of the layers was controlled via x-ray reflection in grazing incidence geometry, from which a rms roughness of about $\sigma = 0.4$ nm for the hard-magnetic FePt layers was obtained. The surface roughness of the interfaces in the layer system does not exceed $\sigma = 0.7$ nm. The FePt layer (nominal composition $Fe_{50}Pt_{50}$) was transformed into the magnetically hard $L1_0$-phase by high vacuum annealing at $T = 800$ K for $t = 15$ min after deposition of FePt. The polycrystalline character of the FePt layer was confirmed via atomic force microscopy and x-ray diffraction. We found that the tetragonal

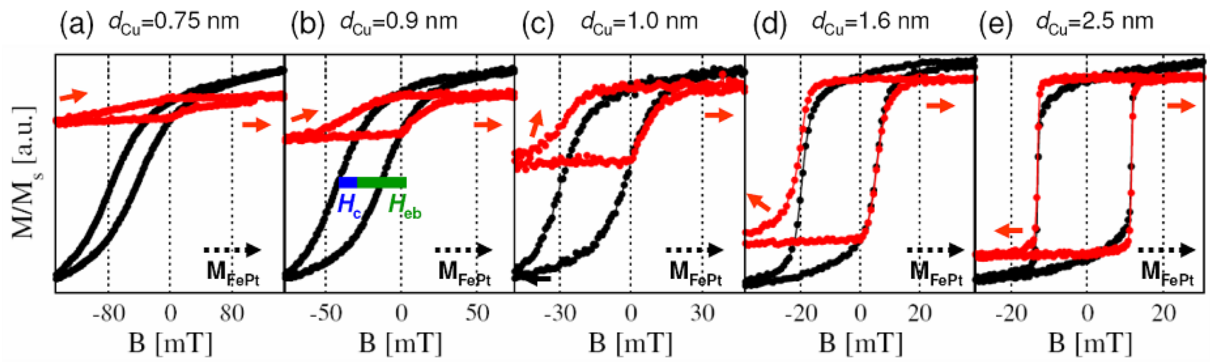

Figure 1. Minor hysteresis loops (black curves) of the Fe/Cu/FePt trilayer, recorded via MOKE, for various values of the Cu interlayer thickness. Apparently, the exchange-bias field H_{eb} and the coercive field H_c, defined in (b), strongly depend on the interlayer thickness. This dependence is displayed in figure 2. The red curves are remanent loops where the field was applied temporarily and the MOKE signal recorded in remanence. From this signal one deduces the remanent coupling angle of the soft-magnetic Fe layer (red arrows) relative to the hard-magnetic easy axis (dotted arrows).

c-axes of the grains were randomly aligned in the plane of the film with an average grain size of $A = (20 + / - 5)$ nm. No preferred direction of the in-plane magneto-crystalline anisotropy after deposition could be detected. However, an in-plane easy axis could be induced by application of an external magnetic field that exceeds the coercive field of FePt which is about $H_{c,\mathrm{FePt}} = 0.65$ T.

The magnetic properties of the layer systems were studied by longitudinal magneto-optical Kerr-effect (MOKE) measurements at room temperature. Figure 1 shows selected minor magnetic hysteresis loops of the layer system for different interlayer thicknesses d_{Cu}. While the black curves are conventional loops, the red curves are remanent loops where the field was only temporarily applied (for $t = 1$ s) and then the MOKE signal afterwards measured in zero field. From the conventional loops (black curves) we have determined the exchange bias field and the coercive field as a function of interlayer thickness, as displayed in figure 3. The bias field decreases exponentially with increasing interlayer thickness. Such behaviour points to a mainly magnetostatic interaction between both films where the coupling constant is given by the Nèel model [8] equation:

$$H_{eb} = \frac{\pi^2 h M}{L d_{Fe} \sqrt{2}} \exp(-2\pi d_{Cu} \sqrt{2}/L). \tag{1}$$

A fit of the measured data resulted in a peak to peak distance of $h = 1.0$ nm and a lateral correlation length of $L = 3.25$ nm. These values are in accordance with the results from the structural characterization. For the Fe saturation magnetization a value of $M = 2.1$ T and for the Fe thickness $d_{Fe} = 10$ nm was used. Oscillating contributions from a RKKY interaction [9] are not detectable, since they are most probably damped due to the influence of interfacial roughness and disorder in the interlayer. The coercive field shows a linear decrease with increasing interlayer thickness. The observed values $H_c > 9$ mT are significantly above the values for uncoupled films which are typically at $H_c < 2$ mT. The enhanced values of H_c for

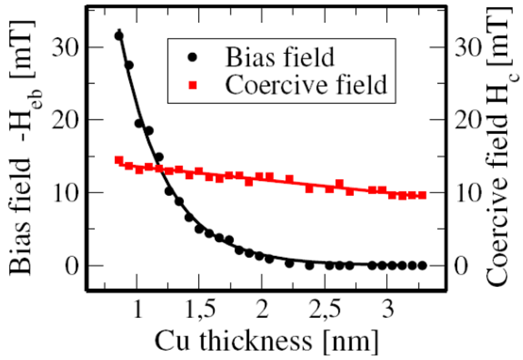

Figure 2. Exchange bias field H_{eb} and coercive field H_c of the minor loops versus the Cu interlayer thickness, indicating respectively an exponential and a linear decrease with increasing interlayer thickness. The solid line for H_{eb} is a fit according to equation (1).

magnetically coupled films are mainly due to the relatively high exchange anisotropy. While the exchange bias field is exclusively determined by the ferromagnetic coupling between the films, the dependence of the soft layer coercivity on the interlayer thickness is less well understood. Possible mechanisms are an inhomogeneous magnetization reversal or an irreversible switching of parts of the hard magnetic layer [10]. In any case, the balance between the bias field and the coercive field determines the remanent coupling behaviour of the two layers. Due to the strong dependence of H_{eb} and H_c on the interlayer thickness, the coupling properties can be adjusted via the thickness of the interlayer. This becomes obvious through the remanent loops displayed in figure 1. For example, at $d_{Cu} = 0.75$ nm we observe that $|H_{eb}| \gg |H_c|$ (figure 1(a)) i.e. the two layers are rather strongly coupled and only ferromagnetic coupling will be observed in remanence independent on the magnitude of the externally applied field. At the other extreme where $|H_{eb}| \ll |H_c|$ (figure 1(e)) at $d_{Cu} = 2.5$ nm the layers are only weakly coupled and the application of external magnetic fields well below the hard magnetic switching field leads to parallel or antiparallel remanent states between the magnetization vectors of both films. In the intermediate region where $|H_{eb}| \approx |H_c|$ (figure 1(c)) at $d_{Cu} = 1.2$ nm the balance of both fields results in the remarkable situation of a nearly complete biquadratic coupling where the magnetization vectors of both films are perpendicular to each other in remanence.

This peculiar coupling behaviour is not restricted to Cu as spacer material, because it is primarily related to the competition between the exchange bias and the coercive field. Therefore, we could observe it also for other interlayer materials, for example, Ta, Ta_2O_5, Cr, $Cr_{35}Ni_{65}$, Al and Al_2O_3. The type of interlayer material only affects the relative magnitude of H_{eb} and H_c. Additionally, for a directly exchange coupled FePt/Fe bilayer, the described effects could also be observed where the coupling was tuned by adjusting the remanent magnetization of the FePt layer. Moreover, an exchange bias training effect, i.e. a modification of the minor loop appearance upon repeated cycling, as reported recently [11], could not be observed. More than 3000 cycles of the minor loops resulted in no significant change of the bias and the coercive field. Another important result is that these coupling mechanisms are not caused by the formation of multi-domain structures, but proceed mainly by coherent rotation of the Fe magnetization direction as is well known for exchange spring magnets [2, 3]. Using the technique of nuclear resonant scattering of synchrotron radiation [3], we found that about 80%

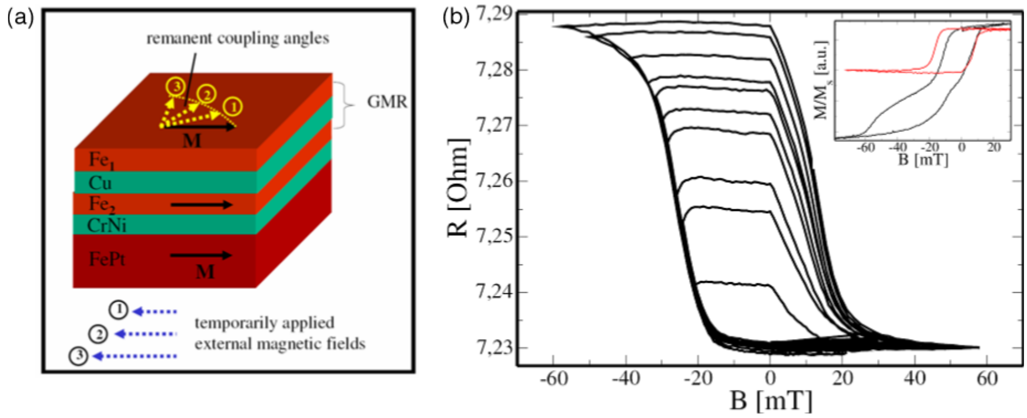

Figure 3. (a) Sketched layer system and working principle of a novel storage device application based on interlayer coupled magnetic films with a GMR($Fe_1/Cu/Fe_2$) element for information reading. (b) Experimental proof of this principle, where 10 different levels could be induced, illustrated by the GMR remanent mode minor loops. The inset displays the corresponding MOKE minor loops, measured in the conventional way (black curve) and using the remanent mode technique (red curve).

of the Fe magnetization is oriented along the direction given by the measured coupling angles and about 20% of the magnetization is disordered e.g. due to domain formation [12].

Thus, one concludes from these observations and the discussion above that the ratio H_{eb}/H_c determines the maximum range of coupling angles that can be remanently adjusted via an external field. Therefore, for the ratio $H_{eb}/H_c = -1$ the coupling angle assumes all values between 0° and 90° while proceeding from positive to negative fields along the remanent loop. This immediately prompts potential applications in magnetic data storage technology, because in this way multiple states per memory cell could be realized as schematically shown in figure 3(a). In such devices, the information is then written via the magnitude of temporarily applied external fields and is stored as in the coupling angle between the magnetization vectors of the films.

However, for future applications, conventional techniques like MOKE or magneto-resistance effects (e.g. giant magnetic resistance (GMR) or tunneling magnetic resistance (TMR)) could be used to read out the stored information encoded via the coupling angle (using e.g. $R \sim \cos$ (coupling angle)). Therefore, we modified the sample system and integrated an additional layer system Fe(7 nm)/Cu(2.5 nm)/Fe(7 nm), sketched in figure 3(a), that enables us to read out the coupling angle via GMR. This GMR layer system is further denoted as $Fe_1/Cu/Fe_2$. To enhance the GMR signal, 0.5 nm Co are deposited at both Cu/Fe interfaces.

The inset of figure 3(b) shows the MOKE minor loops, measured in the conventional mode (black curve) and in the remanent mode (red curve). Here, the ratio H_{eb}/H_c results only for the Fe_1 layer in inducible coupling angles as one can finally see in the remanent minor loop.

To clarify the potential for future applications, we measured GMR (current in-plane geometry) minor loops in the remanent mode, as described above. Figure 3(b) displays different GMR minor loops where only the maximum of the applied field is varied. As it is illustrated, 10 different levels—and therewith 10 different magnetic states—can be remanently stored for externally applied fields within a range of about 40 mT. With improved GMR or TMR layer systems as functionalized reading elements, one can obtain a very low signal-to-noise ratio which allows applications for multilevel and/or analogue recording.

In conclusion, we have performed investigations of the exchange bias effect in interlayer coupled hard/soft ferromagnetic thin films. It appeared that the ratio of the exchange bias field and the soft layer coercive field is the essential parameter that determines the remanent coupling between the layers which can be adjusted by temporarily applied magnetic fields. Based on this principle, novel magnetic storage devices may be designed in which multiple or even continuous magnetic states per memory cell can be generated. The approach presented here allows one to read out these magnetic states via magneto-optical techniques or magneto-resistance effects, thus providing the potential for miniaturization far below the length scales of conventional analogue magnetic recording technology.

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