Alternative solutions for data storage using magnetic films exchange-coupled through non-magnetic layer

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***Abstract*—We describe an alternative solution to encode information in magnetic films that goes beyond the conventional way of digital magnetic recording. In our approach the information is stored via a continuous variable, namely the remanent coupling angle between two magnetic films that are separated by a nonmagnetic spacer layer. Using the technique of nuclear resonant scattering (NRS) [1, 2] we show with good precision, how this coupling angle can be conveniently adjusted with high degree of remanence by shortly applied external magnetic fields. Moreover this effect is explained using a micromagnetic model [3, 4]. Extremely important for future applications of this concept, we demonstrate, that the remanent coupling angles can be read out via magneto-optical or magneto-resistance effects. In principle, this approach allows to design novel memory cells for advance data storage devices, where multiple states per unit cell can be generated and recorded.**

***Index Terms*—Magnetic films, data storage, FePt**

I. Introduction

Magnetic recording of information in thin magnetic films is well established since about 60 years when the first computer hard disk drive was developed by IBM. Fundamental discoveries in basic research has allowed an increasing of the data storage density from the initial value of 2 Kbit/in^2 up to about 60 Gbit/in^2 in 2003 [5] and recently 170 Gbit/in^2 in helium-filled HDDs in 2013. Elementary research highlights in this area, such as the discovery of antiferromagnetic coupling between magnetic layers separated by a nonmagnetic spacer layer [6] or the detection of the giant magnetoresistance effect [7], has initiated intense experimental and theoretical work in this field. It was also found that the interlayer exchange coupling has an oscillatory behaviour (between remanent parallel and antiparallel alignments of magnetisation directions) as function of the spacer layer thickness [8]. This so-called bilinear coupling (BL) can be described with an areal energy density: $E_{BL} = -J_1(m_1 \cdot m_2)$, where m_1 and m_2 are magnetisation vectors of the two ferromagnetic layers and the bilinear constant J_1 is positive for ferromagnetic coupling and negative for antiferromagnetic coupling. The bilinear contributions for magnetic exchange in thin films allow to use even smaller magnetic bits in thin films – applied in recording heads [9] or directly as layer systems in computer hard disks [10]. However, further decrease of the size of memory cells cannot be achieved due to the superparamagnetic limit, below which the magnetisation direction fluctuates due to thermal effects. In this paper we show results - which allow in principle - to design novel memory cells in future data storage devices, where multiple states per unit cell can be generated and used for information storage.

II. The Principle

Fig. 1 shows schematically the principle of storage and a sketch of the layered system used in the experiments.

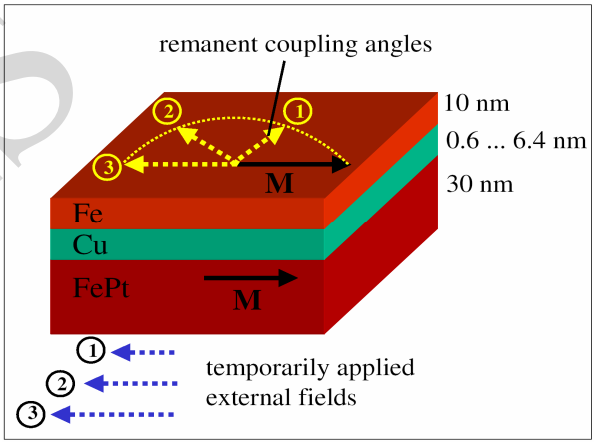


Fig. 1. Design of the samples and the demonstration of the storage principle. Temporarily applied external magnetic fields with different magnitudes can induce different remanent coupling angles between the magnetisation vectors **M** of FePt and Fe.

The results are based on investigations of inducible biquadratic exchange in interlayer coupled thin magnetic films by external fields. Biquadratic coupling can be described phenomenologically with the areal energy density: $E_{BQ} = -J_2(m_1 \cdot m_2)^2$, where J_2 is a negative constant and describing the strength of the biquadratic exchange coupling (BQ). This type of coupling gives remanent orthogonally oriented magnetisation vectors in exchange coupled layer systems. Inhomogeneities, such as magnetic impurities inside the nonmagnetic layer or at the

IJRS

interfaces between layers [11] as well as structure roughness effects at the interlayer interface [3, 12] are mainly responsible for biquadratic exchange. Therefore, if the BL and the BQ coupling types are present in exchange coupled thin films, arbitrarily orientation of magnetisation vectors can be remanently adjusted depending on the balance between BL and BQ coupling. As a consequence, if there is a possibility to modify the magnitudes of the types of coupling one can change the remanent coupling angles between the magnetisation vectors of the films. The problem is that the above specified inhomogeneities which are responsible for biquadratic contributions are not easily reproducible and are also not tunable for example by external fields. Recent studies have shown that a BQ in magnetically coupled thin films can be induced by external magnetic fields [4, 13]. This was studied for hard and soft magnetic layers in direct contact [4] and antiferromagnetically coupled hard and soft magnetic layers with a constant spacer layer thickness [13]. The biquadratic exchange in these layer systems is caused by inhomogeneities of the magnetic anisotropy – in particular by in-plane spatial fluctuations of the hard magnetic layer anisotropy. These fluctuations can be remanently modified by external fields and thus modify the coupling between the films. We studied in detail these mechanisms by investigating the dependence of the field induced biquadratic exchange on the magnitude of the bilinear coupling and on the magnitude of the applied magnetic fields. These dependencies were analysed by very precise measurements of the remanent coupling angle between the magnetisation vectors of soft magnetic Fe and hard magnetic FePt layer which are separated by non magnetic Cu spacer layer. Additionally we show that it is possible to read out the coupling angles with common techniques like the magneto-optical Kerr effect (MOKE) and the giant magnetoresistance effect (GMR).

III. Experimental Results and Discussion

Polycrystalline Fe(10 nm)/Cu(0.6…6.4 nm)/FePt(30 nm) nanolayers were prepared by high vacuum ($p = 3 \cdot 10^{-7}$ mbar) rf-magnetron sputtering in an Ar atmosphere of $p = 1 \cdot 10^{-2}$ mbar. These layer systems were deposited on amorphous Ta seed layer on super polished Si substrates and on top they were finally coated against oxidation by 3 nm of Ta_2O_5. To achieve a continuous variation of the bilinear coupling across the samples, wedge-shaped Cu spacer layer (slope: S_{max} = 3.3 nm/cm) was deposited. The $Fe_{50}Pt_{50}$ layer achieved its $L1_0$-phase structure and became magnetically hard by high vacuum annealing at T = 800 K for t = 15 min. The polycrystalline character of the FePt was determined via atomic force microscopy and x-ray diffraction measurements. We obtained an in-plane texture of the tetragonal c-axes of the grains with an average grain size of L = (20 +/-5) nm. The random distribution of the grains c-axes results in no preferred direction of the in-plane magneto-crystalline anisotropy after deposition. However, an in-plane easy axis can be induced by an external magnetic field that is higher than the coercive field of FePt. The surface quality of the layers was controlled via x-ray reflection in grazing incidence geometry, from which a root-mean-square roughness of about σ = 0.4 nm for the hard-magnetic FePt layers was obtained. The surface roughness of all interfaces of the system does not exceed σ = 0.7 nm.

The magnetic properties of the layer system were characterised by longitudinal MOKE measurements at room temperature. Hysteresis loops of the coupled layer system indicate that the magnetic layers are ferromagnetically coupled over the whole range of Cu thickness because only negative exchange fields were observed.

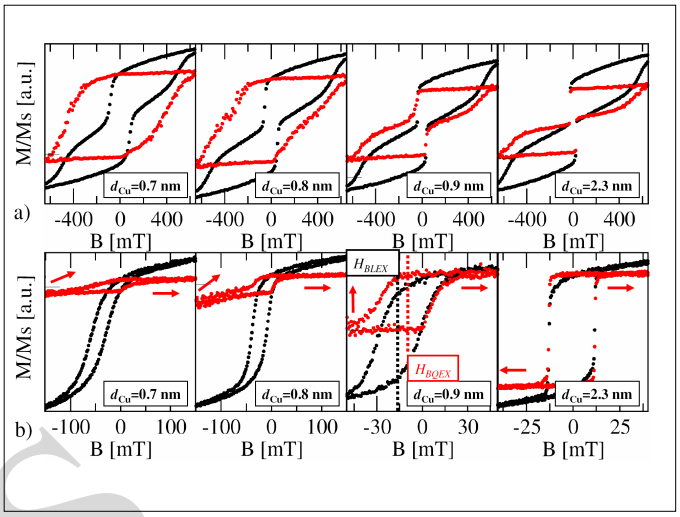


Fig. 2. Room temperature MOKE hysteresis loops for different Cu interlayer thicknesses. The black curves are typical loops - measured with applied fields - the red curves are measurements in remanence mode, where the magnetic fields were temporarily applied for t = 1 s. a) major loops and b) easy-axis minor loops, where only the magnetisation direction of the soft magnetic Fe layer is rotating. Additionally, the definition of the bilinear and biquadratic exchange fields (H_{BLEX}, H_{BQEX}) is demonstrated.

In fig. 2 are displayed some examples of the hysteresis loops for different Cu interlayer thicknesses, in particular major (Fig. 2a) and minor (Fig. 2b) loops (B parallel to the FePt easy axis). The black curves are describing typical loops - measured with continuously applied fields – while the red curves are special measurements in remanence mode, where the magnetic fields were temporarily applied for a finite time period t = 1 s. In this manner each point of the hysteresis loops was measured in remanence mode. One can see, that for a Cu thickness of about d_{Cu} = 2.3 nm the magnetisation of the Fe layer is almost freely adjustable, because the exchange field is negligibly low. For Cu thicknesses less than d_{Cu} = 2.3 nm, biquadratic coupling is induced and thus different coupling angles are remanently adjusted, depending on the magnetic field magnitude and the thickness of Cu. This behaviour is displayed in fig. 2b) with the help of the red arrows inside the minor loop graphics that show the Fe layer magnetisation direction.

From the minor loops we estimated the magnetic exchange fields H_{BLEX} originating from the bilinear (ferromagnetic) coupling between the layers, as a function of Cu thickness.

Two different coupling mechanisms excite the bilinear magnetic exchange fields: firstly, a magnetostatic interaction (so-called Nèel or orange-peel coupling), with an exponential decay [14] and secondly, the RKKY coupling (often referred as quantum well coupling) where the decay is quadratic and oscillating as function of the interlayer thickness d_{Cu} [10, 15]:

$$H_{Ex}(d_{Cu}) = (H_0 / {d_{Cu}}^2)\sin(\phi + 2\pi d_{Cu}/\lambda) + H_s e^{-d_{Cu}/t_s} \quad (1)$$

Here the first term is describing the RKKY coupling field and the second term the magnetostatic (or dipolar) coupling field. The constants H_0, φ, λ corresponds respectively to the maximum exchange field, the phase shift and the scillation period of the RKKY coupling and the constants H_s and t_s are respectively the dipolar field of the magnetostatic interaction and the thickness of the soft layer. Using equation (1) we fitted the bilinear exchange fields as function on the interlayer thickness. The results are displayed in fig. 3a and the estimated fit parameters are shown in Table 1.

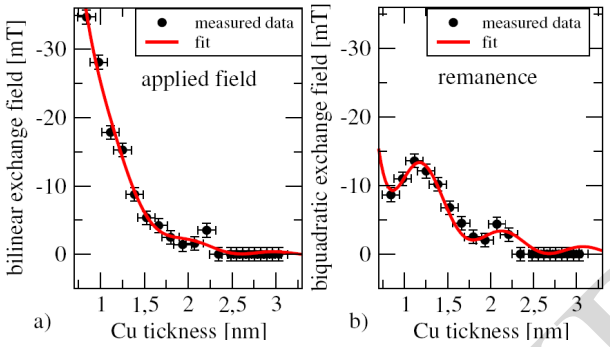


Fig. 3: Magnetic exchange fields as a function of Cu interlayer thickness estimated from MOKE measurements with applied fields a) and in remanence mode b).

Parameter	H_{BLEX}	H_{BQEX}
H_0 [mT nm²]	-2.2	-6.0
Φ	-0.4	-1.0
λ [nm]	0.91	0.91
H_d [mT]	-347	-69.5
T [nm^{-1}]	0.37	0.61

Table 1: Calculated parameters as resulted from the fits using equation (1) with data shown in Fig. 3

However, we measured also easy-axis minor loops in remanence mode, after temporarily applied magnetic fields. The areas of these minor loops are describing the biquadratic coupling energy $E_{BQ} = -J_2(m_1 \cdot m_2)^2$. But the definition of the exchange fields is quite different, because of their asymmetric ~~d~~evolution: After the remanent coupling angles are fully induced, only opposite applied fields are able to rotate the magnetisation vector back to a ferromagnetic alignment. There is no intrinsic reset force due to the biquadratic coupling. Nevertheless we used the definition for the bilinear exchange fields to estimate biquadratic exchange fields H_{BQEX} as function of the interlayer thickness, see Fig. 3b. We fitted these data using the same equation (1), the results of this fit being shown in Fig. 3b. The parameters obtained from the fit are displayed in Table 1. One can see, that the influence of the oscillatory RKKY-coupling is more pronounced for the biquadratic exchange field than for the bilinear exchange field. Vlasko-Vlasov et al. [4] have shown, that the field induced biquadratic coupling of a hard and soft magnetic layer can be described by an adaptation of the fluctuation model developed by Slonczewski [3]. The assumption of this model is that the spatial coupling fluctuations are not caused by thickness variations of the nonmagnetic layer but by the spatial fluctuations of micromagnetic orientations of the hard magnetic layer. This leads to the same biquadratic coupling behaviour as proposed in the model of Slonczewski. In this model, the magnitude of the BQ J_2 depends on the BL RKKY coupling J_1, the size of the micromagnetic orientation (grain size) L, the intralayer exchange stiffness A_s and the layer thickness D [3].

$$J_2 = 4\frac{(J_1)^2 L}{\pi^3 A_s}\coth(\pi\frac{D}{L}) \quad (2)$$

The remanent coupling angle between the magnetisation vectors can be calculated using the following formula: $\cos\theta_{rem} = (1-2f)J_1/2[N(f)J_2 - K_s]$, where the function $N(f)$ is depending on the external fields and accounts, in first order, for the number of rotated micro magnetisations and thus changing effectively the coupling constants J_1 and J_2. This mechanism results in a maximum of induced coupling angles, ~~where~~ when the BL coupling constant J_1 is maximal.

The same mechanisms for the field induced biquadratic coupling were also observed from magnetoresistance measurements, where the resistance change $\Delta R/R$ = [R_{AP}-R_P]/R_P depends on the parallel (P) and antiparallel (AP) orientations of the layer magnetisation vectors. Fig. 4 depicts some results for the current-in-plane (CIP) measurements.

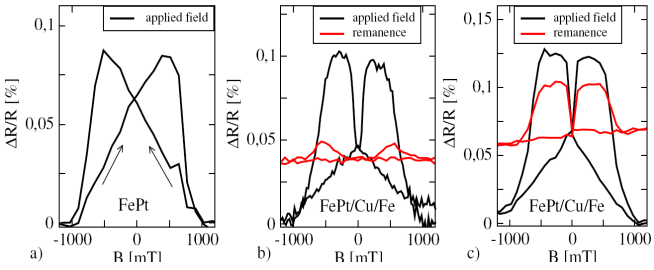


Fig. 4: Magnetoresistance measurements ($\Delta R/R$ = [R_{AP}-R_P]/R_P) of a pure FePt film (a), and the coupled layer systems FePt/Cu/Fe (b, c), where R_{AP} and R_P are the current-in-plane resistances for antiparallel (AP) and parallel (P) alignment of the magnetic moments. The black curves are measurements with applied fields and the red curves are measurements in remanence mode after temporarily applied fields. For a Cu thickness of d_{Cu} = 2.3 nm, the Fe magnetisation direction is almost freely adjustable (c). For Cu thicknesses of d_{Cu} = 0.8 nm, arbitrary directions of the Fe magnetisation are induced by external fields.

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Here we measured again with continuously applied fields (black curves) as well as in remanence mode (red curves) after temporarily applied fields. For Cu layer thicker than d_{Cu} = 2.3 nm, the Fe magnetisation direction is almost freely adjustable (fig. 4c) by external fields while for d_{Cu} = 0.8 nm, the field-induced biquadratic coupling provide arbitrary directions of the Fe magnetisation (fig. 4b). In fig. 4a is displayed the magnetoresistance curve of a pure FePt layer, where a changing of the remanent resistance could not be observed.

We also studied in detail the effects of the field induced biquadratic coupling by a quantitative determination of the coupling angles depending on the induced fields and on the Cu interlayer thickness. The experimental method used here is the time-resolved nuclear resonant scattering of synchrotron radiation at the E = 14.4 keV resonance of ^{57}Fe [1]. From the analysis of temporal beat patterns in the nuclear decay, the magnitude and orientation of magnetic fields at the nuclear sites can be determined with high accuracy. The availability of high-brilliance synchrotron radiation renders this technique very sensitive for the investigation of thin-films and surface magnetism [16].

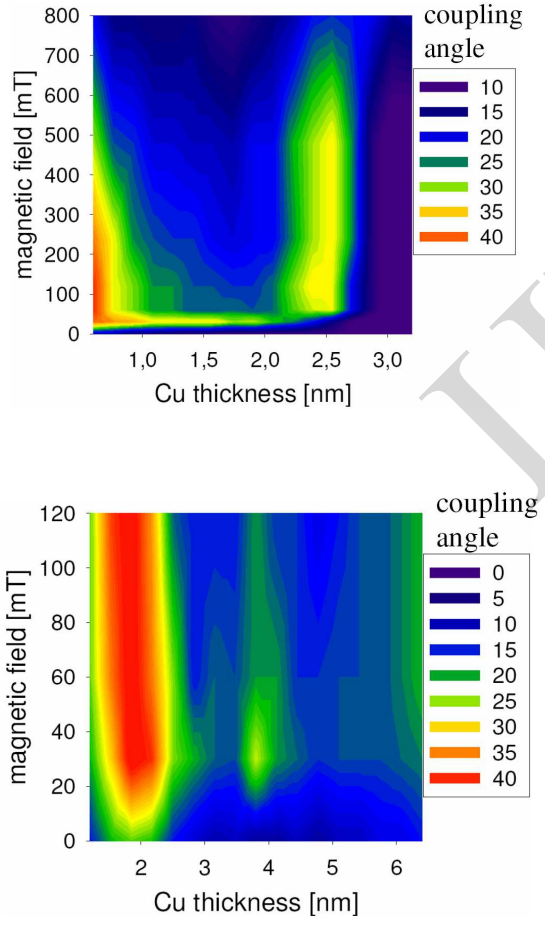


Fig. 5: Remanent coupling angles (colour coded) depending on the Cu interlayer thickness (top) d_{Cu} = 0.6…3.2 nm, (bottom)) d_{Cu} = 1.2…6.4 nm) and the induced magnetic fields.

The experiments were performed at the Nuclear Resonance Beamlines ID18 and ID22N of the European Synchrotron Radiation Facility (ESRF). The samples were mounted in a cryomagnet system with a horizontal transverse field and cooled to a temperature of T = 4 K to increase the coercivity of the hard magnetic layer. For the NRS measurements, a 0.8 nm thick ^{57}Fe layer was embedded in the centre of the Fe layer. This ensured that the hyperfine fields at the ^{57}Fe layer did not contain contributions from the adjacent boundaries that would complicate the data analysis.

For these experiments the samples were magnetised with H = 5.6 T and then different remanent coupling angles were induced using magnetic fields H_r = 5…900 mT in reversed orientation with respect to the magnetisation direction.

From the data analysis according to the procedure described in [2, 16] the direction of the ^{57}Fe in-plane magnetisation vector was determined with an accuracy of +/- 3°. The measured remanent coupling angles as function of the Cu thickness and the induced fields are colour coded and displayed in Fig. 5.

One can see that at special Cu thicknesses - where the bilinear RKKY coupling is maximal - the remanent coupling angles are fully induced. This was observed at two samples, where the variation of the Cu thicknesses is different.

IV. Conclusions

In conclusion, we analysed the field induced coupling effects by different experimental techniques and showed the possibility for a defined remanent adjustment of magnetic orientations by external fields in exchange coupled layer systems. Due to temporarily applied external fields, in-plane spatial fluctuations of the anisotropy axis can be induced as well as changed remanently.

These modified fluctuations results in an effective changing of the bilinear and biquadratic coupling contributions and therefore in different coupling angles between the magnetisation vectors of the soft and the hard magnetic layer.

In future one can image data storage devices, where multiple states per unit cell can be used to store information just by applying of different magnitudes of external fields. Our results open wide perspectives for building future advanced data storage devices with a multi-fold increase of the storage capacity, where multiple magnetic states per unit cell may be used for data storage, simply by applying magnetic fields of different magnitudes. Common techniques like MOKE or GMR can be used to read out the information stored in different magnetic states.

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IJRS

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