



Magnetic switching modes for exchange spring systems ErFe₂/YFe₂/DyFe₂/YFe₂ with competing anisotropies

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ABSTRACT

The magnetization reversal processes of [10 nm ErFe₂/nYFe₂/4 nm DyFe₂/nYFe₂] multilayer films with a (110) growth axis and a variable YFe₂ layer thickness n are investigated. The magnetically soft YFe₂ compound acts as a separator between the hard rare earth (RE) ErFe₂ and DyFe₂ compounds, each of them bearing different temperature dependent magnetic anisotropy properties. Magnetic measurements of a system with $n = 20$ nm reveal the existence of three switching modes: an independent switching mode at low temperatures, an ErFe₂ spin flop switching mode at medium high temperatures, and an YFe₂ dominated switching mode at high temperatures. The measurements are in qualitative agreement with the findings of micromagnetic simulations which are used to illustrate the switching modes. Further simulations for a varied YFe₂ layer thickness n ranging from 2 to 40 nm are carried out. Quantitative criteria are defined to classify the reversal behavior, and the resultant switching modes are laid out in a map with regard to n and the temperature T . A new coupled switching mode emerges above a threshold temperature for samples with thin YFe₂ separation layers as a consequence of the exchange coupling between the magnetically hard ErFe₂ and DyFe₂ layers. It reflects the increasing competition of the two conflicting anisotropies to dominate the magnetic switching states of both RE compounds under decreasing n .

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1. Introduction

Exchange spring magnets attract attention as potential candidates for a set of different applications. Firstly, there is the development of hard disks with ultra high storage densities: Ando and Nishihara implemented an exchange spring triple layer for perpendicular recording media in order to achieve a high signal-noise ratio and signal stability [1]. Victora and Shen suggested the usage of exchange spring multilayers as perpendicular magnetic recording media in order to facilitate the fabrication and to improve magnetic switching properties [2]. Suess et al. showed that the thermal stability of exchange spring recording media can be improved without increasing the coercive field, which is limited by the maximum field of the write head of roughly 1.7 T [3,4]. For thermally assisted magnetic recording (TAR), Thiele et al. used exchange spring media to allow for easier writing under a reduced coercive field above a transition temperature [5].

The ongoing miniaturization of microelectromechanical systems (MEMS) promotes the development of magnetic MEMS (MagMEMS) devices as microsensors and microactuators, since magnetostatic interactions dominate over electrostatic effects on a nanometer scale. Several topical reviews exist [6–8]. Coils are economically and technically not viable as a magnetic flux generator in MagMEMS. Instead, exchange spring magnets, when tailored for a giant energy product and magnetic hardness [9–11], could create high displacement rates in actuators, or high signal output in sensors, respectively.

In the field of spintronics, Kiselev et al. [12] and Xi et al. [13] reported on magnetic motions in a nanomagnet driven by a spin-polarized current, possibly serving as an easily tunable nanoscale microwave generator. With their well defined interlayer domain walls stretching over vast parts of the multilayer, exchange springs are highly suitable for such devices, providing high spin torque yields. Furthermore, the spin torque emerges useful in order to manipulate switching states at comparably small applied fields [14].

The utilization of exchange spring systems for the given applications requires a sound understanding of the switching processes and the magnetic spin configurations involved. These, in

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turn, depend on a set of parameters—the materials of the multilayer compounds with their respective anisotropy, saturation magnetization and exchange constants, the layer geometry and thickness, the temperature, and the applied field direction and field sweep range—and can be customized to individual needs. Asti et al. derived magnetic phase diagrams in terms of layer thicknesses by calculating the differential susceptibility at a nucleation field. In their one-dimensional models, uniaxial anisotropies were assumed with easy axes either in [15] or perpendicular to [16] the film plane.

In this paper, we focus on the magnetization reversal processes in [10 nm ErFe₂/nYFe₂/4 nm DyFe₂/nYFe₂] multilayered exchange spring systems. These Laves phase superlattices can be epitaxially grown in a well-controlled and reproducible way, facilitating the production of samples with varied layer thickness n , but otherwise epitaxially identical. The two rare earth (RE) compounds, ErFe₂ and DyFe₂, are among the materials with the highest magnetic anisotropies. In contrast, the YFe₂ compound bears negligible magnetic anisotropy. The Fe in either of the YFe₂, ErFe₂, DyFe₂ compounds is responsible for the exchange interaction within and across the layers, and the exchange stiffness is widely homogeneous throughout the sample. Consequently, the ratio of the layer thicknesses of hard and soft compounds represents a parameter which allows us to tune the impact of the RE anisotropy on the magnetic switching states independent of intricacies imposed by the exchange interaction.

A further interesting aspect of the investigated system is the pre-strung magnetization configuration of the soft YFe₂ compound: since the YFe₂ layers are sandwiched between two different magnetically hard layers ErFe₂ and DyFe₂ with differing anisotropy properties, a domain wall is present in the intermediate YFe₂ layer even in the remanent state. This is different to simpler systems with only one hard compound, where the magnetization in the soft compound is completely relaxed in the remanence state.

In the following, we present magnetization measurements along the [110] direction of a sample with $n = 20$ nm for a set of temperatures T between 10 and 300 K. They are compared to the results of micromagnetic simulations with OOMMF [17], and the observed switching modes with their respective spin configurations are explained on the basis of the simulation data. Next, the thickness layer n is varied: graphs of the direction cosines of the compound specific magnetizations suggest a quantifiable definition of the switching modes. The switching modes are analyzed and their regimes are mapped with regard to T and n . The limiting curves of the regimes are understood by energy considerations.

2. Method

2.1. Numerical model

We use the OOMMF code [17] for our simulations, with extensions for higher order anisotropy energy terms [18]. For the time evolution, the Landau–Lifschitz–Gilbert equation is employed, determining quasi-static magnetization configuration states by a damped precession of the magnetization.

For the underlying numerical model, we assume a homogeneous magnetization in the (110) film plane, allowing us to represent the system by a 1d chain of computational cells along [110]. The computational cell size of 1 nm³ is sufficiently smaller than the exchange length of either compound material. We further draw on the ferrimagnetism of the REFe₂ materials and assume a rigid exchange coupling of the magnetic moments of the 8 RE and the 16 iron atoms inside a lattice cell (Fig. 1):

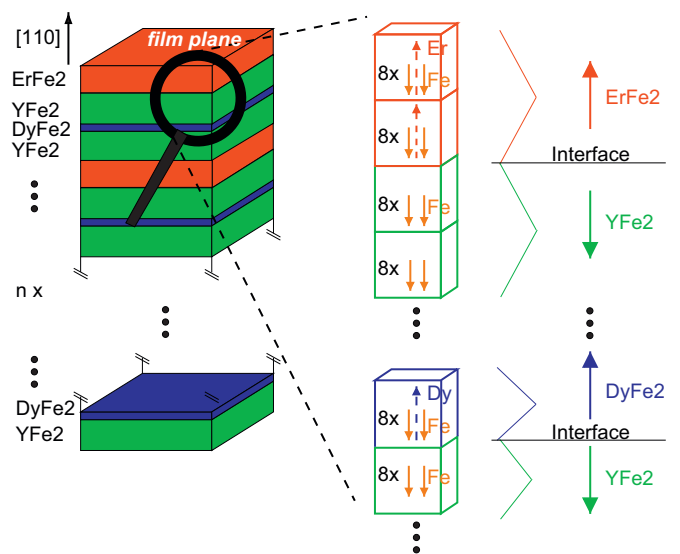


Fig. 1. (Color) Sketch of the underlying numerical model, showing the layers of ErFe₂/YFe₂/DyFe₂/YFe₂ compounds (left), and the rigid coupling of the atomic moments to an effective magnetization for each compound (right). The arrows representing the atomic moments reflect the relative antiferromagnetic alignment of RE and Fe inside a crystal cell and the relative ferromagnetic alignment of Fe across the cells, not the real magnetization directions.

neighboring atoms of the same element couple ferromagnetically (RE–RE and RE–Fe), neighboring atoms of different elements couple antiferromagnetically (RE–Fe). Thus, we can calculate an effective magnetic moment $\mathbf{m}_{\text{eff}}$ of a crystal cell by a simple signed summation of the constituent moments inside. As the magnetic moments of Er and Dy outweigh that of Fe by at least a factor of 2, the effective moments of ErFe₂ and DyFe₂ oppose the moment of the atomic Fe. The magnetic moment of Y is negligible, and the only contribution to $\mathbf{m}_{\text{eff}}(\text{YFe}_2)$ is the Fe moment. Across crystal cells, we only consider the ferromagnetic coupling of the Fe atoms. This results in a positive intra-layer exchange coupling A_{intra} for all compounds, a negative across-layer exchange coupling $A_{\text{across}(\text{RE}-\text{Y})}$ between the effective REFe₂ and YFe₂ moments, and a positive across-layer exchange coupling $A_{\text{across}(\text{RE}-\text{RE})}$ between the effective ErFe₂ and DyFe₂ moments. The approximation of the demagnetizing energy density

$$\varepsilon_{d,i} = \frac{1}{2} \mu_0 \mathbf{M}_i^2 \quad (1)$$

is valid under the condition of homogeneously magnetized thin film slabs i with a magnetization $\mathbf{M}_i$.

2.2. Material parameters

We use the exchange constants $A_{\text{intra}} = A_{\text{across}(\text{RE}-\text{RE})} = -A_{\text{across}(\text{RE}-\text{Y})} = 1.46 \times 10^{-11}$ J/m. Ab initio calculations yield the temperature dependent atomic magnetic moments of Er, Dy, and Fe needed to assemble the effective magnetic moments as described in Section 2.1, and the saturation magnetization for the compounds is achieved by taking into account the cell sizes 0.728 nm/0.732 nm/0.736 nm for ErFe₂/DyFe₂/YFe₂ [19]. The result can be seen in Fig. 2: for low temperatures $\lesssim 200$ K, DyFe₂ and ErFe₂ magnetizations prevail, whereas for temperatures $\gtrsim 200$ K YFe₂ starts dominating over ErFe₂ and increasingly catches up with DyFe₂. For all temperatures considered, the magnetization of DyFe₂ exceeds that of ErFe₂.

The orientation of the lattice cell with its basis vectors [001], [010], [001] in the lab system x, y, z for the crystal growth direction [110] are outlined in Fig. 3. The RE magnetocrystalline (MC) anisotropy of the bulk is described by the phenomenological

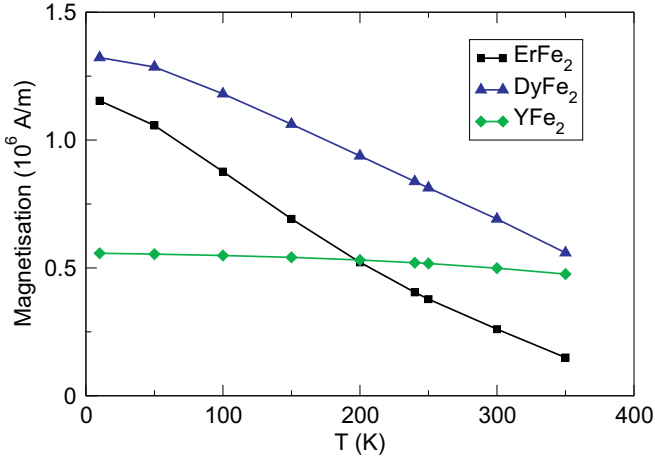


Fig. 2. (Color) Effective magnetization of ErFe_2 (black squares), DyFe_2 (blue triangles), and YFe_2 (green diamonds) as a function of temperature.

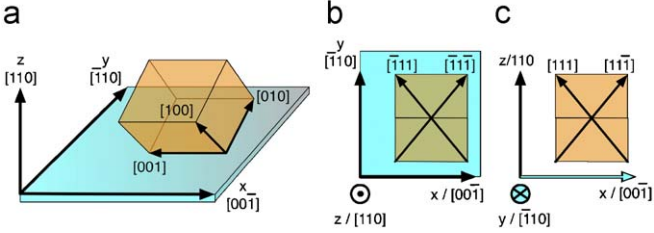


Fig. 3. (Color) (a) Lattice cell (yellow cube) with respect to the film plane (blue). The lab system is spanned by the basis vectors $\mathbf{x}$, $\mathbf{y}$, $\mathbf{z}$, the lattice cell by $[100]$, $[010]$, $[001]$. The crystal is grown in the $[110]$ direction. (b) In-film-plane body diagonals of the lattice cell in an xy cross section (c), out-of-film-plane body diagonals in an xz cross section.

parameters K_1 , K_2 , K_3 of a cubic anisotropy energy density

$$\begin{aligned} \varepsilon_{\text{MC}} = & K_1[\alpha_{100}^2\alpha_{010}^2 + \alpha_{100}^2\alpha_{001}^2 + \alpha_{010}^2\alpha_{001}^2] \\ & + K_2[\alpha_{100}^2\alpha_{010}^2\alpha_{001}^2] \\ & + K_3[\alpha_{100}^4\alpha_{010}^4 + \alpha_{100}^4\alpha_{001}^4 + \alpha_{010}^4\alpha_{001}^4], \end{aligned} \quad (2)$$

where α_{100} , α_{010} , α_{001} are the direction cosines of the magnetization with respect to the crystal lattice $[100]$, $[010]$, and $[001]$ directions. The K_1 , K_2 , K_3 values are taken from calculations extending the Callen–Callen model to second order [20].

Additionally, a shear strain ε_{xy} is present due to the $[110]$ MBE growth direction of the films [21], incorporated in the strain energy density

$$\varepsilon_S = b_2 \varepsilon_{xy} \alpha_x \alpha_y, \quad (3)$$

with the temperature dependent magnetoelastic constant b_2 . The α_x , α_y , α_z are direction cosines of the magnetization with respect to the basis vectors of the lab system. The term can be approximated by the first-order Callen–Callen term $\tilde{K}'_2$ as

$$\varepsilon_S = \tilde{K}'_2[\alpha_z^2 - \alpha_y^2], \quad (4)$$

the values of which are given in Bowden et al. [22]. The energy term (4) is a superposition of two uniaxial anisotropies of identical weight, one with a symmetry axis in z , the other in y with opposite sign. The strain term generally attenuates slower with rising temperature as the MC contribution. Consequently, the total anisotropy as a sum of MC anisotropy and strain term shows temperature dependent characteristics (find visualization of crystal directions in insets of Fig. 4 and in Fig. 3): ErFe_2 has easy magnetization directions along the body diagonals of the lattice

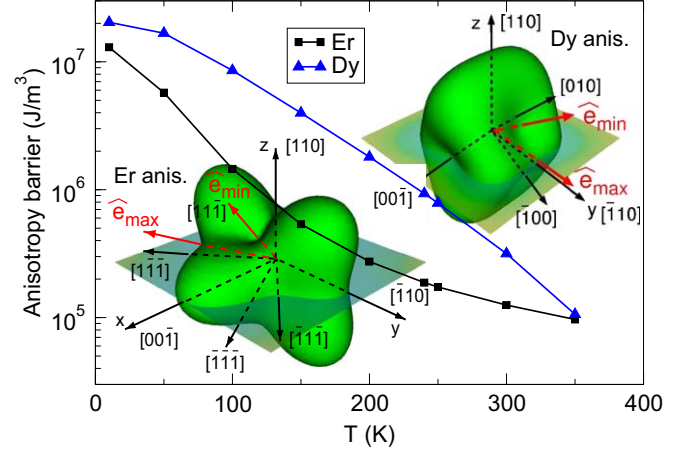


Fig. 4. (Color) Anisotropy energy barriers of Er (black squares) and Dy (blue triangles) as a function of temperature. The energy barrier is the anisotropy difference with regard to a maximum direction ($\hat{\mathbf{e}}_{\text{max}}$) and a minimum direction ($\hat{\mathbf{e}}_{\text{min}}$), as depicted in the insets in the lower left corner (Er) and upper right corner (Dy).

cell $\langle 11\bar{1} \rangle$ for low temperatures (i.e. 10 K). For increasing temperatures, the out-of-plane easy axes move from $[111]/[1\bar{1}\bar{1}]$ towards $[110]$, the in-plane easy axes from $[\bar{1}11]/[\bar{1}\bar{1}\bar{1}]$ towards $[001]$ due to the strain term becoming more pronounced. For DyFe_2 , the out-of-plane easy axes gradually rotate from $[\bar{1}00]/[010]$ towards $[\bar{1}10]$ under rising temperature, and the $[001]$ easy axis eventually turns into a hard axis. Zhukov et al. [23] stated an out-of-plane angle of the easy directions $\theta \approx 14^\circ$ at 290 K. For our simulations, we adjust the $\tilde{K}'_2$ of Bowden et al. [22] seems to underestimate the strain. This is apparent in an excessive θ determined by simulations where the applied field in $[110]$ is gradually relaxed, and the magnetization settles in the out-of-plane anisotropy minimum. After multiplying the $\tilde{K}'_2$ values with a factor of 2.5 we are able to replicate the findings of Zhukov [23].

We analytically determine the anisotropy energy barriers for Er and Dy most relevant in a demagnetizing process along the $[110]$ direction (Fig. 4). Both barriers fade with rising temperature, facilitating switching processes.

The magnetization characteristics of specific $\text{DyFe}_2/\text{YFe}_2$ and $\text{ErFe}_2/\text{YFe}_2$ systems are described elsewhere [24–26]. We will now focus on generalized $[10 \text{ nm ErFe}_2/n\text{YFe}_2/4 \text{ nm DyFe}_2/n\text{YFe}_2]$ systems with different n , and start with $n = 20 \text{ nm}$.

3. Experimental data: the $n = 20 \text{ nm}$ sample

A $[10 \text{ nm ErFe}_2/n\text{YFe}_2/4 \text{ nm DyFe}_2/n\text{YFe}_2]$ superlattice with $n = 20 \text{ nm}$ is grown by molecular beam epitaxy (MBE). The $[110]$ growth direction of the Laves phase materials is in accordance with the strain term contribution to the anisotropy of the numerical model (Eq. (3)). The samples are magnetically characterized along the $[110]$ direction by the use of a vibrating sample magnetometer (VSM).

The resulting hysteresis loops for the total magnetization are presented in the left column of Fig. 5 for four temperatures (a–d). For 10 K (Fig. 5a) the loop features a typical exchange spring appearance insofar as the magnetization smoothly slopes when the applied field relaxes from a maximum positive value—the unwinding of the soft YFe_2 magnetization into a ferrimagnetic alignment. Whereas an exchange spring system with one magnetically hard material shows one step-down indicating the

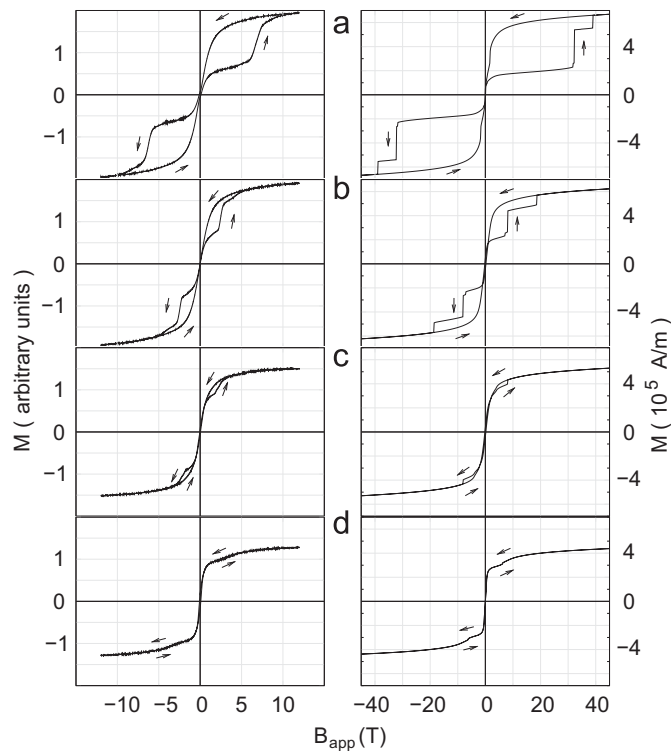


Fig. 5. Overall magnetization curves as a result of measurements (left column) and simulations (right column) for different temperatures with a separation layer thickness 20 nm. The temperatures are 10 K (exp.)/10 K (sim.) (a), 95 K (exp.)/100 K (sim.) (b), 200 K (exp.)/200 K (sim.) (c), 290 K (exp.)/300 K (sim.) (d). The arrows indicate the sweep direction of the applied field.

switching of the hard compound, here we see one larger drop at an applied field B_{S1} of around -6 T, and a smaller one at an applied field B_{S2} of around -8 T. It seems obvious to identify the former with the switching of the ErFe_2 compound into the applied field direction, the latter with that of DyFe_2 : in the case of DyFe_2 , higher anisotropy energy barriers have to be overcome before the switching takes place (Fig. 4). Furthermore, the different step amplitudes match the ratio of the RE layer thicknesses (4 nm:10 nm).

For 95 K (Fig. 5b), the shape of the hysteresis loop is widely unchanged, but the switching fields are substantially decreased, with B_{S1} around -2.5 T and B_{S2} around -4 T. In the hysteresis loop for 200 K (Fig. 5c), the large drop attributed to the ErFe_2 switching has disappeared, with only the small DyFe_2 switching step left at B_{S2} of -2 T. At 295 K (Fig. 5d), the hysteresis loop presents a small kink at a field B_K of approximately -3 T with no notable coercivity. Otherwise, the curve is smooth.

For all four temperatures, there is no coercive field of relevance. This leaves us with three different types of appearance for the hysteresis loops of the $n = 0$ sample: a low temperature (LT) type for 10 and 95 K, a medium temperature (MT) type for 200 K, and a high temperature (HT) type for 290 K.

4. Modeling of hysteresis loops

In order to receive more insight into the detailed spin configurations, we run micromagnetic simulations based on the numerical model outlined in Section 2. The applied field is swept along the $[110]$ axis perpendicular to the film plane from $+60$ to -60 T with a resolution of 160 mT. First, hysteresis loops are generated in order to compare them to the measurements and to confirm the numerical model. The resulting hysteresis loops

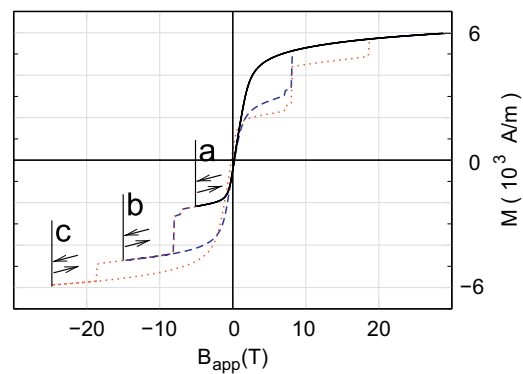


Fig. 6. (Color) Overall hysteresis loop for an YFe_2 layer thickness of 20 nm at $T = 100$ K for different applied field sweeps. The applied field is varied from $+30$ to -4.96 T (solid black line, a)/ -14.88 T (dashed blue line, b)/ -24.96 T (red dotted line, c) and back to $+30$ T to check the reversibility of the corresponding hysteresis loop parts.

(10, 100, 200, 300 K) are placed next to the experimental loops with the same or very similar temperatures on the right column of Fig. 5. For all four temperatures, the shapes of the magnetization curves of the simulations bear a striking resemblance to those of the measurements, featuring all the characteristics described earlier. The switching fields, however, are too large: for 10 K, B_{S1} is -32 T, and B_{S2} -39 T. For 100 K, B_{S1} is -8 T, and B_{S2} -18 T. We find a B_{S2} of -8 T for 200 K, and B_K of -6 T for 300 K. The values deviate roughly by a factor of 2 for 300 K and by a factor of 5 for 10 K. The excessive switching fields of the simulations are a consequence of the 1d model with its inability to nucleate, a fact known as Brown's paradox [27–29]. In spite of this inherent problem, the agreement of the simulation and measurement loops is formidable and justifies further interpretation of the numerical data.

The reversibility of selected sections of the hysteresis loop for a temperature of 100 K is elucidated in Fig. 6 in the case of the simulations: the applied field is swept to a specific target value just beyond the section of interest, and the field sweep direction is reversed. Irreversibilities are then recognizable when the curves for the two different sweep directions are not congruent. The two steps for negative applied fields turn out to be irreversible (Fig. 6b, c), the exchange spring unwinding (Fig. 6a) to be reversible, underpinning the interpretation of the experimental hysteresis loops. The two hard compounds ErFe_2 and DyFe_2 switch independently of each other.

5. Modeling of switching modes

We now explain the different magnetic reorientation processes underlying the LT, MT, HT appearances of the hysteresis loops. For this, we use the numerical data to determine the compound-specific magnetization curves: each numerical cell is represented by one magnetization vector, and for each of the DyFe_2 / ErFe_2 / YFe_2 compounds separately, the magnetization vectors of the numerical cells for the respective layers are averaged. The result is depicted in Fig. 7 for the domains of LT (100 K, Fig. 7a), MT (200 K, Fig. 7b), and HT (300 and 350 K, Fig. 7c, d). Each of the four graphs shows the compound-specific magnetization curves on top. In the middle, the characteristic switching states for the specific ErFe_2 and DyFe_2 magnetization are visualized as 3d vectors on top of the anisotropy energy surfaces of Er and Dy. On the bottom, the Er and Dy anisotropy energies are plotted for the magnetization directions at the respective applied field.

For 100 K (Fig. 7a), the compound-specific magnetization loops confirm the presumed individual switching of the RE compounds

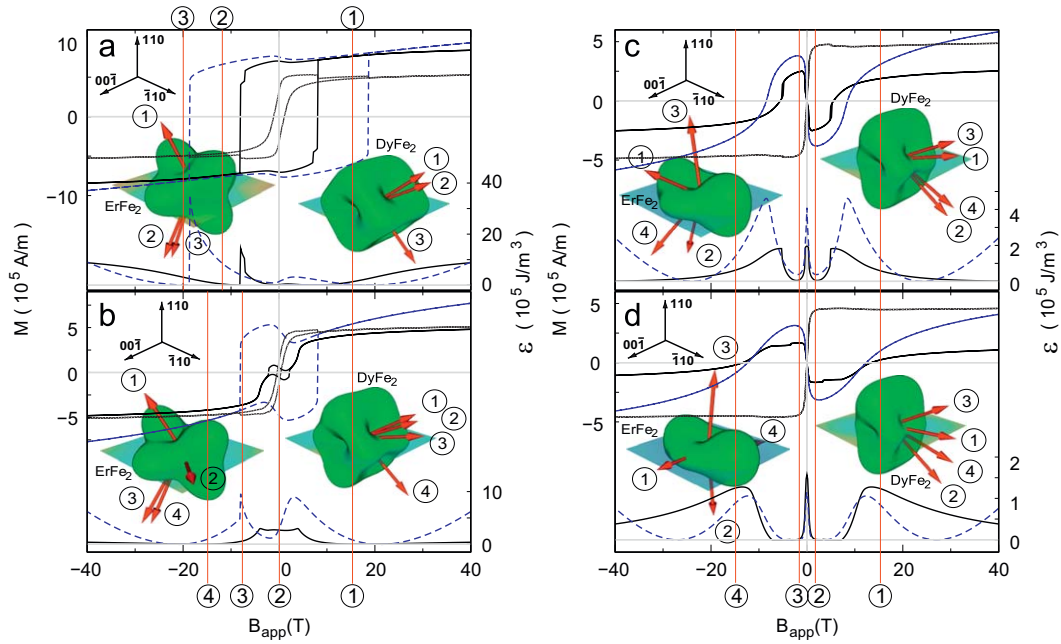


Fig. 7. (Color) Compound-specific magnetization curves and switching states for the temperatures 100 K (a), 200 K (b), 300 K (c), 350 K (d), and an YFe₂ separation layer thickness 20 nm. In the upper section of each graph, the compound-specific magnetization curves in the direction of the applied field [1 1 0] (black solid line for ErFe₂, blue dashed line for DyFe₂, brown checked line for YFe₂) are shown as a result of the simulations. In the lower section of the graphs, the anisotropy energy densities for the RE compounds (same color coding) are depicted for the corresponding magnetization directions. In the insets, characteristic switching states are visualized (ErFe₂ on the left, DyFe₂ on the right): the magnetization of a compound is specified by a red arrow on the green anisotropy surface. Each state is labeled with a number referring to an applied field that is marked by a numbered red horizontal line. The crystallographic directions as an orientation for the anisotropy surfaces are set in the upper left corner of each graph.

and the exchange spring unwinding of the soft YFe₂ compound. For positive applied fields ($\Rightarrow$ state (1)), the RE moments are located in their respective anisotropy energy dips—ErFe₂ at [1 1 $\bar{1}$], DyFe₂ at [0 1 0]. The YFe₂ moments, antiferromagnetically coupled to the RE moments, oppose the applied field direction $\mathbf{B}_{\text{app}}$ at the interfaces, and wind towards $\mathbf{B}_{\text{app}}$ in the interior. At state (1), the majority of the YFe₂ moments is aligned with the strong field, and its magnetization is positive. When the field abates, the YFe₂ moments gradually unwind and their magnetization reverses at positive applied fields. In the remanent state, the YFe₂ moments are antiferromagnetically aligned at the interfaces, towards [0 $\bar{1}$ 0] at the DyFe₂ side, and [$\bar{1}$ $\bar{1}$ 1] at the ErFe₂ side, and uniformly swerve in between. Under a field rising in the reversed direction, the RE moments are gradually dragged out of their anisotropy dips, recognizable from the ascent in the anisotropy energy plots of the compounds at the bottom of the graph. ErFe₂ is the first to switch at -8 T ($\Rightarrow$ state (2)), followed by DyFe₂ at -18 T ($\Rightarrow$ state (3)). Each time, YFe₂ stays aligned with the applied field direction. Both switchings are accompanied by a sharp drop in the corresponding anisotropy energy. We define this the *independent switching mode*, referring to the independent RE switchings.

A new mode applies for 200 K (Fig. 7b); ErFe₂ now reverses via the spin flop direction [$\bar{1}$ 1 $\bar{1}$], embodied in the extra state (2). The ErFe₂ moments rotate into the spin flop state at a positive applied field of around 3 T. The process can be understood by magnetic energy considerations: at high applied fields, both the majority of YFe₂ moments and ErFe₂ moments are aligned with the field direction, with a domain wall around their mutual interface. Exchange coupling tries to push one compound into an antiferromagnetic alignment, but is outbalanced by the large Zeeman energies. When the applied field is sufficiently reduced, the YFe₂ moments at some point start to unwind. If beforehand the effect of the exchange interaction acting on ErFe₂ exceeds the Zeeman energy of ErFe₂ plus the Er anisotropy barrier, then the ErFe₂

moments rotate against the applied field direction into the spin flop state. Whether this condition is fulfilled, depends on the temperature: for rising temperatures the magnetic moment of ErFe₂ sharply decays (Fig. 2), and with it the corresponding Zeeman energy. Additionally, the Er anisotropy energy barrier degrades logarithmically (Fig. 4). Both effects together cause the energy condition to become true above a critical temperature $T_{\text{crit,Er}}$; and a spin flop state is achieved for the ErFe₂ moments. Analysis of the anisotropy energy function shows that there is a distinct minimum around [$\bar{1}$ 1 $\bar{1}$] for temperatures of 200 K or lower, allowing the ErFe₂ moments to settle in this direction. When the field is increased in the opposite direction to -3 T, ErFe₂ is finally dragged out of the spin flop state into state (3) by Zeeman interaction. The DyFe₂ magnetization stays in the [0 1 0] direction until it switches into state (4) / [0 $\bar{1}$ 0] at -8 T. We define this the *ErFe₂ spin flop mode*.

Under a further increase of the temperature to 300 K (Fig. 7c), both DyFe₂ (at 8 T) and ErFe₂ (at 5 T) moments reverse for positive fields already ($\Rightarrow$ state (2)). Whereas in the case of 200 K, the ErFe₂ moments reside in the spin flop state [$\bar{1}$ 1 $\bar{1}$], they now rotate further into [$\bar{1}$ $\bar{1}$ $\bar{1}$], off the applied field direction. The YFe₂ magnetization stays pinned to the field direction, and both reverse together. Also the RE compounds switch ($\Rightarrow$ state (3)) and stay in a direction opposing the applied field. Under a further decreasing applied field, the RE compounds switch a third time towards the applied field direction ($\Rightarrow$ state (4)).

The reason why the ErFe₂ moments do not settle in the spin flop direction is that the anisotropy energy surface of Er has changed for 300 K due to the strain term, and the [$\bar{1}$ 1 $\bar{1}$] direction is now a saddle point. The new triple switching of DyFe₂ can be explained by energy considerations similar to those for ErFe₂ at 200 K, but unlike that case, the anisotropy barrier obstructing access to the spin flop direction ([0 0 $\bar{1}$] for DyFe₂) stays impregnable, and it is energetically favorable for DyFe₂ to reverse

into $[\bar{1}00]$ over the more viable $[\bar{1}10]$ barrier. The critical temperature for the DyFe_2 triple switching $T_{\text{crit,Dy}}$ is higher than $T_{\text{crit,Er}}$ because of the generally stronger Dy anisotropy. The spin flop mode is observed for $T_{\text{crit,Er}} < T < T_{\text{crit,Dy}}$, and for $T > T_{\text{crit,Dy}}$ the YFe_2 dominated switching mode applies. It has to be emphasized that this mode is an extension of the ErFe_2 spin flop mode in a way that the ErFe_2 moments still transit the spin flop direction on their reversals.

A further example of the YFe_2 dominated switching mode is given for 350 K, with displaced ErFe_2 spin directions: for high fields ($\Rightarrow$ state (1)), the ErFe_2 moments are not located around the Er anisotropy minimum any more, but close to $[00\bar{1}]$ instead. Under the high temperature, the YFe_2 magnetization has become so dominant under a vanishing Er anisotropy to be able to push the domain wall at the interface wide into the ErFe_2 layer, thus keeping ErFe_2 from rotating closer to the applied field and to its anisotropy minimum. In the states (2) and (3), the ErFe_2 moments are largely pointing to the anti-field directions $[\bar{1}\bar{1}0]$ and $[110]$; a ferrimagnetic spin configuration with the prevailing YFe_2 . Furthermore, these directions are now energetically favorable with regard to the Er anisotropy, due to the increased importance of the strain term contribution.

6. YFe_2 thickness dependence

So far, we have observed three switching modes for a sample with $n = 20$ nm. The complex underlying reorientation processes were interpreted by micromagnetic modeling. We now take this further and run simulations with a varied n in order to establish a map of switching modes. The corresponding parameter space is composed of a temperature range from 10 to 400 K with a step resolution of 10 K, and a separation layer thickness range $n \in \{2, 5, 7, 10, 12, 15, 17, 20, 22, 25, 27, 30, 32, 35, 37, 40\}$ nm.

6.1. Identification of switching states

As we investigate a large number of magnetization curves, we require quantitative measures to efficiently identify magnetic switching states. The straightforward option is to analyze the compound-specific RE magnetizations, fixed by their direction cosines $\alpha_{x,\text{RE}}$, $\alpha_{y,\text{RE}}$, and $\alpha_{z,\text{RE}}$ with respect to the basis vectors $[00\bar{1}]$, $[\bar{1}10]$, and $[110]$ of the lab system. Per magnetization curve, the maxima $\alpha_{x,\text{RE,max}}$ and $\alpha_{y,\text{RE,max}}$ of each of the compound-specific direction cosines are determined—a measure for the range of the magnetization trajectories of the compounds. We focus on $\alpha_{x,\text{RE,max}}$ and $\alpha_{y,\text{RE,max}}$ as they provide suitable information about possible spin-flop configurations. Plots of these observables as a function of T for a selection of n are given in Figs. 8–12.

In Fig. 8, $\alpha_{x,\text{Er,max}}$ is shown, where high values indicate a small deviation of the ErFe_2 magnetization from the $[00\bar{1}]$ direction, a hard axis of the Er anisotropy. The value at 10 K is around 0.8, independent of n . The huge anisotropy for very low temperatures is the sole crucial factor here to keep the ErFe_2 moment $\arccos 0.8 \approx 37^\circ$ off from $[00\bar{1}]$.

For medium high temperatures between 100 and 250 K, $\alpha_{x,\text{Er,max}}$ generally drops, with a larger gradient for smaller n , and barely notable for n of 15 nm or more. As the anisotropy decreases with temperature, the exchange interaction of the RE compounds becomes more important, amplified by a thinning of the YFe_2 separation layer: the ErFe_2 moments are attracted by the DyFe_2 moments toward the $(00\bar{1})$ plane perpendicular to the $[00\bar{1}]$ direction.

For $\alpha_{x,\text{Er,max}}$ smaller than $0.6 \approx \cos 57^\circ$, the ErFe_2 moments are distorted beyond the direction of its in-plane anisotropy minimum in $(1\bar{1}\bar{1})$. We define this the *coupled switching mode*, as the

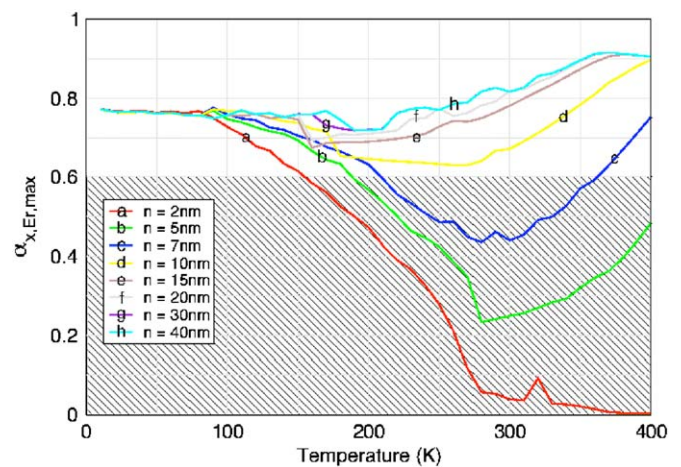


Fig. 8. (Color) Maximum direction cosine $\alpha_{x,\text{Er,max}}$ in $[00\bar{1}]$ of the ErFe_2 magnetization as a function of the temperature for different YFe_2 layer thicknesses. The YFe_2 layer thickness for each curve can be looked up in the legend. The hatched area indicates an $\alpha_{x,\text{Er,max}}$ smaller 0.6, signifying a distortion of the ErFe_2 magnetization toward the DyFe_2 moments.

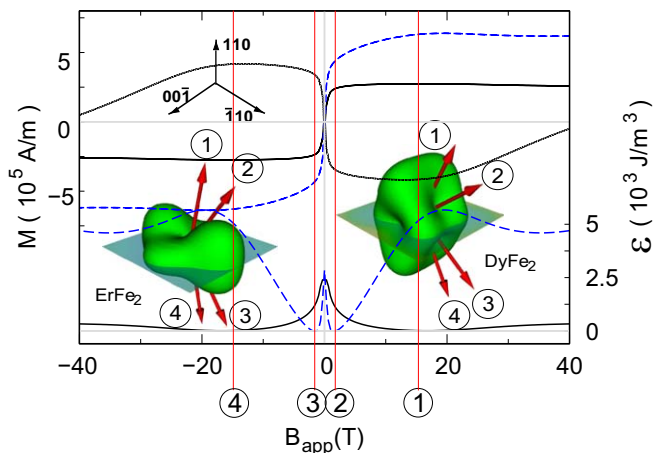


Fig. 9. (Color) Coupled switching mode: compound-specific magnetization curves and switching states for an YFe_2 separation layer thicknesses of 2 nm and a temperature of 290 K. The explanation of the graphs follows Fig. 7.

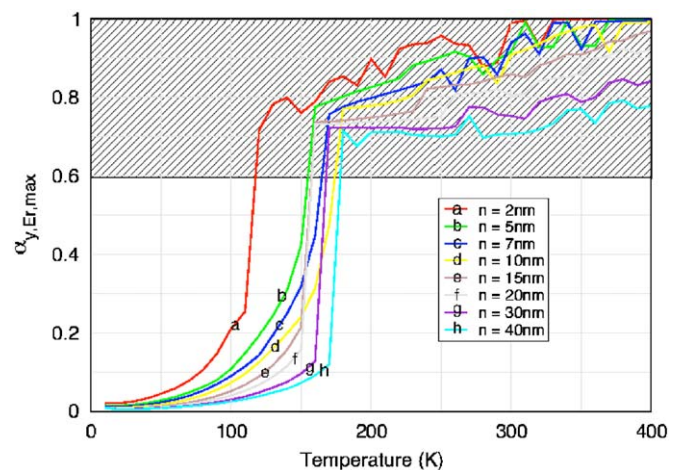


Fig. 10. (Color) Maximum direction cosine $\alpha_{y,\text{Er,max}}$ in $[\bar{1}10]$ of the ErFe_2 magnetization as a function of the temperature for different YFe_2 layer thicknesses. The YFe_2 layer thickness for each curve can be looked up in the legend. The hatched area indicates an $\alpha_{y,\text{Er,max}}$ larger 0.6, signifying spin flop directions of the ErFe_2 magnetization.

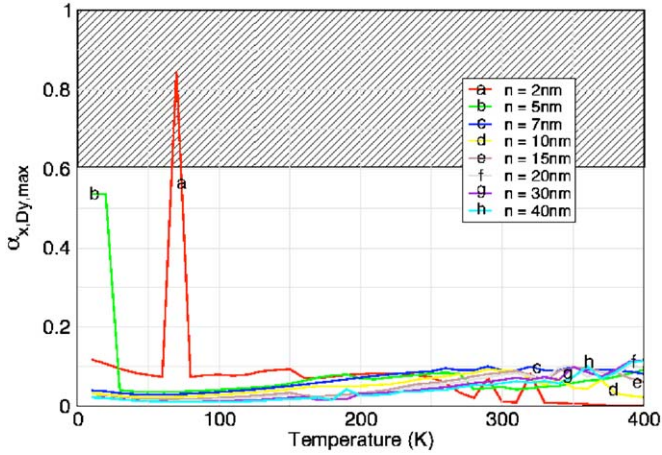


Fig. 11. (Color) Maximum direction cosine $\alpha_{x,Dy,max}$ in $[00\bar{1}]$ of the DyFe₂ magnetization as a function of the temperature for different YFe₂ layer thicknesses. The corresponding YFe₂ layer thickness for each curve can be looked up in the legend. The hatched area indicates an $\alpha_{x,Dy,max}$ larger 0.6, signifying spin flop directions of the DyFe₂ magnetization.

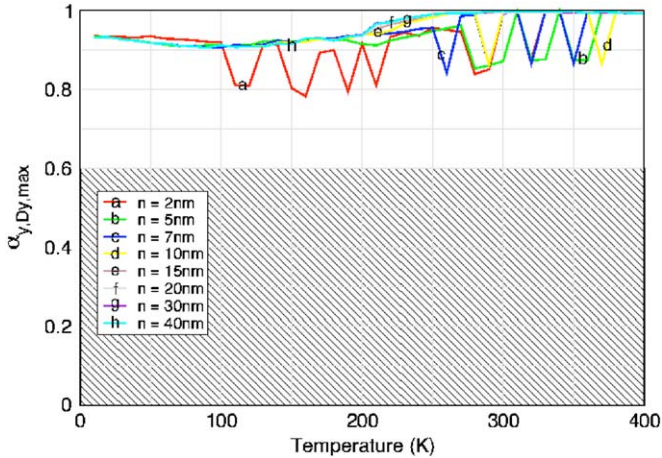


Fig. 12. (Color) Maximum direction cosine $\alpha_{y,Dy,max}$ in $[\bar{1}10]$ of the DyFe₂ magnetization as a function of the temperature for different YFe₂ layer thicknesses. The corresponding YFe₂ layer thickness for each curve can be looked up in the legend. The hatched area indicates an $\alpha_{y,Dy,max}$ smaller 0.6, signifying a distortion of the DyFe₂ magnetization toward the ErFe₂ moments.

ErFe₂ moments are now significantly coupled to the DyFe₂ moments. This mode is not observed in the $n = 20$ nm sample investigated in Section 3 due to the thick magnetic separation layer. An illustration is given in Fig. 9 for a $n = 2$ nm sample: the exchange interaction between the RE compounds is strong enough to force the ErFe₂ moments to reverse from state (2) to state (3) via the $[\bar{1}10]$ direction that is unfavorable with regard to the Er anisotropy.

The maximum direction cosines of samples with $n \geq 10$ nm converge to 0.9 for T reaching 400 K, and the $n = 5$ nm samples show a sharp increase towards this value (unlike the $n = 2$ nm sample). The reason for this high T behavior is the dominance of YFe₂ under a diminishing Er anisotropy (discussed earlier in Section 5) that causes ErFe₂ to increasingly unwind toward the unfavorable $[00\bar{1}]$ direction. YFe₂ starts prevailing at lower T when its layer gets thicker. For $n = 2$ nm, however, YFe₂ never prevails, and $\alpha_{x,Er,max}$ stays around zero up to 400 K.

Fig. 10 pinpoints the spin flop states of the ErFe₂ compound by depicting the maximum direction cosine $\alpha_{x,Er,max}$ of the ErFe₂

magnetization with respect to $[\bar{1}10]$. Low values of $\alpha_{x,Er,max}$ correlate with ErFe₂ moments staying in the $(\bar{1}10)$ plane during the complete magnetization cycle. High values suggest the existence of a spin flop state for at least one point in the hysteresis loop. For temperatures of less than 100 K, the ErFe₂ moments of all samples clearly do not feature a spin flop state. However, when the temperature surpasses the critical value $T_{crit,Er}$, the $\alpha_{x,Er,max}$ sharply ascend to values of over 0.6, marked by the hatched area in the graph, prevailing up to the maximum temperature of 400 K. This ledge confines the regime of the ErFe₂ spin flop mode at the LT side, whereas the transition to the YFe₂ dominated switching mode at the HT side still has to be laid out. Interestingly, $T_{crit,Er}$ is considerably smaller for $n = 2$ nm than for larger n values: the thin YFe₂ separation layer cannot prevent the exchange interaction of the RE compounds; the DyFe₂ moments attract the ErFe₂ moments and facilitate ErFe₂ to switch into the $[\bar{1}1\bar{1}]$ spin flop state.

The occurrence of spin flop states for DyFe₂ in the simulations follows from plots of the maximum direction cosine $\alpha_{x,Dy,max}$ of the DyFe₂ magnetization with respect to $[00\bar{1}]$ in Fig. 11. The $n = 2$ nm sample shows a solitary DyFe₂ spin flop mode for $T = 70$ K: the plot intrudes into the hatched area of magnetization directions that are elongated from $[00\bar{1}]$ by more than 57° . Otherwise, no DyFe₂ spin flop states are observed. The Dy anisotropy energy barrier separating the out-of-plane minimum from the in-plane spin-flop minimum is too high to be crossed—ignoring the one isolated exception.

Finally, Fig. 12 with its plots of the maximum direction cosine $\alpha_{y,Dy,max}$ of the DyFe₂ magnetization with respect to $[\bar{1}10]$ suggests that the DyFe₂ moments cannot be forced out of their natural $(00\bar{1})$ plane by exchange coupling with ErFe₂. No plots intrude into the hatched area of the graph marking the range where the magnetization is considerably elongated towards $[00\bar{1}]$. As soon as relevant exchange interaction of the RE compounds emerges, DyFe₂ takes control over ErFe₂ (and not vice versa).

Finally, a numeric criterion is required to identify the YFe₂ dominated switching mode. Following the definition of this mode in Section 5, both RE compounds show a switching against the applied field direction. This is easily recognized for DyFe₂—a change of sign of the $[110]$ magnetization component for positive B_{app} . However, this condition is not sufficient in the case of ErFe₂: in the vicinity of the in-plane spin flop state $[\bar{1}1\bar{1}]$, the $[110]$ magnetization component of ErFe₂ can change sign without any switching. Looking at all three magnetization components of the ErFe₂ compound in Fig. 13 for $T = 220$ K (a, ErFe₂ spin flop mode) and $T = 230$ K (b, YFe₂ dominated switching mode) provides us with an unambiguous ErFe₂ switching criterion. While the $[110]$ component changes sign at $B_{app} \approx 2.5$ T for both 220 and 230 K, the $[\bar{1}10]$ component drops only for $T = 230$ K when the ErFe₂ moments snap into the $[\bar{1}1\bar{1}]$ direction. Thus, the magnetization decline in $[110]$ in combination with the sign change in $[\bar{1}10]$ marks the ErFe₂ reversal against the applied field.

6.2. Phase diagram

We can now map the regimes of different switching modes on a T/n landscape (Fig. 14). In a nutshell, the regime of the individual switching mode is at the LT side, the regime of the YFe₂ dominance mode in the HT/ high n corner, with the regime of the ErFe₂ spin flop mode stretching between the two. The regime of the coupled switching mode is placed on the HT section of the low n edge. It is not an independent mode but rather an extension to one of the former modes. Thus, the coupled switching regime is

superposed to either the ErFe_2 spin flop regime or the YFe_2 dominance regime. We ignore the solitary DyFe_2 spin flop mode at 70 K for $n = 2$ nm.

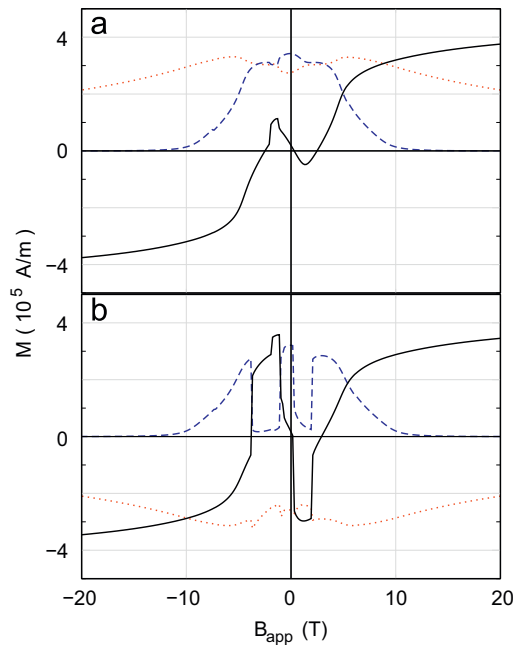


Fig. 13. (Color) ErFe_2 magnetization components in $[1\ 1\ 0]$ (black solid line) / $[\bar{1}\ 1\ 0]$ (blue dashed line) / $[0\ 0\ 1]$ (red dotted line) direction for 220 K (a) and 230 K (b): the snapping of the ErFe_2 magnetization in the case of 230 K is indicated by the drop of the $[\bar{1}\ 1\ 0]$ component for about 1.5 T applied field.

The divide between the independent switching regime and ErFe_2 spin flop regime runs along a roughly vertical line with temperatures around 150–170 K for $n > 2$ nm. The increasing mutual RE exchange coupling for low n assists the ErFe_2 moments in reversing via the spin flop mode, and the ErFe_2 spin flop regime stretches further out to 120 K for smallest YFe_2 separation.

The conditions for the YFe_2 dominance are a sufficiently high temperature in order to truncate the anisotropy barriers, and an adequately thick YFe_2 layer to outweigh the RE compounds. Consistently, the regime is found in the high T /high n corner, in a segment-like area delimited to $T = 220$ K for maximum n , and $n = 5$ nm for maximum T .

The regime where the ErFe_2 moments tend to couple to the DyFe_2 moments is located in the low n area where the magnetic separation barely impedes the mutual RE exchange coupling. It extends to a peak $n = 7$ nm between $T = 210$ and 360 K. The decay of the Er anisotropy under a rising temperature facilitates the distortion of the ErFe_2 by exchange coupling; this is reflected in the curved LT border of the coupled switching regime that extends further to $T = 160$ K for $n = 2$ nm, compared to $T = 210$ K for $n = 7$ nm.

7. Conclusion

Magnetic measurements of a $[10\text{ nm } \text{ErFe}_2/20\text{ nm } \text{YFe}_2/4\text{ nm } \text{DyFe}_2/20\text{ nm } \text{YFe}_2]$ system indicate the existence of three different switching modes over a temperature range from 10 to 300 K. Micromagnetic simulations can reproduce these experimental results and give insight into the detailed spin configurations. Furthermore, the simulations are used to map the switching

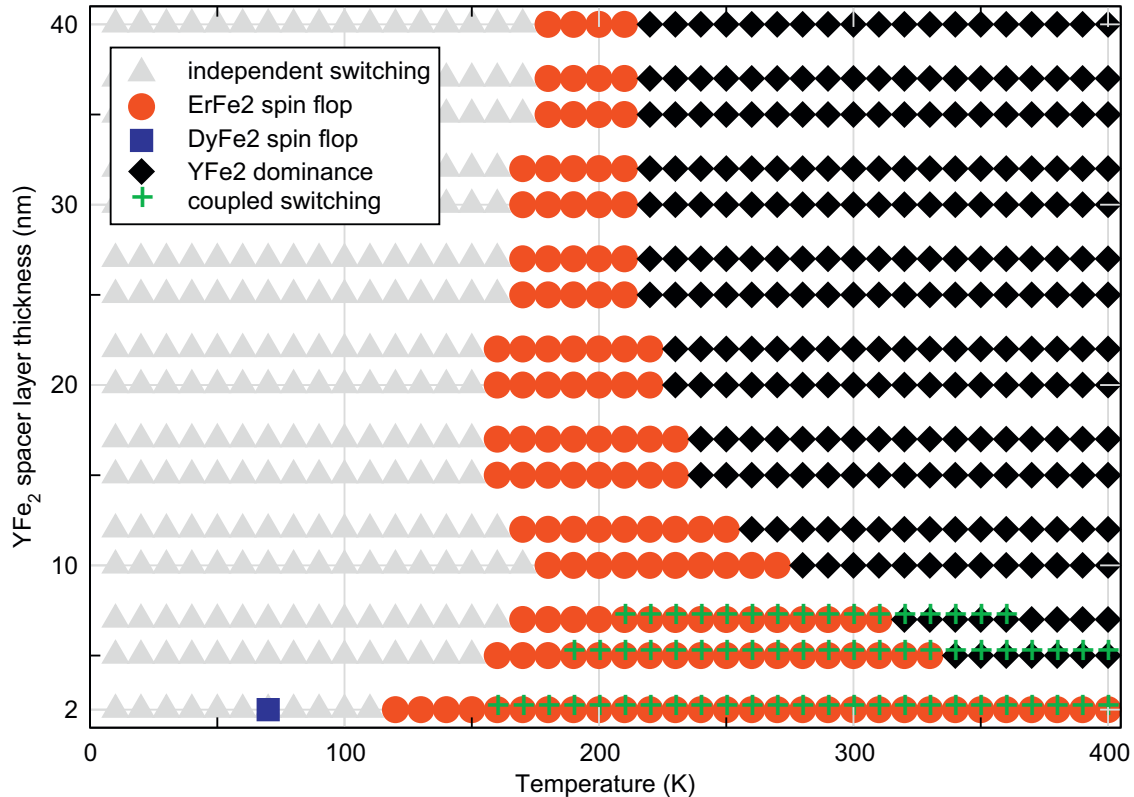


Fig. 14. (Color) Switching modes for different temperatures and YFe_2 separation layer thicknesses as a result of simulations using the numerical model given in Fig. 1. The gray triangles pointing up represent the independent switching mode, where the magnetizations of both RE compounds hysteretically switch into the direction of the applied field. The red circles indicate the ErFe_2 spin flop mode. The black diamonds signify the YFe_2 dominance mode with RE unwinding against the applied field direction. Superimposed green crosses refer to a distortion of the ErFe_2 moments toward the DyFe_2 switching plane (00 $\bar{1}$), the coupled switching mode. The solitary DyFe_2 spin flop state is denoted by a blue square.

modes of a configurable system with a variable YFe_2 layer thickness. We find the generalized switching modes observed for particular $\text{DyFe}_2/\text{YFe}_2$ [24,25] and $\text{ErFe}_2/\text{YFe}_2$ [26] multilayers: a mode of independent switching of the RE compounds into the applied field direction with exchange spring winding of the YFe_2 compound at LT, a switching mode where the ErFe_2 moments reverse via an intermediate spin flop state at MT, and an YFe_2 dominated switching mode with an unwinding of the RE compounds against the applied field direction at HT.

Interestingly, system with two differing magnetically hard materials features competition between their respective anisotropies. This becomes manifest for small n values when the DyFe_2 and ErFe_2 moments attract each other via the Fe–Fe exchange interaction, as transmitted through the YFe_2 layers. This is the coupled switching mode which is not found on a system with only one hard material: the switching states of both ErFe_2 and DyFe_2 compounds are conjointly located in one plane, and it turns out to be the Dy anisotropy that dominates the competition.

Understanding the manifold switching states present in this accurately reproducible and configurable system will hopefully prove valuable in future for the design of new generation magnetic devices.

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