Magnetization reversal via perpendicular exchange spring in FePt/FeRh bilayer films

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We present a theoretical analysis of the magnetization reversal process in a bi-layer structure with hard and soft (with metamagnetic transition) magnetic layers on an example of an FePt/FeRh bi-layer. The latter leads to the formation of a new type of exchange spring which results in a significant reduction of the switching field in the temperature range of the metamagnetic (from antiferromagnetic to ferromagnetic state) transition in an FeRh layer. Analytic expressions for nucleation and switching fields are presented along with results of numerical micromagnetic simulations. The reduction of the switching field due to the metamagnetic transition is controlled by the following microscopic parameters: (i) the interfacial exchange coupling parameter J_{12}; (ii) saturation magnetization of the FeRh layer in a ferromagnetic phase; (iii) the metamagnetic transition temperature. The switching field dependence on the J_{12} parameter is shown to saturate quickly as it approaches the bulk exchange interaction value which has been evaluated using first-principles method used also to verify the electronic nature of the metamagnetic transition. Theoretical results are discussed in the context of recent experimental observations.

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I. INTRODUCTION

In recent years there was considerable progress in the fabrication of new magnetic materials with desired properties combining different media on a nanoscale. An example of that are soft-hard magnetic nanocomposites such as NdFeB/Fe where the large saturation magnetization of Fe is combined with the high anisotropy of a NdFeB alloy.[1] Another characteristic example is giant and tunneling magnetoresistance and spin momentum transfer effects in multilayer films which consist of periodic ferromagnet/ferromagnet structures with nonmagnetic spacers.[2] The spin dynamics, transport in such systems and the magnetization reversal mechanisms are of great importance for a new generation of ultra-high density magnetic storage, magnetic field sensors, permanent magnets, etc. To predict and to control the properites of nanostructured materials it is necessary to have a deep physical picture of intrinsic processes responsible for their applications. One of the possibilities to control magnetic properties is to use materials which under certain conditions (changing pressure, temperature, magnetic field) undergo antiferro-ferro magnetic transition. Although the phenomena of metamagnetism in FeRh alloys (an abrupt increase of magnetization) was discovered in the 1930s,[3] its influence on the switching properties of layered magnetic materials has not been studied. We consider below the physical background and conduct switching field calculations of a system consisting of a high anisotropy ferromagnetic layer with perpendicular anisotropy and a soft metamagnetic layer. The temperature induced magnetization of metamagnetic layer will influence drastically magnetic properties of the composite. This system is of interest from both a fundamental and technological point of view, for instance in magnetic recording applications.

One of the central problems in a high density magnetic recording is thermostability of the written information on the long time scale.[4] This thermostability at given temperature T can be evaluated via the ratio of the anisotropy energy to the thermal energy K_uV/k_BT, where K_u is the uniaxial anisotropy constant, V is the particle (grain) volume and k_B is the Boltzmann constant. The traditional approach uses an increase of K_u to compensate for the small grain sizes required at high areal densities, but this inevitably leads to increasing of the switching field (coercivity) of magnetic media. In recording applications the magnetic field, which can be delivered by the write head is limited to approximately 10 kOe. To overcome this problem the concept of the Heat Assisted Magnetic Recording (HAMR) was introduced. A high-power laser beam was used to heat the magnetic medium and to reduce the anisotropy and switching fields.[5] The basic idea of the HAMR approach is to write bits of information at an elevated temperature (T_w) close to the Curie temperature (T_c), where the switching field is small, and store the information at room or slightly elevated temperature, where the thermostability ratio is high.[6] To achieve significant areal density advantage, the use of high anisotropy intermetallics such as ordered $L1_0$ phase of FePt has been suggested.[7] However, very large anisotropy ($K_u \sim 7\times 10^7$ erg/cc in bulk) requires a very high writing temperature, but the high temperature heating leads to many related problems (laser beam delivery, lubricant stability, etc.). That is why it is very desirable to reduce T_w while keeping the high thermostability ratio at the storage temperature.

In this paper we will consider theoretically magnetization reversal in bi-layer composite media comprised of high anisotropy layer and soft metamagnetic layer on example of FePt/FeRh bi-layers. In particular, this calculation will allow us to formulate an alternative approach to reducing of the switching field of the magnetic recording media. It was established earlier that an ordered b.c.c. alloy FeRh undergoes a metamagnetic transition from antiferromagnetic (AFM) to

ferromagnetic (FM) state; see for instance Refs. 3 and 8. A recent publication by Gruner *et al.*[9] contains a rather complete summary and references on the AFM-FM transition problem. The transition temperature (T_{tr}) depends strongly on an alloy composition and can be tuned within a wide range. Very recently it was experimentally demonstrated by Thiele *et al.*[10] that the unusual properties of the soft FeRh layer might be used to reduce considerably the writing temperature of the composite FePt/FeRh media. The switching field of the FePt/FeRh bi-layer can be reduced some 2–3 times by heating above the AFM-FM transition point due to interlayer coupling between the FePt and ferromagnetic FeRh layers.[10] The theoretical treatment of these experiments is still lacking. We will develop an adequate model of the bi-layer hard-ferromagnet/metamagnet film and show that the switching process in such a bi-layer above the AFM-FM transition temperature can be described via a new kind of "exchange spring" mechanism. The exchange spring mechanism of magnetization reversal has been known before (see Ref. 11 and references therein). A conventional exchange spring envolves an in-plane magnetization rotation (similar to the Bloch domain wall), whereas in our case the perpendicular anisotropy of FePt is combined with in-plane shape anisotropy of a metamagnetic layer producing a novel ("perpendicular") type of exchange spring. Applying a magnetic field perpendicular to the film plane, the "exchange spring" (strongly nonuniform magnetization distribution), located mainly in the soft FeRh layer, helps to switch the hard FePt layer. The paper is composed in four sections. In Sec. II we describe analytical and micromagnetic models of the FePt/FeRh bi-layer. In Sec. III we discuss the obtained results together with the calculation of model parameters from first principle band structure simulations. Finally, the summary is given in Sec. IV.

II. DESCRIPTION OF THE MODELS

The problem of magnetization reversal in composite media (bi-layer film) consisting of hard/soft magnetic layers in a perpendicular magnetic field is considered by analytical and numerical Langevin dynamics (LD) methods. We consider, in particular, bi-layer FePt/FeRh films. The bottom FeRh layer undergoes an antiferromagnetic to magnetically soft ferromagnetic phase transition at a temperature of about T_{tr} $=330$ K.[8] Hence, upon heating to temperatures above T_{tr}, an additional magnetization of the FeRh-layer appears resulting in a reduction of the coercivity H_c (switching field) of the bi-layer film. The saturation magnetization values were assumed to be $M_1=1100$ and $M_2=1270$ emu/cm^3 and the anisotropy constant values of 2×10^7 erg/cm^3 for the FePt layer and zero for the FeRh layers, respectively. Let the Oz axis be directed perpendicularly to the layers, the magnetic field and easy axis of the hard (FePt) layer be directed parallel to Oz. The coordinate $-d_1\leqslant z<0$ corresponds to the hard and $0<z\leqslant d_2$ corresponds to the soft (FeRh) layer. To describe the layer magnetizations we can use only polar angles $\theta_1(z)$, $\theta_2(z)$ due to the axial symmetry of the problem.

A. Analytical model

We will consider first a continuum approximation where some simple analytical expressions will be obtained. For the analytical model it is assumed that the uniaxial magnetic anisotropy in the FePt layer is sufficiently strong and this layer is thin such that any nonuniform magnetization process can be ignored and reversal is coherent. The magnetization of the soft FeRh layer may be nonuniform or uniform depending on the layer thickness and strength of the interlayer exchange interaction. The total magnetic energy density of the bi-layer film can be written in the form

$$F = F_1(\mathbf{m}_1)\nu_1 + F_2(\mathbf{m}_2)\nu_2 - \frac{1}{V}\int dS J_{12}\mathbf{M}_1\mathbf{M}_2, \qquad (1)$$

where $\mathbf{M}_j$ are the layer magnetizations (nonuniform, in general), $\nu_j=d_j/d$ are the relative layer thickness, $d=d_1+d_2$ is the total film thickness, J_{12} is the interlayer exchange integral, $\mathbf{m}_j=\mathbf{M}_j/M_j$, $j=1,2$.

We neglect the dependences of the layer magnetization on in-plane coordinates x, y. The magnetic anisotropy of the FePt layer given by the first order uniaxial anisotropy constant K_1 is strong and the corresponding correlation length $\sqrt{A_1/K_1}\approx2$ nm is small.[12] This allows us to consider uniform magnetization distribution for the hard layer $\theta_1(z)=\theta_1$ and write the layer energy density as

$$F_1(\mathbf{m}_1) = -K_u\cos^2\theta_1 - H_z M_1\cos\theta_1,\ K_u = K_1 - 2\pi M_1^2. \qquad (2)$$

The energy density of the second (soft) layer is (we omit the index $\theta_2\rightarrow\theta$, and use the definition $d_2=L$)

$$F_2(\mathbf{m}_2) = M_2^2\frac{L_{ex}}{L}\int_0^{L/L_{ex}} dz\left[\frac{1}{2}(\theta')^2 + \Phi(\theta)\right],$$

$$\Phi(\theta) = \frac{1}{2}h_a\cos^2\theta - h\cos\theta, \qquad (3)$$

where $h_a=2K_2'/M_2^2$, $h=H_z/M_2$ are the dimensionless fields, $K_2'=-K_2+2\pi M_2^2$, $L_{ex}=\sqrt{2A}/M_2$ is the exchange length of the soft layer (assuming its anisotropy constant $K_2\approx0$) and $z/L_{ex}\rightarrow z$ substitution is used. We neglect crystalline and induced anisotropy of the FeRh layer accounting here only the shape in-plane anisotropy. We get the estimation of L_{ex} $=12$ nm for the FeRh layer.

We assume that we have no surface anisotropy on the surfaces of the soft layer $z=0$ and $z=L$. Miniminization of the energy F_2 with respect to the function $\theta(z)$ leads to the differential equation

$$\theta'' + \frac{1}{2}h_a\sin 2\theta - h\sin\theta = 0, \qquad (4)$$

which is solved by using the boundary conditions (surface torque equations)

$$\frac{\partial\theta}{\partial z} = a\sin(\theta_0-\theta_1),\quad z=0 \text{ and } \frac{\partial\theta}{\partial z}=0,\quad z=L. \qquad (5)$$

Here the dimensionless exchange parameter is $a=(J_{12}/L_{ex})\times(M_1/M_2)$, and $\theta_0=\theta(0)$, $\theta_L=\theta(L)$.

Minimization of the total energy (1) with respect to the angle θ_1 taking into account Eq. (5) for θ_0, θ_L leads to deter-

mination of the hysteresis loop characteristics, such as nucleation field, remanent magnetization and switching field. The nucleation field (H_n) of the bi-layer is determined mainly by the soft layer. This field can be found from linearized equations (4) and (5) assuming $\theta(z) \ll 1$. We derived the following equation to describe it: $\kappa \tan(\kappa L) = a$, where $\kappa^2 = (H_a - H_n)/M_2$, $H_a = 2K_2'/M_2$. This equation has the following solutions within the limit of weak ($a \ll 1$) and strong interlayer coupling ($a \gg 1$),

$$H_n = H_a - \frac{J_{12}}{L} M_1, \quad H_n = H_a - \left(\frac{\pi}{2}\right)^2 \left(\frac{L_{ex}}{L}\right)^2 M_2. \tag{6}$$

The solution of the variational problem for the total magnetic energy of the bi-layer yields for strong enough interlayer coupling ($a \gg 1$) the following expression for the remanent magnetization $M_r = \langle M_z \rangle (H=0)$:

$$M_r = M_1 \frac{d_1}{d} + M_2 \frac{\pi}{2} \frac{L_{ex}}{d} \sqrt{\frac{M_2}{H_a}}, \tag{7}$$

where d_1 is the FePt layer thickness. The role of $L = d_2$ (the FeRh layer thickness) plays the soft layer exchange length L_{ex}. The switching field (above T_{tr}) can be calculated from the stability equation $\partial^2 F / \partial \theta_1^2 = 0$ as

$$H_{a1} \cos 2\theta_1 + H \cos \theta_1 + \frac{J_{12}}{d_1} M_2 \cos(\theta_1 - \theta_0) = 0,$$

$$H_{a1} = 2K_u / M_1, \tag{8}$$

where the angles θ_0, θ_L, θ_1 obey the equilibrium equation and the boundary conditions (5),

$$\frac{\partial F_1}{\partial \theta_1} v_1 + M_2^2 \frac{L_{ex}}{d} a \sin(\theta_1 - \theta_0) = 0,$$

$$\frac{1}{\sqrt{2}} \int_{\theta_0}^{\theta_L} \frac{d\theta}{\sqrt{\Phi(\theta) - \Phi(\theta_L)}} = L,$$

$$\sqrt{2} \sqrt{\Phi(\theta_0) - \Phi(\theta_L)} = a \sin(\theta_0 - \theta_1). \tag{9}$$

The set of the variables $\theta_1 = 0 + O(J_{12})$, $\theta_0 = \theta_L = \pi - O(J_{12})$ satisfies Eqs. (9) and gives the following simple expression for the bi-layer switching field:

$$H_{sw}(T) = -H_{a1}(T) + \frac{J_{12}}{d_1} M_2(T) \times \left[1 + \frac{J_{12}}{L} \frac{M_1(T)}{(H_{a1}(T) - 4\pi M_2(T))}\right]. \tag{10}$$

This expression is valid for weak interlayer exchange coupling but reflects the main physics of magnetization reversal in this composite media. The shift of the switching field of the FePt layer occurs above T_{tr}, and it is proportional in the main approximation to the product $J_{12} M_2(T)$ and is inversely proportional to the FePt layer thickness d_1 (surface effect). In the case of stronger exchange coupling the switching field can be obtained from the solution of the system of Eqs. (9) and substituting these solutions to Eq. (8). The expression for the switching field used by Thiele *et al.*[10] and some other authors (see, for instance, Ref. 11) can be justified only within the full coupling limit (the atomic value of the interlayer exchange integral) and for ultrathin layers with thicknesses of about a few *nm*. Equations (8) and (9) yield the switching field for an arbitrary value of the interlayer exchange coupling within the model. We note that the boundary condition (5) at the interface ($z=0$) should be essentially modified within the strong exchange coupling limit to reflect the continuous transition from the micromagnetic approach to an atomistic consideration. This modification will be considered elsewhere. We consider that in general, the continuous micromagnetic model will be inadequate in the strong coupling limit and a discrete approach involving the interatomic exchange integrals is needed in this case.

B. Discrete micromagnetic model

To justify the analytical expressions and to obtain the switching field value in the full interlayer exchange range we performed discrete micromagnetic simulations. The micromagetic model consists of a set of infinite parallel atomic planes, reflecting the high quality of the film in the *xy* direction. Consequently, the total system may be represented as a chain of atomic magnetic moments with magnetostatic energy corresponding to that of infinitely charged planes in accordance with Eqs. (2) and (3). The total energy density of the system (normalized to the system volume V) has the form

$$F = \frac{1}{d} \left\{ -\sum_i K_i (m_i \vec{e}_i)^2 c_i - M^i (\vec{H} \vec{m}_i) c_i - \frac{J_{ex}^i}{a_i^2} (\vec{m}_i \vec{m}_{i+1}) + 2\pi {M^i}^2 m_i^{z^2} c_i \right\}, \tag{11}$$

where c is the out-of-plane interatomic distance, a is the in-plane interatomic distance, $\boldsymbol{m}_i$ is the atomic magnetic moment normalized to saturation magnetization M^i and $\boldsymbol{e}_i$ is the anisotropy direction in the i-th layer.

The hysteresis cycle was calculated using the Langevin dynamics simulation, i.e., integrating the Landau-Lifshitz-Gilbert (LLG) equation of motion for the layer magnetizations with the energy density (11) and a random field representing temperature fluctuations. The inclusion of the random term of the order of $10^{-5} H_{a1}$ in the hard and soft layers was necessary to push the system from unstable extrema corresponding to the anisotropy maxima, at which there is no torque in the LLG equation. The simulations were run for a system consisting of 100 FePt and 200 FeRh atomic planes. The interatomic distance parameter was chosen to be 4×10^{-8} cm and the bulk interatomic exchange of 10^{-13} erg. The interlayer exchange, $J_s = a^2 M_1 M_2 J_{12}$ ($J_{ex}^i = J_s$ at the interface), where the index i belongs to the FePt layer and $i+1$ belongs to the FeRh layer) was varied from 10^{-15} erg to that of the bulk exchange integral. This exchange integral was estimated for the FePt(001)/FeRh(001) interface by *ab-initio* calculations.

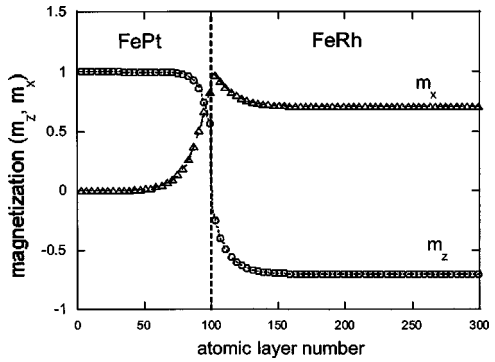

FIG. 1. Calculated magnetization distribution across the FePt/FeRh bi-layer structure using the model with 100 for FePt and 200 atomic planes for FeRh. Left panel: the normalized M_z (circles) and M_x (triangles) components of magnetization as a function of the atomic plane number. Right panel: orientation of the atomic planes magnetization (with each 10-th layer shown). $H_z=-0.5\ H_{a1}$.

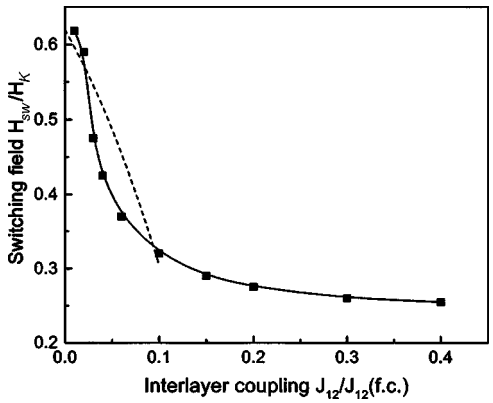

FIG. 2. Dependence of the switching field of the bi-layer FePt/FeRh film on the interlayer exchange coupling constant J_{12}. The dashed line corresponds to the solution given by Eq. (10). The number of the FePt planes is 100, the number of FeRh planes is 200. $K_1=2\ 10^7$ erg/cm^2, $M_1=1100$ G, $M_2=1270$ G. The intralayer exchange integral is 10^{-13} erg.

III. RESULTS AND DISCUSSION

A typical hysteresis cycle consists of two parts. The first part corresponds to the nonuniform magnetization rotation in the soft layer and has a typical shape of that of the hysteresis cycle when the external field is applied along the hard anisotropy axis. The second part corresponds to magnetization jump to the field direction (switching of the FePt layer). Figure 1 shows the form of the magnetization distribution ("exchange spring") across the film thickness. This magnetization nonuniformity can be treated as a Neel-like domain wall. Penetration of the wall into both hard and soft layers is clearly seen. The form of the wall slightly changes when the applied field becomes more negative. The simulations confirmed our initial assumption that the polar magnetization angle φ is practically constant during the magnetization reversal. Note that formally the profiles of magnetization components presented in Fig. 1 are similar to the calculation of an easy-axis/easy-plane TbFeCo/PtCo bi-layer by Hu *et al.*[12] within a continuous micromagnetic model. However, they used the boundary conditions on the interface within the strong coupling limit ($\theta_0=\theta_1$) and did not account for any difference of the interface and bulk exchange integrals. In contrast, in our analytical model based on the boundary conditions given by Eq. (5) and its numerical realization, we allow arbitrary values of the interface exchange integral and nonzero jump of the magnetization angle on the FePt/FeRh interface.

Figure 2 presents a calculated dependence of the coercive field on the value of the interlayer exchange parameter. The interlayer exchange integral J_{12} is given in units of its maximal value $J_{12}^{\text{f.c.}}$ which corresponds to an atomistic interlayer exchange integral on the FePt/FeRh interface. The $J_{12}^{\text{f.c.}}$ can be found from the equation $J_{12}^{\text{f.c.}}=IS_1S_2/a^2M_1(0)M_2(0)$, where I is the surface interatomic Fe(Pt)–Fe(Rh) exchange integral and S_1, S_2 are the effective spins of the layers. The switching field as a function of the exchange coupling J_{12} sharply decreases with $J_{12}/J_{12}^{\text{f.c.}}$ ratio increasing and practically saturates at $J_{12}/J_{12}^{\text{f.c.}}\approx 0.1$. The actual value of the ratio $J_{12}/J_{12}^{\text{f.c.}}$ depends strongly on the quality of the FePt/FeRh interface. We consider that the value $J_{12}/J_{12}^{\text{f.c.}}\sim 0.05-0.1$ is a reasonable estimation of the coupling strength for the FePt/FeRh bi-layer interface. It should be noted that the coercive field drops rapidly with increasing $J_{12}/J_{12}^{\text{f.c.}}$ and than saturates at the values of $J_{12}/J_{12}^{\text{f.c.}}$, which are considerably lower than the full coupling limit. For $J_{12}=0$ the simulations give $H_{sw}/H_K=0.618$ ($H_K=2K_1/M_1$) in good agreement with Eq. (10)—$H_{sw}/H_K=1-(4\pi M_1{}^2/2K_1)=0.62$. Equation (10) corresponds to an initial decreasing part of the dependence $H_{sw}(J_{12})$ on J_{12} and is approximately valid at $J_{12}/J_{12}^{\text{f.c.}}<0.1$ (see Fig. 2). The numerical simulations showed that the function $H_{sw}(J_{12})$ saturates practically at $J_{12}/J_{12}^{\text{f.c.}}>0.1$. Also, analytical Eq. (7) with the parameters as in numerical simulations yield the remanence magnetization $M_r=0.21\langle M_s\rangle$, where $\langle M_s\rangle=M_1\nu_1+M_2\nu_2$. This value is also in good agreement with the results of the LD simulations for the interlayer exchange integral I in the range from 10^{-14} to 10^{-13} erg.

The switching field H_{sw} is plotted as function of temperature in Fig. 3 on the basis of Eq. (10). We used the relation $H_{a1}(T)=\alpha M_1(T)$ for the FePt layer[13] and have found the temperature dependences of the layer magnetizations $M_1(T)$, $M_2(T)$ from a solution of mean-field equations using the Brillouin functions with $S_1=S_2=3/2$. The temperature dependence of the FeRh layer magnetization M_2(T) was calculated for $T>T_{\text{tr}}$ assuming that a hypothetic FM-phase is stable also at $T<T_{\text{tr}}$ with the value $M_2(0)$ calculated using an accurate band structure method. To plot the temperature dependence of the switching field H_{sw}(T) in Fig. 3 we used the values $M_2(\text{T}_{\text{tr}})=930$ G, $T_{\text{tr}}=460$ K and $T_{c2}=730$ K from the experiment by Thiele *et al.*[10] on FePt/FeRhIr bi-layer films. A considerable reduction of the value of H_{sw}(T) of the bi-layer in the vicinity of the FeRh AFM-FM transition temperature is clearly demonstrated. This effect can be explained as follows. Just above the metamagnetic phase transition temperature T_{tr} magnetization of FeRh layer increases sharply up to the value M_2(T). This magnetization is exchange coupled to the FePt magnetization. Applying perpen-

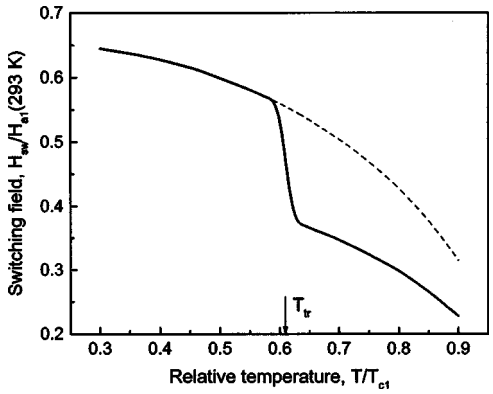

FIG. 3. Dependence of the switching field of the bi-layer FePt/FeRh on temperature crossing the AFM-FM transition point. The exchange coupling parameter is $J_{12}/d=1$. The solid line was calculated from Eq. (10), the dashed line corresponds to the isolated FePt layer. The temperature is in units of $T_{cl}=750$ K of the FePt layer. The transition temperature $T_{tr}=460$ K corresponds to the $Fe_{48}Rh_{49}Ir_3$ metamagnetic layer (Ref. 10).

dicular to the film plane magnetic field this coupling results in developing the exchange spring (strongly nonuniform magnetization distribution) in the soft FeRh layer and a considerable reduction of the switching field of a bare FePt layer. If the AFM-FM transition is sharp this leads to the strong temperature dependence of the switching field (jump) of the composite media crossing the transition point (T_{tr}) of the FeRh layer. The jump in the intrinsic switching field H_{sw}(T) results in more smooth, but experimentally observable, jump in temperature dependent coercivity H_c(T). To compare with the Thiele *et al.* experiment[10] we estimated the dependence H_c(T) by the Sharrock law[4] assuming small dispersion of the easy axis of 5–6° with respect to the film normal. The agreement between the calculated and measured values of H_c(T) is satisfactory if in the Sharrock law we use the activation volume $V=0.24\times10^{-18}$ cm^3. This value corresponds to the nonuniform in film plane reversal mode in the FePt layer which nucleates at the FePt/FeRh interface. The value $V^{1/3}=6.2$ nm corresponds approximately to the FePt domain wall width $\delta=\pi\sqrt{A_1/K_1}\approx6$ nm. But a detailed description of the nonuniform in the film plane magnetization reversal is beyond this paper and will be considered elsewhere.

We also evaluated microscopic parameters which according to the above analysis control the effect of switching field reduction in the FePt/FeRh bi-layer system. In particular, the magnetization saturation values at 0 K [$M_1(0)$ and $M_2(0)$], interfacial exchange interaction constant J_{12} and a critical temperature of the FM-PM transition (for FeRh) appear as the main model parameters. The AFM-FM transition temperature (T_{tr}) controls temperature range where the switching field is sharply reduced (see Fig. 3). Thus the mechanism of the metamagnetic transformation emerges as an important factor, which may affect applications of the analyzed here effect of the perpendicular exchange spring in FePt/FeRh bi-layers. Gruner *et al.*[9] performed statistical simulations for AFM-FM metamagnetic transformation in FeRh with the Blume-Capel model Hamiltonian inspired by the first-principles total energy calculations. Results of these simulations in general support the electronic origin of the AFM-FM metamagnetic transformation. Our calculations of the magnetic interactions parameters have been performed with the first-principles band structure technique[14,15] and allow us to demonstrate directly that the AFM-FM transition in FeRh is triggered by electronic instabilities rather than the lattice expansion. In contrast with previously reported results[9] to evaluate saturation magnetization we employ a full potential band structure method based on the use of liner-muffin-tin orbitals (FLMTO)[15] which allows for a more accurate evaluation of the atomic magnetic moments. The local density approximation with generalized gradient correction yields $M_1(0)=1320$ G and $M_2(0)=1540$ G. The later characteristic cannot be directly measured due to the FM-AFM transition which occurs at about 100–200 °C. The exchange interaction parameters between atomic layers also has been evaluated using the method proposed in Ref. 14 by calculating total energy of the many-electron system (FePt/FeRh) with a noncollinear arrangement of the spin moments. These calculations in combination with the Stoner's model[13] (to account for the difference in the induced atomic moments for Pt $m_{Pt}=0.36\mu_B$ and Rh $m_{Rh}=1.03\mu_B$) allow us to estimate the maximum value of J_s for the case of an ideal [atomically sharp (001) textured] interface which appears to be about 0.6×10^{-13} erg.

IV. CONCLUSIONS

The magnetization reversal in the FePt/FeRh bi-layer film is described as field-evolution of the domain wall in the soft FeRh layer ("exchange spring"), which induces switching of the hard FePt layer magnetization via the interlayer exchange coupling. This new kind of "exchange spring" can be represented as a Neel-like domain wall localized at the FePt/FeRh interface and penetrating mainly to the soft (FeRh) layer. The exchange and magnetostatic energy stored in this wall increase with the applied field and lead to a decrease of the energy barrier and result, eventually, in the magnetization switching of the FePt layer in a magnetic field which is considerably lower than the switching field of the bare FePt film. The switching process can be described as propagation of the domain wall through the FePt layer starting from the FePt/FeRh interface.

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