Precessional reversal in exchange-coupled composite magnetic elements

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Magnetization reversal in composite exchange-coupled dual-layer magnetic elements can occur in the regime of precessional reversal. Compared to the regime of damping reversal in composite elements, the regime of precessional reversal exhibits substantially reduced reversal fields with modified angular dependence. Precessional reversal in the composite elements can occur for write field rise times of more than an order larger than those in homogeneous (single-layer) elements. Such long rise times can be achieved in practical writing systems even for materials with an ultrahigh anisotropy. The identified phenomena have potential applications in high density hard drives and magnetic random access memory systems. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2801362]

Precessional reversal in exchange-coupled composite magnetic elements is investigated. It is shown that, in addition to substantially reduced reversal fields, a remarkable property of precessional reversal in such elements is that it allows for write field rise times an order of magnitude greater than those in homogeneous elements.

Modern trends in constructing magnetic storage and memory devices with ultrahigh density[1–3] lead to the requirements of using magnetic elements of small size and high thermal stability. The high density and small size require fast switching rates, whereas the high thermal stability may require using magnetic elements with high anisotropy. One strategy to achieve fast reversal with reduced reversal field is to use the phenomenon of precessional reversal, which allows for reversal fields significantly below the classical Stoner-Wohlfarth limit.[4] However, for (macroscopically) homogeneous magnetic elements, this phenomenon occurs only when the write magnetic field rise time is on the order of a precessional oscillation time in the material.[5–9] For materials with ultrahigh anisotropy the required write field rise times can be extremely short, which often is unachievable in practical write systems. If one could identify structures that lead to precessional reversal for write field rise times substantially longer than the half-precessional time, it could allow using the phenomena of precessional reversal in a wide range of applications.

Recently, exchange-coupled composite structures, which comprise layers with high and low coercivities coupled ferromagnetically through their common interfaces, were proposed to reduce the reversal field and enhance the thermal stability of magnetic elements.[10,11] These structures were extensively investigated and many of their important properties have been identified.[10–13] However, their dynamic behavior in the regime of precessional reversal has not been studied.

In this letter, dynamics of precessional reversal in exchange-coupled dual-layer magnetic elements is studied by means of micromagnetic simulations. Dependences of the element's reversal field and required head field rise time on the element parameters and write field angle are carefully explored. The demonstrated increase of the required head field rise time can allow using conventional write systems even for elements with a very high anisotropy. These structures and phenomena can find important applications in high density hard drives and magnetic random access memory (MRAM) components.[3]

Consider a composite dual-layer magnetic element of square horizontal cross sectional of size w, which in the vertical dimension comprises a hard (bottom) layer of thickness t_h and uniaxial vertical ($\hat{\mathbf{y}}$ directed) anisotropy with a high anisotropy energy K_h and a soft (top) layer of thickness t_s and $K_s=0$ [see the inset in Fig. 1(a)]. Both layers are characterized by a damping constant α and saturation magnetization M_s. The layers are coupled ferromagnetically with exchange energy per surface area J_s. An external magnetic field $\mathbf{H}_{\text{ext}}$ applied under an angle φ to the vertical axis in the x-y plane is $\mathbf{H}_{\text{ext}}=-H_a[1-2\exp(2t/\tau)](\hat{\mathbf{x}}\cos\varphi+\hat{\mathbf{y}}\sin\varphi)$, where H_a is the field strength and τ is the field rise time from 0 to H_a. When H_a is higher than a certain reversal field H_r, the magnetization state reverses from $\hat{\mathbf{y}}$ to $-\hat{\mathbf{y}}$ direction. The values of H_r and magnetization dynamics significantly depend on φ and α.

The magnetization reversal was studied numerically by investigating solutions of the Landau-Lifshitz-Gilbert equation, which includes the precessional and damping terms calculated based on the effective magnetic field comprising the Zeeman, anisotropy, exchange, and magnetostatic compo-

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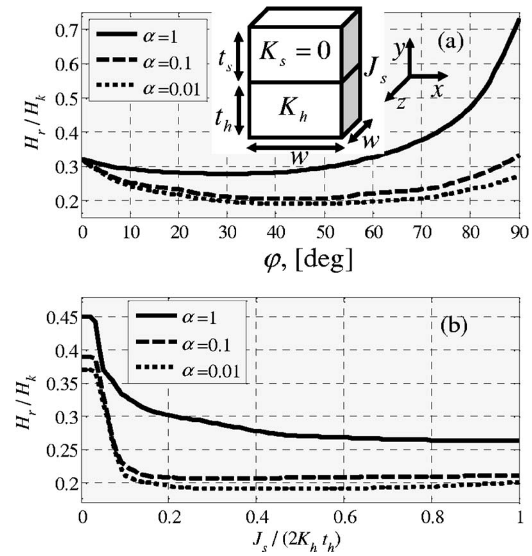

FIG. 1. Normalized reversal field for field rise time τ=0 as a function of (a) the external field angle for $J_s/(2K_h t_h) \approx 0.32$ and (b) the normalized exchange coupling for φ=45°.

nents. The composite element was discretized into small cubic cells with nonuniform magnetization allowed in each cell.[14] The cell size was chosen to assure fully convergent and accurate results. In all simulations, the structure parameters were chosen as w=10 nm, $t_s=t_h$=5 nm, M_s =500 emu/cc, $K_h=3.75\times10^6$ erg/cc, and $H_K=2K_h/M_s$ =15 kOe. The exchange constant was assumed to be A $=0.25\times10^{-6}$ erg/cm corresponding to the exchange length of $l_{ex}=A^{1/2}/M_s$=10 nm. The values of φ, τ, and J_s varied as discussed next.

First, we assume that the external field is applied instantaneously (i.e., τ=0) and study the reversal field H_r for small and large damping constants α. Figures 1(a) and 1(b) depict the reversal field H_r as a function of the angle φ and exchange coupling energy J_s, respectively. In Fig. 1(a), which shows H_r vs φ for a given J_s, it is found that for external fields applied by φ=0, the reversal field is identical for any α. However, the situation changes for tilted fields ($\varphi \neq 0$). The curve for a large damping constant α=1, which corresponds to the regime of damping reversal, agrees well with the curves obtained in other works.[10,11,15] The reversal field is found to decrease substantially with a decrease of the damping constant (e.g., α=0.1 and 0.01 as compared to α =1). For example, the decrease is about 30% for φ=45° and it is more than twofold for larger angles. In addition, for low α (and τ), the angular dependence of H_r becomes essentially symmetric with a minimum around φ=45°. Moreover, apart of small angular ranges around φ=0 and φ=90°, the angular dependence of H_r has only minor deviations from its minimal value. This behavior is different compared to often demonstrated results where the angular dependence is asymmetric and maximal reversal fields are obtained for φ =60°–90°.[10,11,15] In Fig. 1(b), which shows H_r vs J_s for a given φ=45°, it is evident that H_r is substantially smaller for smaller α for all values of J_s. The maximal relative decrease of H_r for small α, i.e., the ratio between H_r for a small α =0.01 and a large α=1 is found at $J_s/(2K_h t_h) \approx 0.1$. Our additional simulations show that the reversal field reduction is even more pronounced for larger ratios of t_s/t_h and saturation magnetization M_s of the soft layer.

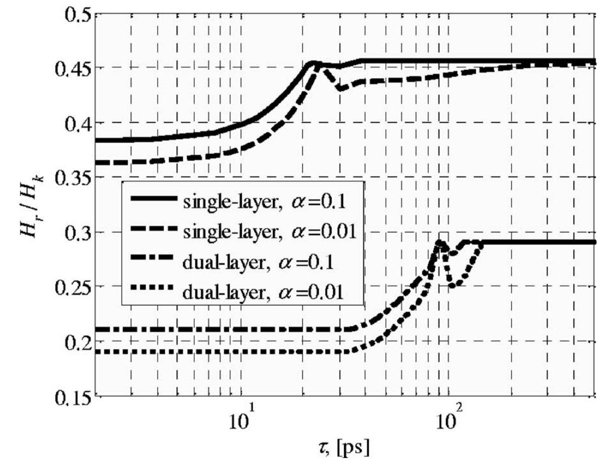

FIG. 2. Normalized reversal field vs rise time for external field with φ =45° and $J_s/(2K_h t_h) \approx 0.32$ for single- and dual-layer elements.

The reduction and change of behavior of H_r for decreased α are associated with the phenomenon of precessional reversal. As elucidated next, precessional reversal in composite elements has several unique properties as compared to precessional reversal in homogeneous elements.[5–7]

An important practical parameter characterizing the operation of the considered structures is the external field rise time that can lead to reversal in the precessional regime. To this end, Fig. 2 shows H_r applied at an angle of 45° as a function of the rise time τ and low damping constant α. The dual-layer element parameters are the same as in Fig. 1(a) and $J_s/(2K_h t_h) \approx 0.32$. The homogeneous (single-layer) elements are with size/parameters identical to those of the hard (bottom) layer of the dual-layer element. It is found that the reversal fields in both dual- and single-layer elements decrease rapidly from a level H_{high} to a level H_{low} with decreasing τ. The transition will be characterized by times $\tau_{0.2}$ and $\tau_{0.8}$ defined as rise times that lead to the reversal field levels $H_{low}+0.2(H_{high}-H_{low})$ and $H_{low}+0.8(H_{high}-H_{low})$, respectively. For rise times $\tau < \tau_{0.2}$, reversal occurs in the precessional regime characterized by the reduced reversal fields, as in Fig. 1(a). For $\tau > \tau_{0.8}$, reversal occurs in the damping regime characterized by significantly higher reversal fields; damping reversal can be described by several models including the Stoner-Wohlfarth model for single-layer elements[4] and two-spin or chain models for composite elements.[12,13,16] In the regime of damping reversal, H_r is essentially identical for any α and its angular dependence is given by the full line in Fig. 1(a). It is further evident that while qualitative behavior of all curves in Fig. 2 is similar, the times $\tau_{0.2}$ (i.e., the rise time required for precessional reversal to occur) for the dual-layer element are much larger than those for the single-layer element.

To characterize the rise times $\tau_{0.2}$ and $\tau_{0.8}$, Fig. 3 depicts their dependence on the angle and the coupling energy. In Fig. 3(a), for the dual-layer element, $\tau_{0.2}$ and $\tau_{0.8}$ are obtained in the ranges of 50–110 ps and 84–250 ps, respectively. The dependence is essentially flat with some increase toward the angles $\varphi < 15°$ and $\varphi > 75°$. For the single-layer element, $\tau_{0.2}$ and $\tau_{0.8}$ are 11 and 20 ps, respectively. The value of $\tau_{0.8}$ obtained for the single-layer element matches the single precessional time in a homogeneous element, which approximately is given by $2\pi/\gamma H_K$=23.6 ps. The values of $\tau_{0.2}$ and $\tau_{0.8}$ for the dual-layer element are from more than 5 to 10 times larger than those for the single-layer elements.

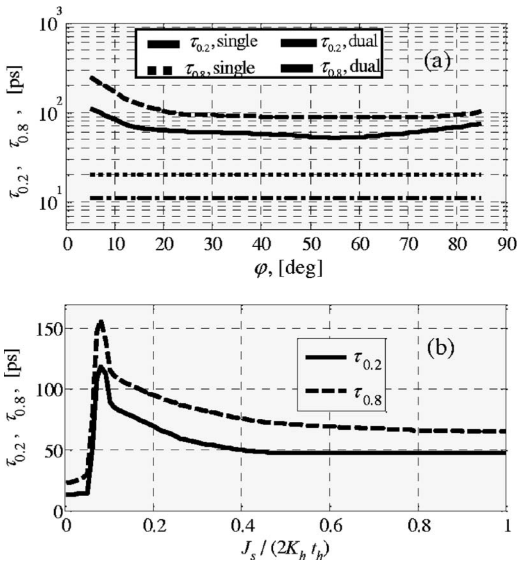

FIG. 3. Characteristic rise times as a function of (a) the external field angle for $J_s/(2K_h t_h) \approx 0.32$ and (b) the normalized exchange coupling for $\varphi = 45°$.

Figure 3(b) shows the dependence of $\tau_{0.2}$ and $\tau_{0.8}$ on J_s. For very weak exchange ($J_s/2K_h t_h \leq 0.05$), the characteristic rise times $\tau_{0.2}$ and $\tau_{0.8}$ have values close to those obtained for the homogeneous element. With increase of J_s, $\tau_{0.2}$ and $\tau_{0.8}$ increase rapidly and reach (significant) maximal values of $\tau_{0.2} = 110$ ps and $\tau_{0.8} = 160$ ps at $J_s/2K_h t_h = 0.09$. It is worthwhile mentioning that the optimal $J_s/(2K_h t_h) = 0.09$ leading to the maximal $\tau_{0.2}$ and $\tau_{0.8}$ corresponds to the largest ratio between H_r for high damping ($\alpha = 1$) and low damping ($\alpha = 0.01$) regimes [see Fig. 1(b)], thus showing an intimate relation between the rise time and the decrease of the reversal field. Further increase of J_s ($J_s/2K_h t_h > 0.09$) leads to decrease of $\tau_{0.2}$ and $\tau_{0.8}$. For large values of J_s ($J_s/2K_h t_h \geq 0.4$), $\tau_{0.2}$ and $\tau_{0.8}$ have nearly constant values of $\tau_{0.2} = 42$ ps and $\tau_{0.8} = 65$ ps. This behavior can be explained as follows. With very weak J_s, the effect of exchange coupling is negligible. The hard-layer reversal is mostly by a larger magnetic field, whereas the soft layer affects the hard-layer reversal through a weak magnetostatic field. On the other hand, for very large J_s, the composite element reverses nearly uniformly and behaves like a homogeneous element with a reduced coercivity. In the limit of an infinitely large l_{ex} and J_s, the effective coercivity is expected to be $H_k/2$, which provides estimates on the characteristic rise times of $\tau_{0.2} = 24$ and $\tau_{0.8} = 44$ in this limiting case. These values indeed agree with our results. With intermediate values of J_s around $J_s/(2K_h t_h) = 0.1$, the soft and hard layers reverse separately but with strong interactions. The magnetization in the soft layer starts reversing with smaller field but relatively slowly because of the coupling to the hard layer, and the soft-layer reversal initiates the magnetization reversal in the hard layer. Therefore, the delay in the onset of the hard-layer reversal explains the increase of the required rise time.

We have studied precessional reversal for various structure parameters. With a fixed value of α for the hard layer and varied values of α for the soft layer, a similar trend of reversal field and rise time was found. Increase of the required rise time was found to be even more pronounced for larger ratios of t_s/t_h, which was associated with the existence of a domain wall in the soft layer.[16] This substantial increase of the required rise time is a remarkable property of ferromagnetically coupled dual-layer elements. The longer rise times for lower reversal fields is crucial in various applications because they can be practically achievable by (extensions of) existing technologies even for structures implementing materials with very large coercivities.

In conclusion, we demonstrated that reversal in exchanged-coupled dual-layer magnetic elements can occur in the regime of precessional reversal, which is characterized by several unique properties. Compared to damping reversal, the precessional reversal fields are substantially reduced. The reversal field under precessional reversal has a weak angular dependence over a wide angular range. A remarkable property of precessional reversal in exchange-coupled composite (dual-layer) elements is that it can occur for write field rise times of an order larger than those in single-layer (homogeneous) elements. The required rise time can be controlled by varying the strength of the coupling. For a given structure, an optimal value of the exchange energy can be found that leads to the maximal rise time permitting for precessional reversal regime. The increased rise times can be achieved in practical write systems even for materials with ultrahigh coercivities. Characteristics of the identified phenomena can be further controlled by tuning separately the parameters of the soft and hard layers as well as the external field time dependence. Similar phenomena are expected to occur in more complicated, e.g., multilayered, composite media. The identified phenomena are anticipated to find important applications to construct high density hard drives implementing composite patterned media and MRAM systems.[3]

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