Microwave assisted magnetization reversal in composite media

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Magnetic reversal in exchange-coupled composite elements under microwave fields is characterized by several unique properties including reduced reversal fields, microwave fields, microwave resonant frequencies, and reduced sensitivity to anisotropy distributions as compared to homogeneous elements. We find that reversal can occur in uniform and nonuniform regimes. The uniform regime is characterized by coherent spin precession enhancement by the microwave field. In the nonuniform regime domain walls in the soft layer mediate reversal and under linearly polarized microwave fields, can lead to a formation of localized reversal/nonreversal areas in the “applied field-frequency” phase plane. © 2009 American Institute of Physics. [DOI: 10.1063/1.3133354]

A major limitation to the continued evolution of high-density magnetic recording is the superparamagnetic effect, which leads to spontaneous reversal when magnetic particles become too small.12 Overcoming the superparamagnetic effect requires using materials with a very high anisotropy, which often translates into an excessively high reversal fields. Several methods including heat-, precessional reversal-, and microwave-assisted magnetic recording schemes have been proposed to solve this writability problem.3–11 Microwave assisted magnetic recording (MAMR) schemes allow for low reversal fields even for media with high anisotropy.6,9 The reversal field reduction is due to resonant energy pumping occurring when the microwave frequency matches the medium ferromagnetic resonance (FMR) frequency. MAMR relies on our ability to generate local microwave fields of sufficiently high frequency and strength. Such microwave fields can potentially be generated using spin-torque driven oscillators.11,12 Combined with a conventional recording head, they can result in a system that generates both switching fields and assisting local microwave fields. However, there are also several obstacles that may complicate practical implementations of MAMR schemes. For high anisotropy materials, the required microwave field strength and frequency may be very high. Another important potential problem is associated with inherent fluctuations of the medium anisotropy field. Such fluctuations lead to significant fluctuations of the FMR frequency and reversal field, which result in high bit error rates.

In this letter we describe MAMR mechanisms in composite elements comprising exchange-coupled soft and hard sections under linearly polarized microwave field.13–17 Such composite elements have been recently shown to be attractive for magnetic recording due to their reversal and thermal stability properties.13–19 We show that composite elements have several unique properties important for MAMR. Composite elements with high anisotropy hard sections can be reversed with low reversal fields, microwave fields, and microwave frequencies. We demonstrate that reversal field dependences in composite elements are different in the regimes of coherent and incoherent reversal and the reversal dynamics may exhibit surprising behaviors. In addition, we show that fluctuations of the reversal fields caused by fluctuations of the anisotropy field are substantially reduced compared to those for homogeneous elements.

The elements investigated comprise exchange-coupled soft (top) and hard (bottom) sections (see the inset in Fig. 1). The hard section has a vertical uniaxial anisotropy energy $K_h$ and size $w, w, t_h$ in the $x, y, z$ dimensions. The soft section has a vanishing anisotropy and size $w, w, t_s$. Both sections have a damping constant $\alpha$, saturation magnetization $M_s$, and exchange length $l_{ex} = \sqrt{A/M_s}$ where $A$ is the exchange constant. The sections are coupled ferromagnetically over their common interface with surface energy $J_s$. An external magnetic field simultaneously comprises a switching field and a microwave field. The switching field is applied with an angle

![FIG. 1. Reversal field vs $f_{mic}$ for different elements with $H_{0}=60$ kOe, $\alpha=0.1$, $l_{ex}=1.5w$, and $t_s=1.5w$. (a) $H_{mic}=0.05H_0=3$ kOe, $t_s=1.5w$; (b) $H_{mic}=0.07H_0=4.2$ kOe, $t_s=1.5w$ for the composite element, and $H_{mic}=0.14H_0=8.4$ kOe, $t_s=1.5w$ (where $t_s$ is the height) for the homogeneous element. The shadowed areas represent the conditions under which reversal occurs.]

$\text{soft}$

$\text{hard}$

$\text{homogeneous}$

$\text{soft}$

$\text{hard}$

$\text{homogeneous}$

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45° to the vertical (z) axis in the x-z plane and it has the time dependence $H_r \text{erf}(2\tau / \tau)$, where $H_r$ is the reversal field and $\tau$ is the switching field rise time. The microwave field is applied along the x axis and it has an amplitude $H_{mw}$ and frequency $f_{mw}$. For a given $H_{mw}$, when the microwave frequency matches a FMR frequency $f_{mw}^{res}$ of the element the reversal field $H_r$ reaches its minimum $H_r^{res}$.

Magnetization reversal is studied by numerically solving the Landau–Lifshitz–Gilbert equation with discretization chosen to obtain full convergence. For all presented results, $\lambda = 10^{-6}$ erg/cm, $\alpha = 0.1$, $M_s = 1250$ emu/cm$^3$, $J_s = 17$ erg/cm$^2$, $\tau = 0.1$ ns, and $t_s = 1.5w$. More simulations with a wide range of $\alpha$, $\tau$, and $J_s$ were also pursued with results qualitatively similar to those presented. All results are scalable with respect to the ratios $M_s / H_K$ and $w / l_{ex}$. Thermal stability of all (composite and homogeneous) elements is determined by the domain wall energy $E_{dw} = 4w^2 \sqrt{AK_h}$ in the hard section provided $t_s$ is larger than the domain wall length $l_{dw} = 4t^4/\sqrt{AK_h}$. The chosen parameters are representative of materials that may be used for high-density recording media (e.g., FePt). For example, a medium comprising an array of elements with pitch of 8 nm and $w = 5$ nm $t_s = 1.5w = 1.15t_{dw}$ would result in a recording density of 10 Tbit/in$^2$ with thermal barrier of around 100k$\theta_F$ (with $T = 400$ K), which was confirmed numerically via the elastic band method.

First, we compare $H_r$, $H_{mw}$, and $f_{mw}$ for composite and homogeneous elements. Figure 1 depicts $H_r$ versus $f_{mw}$ for different elements with $H_K = 60$ kOe. The reversal field dependences for all elements exhibit deep minima. The homogeneous element and composite element with a thin soft section exhibit a typical behavior attributed to MAMR, i.e., resonant curves with deep minima are obtained and reversal occurs for any values of $H_r$ greater than the reversal field $H_r$ (this is visualized by the shadowed areas in Fig. 1). For the composite element with a thicker soft section, the behavior is completely different. For this case, reversal is only possible in a certain areas in the $H_r / f_{mw}$ plane. Two areas are observed. The top area is the same as that obtained without any microwave field. The bottom (relatively small) area only exists under microwave field and is related to resonance phenomena. Surprisingly, there is a gap between these two areas in which no reversal occurs.

From Fig. 1, for the homogeneous element, the minimal reversal field is $H_r^{res} = 0.19H_K$ and the corresponding frequency is $f_{mw}^{res} = 105$ GHz. The resonant frequencies scale with the anisotropy, are very high, and may be hard to realize in practical systems. On the other hand, for the composite elements, $f_{mw}^{res}$ drops substantially. For example, for the element with $t_s = 1.5w$, $f_{mw}^{res}$ is around 20 GHz. The reduction of $f_{mw}^{res}$ is accompanied with a significant reduction of $H_r^{res}$, e.g., for the elements in Fig. 1, $H_r^{res}$ can be below 0.09$H_K$. Another important finding is that these reduced $f_{mw}^{res}$, and $H_r$ are obtained for low microwave fields $H_{mw}$. For composite elements of $t_s = 0.75w$, the microwave field is $H_{mw} = 0.07H_K$; for composite elements of $t_s = 1.5w$, the microwave field is $H_{mw} = 0.05H_K$. These can be further reduced at a cost of some increase of $H_r$. These low $H_{mw}$ should be compared to a significantly larger $H_{mw} = 0.14H_K$ for the homogeneous element.

The obtained resonant behavior of $H_r^{res}$ is associated with resonant effects. When the microwave frequency is near a FMR frequency, the system can efficiently absorb and accumulate energy from the microwave field. For homogeneous elements, the FMR frequencies are determined mainly by anisotropy field $H_K$. For composite elements, the FMR frequencies are determined mostly by the external fields parameters, the element material parameters $H_K$ and $J_s$, and the element geometrical parameters. The obtained FMR frequency reduction is due to the fact that the effective field in the soft section of the elements is given only by the weak external and coupling fields. Reversal in the soft section assists reversal in the hard section thus reducing $H_r$ and $H_{mw}$. Depending on the thickness of the soft and hard sections reversal can occur in uniform or nonuniform regimes.

For thin elements, precession and reversal in both soft and hard sections occurs coherently but the spin angle in the sections depends on coupling. Precession is first enhanced coherently in the soft section leading to initiation of the soft section reversal. This assists reversal in the hard section thus leading to the reduction of the element’s reversal field. The FMR frequency is reduced due to lower soft section effective field.

For thicker elements, precession and resonant reversal occurs incoherently (Fig. 2). When the applied field and the soft section thickness are such that a domain wall in the soft section cannot completely fit [Fig. 2(a)], precession in the top (free) end of the soft section is enhanced and its top part is reversed. This reversal propagates from the top to the bottom end of the soft section and then it assists reversing the hard section. The associated required energy is low, hence the significant reduction of the reversal field. The effective field in the top end of the soft section is low, which results in a significant reduction of the FMR frequency. When the applied field and the soft section thickness are such that $t_s$ is sufficiently greater than the domain wall in the soft section, the mechanism of the reversal is very different [Fig. 2(b)]. First a domain wall is formed in the top part of the soft section and it starts propagating. However, the linearly polarized microwave field affects differently the two sides of the domain wall (since the considered linearly polarized microwave field contains two circular polarized fields with opposite polarization sense). As a result the microwave field cannot pump energy into the system anymore and the domain wall stops at the top part of the soft section. If the fields $H_{mw}$ and $H_a$ are removed at this stage, the domain wall moves back and no reversal occurs. For sufficiently large $H_a$, reversal occurs regardless of the presence of the microwave field (the upper reversal area for the composite elements in

![FIG. 2. (Color online) Schematic representation of the magnetization time evolution the incoherent mode: (a) for moderate soft-section thicknesses, a domain wall is formed in the soft section assisting reversal; (b) for sufficiently large soft section thicknesses, the domain wall stops at the top part of the soft section with no reversal.](http://apl.aip.org/apl/copyright.jsp)
Deviations of $H_r$ lead to more than 50% deviations of $H_r$. This behavior may lead to severe limitations on MAMR if homogeneous elements are used. The situation is very different for composite elements, where deviations of $H_r$ and $f_{mw}^{res}$ are substantially reduced and the area of reversal of these two cases overlap with each other for a major part on the phase graphs. For the composite element with $t_r=0.75w$, deviations of $f_{mw}^{res}$ are only 3% for 10% deviations of $H_K$, which represents a fivefold improvement over the homogeneous element. For $t_r=1.5w$, the reversal areas are slightly shifted but there is an overlapping area where almost no dependence of $f_{mw}^{res}$ and $H_r$ on $H_K$ is present. The reduction of the deviations of $f_{mw}^{res}$ has a physical source similar to that leading to the reduction of $f_{mw}^{res}$ itself, i.e., $f_{mw}^{res}$ are significantly affected by the soft section where the field is mostly given by the external and exchange fields but not by $H_K$. This significant improvement correlates with results obtained for conventional domain wall assisted reversal. Due to the potential improvements to bit error rates, this weak sensitivity to the anisotropy field distribution is a crucial advantage of composite elements over homogeneous elements.

In conclusion, we investigated reversal properties of exchange-coupled composite elements. Composite elements allow for a significant reduction of the reversal field, the microwave field, and the FMR frequency as compared to homogeneous elements. MAMR behaviors in the coherent and incoherent modes are completely different due to the phenomena associated with domain wall formation and propagation. In addition, the reversal field for composite elements can be much less sensitive to the element anisotropy field distributions, which is crucial to allow reducing bit error rates.

Fig. 1(a)]. This behavior explains the surprising gap of non-reversal in Fig. 1(a).

We also considered other angles of linearly polarized microwave fields with respect to the easy axis and found that the size and shape of reversal/nonreversal areas can be modified depending on the field angles, strength, and soft section length. Under circularly polarized fields the phenomena of the reversal field, microwave field, and FMR frequency reduction are preserved but the reversal/nonreversal areas are absent, which is associated with a different magnetization dynamics behavior.

MAMR performance may be restricted not only by the limitation on maximally achievable head fields and microwave frequencies but also by deviations of the reversal field $H_r$ caused by random distributions of the element parameters. Among them, random distributions of the anisotropy field $H_K$ can have a crucial influence as they may lead to significant deviations of $f_{mw}^{res}$ and $H_r$. For homogeneous elements, deviations of $f_{mw}^{res}$ scale linearly with deviations of $H_K$. Deviations of $H_r$ can be even more significant due to the resonant nature of the MAMR reversal phenomena. As shown next, composite elements allow significantly reducing the deviations of $f_{mw}^{res}$ and $H_r$.

Figure 3 compares the dependence of $H_r$ versus $f_{mw}^{res}$ and $H_K$ for composite elements of different $t_r$ and a homogeneous element. For the homogeneous element (shown in Fig. 3(b)), $f_{mw}^{res}$ is linearly proportional to $H_K$, e.g., 10% deviations of $H_K$ lead to about 10% deviations of $f_{mw}^{res}$. Deviations of $H_r$ are substantially more significant, e.g., 10% deviations of $H_K$ lead to more than 50% deviations of $H_r$. This behavior may lead to severe limitations on MAMR if homogeneous elements are used. The situation is very different for composite elements, where deviations of $H_r$ and $f_{mw}^{res}$ are substantially reduced and the area of reversal of these two cases overlap with each other for a major part on the phase graphs. For the composite element with $t_r=0.75w$, deviations of $f_{mw}^{res}$ are only 3% for 10% deviations of $H_K$, which represents a fivefold improvement over the homogeneous element. For $t_r=1.5w$, the reversal areas are slightly shifted but there is an overlapping area where almost no dependence of $f_{mw}^{res}$ and $H_r$ on $H_K$ is present. The reduction of the deviations of $f_{mw}^{res}$ has a physical source similar to that leading to the reduction of $f_{mw}^{res}$ itself, i.e., $f_{mw}^{res}$ are significantly affected by the soft section where the field is mostly given by the external and exchange fields but not by $H_K$. This significant improvement correlates with results obtained for conventional domain wall assisted reversal. Due to the potential improvements to bit error rates, this weak sensitivity to the anisotropy field distribution is a crucial advantage of composite elements over homogeneous elements.

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