Microwave assisted magnetization reversal and multilevel recording in composite media

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Abstract

Microwave assisted magnetic reversal (MAMR) is studied for media comprising exchange-coupled composite elements comprising soft and hard layers. Reversal in such elements occurs under substantially reduced reversal fields, microwave fields, and microwave resonant frequencies as compared to those for homogeneous elements. Reversal can occur in uniform modes as well as non-uniform domain-wall assisted modes depending on the soft layer thickness. In addition, a multilevel MAMR scheme is suggested where the recording media comprise multiple levels of elements with each level having a distinct resonant frequency. These levels are addressed individually by tuning the frequency of the microwave field.

1. Introduction

A major limitation to increasing magnetic recording areal densities is the superparamagnetic effect, which leads to spontaneous reversal when magnetic particles become too small[1,2]. Overcoming the superparamagnetic effect requires using materials with very high anisotropy, which translates into excessively high reversal fields. Several methods including heat-, precessional reversal-, and microwave-assisted- magnetic recording schemes have been proposed to solve this writability problem[3-15]. Microwave-assisted magnetic reversal (MAMR) significantly reduces the reversal field when the microwave field frequency matches the ferromagnetic resonance (FMR) frequency of the media elements[10,12,13]. However, for ultra-high densities the required reversal fields as well as microwave fields and frequencies can still be too high for MAMR schemes using media with homogeneous elements. Provided that the writability and thermal stability problems are overcome, exploiting the resonant properties of the reversal fields may also suggest novel approaches for high density magnetic recording.

This paper studies MAMR in composite media comprising magnetic elements composed of soft and hard sections coupled ferromagnetcally[5,16-18]. MAMR in such media occurs at significantly lower reversal fields, microwave fields, and microwave frequencies compared to those of media based on conventional homogeneous elements. These properties are critical for practical implementations of MAMR schemes for ultra-high density recording. In addition, we show that MAMR schemes can be used for multilevel recording, in which each layer has a distinct FMR frequency and is addressed by tuning the microwave frequency.

2. MAMR in composite elements

Consider a dual-layer composite magnetic element composed of hard and soft sections. The (bottom) hard section is of size w, w, d_h in the x, y, z dimensions, with vertical uniaxial anisotropy energy density K_h. The (top) soft section is of size w, w, d_s with vanishing anisotropy. The sections are coupled ferromagnetically through their common interface with surface exchange energy density J_s. Both layers have damping constants $\alpha = 0.1$, saturation magnetization M_s, and exchange length $l_{\text{ex}} = \sqrt{A}/M_s = w$, where A is the exchange constant. The element are subject to an external field, which comprises an applied bias field (serving as a switching field) and a microwave field (serving as an assisting field). The bias field is applied at an angle of 45° with respect to the easy axis in the $x-z$ plane with a time dependence $H_a \text{erf}\left(2t/\tau\right)$, where H_a is the field amplitude and τ is the rise time. The microwave field has a frequency f_{mw}, amplitude H_{mw}, and it is applied along the x axis. For given H_{mw} and f_{mw}, there is a minimal bias field amplitude, referred to as reversal field H_r, that leads to the reversal of the element over a reversal time t_r, defined as the time required for the magnetization vertical component to reach the opposite level of $0.9M_s$. All results are obtained by numerically solving the Landau-Lifshitz-Gilbert equation taking into

account all effective fields and assuring numerical accuracy[6-8]. When arranged in an array, the elements in Fig. 1 can be used to construct media for high-density magnetic recording. For example, a bit patterned media with pitch of 8nm and $w = d_h = 5\,\text{nm}$ results in a recording density of $10\,\text{Tbit}/\text{in}^2$ with thermal stability above $70\,k_B T$ with the Bolztman constant k_B and temperature $T = 400\ K$. The chosen parameters are representative of practical materials for high-density recording, such as FePt.

The reversal behavior of composite and homogeneous elements is studied and compared for $H_K = 2K_h / M_s = 60\,\text{kOe}$, $M_s = 1250\,\text{emu/cm}^3$, $J_s = 11.25\,\text{ergs}/\text{cm}^2$, and $d_h = w = 5\,\text{nm}$. Figure 1 shows the reversal time t_r as a function of the reversal field H_r and microwave frequency f_{mw} for homogeneous and composite elements. Dark regions represent non-reversal while brighter regions show finite reversal times (in pico-seconds). Figure 1(a) depicts the results for a homogeneous element of thickness $d_h = 2w$ for $H_{mw} = 0.14 H_K$. A resonance dip in the reversal field with the minimal reversal field $H_r^{res} = 10\text{kOe} \cong 0.17 H_k$ is obtained for the minimal (resonant) frequency of around $f_{mw}^{res} = 120\text{GHz}$. These microwave field and frequency are very high and may be hard to achieve in practical recording systems. For composite element, however, the situation is different. Figures 1(b) and (c) show the results for composite elements with $d_s = w/2$ and $d_s = w$, respectively. The microwave field for the results in Figs. 1(b) and (c) was $H_{mw} = 0.07 H_K$, which is half of that used for the homogeneous element in Fig. 1(a). The resonant frequency decreases significantly being around $f_{mw}^{res} = 42\text{GHz}$ and $f_{mw}^{res} = 23\text{GHz}$ for $d_s = w/2$ and $d_s = w$ cases, respectively. The corresponding minimal reversal fields also decrease significantly to a level of $H_r^{res} = 6.6\text{kOe} \cong 0.11 H_K$ and $H_r^{res} = 4.8\text{kOe} \cong 0.08 H_K$, respectively. Moreover, comparing these two figures, it is observed that the reversal times for composite elements are about half of that for the homogeneous element and vary smoothly as a function of the applied field and frequency. These substantially lower resonant frequencies, microwave fields, reversal fields, and reversal times are important to allow for practical applications of the MAMR recording schemes. The slowly changing and narrowly distributed reversal time suggests a more stable switching for composite elements.

It should be noted that the energy barriers for the two cases homogeneous and composite elements in Fig. 1 are mostly determined by the domain wall energy given by $E_{dw} = 4w^2\sqrt{AK_h} = 70 k_B T$ (with $T = 400K$) since the element's size is greater than the domain wall length given by $d_{dw} = 4\sqrt{A/K_h} \approx 4.2\,\text{nm}$. Therefore, the aforementioned gains for the composite elements are obtained without sacrificing the thermal stability[19,20].

The resonant behavior in Fig. 1 reflects the ferromagnetic resonances properties of the considered elements. Two reversal mechanisms are observed in the reversal dynamics as shown schematically in Fig. 2. For thin composite elements with thickness below the domain wall length, precession is first enhanced

coherently in the soft layer, and then it, in turn, assists reversal in the hard layer. The resonant frequency in this case is mainly determined by the properties of the soft layer and the inter-layer coupling field, which is smaller than H_K, thus leading to FMR frequency reduction. For thick composite elements with layers thicker than the domain wall length, the reversal in the soft layer is incoherent. The reversal starts in the top part of the soft section and then a domain wall is formed in the soft section. The domain wall propagates though the soft and subsequently through the hard section. The resonant frequency in this case is mainly determined by the external field with the exchange field. These two fields are much smaller than the anisotropy field H_K thus leading to a significant FMR frequency reduction. In addition, since the influence of ferromagnetic coupling through common interface is weak on the spins in upper part of soft layer, they can be easily switched under a weak bias field resulting in a lower reversal field.

3. MAMR for multilevel recording

From the results shown in Fig. 1 it is clear that the FMR frequencies can be tuned in a wide range by either changing the anisotropy field in the case of homogeneous elements or by changing the anisotropy field, coupling, and geometrical parameters in the case of composite elements. The possibility to tune the FMR and reduce the reversal field near this frequency suggests a novel multilevel recording scheme. The proposed media comprise several layers, where each layer has a different FMR frequency (Fig. 3(a)). The microwave field is used to assist reversing elements in different levels by tuning the microwave frequency to the FMR frequency of the layer being recorded. This method is anticipated to result in a reliable multilevel recording scheme with a number of advantages over currently considered multilevel recording methods. For example, there expected to be no need in multi-pass recording since every level can be addressed independently. This scheme does not require addressing the elements in different layers by different strength of the reversal field and can allow for a smaller separation between the layers. In addition, a recording system that can generate microwave fields at several frequencies potentially can address several levels simultaneously thus increasing the recording speed.

To demonstrate the possibility of recording elements with different FMR frequencies independently, we consider an example of a two-level system comprised of homogeneous elements (Fig. 3(a)). In this system, the element in Layer 1 and Layer 2 have anisotropy $H_{K1} = 15\text{KOe}$ and $H_{K2} = 12\text{KOe}$, respectively. All elements are of size $w \times w \times w$ with $w = 10\text{nm}$ and have $M_s = 500\,\text{emu/cm}^3$. The separation between the layers is w. The microwave and bias fields are applied simultaneously to both layers. Figure 3(b) shows the final magnetization states in the two layers as a function of microwave frequency and the bias field. Area I and II respectively represent regimes of non-reversal and reversal of both layers. Area III and Area IV respectively represent regimes where Layer 1 and Layer 2 can be reversed individually. In practical systems, due to the gradient of head fields, the field is weaker on the layer farther from the head pole and it is reasonable to put the layer with lower anisotropy farther than the layer with higher anisotropy. From Fig. 3 it is evident that the field and element parameters can be found

that lead to individual switching of the layers with different resonant frequency. Various media elements can be used. For example, composite elements in Fig. 1 offer a great flexibility in tuning the structure parameters.

4. Summary

In conclusion, we showed that MAMR in exchange-coupled composite elements is allowed for significantly reduced reversal bias fields, microwave fields, microwave frequencies, and reversal times. Reversal mode can be uniform or non-uniform. In the latter case, domain walls in the soft section of the composite elements initiated by the assisting microwave field play an important role. Utilizing the ability to tune the FMR frequency, we suggested a multi-layer recording scheme. In this scheme, elements at different levels are designed to support FMR at different frequencies and they are addressed by a properly tuned microwave field.

1 H. J. Richter, J. Phys. D-Appl. Phys. **40,** R149-R177 (2007).
2 M. P. Sharrock, J. Appl. Phys. **76,** 6413-6418 (1994).
3 G. Bertotti, C. Serpico, and I. D. Mayergoyz, Phys. Rev. Lett. **86,** 724 (2001).
4 K.-Z. Gao, E. D. Boerner, and H. Neal Bertram, Appl. Phys. Lett. **81,** 4008-10 (2002).
5 K.-Z. Gao and J. Fernandez-de-Castro, J. Appl. Phys. **99,** 08K503 (2006).
6 B. Livshitz, R. Choi, A. Inomata, N. H. Bertram, and V. Lomakin, J. Appl. Phys. **103,** 07C516 (2008).
7 B. Livshitz, A. Inomata, N. H. Bertram, and V. Lomakin, Appl. Phys. Lett. **91,** 182502 (2007).
8 V. Lomakin, R. Choi, B. Livshitz, S. Li, A. Inomata, and H. N. Bertram, Appl. Phys. Lett. **92,** 022502 (2008).
9 V. Lomakin, S. Li, B. Livshitz, A. Inomata, and N. Bertram, IEEE Transactions on Magnetics (2008).
10 K. Rivkin and J. B. Ketterson, Appl. Phys. Lett. **89,** 252507-3 (2006).
11 J. J. M. Ruigrok, R. Coehoorn, S. R. Cumpson, and H. W. Kesteren, J. Appl. Phys. **87,** 5398-5403 (2000).
12 W. Scholz and S. Batra, J. Appl. Phys. **103,** 07F539-3 (2008).
13 Z. Z. Sun and X. R. Wang, Phys. Rev. B **74** (2006).
14 C. Thirion, W. Wernsdorfer, and D. Mailly, Nat Mater **2,** 524-527 (2003).
15 J. G. Zhu, X. C. Zhu, and Y. H. Tang, IEEE Trans. Magn. **44,** 125-131 (2008).
16 A. Y. Dobin and H. J. Richter, Appl. Phys. Lett. **89,** 62512-1-3 (2006).
17 E. E. Fullerton, J. S. Jiang, M. Grimsditch, C. H. Sowers, and S. D. Bader, Phys. Rev. B **58,** 12193 (1998).
18 M. Grimsditch, R. Camley, E. E. Fullerton, J. S. Jiang, S. D. Bader, and C. H. Sowers, J. Appl. Phys. **85,** 5901-5904 (1999.).
19 D. Suess, T. Schrefl, S. Fahler, M. Kirschner, G. Hrkac, F. Dorfbauer, and J. Fidler, Appl. Phys. Lett. **87,** 12504-1-3 (2005).
20 R. H. Victora and X. Shen, IEEE Trans. Magn. **41,** 537-42 (2005).

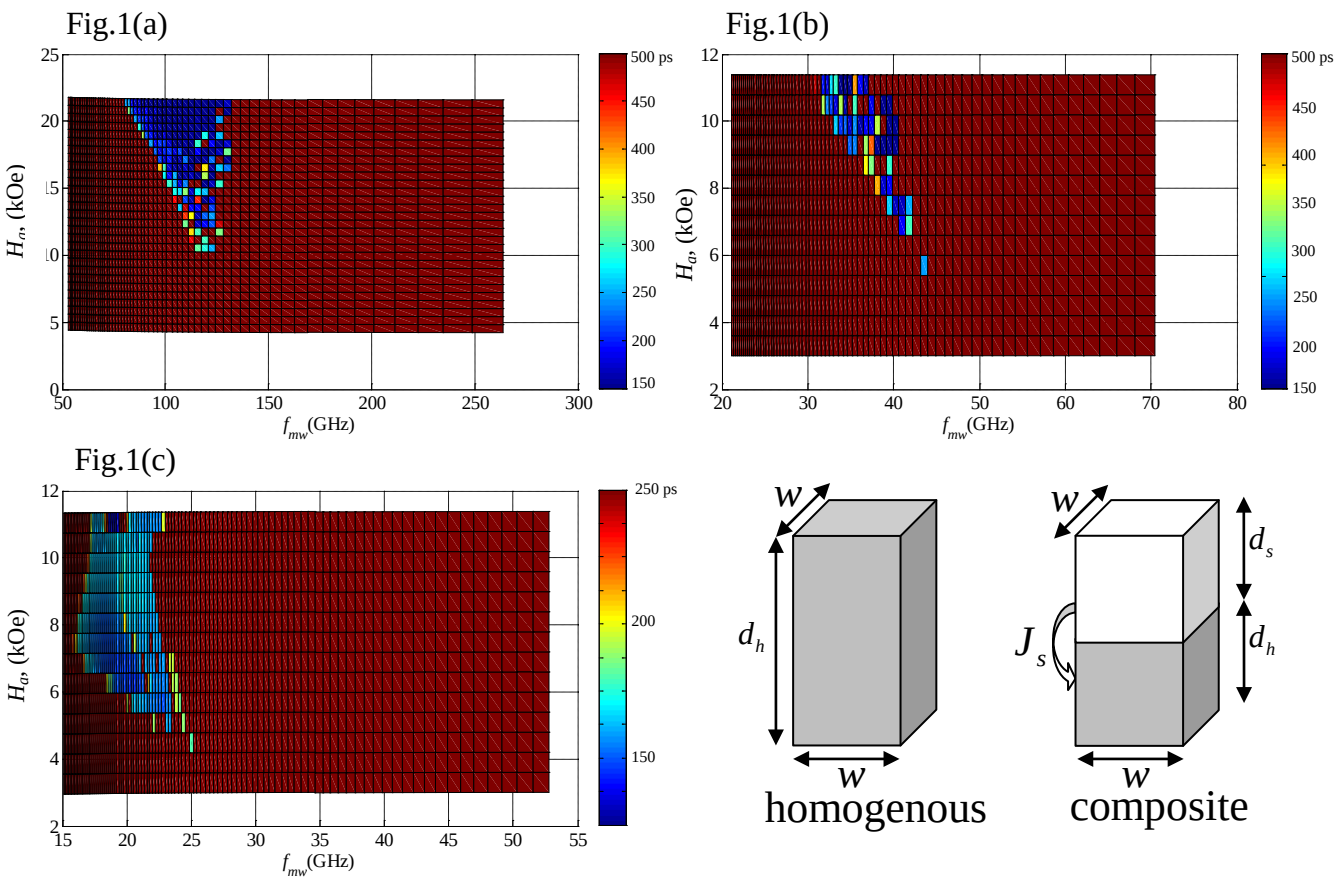

Fig. 1: Color map of the reversal time (given in picoseconds in the color bar) vs. the microwave frequency f_{mw} and applied bias field H_a for $H_K = 60\,\text{kOe}$, $M_s = 1250\,\text{emu/cm}^3$, $J_s = 11.25\,\text{ergs/cm}^2$, $\tau = 0.1\text{ns}$ and $\alpha = 0.1$. (a) homogeneous element with $d_h = 2w$; (b) composite element with $d_h = w, d_s = w/2$; (c) composite element with $d_h = w, d_s = w$.

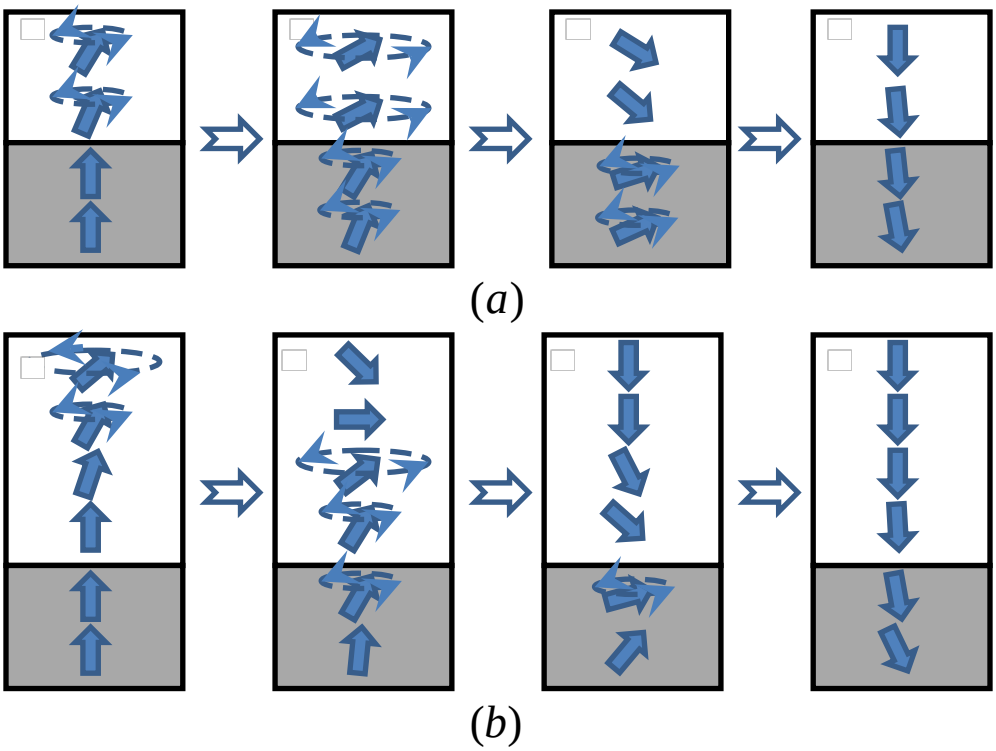

Fig. 2: Schematic representation of the spin time evolution in the regime of (a) uniform and (b) non-uniform (microwave assisted domain wall) reversal.

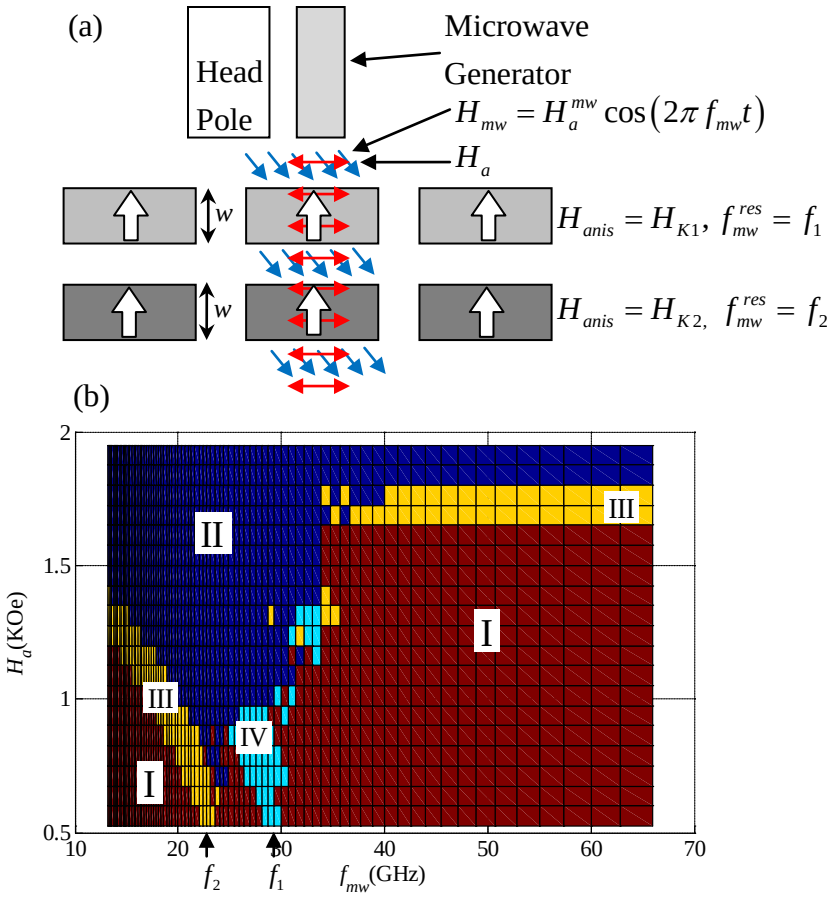

Fig. 3: (a) Schematic representation of a multi-layer microwave-assisted magnetic recording system; (b) A reversal pattern of double layer recording system. Four different areas represent different magnetization states of in a two-layer structure comprising homogeneous elements for different microwave frequencies. Area I corresponds to no-switching of any layer. Area II corresponds to switching of both layers. Area III corresponds to switching of the lower layer only. Area IV corresponds to switching of the upper layer only. The results are given for $H_a^{mw} = 2.25\,\text{kOe}$, $\alpha = 0.1$, $d_h = w$, $H_{K1} = 15\,\text{kOe}$, and $H_{K1} = 12\,\text{kOe}$.