TOPICAL REVIEW — Magnetism, magnetic materials, and interdisciplinary research

Writability issues in high-anisotropy perpendicular magnetic recording media*

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Challenges and recent developments associated with writability issues in high-anisotropy perpendicular recording media are reviewed. The writing field is limited by the high coercivity caused by the high anisotropy. Some new alternatives are proposed to solve the writability issues, including texture-tilting-assisted, domain-wall-assisted, energy-assisted magnetic recording technologies, and so on. In addition, we propose new alternatives for the next-generation of magnetic recording media.

Keywords: magnetic recording media, high anisotropy, writability, switching field

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1. Introduction

With the fast development of information technology, there is a rapidly growing need for better information storage devices. Among the various storage media, hard disk drive (HDD) storage is still the primary storage device, primarily due to its high density and low price.[1] Over the past several decades, magnetic recording technology has undergone a transition from longitudinal to perpendicular in conventional magnetic recording.[2,3] The use of perpendicular recording technology has facilitated a great increase in areal density. However, more recently, the increase in areal density has slowed down because of the fundamental limits in the grain size of the magnetic materials, the reduction of which spontaneously reverses the magnetization to superparamagnetism. Thus far, several methods have been proposed to avoid the superparamagnetic limit, such as the use of materials like $L1_0$-FePt and $L1_0$-CoPt that have a high magnetocrystalline anisotropy (K_u). Such materials can be used to overcome the adverse effect of the reduced grain size.[4,5] Although $L1_0$-FePt and $L1_0$-CoPt thin films have been tailored to achieve the desired grain size and exchange decoupling,[6,7] writing information on such media is still a challenge for the current write heads, as the high anisotropy of these materials results in an unfavorable increase in coercivity. To overcome this problem, some new recording alternatives have been proposed to provide an expected write field around several kOe.

This article aims to provide a detailed overview of the challenges and recent developments in high-anisotropy perpendicular recording media and possible methods for improving writability without losing thermal stability. So far, three main concepts have been proposed to resolve the writability issue, including texture tilting assisted magnetic recording,[8,9] domain-wall-assisted magnetic recording,[10,11] and energy-assisted magnetic recording.[12,13] Herein, we will review the advantages and specific challenges associated with these technologies and the possibility of realizing ultrahigh areal density recording media.

2. Texture-tilting-assisted magnetic recording

Texture-tilting-assisted magnetic recording is a recording scheme in which the magnetic recording is accomplished by tilting the easy magnetization axis that depends on the crystallographic texture of the magnetic material comprising the recording medium. This mode allows reducing the coercivity of high K_u media, thereby leading to an improvement in writability. In principle, there are two ways to fabricate this design: one is to artificially tilt the easy magnetization axis by an oblique surface fabrication method, the other is to retain the natural tilt of the easy magnetization axis by controlling the relative textures.

2.1. Artificial-tilted media

Wang *et al* first proposed a tilted-axis magnetic medium, with its easy axis tilted 45°, in order to improve writability and overcome the high sensitivity of the switching field distribution in perpendicular recording systems.[14] Its feasibility was later verified by some micromagnetic simulations.[15,16] Figure 1 shows a schematic diagram of tilted magnetic me-

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dia with a single-pole write head and a plot of the normalized switching field versus the tilt angle.[9] The medium consists of perpendicular grains with their easy magnetization axes tilted by 45° with respect to the perpendicular direction. As can be seen from Fig. 1(b), titling the easy-axis direction by an angle of 45° results in minimum switching field H_s. This switching field is only half of that observed in perpendicular media with a tilt angle of zero. Moreover, the tilted medium achieves a much better tolerance of switching-field distribution, which is one of the key parameters for realizing a higher signal-to-noise ratio. In addition, a tilted medium exhibits a much faster magnetization switching speed when compared to the untilted perpendicular media, primarily due to the large reversal torque.[17] According to the theoretical studies, at $K_u = 7\times10^6$ erg/cm^3, the areal density of a tilted medium could be more than 62% higher than that of the perpendicular media. Therefore, tilting the easy magnetization axis in magnetic recording media is becoming one of the effective methods to improve the writability without compromising the thermal stability.

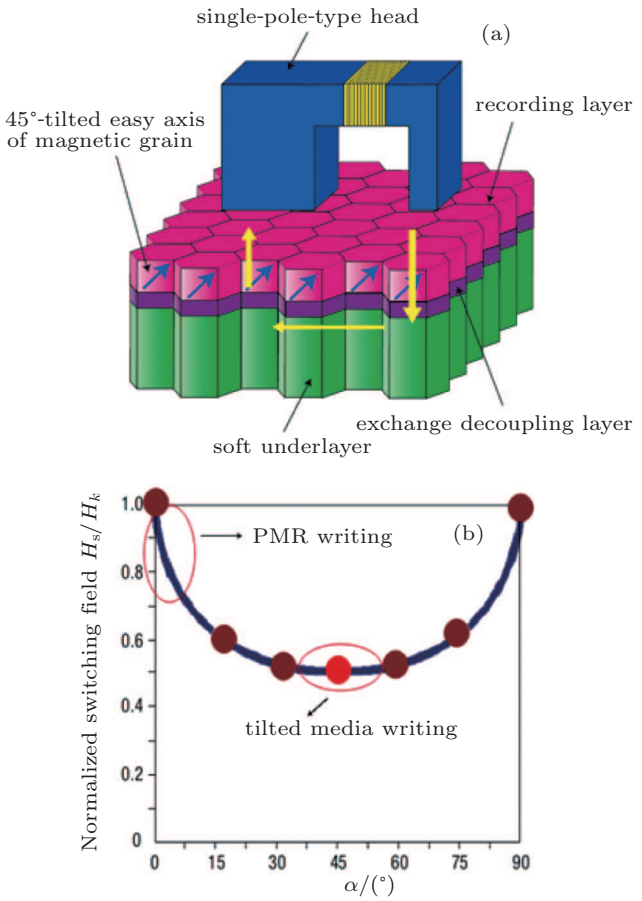


Fig. 1. (a) Schematic illustration of a tilted magnetic medium with a single-pole write head. (b) Normalized switching field (H_s/H_k; H_k is the magnetic anisotropy field) versus the angle (α) between the external field and the easy axis of a grain, exhibiting a uniform magnetization reversal.[9]

So far, several approaches have been proposed to obtain tilted media. One such method combines the advantages of oblique sputtering and collimated sputtering to fabricate artificially tilted CoCrPt recording media.[14,18] In a study, $L1_0$-FePt nanoparticles with artificial-tilted c axis were assembled onto MgO(110) substrates consisting of self-organized grooves, as shown in Figs. 2(a) and 2(b).[19] Here, each $L1_0$-FePt nanoparticle acts like a single crystal, with its c axis being tilted 45° from the substrate normal. In addition, another study demonstrated $L1_0$-FePt films with different easy-axis orientations deposited onto the pyramid-type Si substrates by a chemical etching process (Fig. 2(c)).[20] When the magnetic field is applied along the perpendicular direction, the magnetization reversal of the grains in the tilted easy axis is favored first, followed by the magnetization reversal of the whole film. In this way, it is possible to obtain a tilted medium with small coercivity, suitable angle, and high squareness. Therefore, the use of preprocessing substrates and the oblique sputtering methods are favorable for the fabrication of artificially-tilted recording media.

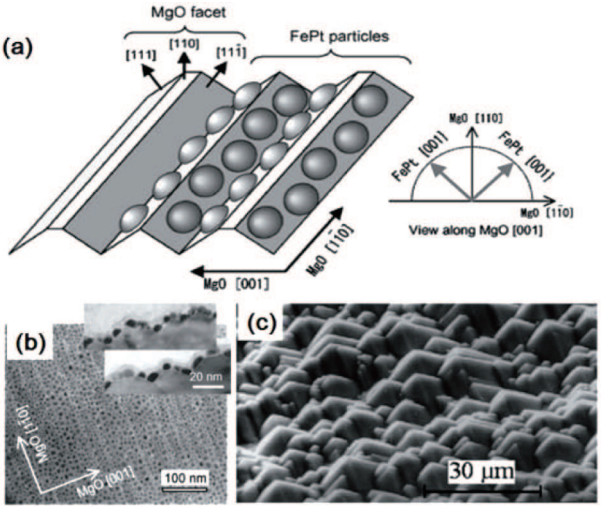


Fig. 2. (a) Schematic illustration of the MgO substrate with different facet structures and FePt particles grown thereon. (b) TEM image of the FePt nanoparticles grown onto the faceted MgO(110) substrate, the insets show representative cross-sectional TEM images taken along the MgO [1$\bar{1}$0] zone axis.[19] (c) SEM image of the pyramid-type Si substrate after the chemical etching process.[20]

Besides those, Albrecht *et al* fabricated Co/Pd magnetic multilayers with an artificially tilted easy axis through the curved surfaces of spherical nanoparticles.[21] Figure 3(a) shows a schematic diagram of a Co/Pd magnetic film with uniformly distributed anisotropy deposited on a nanosphere. Figure 3(b) shows the switching field (H_s) as a function of the angle (θ) of the applied field.[21] We can see that the minimum H_c appears at about 45°, which is similar to the simulated results of the tilted media.[15] Furthermore, the average anisotropy axis can be tuned to the required angle by changing the deposition direction, as shown in Fig. 3(c). The nanostructures with tilted magnetic anisotropy that are fabricated by this method are monodisperse and single-domain and have a

uniform magnetic anisotropy. Therefore, these nanostructures are expected to provide higher density, higher thermal stability, and faster switching compared to those of the conventional perpendicular magnetic recording systems. This seems to be an ideal path for the fabrication of artificially-tilted media.

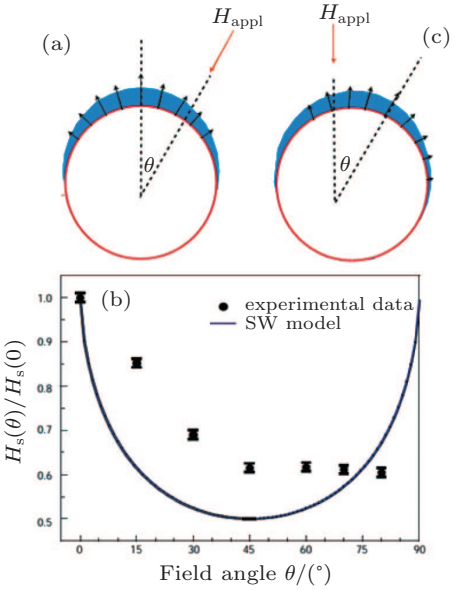


Fig. 3. (a) Schematic diagram of a Co/Pd magnetic film deposited onto a nanosphere. (b) Switching field (H_s) plotted as a function of the angle (θ) of the applied field. (c) The average anisotropy axis can be tuned to the required angle by changing the deposition direction.[21]

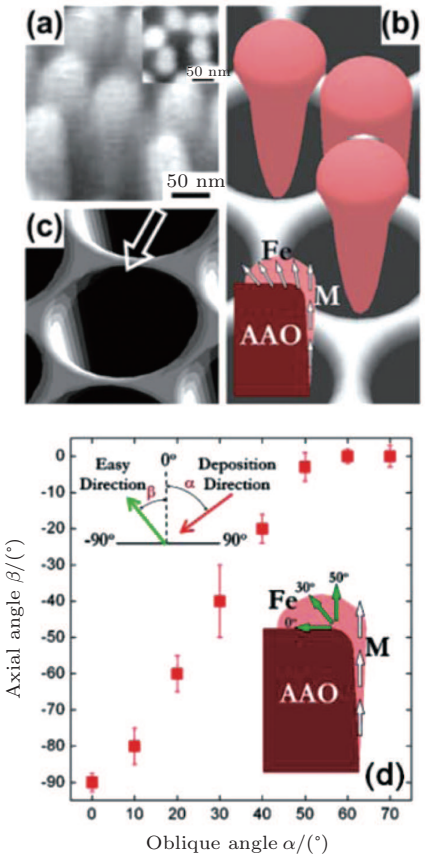


Fig. 4. (a) Tilt-view and plane-view (inset) SEM images. (b) Schematic illustration of 50° obliquely deposited Fe arrays. (c) Simulation of obliquely projected light. (d) Axial angle (β) plotted as a function of the oblique angle (α).[22]

Recently, a self-assembled Fe array with tilted magnetic anisotropy was fabricated on a nanoporous anodic aluminum oxide (AAO) template via oblique evaporation.[22] The sterns are formed perpendicularly on the unshadowed inner walls; an out-of-plane shape anisotropy is induced by controlling the oblique angle and the nominal thickness (Figs. 4(a)–4(c)). The 45°-tilted magnetic anisotropy with independent magnetization reversal is obtained at an oblique angle of about 27.6° (Fig. 4(d)). This mechanism essentially meets the requirements for 45°-tilted recording media, and it could be further extended to ultrahigh-density magnetic recording media with high magnetocrystalline anisotropy.

2.2. Naturally-tilted media

Artificially-tilted media can be fabricated by oblique sputtering on preprocessed substrates/seeds with oblique or spherical surface variations. However, the oblique sputtering approach may lead to a large switching field distribution in recording media. To overcome the above-mentioned drawbacks, naturally-tilted textures with a tilted easy magnetization axis, such as (101) or (111) textures of $L1_0$-FePt, can be fabricated, wherein the easy magnetization axis is directly oriented 36°–45° with respect to the surface normal of the medium. The respective advantages of naturally-tilted and artificially-tilted media are similar.[24]

Lately, high-anisotropy $L1_0$-CoPt and $L1_0$-FePt films having naturally a tilted (111) easy magnetization axis have been reported.[25,26] Room-temperature angular remanence measurements (ARM) of $L1_0$-CoPt were carried out in order to determine the geometrical arrangement of the easy axis in the film (Fig. 5).[25] The ARM curves provide evidence of four out-of-plane maxima at $\alpha \sim 36° + \pi$ and $144° + \pi$, within both the (110) and the $(\bar{1}10)$ planes. The maximum coercivities ($\sim$ 4.8 kOe) are observed when the field is applied along each maxima direction of the ARM curves (Fig. 5(c)). The observed behavior is consistent with the presence of four easy axes with mutually orthogonal in-plane projections symmetrically tilted at an angle of 36° with respect to the film plane. Such a system can decrease the writing field to approximately 75% of the value along the easy direction without loss of the thermal stability, so such materials are considered to have potential for use in perpendicular recording media.

Above all, both the artificially-tilted and the naturally-tilted media have certain roles to play in improving the writability of perpendicular magnetic recording without decreasing the thermal stability. However, the preparation conditions are relatively rigorous, especially in the case of the artificially-tilted media. This tends to limit their practical applications in magnetic recording media to some extent. Therefore, some new technologies are still required to realize high writability of $L1_0$-FePt-based recording media.

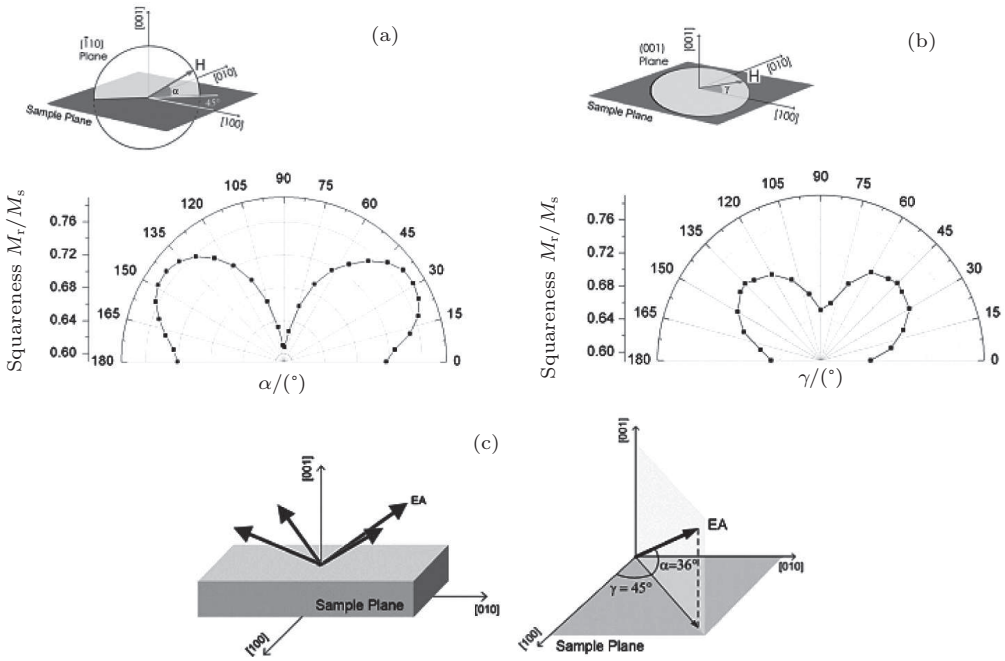


Fig. 5. ARM curves in the planes of the MgO substrate: (a) $(\bar{1}10)$ and (b) (001). (c) Schematic illustration of a four-tilt easy axis model.[25]

3. Domain-wall-assisted magnetic recording

Another viable strategy to reduce the switching field of a medium is domain-wall-assisted recording, including exchange-spring (ES),[10] exchange-coupled composite (ECC),[11] and exchange-coupled graded (ECG) recording media.[27] All of them are composed of both hard and soft magnetic layers, which are coupled by a sharp or graded interface, as shown in Fig. 6. Here, the hard layer with high K_u provides a high energy barrier to maintain a high thermal stability, while the soft layer with high saturation magnetization reverses at a low applied field. The domain wall at the hard/soft interface provides an additional exchange field to apply on the hard magnetic layer, which helps to reduce the switching field of the recording media. Thus, soft/hard composite media can improve the writability while still maintaining a high thermal stability. This idea is very attractive because the method for preparing the medium is easier than that of the above mentioned texture-tilting-assisted media.

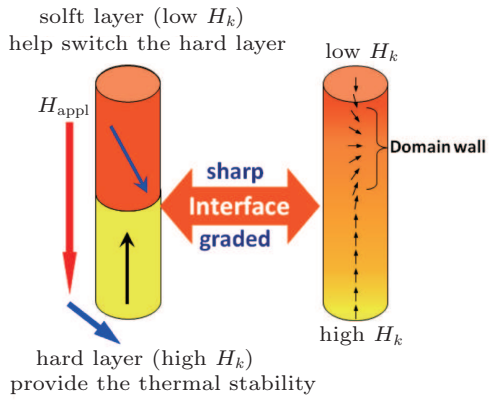


Fig. 6. Schematic illustration of the domain-wall-assisted recording.

3.1. Exchange-spring media

In 2005, Suess first introduced the exchange-spring scheme in perpendicular magnetic recording media.[10,28] In this medium, the soft magnetic layer is directly coupled with the hard magnetic layer by the soft/hard interface. Figure 7 shows the simulated magnetic reversal process and hysteresis loop of an exchange-spring medium.[29] As can be seen from the magnetic reversal process, the magnetization of the hard layer reverses with the help of the soft layer. The switching field of the soft/hard bilayer is determined by the pinning field at the soft/hard interface, which is defined as

$$H_p = \frac{1}{4} \times \frac{2(K_{hard} - K_{soft})}{J_s}, \quad (1)$$

where K_{hard} and K_{soft} are the anisotropies of the hard layer and the soft layer, respectively, and J_s is the saturation magnetization of the hard layer. When the anisotropy of the soft layer K_{soft} is zero, we can obtain the maximum reduction of coercivity, which is almost one quarter of that of the hard layer.[30] Therefore, the ES medium is considered very effective in reducing the switching field and improving the writability in perpendicular recording media. Furthermore, Dobin[31] and Goll *et al*[32,33] performed micromagnetic simulations to analyze the influences of the soft layer's thickness on the nucleation field, the coercivity, and the magnetization reversal mechanism of ES media.

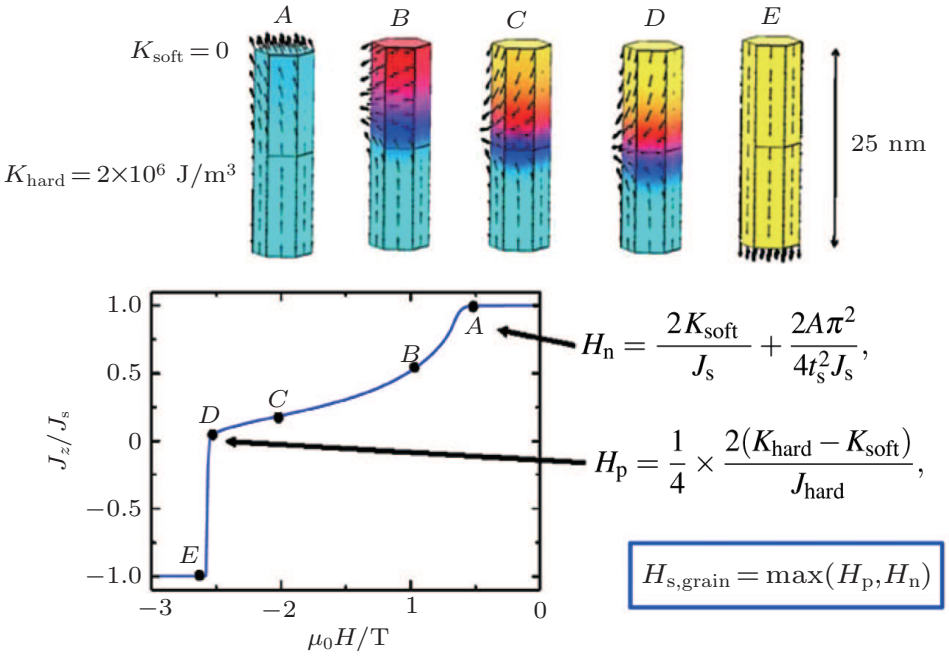


Fig. 7. (a) Magnetic reversal process and (b) hysteresis loop of the exchange-spring media.[29]

On the basis of the theoretical studies, Casoli *et al* successfully prepared $L1_0$-FePt/Fe exchange-spring films.[34,35] In their study, an FePt layer was first deposited onto the MgO(001) substrate at a high temperature in order to achieve an ordered $L1_0$-FePt hard layer with high anisotropy. Different deposition temperatures were tried. Subsequently, Fe soft layers of different thicknesses were deposited onto the samples at room temperature. Figure 8 shows the perpendicular hysteresis loops of the $L1_0$-FePt/Fe bilayer samples with Fe soft layers of different thicknesses and different FePt layer deposition temperatures (T_s).[35] Although the thickness of the Fe layer (t_{Fe}) is relatively small, the coercivity of the bilayer is much less than that of the single FePt layer without an Fe layer. This indicates that high-anisotropy perpendicular systems with moderate coercivity can be easily obtained by controlling the thickness of the Fe soft layer.[36] In addition, the morphology of the interface layer was found to depend on the substrate temperature. As shown in Fig. 9, separate FePt islands were formed at $T_s = 410$ °C, while only semi-continuous FePt patterns were formed at $T_s = 390$ °C due to the lower surface mobility.[35] If the thickness of the Fe soft layer is fixed, then the morphology of the FePt/Fe interface can be controlled to tune the magnetic regime from rigidly magnetic to exchange-spring magnetic due to the hard/soft interlayer coupling. Accordingly, the characteristics of the hysteresis loop can be tuned, as shown in Figs. 8(c) and 8(f).

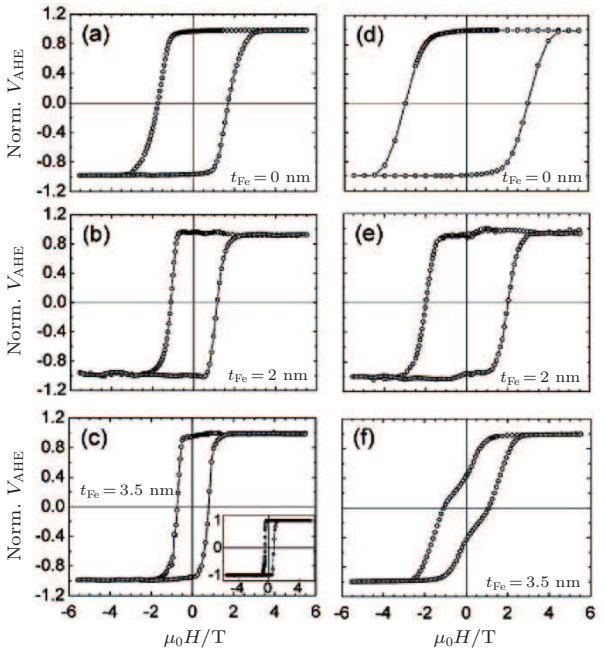


Fig. 8. Perpendicular hysteresis loops of $L1_0$-FePt/Fe bilayers with different substrate temperatures (T_s): (a)–(c) $T_s = 390$ °C, and (d)–(f) $T_s = 410$ °C.[35]

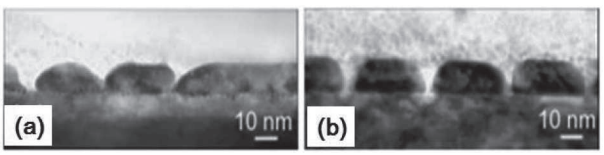


Fig. 9. Cross-sectional TEM images of FePt layers with (a) $T_s = 390$ °C and (b) $T_s = 410$ °C.[35]

3.2. Exchange-coupled composite media

Meanwhile, during the developmental studies of exchange-spring media, Victora *et al* theoretically proposed exchange-coupled composite (ECC) media for perpendicular recording.[11,37] A typical ECC structure is composed of a soft layer and a hard layer, similar to the structure of the exchange-spring media. However, the soft and the hard layers are coupled indirectly via a nonmagnetic interlayer, the thickness of which controls the exchange interaction between the layers. When an appropriate interlayer thickness is introduced, the switching field can be even lower than that in the corresponding ES media. So far, a few experimental studies have focused on this scheme. Wang *et al* were first to fabricate ECC media with CoPd or CoCrPt as the hard layer.[38,39] Figure 10 shows the exchange coupling dependence of remnant coercivity and thermal stability of the $[Co/PdSiO]_{16}$/PdSi/FeSiO films with different PdSi interlayer thicknesses.[38] The minimum coercivity corresponds to a PdSi thickness (t_{PdSi}) of 0.75 nm. In the case of a strongly coupled exchange-spring medium ($t_{PdSi} = 0$ nm), H_c is 5.30 kOe, which is larger than that of the ECC structures. However, for the exchange-decoupled case ($t_{PdSi} = 4$ nm), H_c is increased to 7.89 kOe, which is close to the coercivity of a single hard layer ($H_c = 8.12$ kOe). As seen from Fig. 10, the thermal stability factor K_uV/k_BT is almost constant for all the cases. These results clearly show that the coercivity can be tuned by controlling the interlayer coupling strength while still maintaining the thermal stability. Furthermore, O'Grady *et al* reported the effects of other kinds of nonmagnetic interlayers, such as Pt and Pd layers, on the magnetic properties and recording features of hcp-CoCrPt ECC media.[40,41] They also observed similar trends in the coercivity. In addition, magnetic interlayers were also used to adjust the coupling strength between the soft and the hard layers. For instance, Tang *et al* used CoCr as the magnetic interlayer, the magnetization of which is lower than that of the soft layer. According to their study, not only the interlayer thickness but also the saturation magnetization between soft and hard layers contribute to the weakening of the exchange coupling between the two magnetic layers, thereby effectively decreasing the coercivity of the ECC media.[42,43] In simple terms, the ECC media can improve writability even more than the corresponding exchange-spring media.

3.3. Exchange-coupled graded media

On the basis of the studies of ES and ECC media, researchers theoretically proposed exchange-coupled graded media with a multilayer structure.[27] In the ECG media, the anisotropy gradually decreases layer by layer from the hard layer to the soft one. The thermal stability of the graded media depends on the anisotropy of the hardest terminal layer. It is supposed that by increasing the number of layers in the exchange-spring media from two layers to N layers to form a multilayer structure of the ECG media, the anisotropy difference of adjacent layers is decreased, resulting in a smaller pinning field at the interface. The following equation gives the relations between the pinning field H_p, K_u and the number of layers N:

$$H_p = \frac{1}{4}\frac{2(K_{n+1} - K_n)}{J_s} = \frac{1}{4(N-1)}\frac{2K_{hard}}{J_s}, \tag{2}$$

where K_{n+1}, K_n, and K_{hard} are the anisotropies of any two adjacent layers and the hardest layer, respectively; and J_s is the saturation magnetization of the hardest layer. Obviously, the more layers, the lower the pinning field. As the multilayers are extended to graded media with constantly varying anisotropy, the pinning field can be rewritten as

$$H_p = (2/J_s)\sqrt{AK_{hard}/t_G}, \tag{3}$$

where A and t_G are the exchange coefficient and the gradient thickness, respectively. Obviously, the pinning field, which depends on the switching field, can be reduced by increasing the gradient thickness t_G.

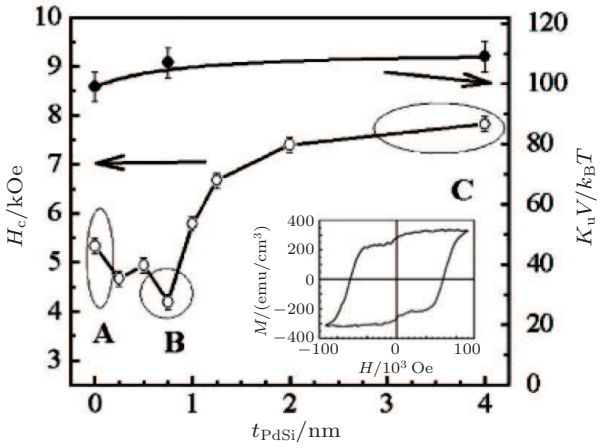


Fig. 10. Exchange coupling dependence of remnant coercivity and thermal stability of $[Co/PdSiO]_{16}$/PdSi/FeSiO films with different PdSi interlayer thicknesses.[38]

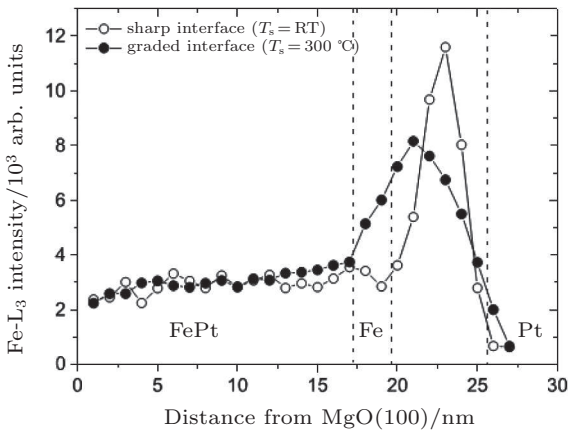


Fig. 11. Fe content across the $L1_0$-FePt/Fe bilayers with sharp and graded interfaces between the hard and the soft layers measured by EELS.[44]

Several studies have attempted to experimentally generate the graded media. Goll *et al* were the first to demonstrate experimentally the fabrication of epitaxial $L1_0$-FePt/Fe graded media by depositing some of the Fe layers at elevated temperatures.[44,45] Figure 11 gives the Fe content across the $L1_0$-FePt/Fe bilayers with sharp and graded interfaces between the hard and the soft layers, as measured by electron energy-loss spectroscopy (EELS).[44] The results indicate that a graded interface is formed between the $L1_0$-FePt and Fe phases due to the interdiffusion between layers at 300 °C, which in turn results in a continuous change of the magnetocrystalline anisotropy. This leads to lower coercivity than that in a corresponding medium with a sharp interface. In another study, $L1_0$-CoPt-Ta_2O_5 and FePt-TiO_2 exchange-coupled multilayer media with well isolated magnetic grains were fabricated by adjusting the Ta_2O_5 or TiO_2 content layer-by-layer.[46,47] Similarly, another study demonstrated the fabrication of FePt-C graded films by varying the substrate temperature layer by layer to control the ordering degree.[48,49]

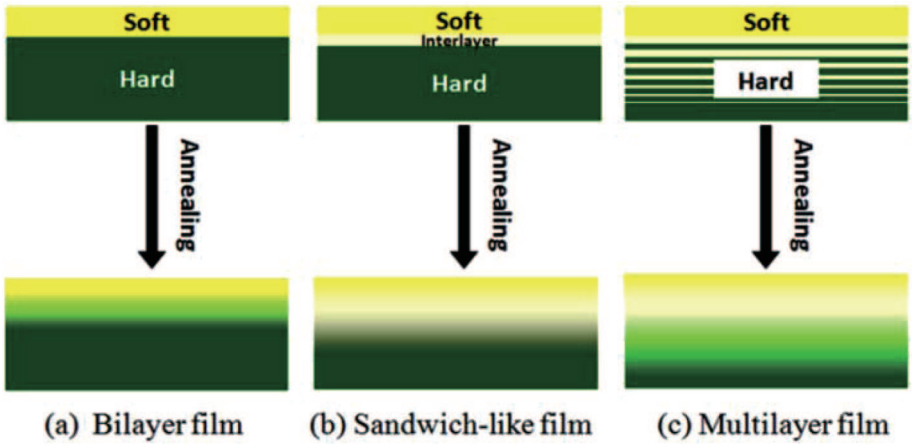


Fig. 12. Schematic diagrams of three types of structures ((a) bilayer film, (b) sandwich-like film, (c) multilayer film) before and after annealing.

As can be seen from Refs. [44]–[49], it is clear that a higher substrate temperature provides kinetic energy for the atoms, promoting interdiffusion between the soft and the hard layers. Therefore, we proposed using a post-annealing method to form a graded media, which is considered to be a very effective method for realizing interdiffusion between different layers.[50] Graded films can be prepared by changing the annealing parameters, such as temperature, heating rate, and time.[51,52] Our group combined sputtering and post-annealing treatment to fabricate a series of $L1_0$-FePt graded films with continuously varying anisotropy on glass substrates. Figure 12 shows a schematic diagram of three types of structures from bilayer to multilayer before and after annealing. The graded thickness t_G can be tuned by the structural design and the annealing temperature of the multilayers, in which the nonmagnetic layers are used to adjust the anisotropy distribution.

When the bilayer films are annealed at a higher temperature, a graded interface is easily formed as a result of the interface interdiffusion. Figures 13(a) and 13(b) show the compositional depth profiles of FeAu(soft)/FePt(hard) films before and after annealing at 550 °C.[53] Obviously, post-annealing can promote the interdiffusion between two magnetic layers to increase the graded thickness, which plays a crucial role in reducing the pinning field. When compared with the films with sharp interfaces, the graded interface is much more suitable for reducing coercivity.[54] If an Ru interlayer is inserted between the hard $L1_0$-FePt and the soft Fe layers to form the structure in Fig. 12(b), a large graded thickness can be obtained in the $L1_0$-FePt/Fe graded film after annealing. Figure 13(c) shows a plot of H_c as a function of the Ru interlayer thickness for $L1_0$-FePt/Ru/Fe films. The minimum coercivity, only 60% of that of the $L1_0$-FePt (20 nm)/Fe (3 nm) film, appears at $y = 1$ nm. Such a large reduction in coercivity indicates that the Ru interlayer can effectively tailor the coercivity of the $L1_0$-FePt/Fe films. Moreover, δM curves (Fig. 13(d)) show that the intergrain exchange interaction is sustantially reduced due to the diffusion of the nonmagnetic interlayer, which is especially important for the practical application of data storage.

The graded $L1_0$-FePt:C/Fe films with continuously varied anisotropy were experimentally realized by varying the concentration of C in the FePt hard layer. The inclusion of a nonmagnetic C layer not only tailors the gradient of the anisotropy, but also weakens the intergrain exchange interaction.[55,56] The magnetization reversal process of the graded film was simulated by using an object-oriented micromagnetic framework (OOMMF) software.[57] The simulated hysteresis loops and magnetization reversal process of the multilayer graded films are shown in Figs. 14(a) and 14(b).[57] The results indi-

cate that the coercivity of the multilayer graded film decreases gradually with a decrease in the K_u difference between the Fe soft layer and the adjacent FePt hard layer. The thermal stability of the graded media can be determined only by the magnetic properties of the hardest magnetic part of the media. Here, the magnetization reversal process is in accord with the domain-wall-assisted reversal mechanism. Zha *et al* also prepared a series of FePtCu graded films by adopting the post-annealing method.[58,59] It is well known that CoPt has higher ordering temperature than FePt. Hence, $L1_0$-FePt(hard)/CoPt(soft) graded films can be fabricated by post-annealing, taking advantage of the difference in the ordering temperature between $L1_0$-FePt and $L1_0$-CoPt.[60] Therefore, the post-annealing treatment is considered to be a feasible way to prepare exchange-coupled graded media with constantly varied anisotropy. Besides, the ion implantation technique has also been used to achieve CoCrPt-SiO_2 anisotropy-graded media. By this method, a small coercivity and a narrow switching field distribution (SFD) can be achieved by increasing the implantation dose.[61] Similarly, $L1_0$-FePt anisotropy-graded magnetic media can be obtained by Ar^+ ion irradiation.[62] Suess *et al* predicted that a graded medium should be capable of ultrahigh-density recording of up to 5–10 Tbit/in.^{2} if the grain size is assumed to be 3.2 nm.[29] The above experimental results indicate that the graded media are more suitable than the ES media for reducing coercivity and SFD. In short, the graded media provide an effective approach to improve the writability of $L1_0$-FePt recording media.

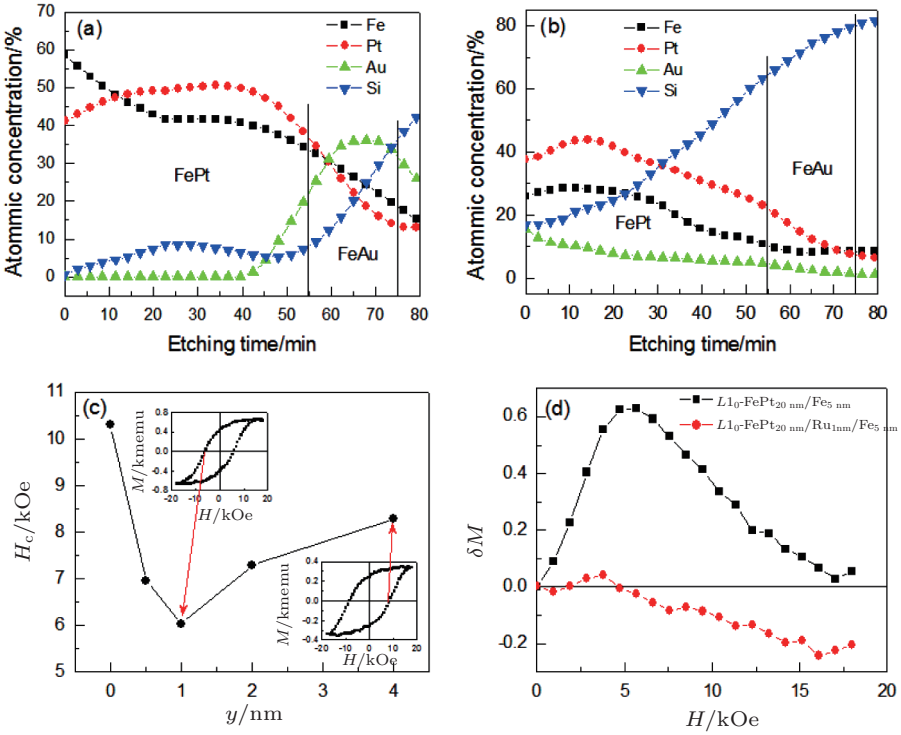


Fig. 13. Compositional depth profiles of FeAu/FePt films (a) before and (b) after annealing. (c) The H_c as a function of the Ru interlayer thickness for $L1_0$-FePt (20 nm)/Ru (y nm)/Fe (3 nm) ($y = 0$ nm, 0.5 nm, 1 nm, 2 nm, 4 nm) films. Insets are the hysteresis loops corresponding to $y = 1$ nm and 4 nm. (d) The δM curves of $L1_0$-FePt (20 nm)/Fe (3 nm) and $L1_0$-FePt (20 nm)/Ru (1 nm)/Fe (3 nm) films.[53,54]

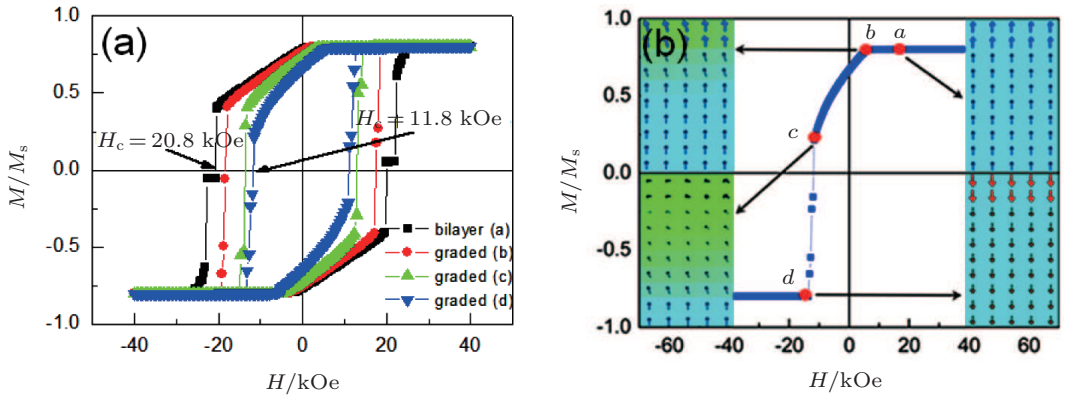


Fig. 14. (a) Simulated hysteresis loops of graded films with different structures and (b) magnetization reversal process of the graded (d) film.[57]

A graded structure with continuously varying K_u can control the coercivity while maintaining thermal stability. In addition, nonmagnetic additives serve to adjust the anisotropy gradient as well as weaken the intergrain interactions in order to effectively improve the signal-to-noise ratio of the media. Given these considerations, the domain-wall-assisted media are more effective for realizing higher writability without loss of the thermal stability.

4. Energy-assisted magnetic recording

In order to overcome the limit of the writing field, energy-assisted magnetic recording is an option for extending the areal density to 1 Tb/in.^{2} and beyond. Some forms of energy are provided to reduce the switching field, as in microwave-assisted magnetic recording (MAMR)[12] and heat-assisted magnetic recording (HAMR, or thermal-assisted magnetic recording).[63] In the forthcoming section, we will introduce the working principles and design challenges associated with these methods.

4.1. Microwave-assisted magnetic recording

The microwave-assisted recording mechanism in a perpendicular recording geometry was proposed on the basis of the phenomenon of ferromagnetic resonance.[12,64] Figure 15 shows the principle of microwave-assisted magnetic recording.[65] In the absence of an alternating-current (AC) field, the magnetization of the grain will be static along the easy axis in the initial direction. On the other hand, in the presence of an AC field, the magnetization precession will increase its precessional angle and irreversibly gyro downward within the duration of the pulsed reversing field. The switching field can be reduced by applying such a localized AC field at an appropriate resonant frequency along the direction transverse to the easy axis. However, this technique requires a device that can supply an AC magnetic field ($H_{ac} = 0.1H_k$) at microwave frequencies of tens of GHz in order to write the $L1_0$-FePt or $L1_0$-CoPt high K_u media. The spin torque oscillators (STO) that consist of multiple layers have been designed and fabricated to generate a localized AC field in the required microwave frequency regime.[66,67]

In addition, some experiments were attempted that used the microwave energy to assist the switching in perpendicular recording media. For instance, Boone *et al* experimentally investigated microwave-assisted switching in monolayer and bilayer CoCrPt-based hard magnetic thin films.[68,69] According to their study, the coercivity can be reduced by only 8% under a broad frequency range at a low temperature of 4 K. Similarly, Nozaki *et al* experimentally realized a significant reduction in coercivity up to 30% in microwave-assisted switching with a frequency of about 15 GHz in a perpendicular recording medium at room temperature (Fig. 16).[70] Although the reduction of the switching field in MAMR has been observed, it is not sufficient to write the high K_u materials for ultrahigh density media. This goal could be achieved by combining the MAMR and other recording technologies. For example, Bashir *et al* presented the behavior of single-phase media and exchange-spring media under a microwave field. The frequency required to realize the maximum reduction of the switching field is smaller in exchange-spring media than that in single-phase media.[71,72] However, the performance of the MAMR is limited to ECG media because of the need for different frequencies for each layer.[73] In addition, researchers have theoretically predicted the MAMR on bit-patterned media with ultrahigh areal recording density.[74,75] In a nutshell, the MAMR can be considered to be an effective pathway to reduce the switching field of high K_u materials.

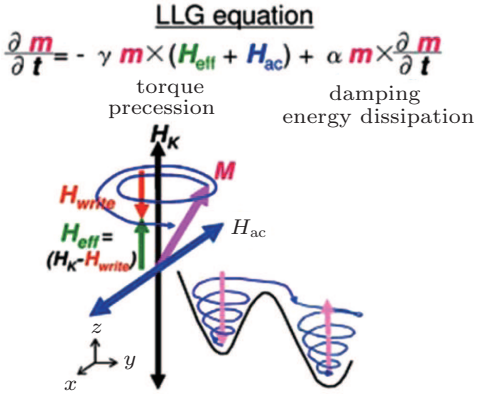


Fig. 15. Principle of MAMR recording.[65]

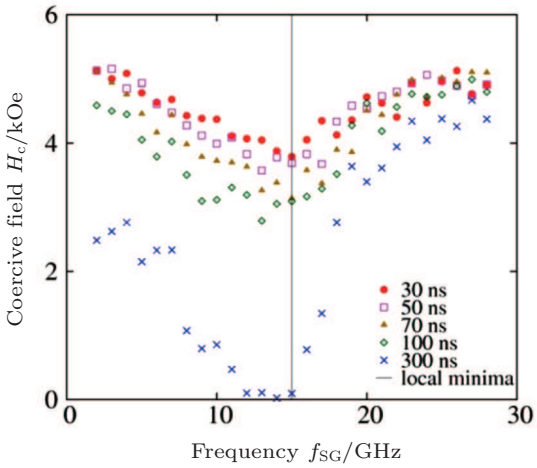


Fig. 16. Coercive field as a function of f_{SG} of the microwave impulse.[70]

4.2. Heat-assisted magnetic recording

Heat-assisted magnetic recording (HAMR) has proven to be one of the most promising technologies to improve the writability of high K_u materials.[76] Figure 15 shows the working principle and the scheme of HAMR. In principle, the coercivity of hard magnetic materials drops continuously with

increasing temperature and vanishes at the Curie temperature. In the case of high K_u $L1_0$-FePt, the coercivity can be reduced substantially below the writing field when the medium is temporarily heated. Subsequently, the information is stored upon cooling the medium, and the magnetization is frozen in a stable state, as shown in Fig. 17(a).[77,78] However, heat-assisted recording must couple a laser light to heat the recording layer, as shown in Fig. 17(b). This, in turn, increases the complexity of the HDD. Compared to the MAMR, the heat-assisted energy is provided directly to the atomic lattice, rather than to the spins.

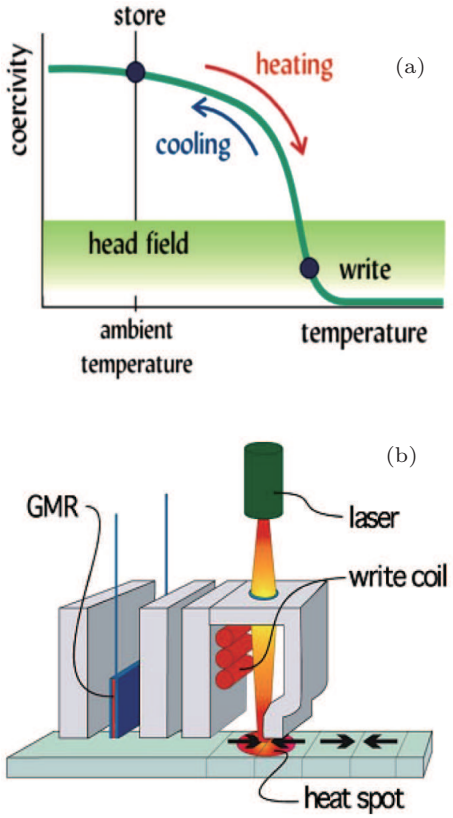


Fig. 17. (a) Principle and (b) scheme of heat-assisted magnetic recording.[78]

Based on the principle of the HAMR, optimization or reduction of the Curie temperature in high K_u media can probably serve as a key to some design solutions. Thiele *et al* found steady reductions of anisotropy and Curie temperature by increasing the Ni content in epitaxial $Fe_{55-x}Ni_xPt_{45}$ thin films.[79] On the other hand, Cu doping in $L1_0$-FePt, instead of Ni doping, was reported to marginally reduce the Curie temperature,[80] as shown in Fig. 18(a).[81] In addition, a novel FePt/FeRh exchange-coupled structure was proposed for the HAMR media.[82,83] The FeRh layer is antiferromagnetic at room temperature. Upon heating, the antiferromagnetic FeRh layer becomes ferromagnetic with a large magnetic moment and a low anisotropy, leading to a significant reduction in coercivity due to the formed ES $L1_0$-FePt/FeRh system (Fig. 18(b)). This result is entirely consistent with the working principle of the HAMR, as shown in Fig. 17(a). These features open intriguing possibilities for using FePt-based $L1_0$-alloys in heat-assisted magnetic recording, as such a design is expected to alleviate the heating intensity. However, the choice of light source and the energy transmission are the keys. Commercially available lasers with wavelengths on the order of several hundred nanometers are too large to be used in the HAMR due to a narrow track width below 60 nm for ultrahigh density of 1 Tb/in.^{2} Moreover, heat might diffuse to the neighboring bits, increasing thermal erasure, especially when the cooling rate is slow. In order to achieve the required spot sizes, a near-field plasmonic transducer has been proposed to efficiently convert the incident laser light from a large focused spot to a smaller one. This could be the optimal choice for ultrahigh-density heat-assisted recording media.[84,85]

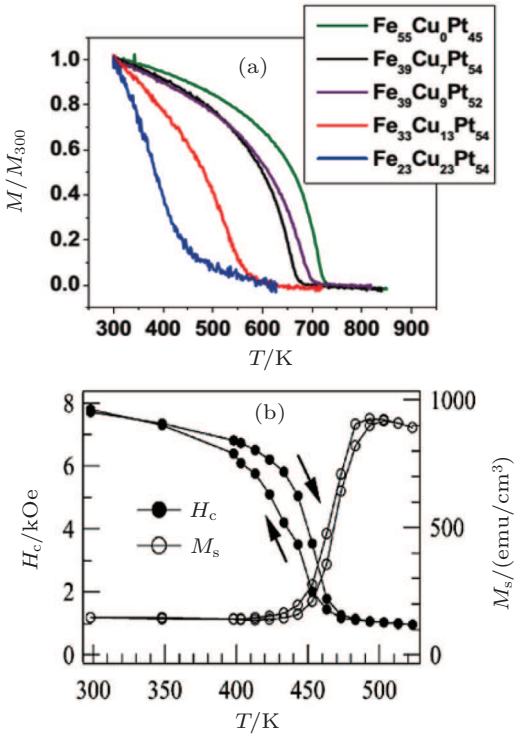


Fig. 18. Temperature dependence of magnetization and coercivity for (a) FeCuPt continuous films with different compositions[81] and (b) FePt/FeRh film under a process of heating and then cooling.[82]

Whether it is microwave assisted or heat assisted, energy-assisted magnetic recording is important in improving the writability of high K_u media. However, some significant engineering challenges still need to be resolved.[86,87]

5. Conclusion and outlook

In summary, this article provides a review of the challenges and recent developments in the writability issues for high-anisotropy perpendicular recording media. Many schemes, including texture-tilting-assisted, domain-

wall-assisted, and energy-assisted magnetic recording technologies, have been proposed to enhance writability. Nevertheless, each has its own fatal flaw that limits its application for ultrahigh areal density recording media. Moreover, a mere improvement of writability is not enough in the face of the three-way tradeoff – the well known "trilemma" – in the current state of the art of perpendicular recording media. Intensive effort is needed to promote valuable applications of these schemes. To break the ultimate superparamagnetic limit of future magnetic recording storage, a combination of various technologies, such as ECC/BPM and HAMR/BPM, may be the most effective way to cope with the tradeoff and realize an ultrahigh areal density for $L1_0$-FePt with high anisotropy materials.

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