
A review of $L1_0$ FePt films for high-density magnetic recording

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Abstract: In this paper, we have reviewed the current status of the study of $L1_0$ FePt alloy films for the application for ultra-high-density magnetic recording. For practical realisation of $L1_0$ FePt as recording media, issues such as decreasing preparation temperature, easy axis control, and reduction in media noise must be solved. The Ag-doping and strain-inducing methods are the most promising to lower the ordering temperature. However, the films using Ag-doping and strain-inducing method usually showed lower coercivity due to significant amount of defects in the film. Two methods, epitaxial growth and non-epitaxial growth, were introduced to control the easy axis and each method had its advantages and disadvantages. Media noise was also reduced by pinning method.

Keywords: FePt; magnetic recording media.

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1 Introduction

The areal densities of hard disk drives increased over 100% per annum during the late 1990s, and the 80–100 Gbit/in² longitudinal media was commercialised last year. The increases in data density, data rate, and other performance metrics have generally been achieved by scaling to make the read–write head smaller, the medium thinner and higher in coercivity, and the head-medium spacing smaller. Since the performance of media is limited by noise originating from the granular microstructures of the thin film, there exists the necessity to decrease the grain size. For current Co-based longitudinal media, the magnetic grains become thermally unstable (super-paramagnetic) when the grain size is reduced to below 8 nm in diameter. In the super-paramagnetic regime, the magnetic grains are so small that thermal energy will be sufficient to spontaneously reverse the magnetisation, resulting in loss of the recorded signal. The increase in coercivity also requires very high head field, which is unavailable from the ring writing head used currently in the longitudinal magnetic recording.

To meet the above technical requirements, opportunities exist for perpendicular magnetic recording media and patterned media. The perpendicular recording media promises several key advantages over longitudinal media (Wood et al., 2001), e.g.,

- the higher head field in the pole-head/soft-underlayer configuration allows the use of the media with high coercivity and high anisotropy energy density, K_u , which in turn permits smaller and thermally stable media grains
- sharp transitions on relatively thick media that can include more grains per unit area for a given grain volume
- strong uniaxial orientation of the perpendicular media leads to a tight switching-field distribution, sharper written transition and higher signals and lower noise.

These properties of perpendicular media could enable the realisation of ultra-high areal density in magnetic recording. Simulation has shown that perpendicular recording density can exceed 1 Tbits/in² (Wood et al., 2001). The 170 Gb/in² and 240 Gb/in² hard disk drive have been demonstrated by Seagate (<http://seagate.com>) in 2003 and Hitachi (Moser et al., 2005) in 2005 using CoCr-based alloy perpendicular media. The intrinsic properties of Co alloy media with relatively low anisotropy, however, can only support a maximum areal density of 500 Gbits/in².

The $L1_0$ ordered FePt films with Face-Centred-Tetragonal structure (*FCT*) have attracted much attention in recent years owing to their large magneto-crystalline anisotropy (7.0×10^7 erg/cc), maintaining the thermal stability with grain size reduced to 2.6 nm. These properties render the $L1_0$ FePt as a promising candidate for ultra-high-density recording media (Weller et al., 2000). Practical applications of FePt

media films face technical challenges, including desirable reduction in ordering temperature, control of the FePt (001) texture and decrease in media noise, as follows:

- *High temperature required for phase transformation from Face-Centred-Cubic (FCC) to $L1_0$ phase.* This phase transformation for bulk FePt alloy occurs above 1000°C, whereas that for FePt alloy thin films exceeds 500°C. Lower ordering temperature for $L1_0$ phase transformation is desired for practical applications, especially for depositing the media on glass substrate.
- *Control of FePt (001) texture.* FePt films deposited by physical vapour deposition generally show the (111) preferred orientation since the (111) plane is closest packed with lowest surface energy. For FePt perpendicular media, it is desirable to achieve the (001) texture since the uniaxial magnetocrystalline anisotropy is aligned with the *c*-axis.
- *Reduction in media noise.* The media noise mainly originates from the transition noise. The reduction of magnetic domain size to decrease media noise is therefore required.

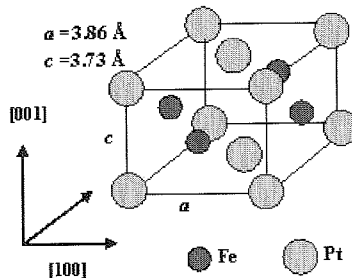
In this paper, an overview of recent progress in $L1_0$ FePt films for high-density perpendicular media is presented. The chemical ordering of $L1_0$ FePt, control of (001) texture by epitaxial and non-epitaxial growth and reduction of magnetic domain size are discussed. An outlook to the future research in this area is provided.

2 $L1_0$ chemical ordering

The $L1_0$ FePt phase (Figure 1) belongs to the $P4/mmm$ space group, with the configuration of alternating layers of Fe and Pt atoms stacked along the [001] direction. Generally, the as-deposited FePt films show chemically disordered *fcc* phase and are magnetically soft. To obtain $L1_0$ FePt films, in situ heating or post-deposition annealing is required. The annealing temperature is generally higher than 500°C, which is impractical for hard disk drive industry. It is, therefore, essential to reduce the ordering temperature and enhance the ordering parameter. The approaches to decrease ordering temperature may be divided into three categories:

- promotion of $L1_0$ ordering by element addition
- strain- or stress-induced $L1_0$ ordering
- others such as irradiation-induced ordering.

Figure 1 Schematic diagram of crystalline structure of $L1_0$ ordered FePt



2.1 Promotion of $L1_0$ ordering by elemental doping

Elements such as Cu and Ag have been most effective as dopants in FePt to promote ordering. Maeda et al. (2002a) reported that with the addition of the optimised 15% Cu into FePt alloy, the ordering temperature was reduced to 300°C. The coercivity of $(\text{Fe}_{46.5}\text{Pt}_{53.5})_{85}\text{Cu}_{15}$ film exceeded 5 kOe whereas undoped FePt film remained magnetically soft. It was found that the ternary alloy of FePtCu was formed (Kai et al., 2004) and the Fe site in the lattice was substituted by Cu. It was argued that the Gibbs free energy of FePtCu alloy was smaller than that of FePt and thus the driving force for the fcc - $L1_0$ transformation was enhanced (Maeda et al., 2002b). Takahashi et al. (2002) also reported that the ordering temperature of FePtCu film was reduced. The coercivity was 8 kOe and the ordering parameter was equal to 1 after annealing at 400°C. The coercivity and the ordering parameter of undoped FePt films remained very low at the same temperature. The optimised composition was found to be $(\text{FePt})_{96}\text{Cu}_4$. The Cu addition enhanced diffusion-driven phase transformation since Cu-doping decreased the melting temperature of the alloy. The contradictory results, however, had been reported by Wierman et al. (2004) and Sun et al. (2003). They found that Cu decreased the film coercivity and did not significantly improve the $L1_0$ ordering process. They suggested that the decrease in ordering temperature by Cu-doping was due to deviation from the equiatomic FePt composition, which would alter the ordering kinetics (Wierman et al., 2003). Barmak et al. (2005) demonstrated by using differential scanning calorimetry that the ordering temperature showed a large dependence on Fe:Pt ratio.

The effects of Ag addition on the $L1_0$ ordering of thin FePt films have also been reported (Platt et al., 2002; Zhou et al., 2003). The coercivity of the FePt–Ag increased with Ag-doping. In-plane and out-of-plane coercivities as a function of the Ag-content are shown in Figure 2. When the Ag-content was 30 vol.%, the coercivity was at a maximum. The increase in coercivity was attributed to both the increase in the ordering degree and the change in magnetisation reversal from domain wall motion to rotation mode upon Ag addition. Kang et al. (2003a) reported that with 15% Ag addition in FePt nanoparticles, the coercivity of the nanoparticles assembly was more than 10 kOe after 500°C annealing. Without Ag addition, FePt nanoparticles assembly was only 2 kOe. In this case, both FePt and FePt–Ag nanoparticles were well separated. The increase in coercivity of FePt–Ag may, therefore, be attributed to the increase in $L1_0$ ordering and magnetocrystalline anisotropy. The promotion of $L1_0$ ordering with Ag addition may be explained as follows (Chen et al., 2000; KitaKami et al., 2001): Ag has low solubility with both Fe and Pt. Furthermore, Ag has low surface energy that promotes segregation. When Ag is incorporated in FePt nanoparticles, it diffuses out of the particles upon heating, resulting in the creation of vacancies in the FePt lattices. This enhances the kinetics of the $L1_0$ ordering and thus decreases the ordering temperature. However, we found that when Ag overlayer was deposited on FePt films at the temperature of 400°C, $L1_0$ ordering was also promoted (Zhao et al., 2003). Figure 3 shows the in-plane X-ray Diffraction (XRD) scans of FePt thin films with different thicknesses of Ag overlayer, using an incident X-ray angle of 0.5°. The FePt film without Ag overlayer mostly showed the fundamental peaks [(111), (200) and (022)] of the FePt alloy and only a weak superlattice peak (110) of the $L1_0$ FePt phase in the spectrum. Upon introduction of 1 nm Ag overlayer, the superlattice (110) peaks became stronger and other superlattice peaks such as (201) and the weak (221) and (003) peaks appeared. The hysteresis loops

of FePt films with various Ag overlayer thicknesses are shown in Figure 4 and the out-of-plane and in-plane coercivities are summarised in Table 1. The coercivity also increased from 1.0 kOe to 6.4 kOe with a deposited 4 nm Ag overlayer. The mechanisms of the $L1_0$ ordering promotion by the Ag overlayer should be quite different from that of the FePt–Ag composite films since there is no vacancy created in the FePt lattice. Further investigations on the effects of co-deposited Ag and Ag overlayer on ordering of FePt are warranted.

Figure 2 Coercivity of the Glass/CrRu (30 nm)/Pt(4 nm)/FePt–Ag films as a function of Ag volume fraction (substrate temperature 400°C)

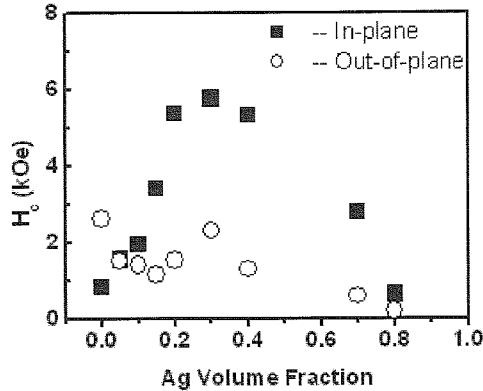


Figure 3 In-plane XRD scans of FePt thin films with different thicknesses of Ag overlayer with an incident angle of 0.5°

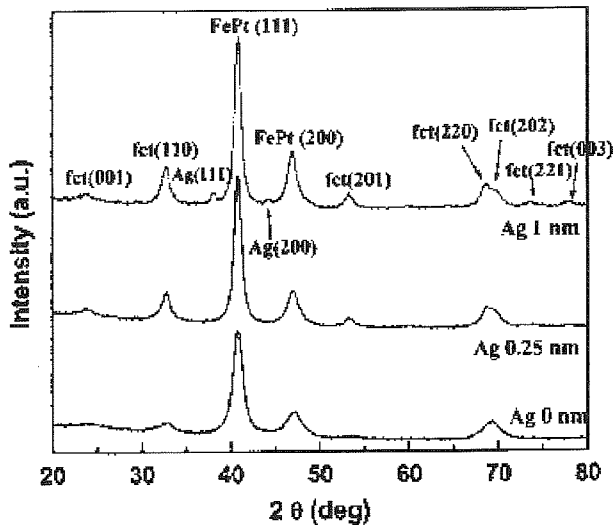
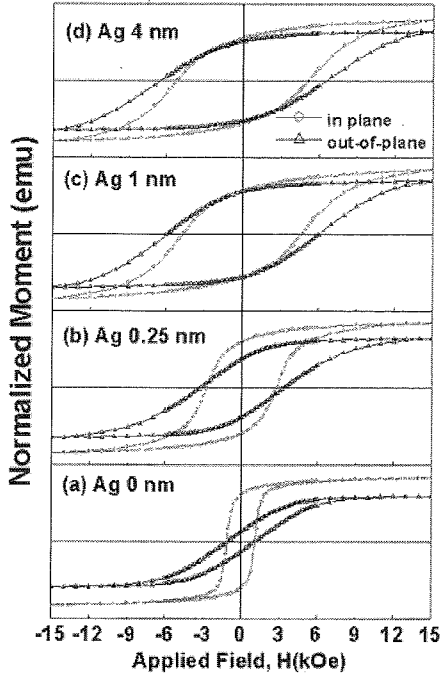


Figure 4 Hysteresis loops of Glass/FePt/Ag films with various Ag overlayer thickness**Table 1** In-plane coercivity and out-of-plane coercivity of FePt films with different structures

Sample	Film structure	H_c (Oe) (in-plane)	H_c (Oe) (out-of-plane)
A	Glass/FePt (15 nm)	1098	1045
B	Glass/FePt (15 nm)/Ag0.25 nm	2751	3288
C	Glass/FePt (15 nm)/Ag1 nm	4685	5980
D	Glass/FePt (15 nm)/Ag4 nm	5107	6398

2.2 Strain- or stress-induced $L1_0$ ordering

When the phase transformation from *fcc* to $L1_0$ phase occurs, the lattice constant a becomes larger and lattice constant c becomes smaller. One can easily imagine that as a force presses on a surface of a cube or stretches along a surface, the cube will deform to a tetragonal shape.

Based on this simple principle, several groups developed various methods to promote the phase transformation from *fcc* to $L1_0$ phase (Suzuki et al., 1999; Hsu et al., 2001; Xu et al., 2002; Ding et al., 2005a; Lai et al., 2004). Suzuki et al. successfully fabricated $L1_0$ ordered FePt film at temperature of 400°C using the high-pressure sputtering. It is suggested that the compressive stress along the c -axis resulted from high gas pressure (100 Pa) favoured the formation of the $L1_0$ phase. The $L1_0$ FePt film was also prepared at 275°C by the so-called dynamic stress. In this method, FePt films were deposited on Cu underlayer/HF-cleaned Si (100) substrate, followed by post-deposition annealing. With increasing annealing temperature up to 250°C, the stress increased owing to the difference in thermal expansion coefficient between Cu film and the Si substrate.

The stress increased with further increasing temperatures owing to formation of Cu_3Si . With the completion of reaction of Cu and Si, the stress tended to relax. It was demonstrated the $L1_0$ ordering of FePt films was closely related to the change of the stress. Note that the ordering of FePt films associated with the lattice distortion was achieved by the contraction along [111], not [001].

When a thin film with certain lattice mismatch with the substrate is deposited, the lattice parameter of the film could either expand or shrink in the film direction depending on the negative or positive mismatch. For a negative lattice mismatch, i.e., the lattice constant of film is less than that of substrate; the lattice constant could be expanded in the film direction and shrunk in the film normal direction. There exists a critical film thickness. Beyond the critical thickness, the strain induced by the lattice mismatch would be relaxed by forming defects such as dislocations and the lattice constant of the top part of the film will revert to the un-strained value. It has been suggested that the lattice mismatch at the interface between FePt film and underlayer may expand the a -axis and shrink the c -axis of the FePt film, favouring the ordering at low temperatures. For example, Ag underlayer on Si substrate and CrX underlayer were used to fabricate the $L1_0$ FePt films at low temperature (Hsu et al., 2000, 2001). The relationships between the lattice mismatch and the chemical ordering of the FePt films, and their magnetic anisotropic constant have been investigated (Ding et al., 2005a). The 20-nm-thick FePt films were sputtered on MgO (200) single-crystal substrates with or without intermediate layers at 350°C. The 30-nm-thick Pt, Cr, $\text{Cr}_{95}\text{Mo}_5$, and $\text{Cr}_{90}\text{Mo}_{10}$ intermediate layers were used to adjust the lattice mismatch. Table 2 listed the calculated lattice constant of the intermediate layers grown on both the MgO and glass substrates and lattice mismatch between different intermediate layers and FePt films as measured using XRD. Figure 5 summarises the lattice constants of a (a) and c (b), the tetragonality represented by c/a (c), the long-range order parameter S (d), and the magnetocrystalline anisotropy energy, K_u (e) with respect to the lattice mismatch. The long-range ordering parameter S was characterised by the integrated intensity ratio between the FePt (001) and (002) peaks. The results showed that the c -value decreased with increasing lattice mismatch from about 2.23% to 6.33%. Upon further increase in lattice mismatch, c increased in turn. On the other hand, the variation of a illustrated a reversal behaviour to that of c with the increased lattice mismatches. The value of c/a held a minimum ($c/a = 0.9466$) for lattice mismatch near 6.33%. The chemical ordering and anisotropy held maximum values when lattice mismatch was 6.33% where c/a held a minimum. These results indicated that there was a critical lattice mismatch near 6.33%, which was most favourable for improving the chemical ordering of FePt films.

It was reported that based on the lattice mismatch-induced phase transformation, the ordering of FePt films occurred even at the temperature as low as 200°C, as indicated by the large magnetocrystalline anisotropy (Chen et al., 2005a). The magnetic properties of FePt films with a structure of Glass/CrRu (30 nm)/Pt (4 nm) deposited at different temperatures are listed in Table 3. It can be found that FePt films with uniaxial anisotropy constant higher than 1×10^7 erg/cm³, and high magnetic squareness were obtained at substrate temperatures of 250°C.

Table 2 Lattice constants of the intermediate layers, epitaxial relationships, and lattice mismatches

Sample	Intermediate layer	a_1 (Å)	a_2 (Å)	Epitaxial relationship	ϵ (%)
A	Pt	3.9281	3.9231	MgO(100)<001> Pt(100)<001> FePt(001)<100>	2.23
B	Cr	2.8839	2.8776	MgO(100)<001> Cr(100)<110> FePt(001)<100>	5.88
C	Cr ₉₅ Mo ₅	2.8976	2.8912	MgO(100)<001> Cr(100)<110> FePt(001)<100>	6.33
D	Cr ₉₀ Mo ₁₀	2.9152	2.9114	MgO(100)<001> Cr(100)<110> FePt(001)<100>	6.89
E	MgO	4.2112		MgO(100)<001> FePt(001)<100>	8.86

a_1 : Lattice constant of intermediate layer (grown on MgO).
 a_2 : Lattice constant of intermediate layer (grown on glass).
 Σ : Lattice mismatch.

Figure 5 Lattice constants of a (a) and c (b), tetragonality represented by c/a (c), long-rang order parameter S (d), and uniaxial magnetic anisotropy energy K_u (e) as a function of lattice mismatch

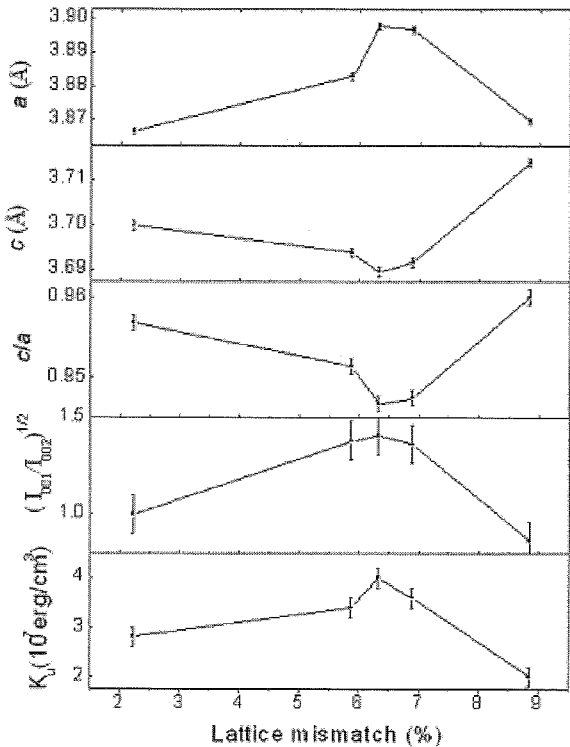


Table 3 Uniaxial magnetic anisotropy energy (K_u), Magnetic squareness ($M_{r,l}/M_{S,l}$) and coercivity (H_{CL} , H_{Cl}) for FePt films deposited at different substrate temperatures (T_s)

T_s (°C)	K_u (erg/cc)	$M_{r,l}/M_{S,l}$	H_{CL} (Oe)	H_{Cl} (Oe)
150		0.04	164	436
200	7.6×10^6	0.91	1317	842
250	1.0×10^7	0.98	1435	1081
300	1.4×10^7	0.98	1856	1599
350	1.8×10^7	0.98	2178	1268

2.3 Other approaches for $L1_0$ ordering

Other approaches have also been investigated to decrease the ordering temperature and increase the ordering parameter. Ravelosona et al. (2000) investigated the ordering process of FePt films by 130 keV He ion irradiation. The ordering parameter- S increased up to 0.3 and 0.6, respectively, when the disorder ($S \sim 0$) and partially ordered ($S \sim 0.4$) FePt films were irradiated by He ion with fluencies 4×10^{16} ions/cm² at 280°C. The beam interaction led to atomic displacements and the heating promoted atomic re-arrangements and lattice relaxation. With increasing energy of He ion (2 MeV) and beam current (1.25–6 μ A), high ordered $L1_0$ FePt films were obtained (Lai et al., 2003). The coercivity of the films exceeded 5700 Oe after the disordered FePt was irradiated at beam current 1.25 μ A with ion fluencies of 2.4×10^{16} ions/cm². The high beam current caused direct beam heating on sample. In addition, the irradiation-induced heating process provided efficient microscopic heat transfer and created excess point defects, which significantly enhanced the diffusion and thus promoted the formation of $L1_0$ ordered FePt films. It was also reported that $L1_0$ ordered FePt film could be obtained by 350°C post-annealing of FePt film deposited on AuCu underlayer (Zhu and Cai, 2005). The ordering of AuCu underlayer at low temperature coherently induced the disorder–order transformation of FePt films.

3 Control of FePt (001) texture

3.1 Epitaxial growth

The epitaxial growth of FePt (001) textured films requires the substrates or underlayers to have a similar atomic configuration to that of FePt (001) plane and small lattice mismatch. Substrates or underlayers used are MgO (100), SrTiO₃ (100), Cr (200), Ag (200) with epitaxial relationship FePt (001) $\langle 100 \rangle \parallel$ MgO (100) $\langle 001 \rangle$, FePt (001) $\langle 100 \rangle \parallel$ SrTiO₃ (100) $\langle 001 \rangle$, FePt (001) $\langle 100 \rangle \parallel$ Ag (100) $\langle 001 \rangle$, and FePt (001) $\langle 100 \rangle \parallel$ Cr (100) $\langle 110 \rangle$. The lattice mismatch of FePt with MgO, SrTiO₃, Ag and Cr (200) are 8.5%, 2%, 7.1%, and 5.8%, respectively. Although FePt (001) textured films had been produced using the MgO (100) and SrTiO₃ (100) single-crystal substrates by Molecular Beam Epitaxy (MBE), sputtering and laser ablation, they are not suitable for practical application because of the costly single-crystal substrates (Lairson and Clemens, 1993; Visokay and Sinclair, 1995; Farrow et al., 1996; Yang et al., 2002; Ding et al., 2005b). FePt (001) preferred films were also grown on Ag (100) underlayer/Si (100)

substrate (Hsu et al., 2000). Very thick Ag films made it very difficult for application of double-layered FePt perpendicular media. Since Ag has a low melting point and low surface energy, it is difficult to maintain small grain size at high temperatures. The MgO (100) and CrX (200) ($X = \text{Ru}, \text{Mo}, \text{W}, \text{Ti}$) underlayers are very promising for practical applications. A few literatures reported the fabrication of FePt (001) textured film on MgO (100) underlayers (Suzuki et al., 1999; Jeong et al., 2002; Kang et al., 2003b, 2004; Platt et al., 2002). In the following part, FePt (001) textured films grown on CrRu underlayer are discussed.

The lattice mismatch between Cr (200) and FePt (001) is $\sim 5.8\%$. In Section 2.2, it was shown that when the lattice mismatch was 6.33%, FePt film had the largest magnetic anisotropy. For practical applications of $L1_0$ FePt films in ultra-high-density magnetic recording, it is necessary to deposit CrX (200) textured film on glass substrates. It has been reported that among Ru, Mo, W and Ti, CrRu had the best (200) texture on the glass substrate and thus FePt (001) texture (Ding et al., 2005c; Chen et al., 2006). By adjusting Ru contents in the CrRu alloy, the lattice constant of Cr underlayer could be tailored to desired lattice mismatch.

Figure 6 shows θ - 2θ XRD spectra of $\text{Cr}_{100-x}\text{Ru}_x$ (80 nm) / FePt (20 nm) films with x (at.%) varying from 0 to 11.6. With the increase in the Ru content, the Cr (002) peaks shifted to a lower angle, indicating the increase in Cr lattice constant. For the sample without Ru in the Cr underlayer, the FePt (111) peak and Cr (110) peak with weak intensities were observed. However, with addition of a small amount of Ru in the Cr underlayer, the Cr (110) and FePt (111) peaks disappeared, and good FePt *fcc* (001) texture was obtained. The intensity of FePt (001) peak increased with Ru content up to 9.0 at.%. Further increasing the Ru content in the Cr underlayer resulted in a dramatic decrease in the FePt (001) peak intensity.

Figure 6 XRD θ - 2θ scans of $\text{Cr}_{100-x}\text{Ru}_x$ /FePt films with x

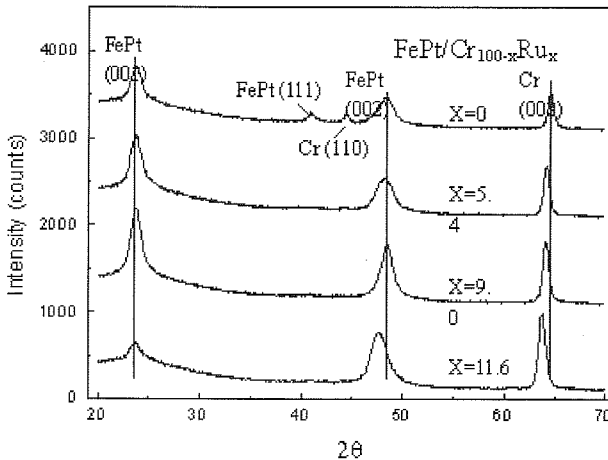
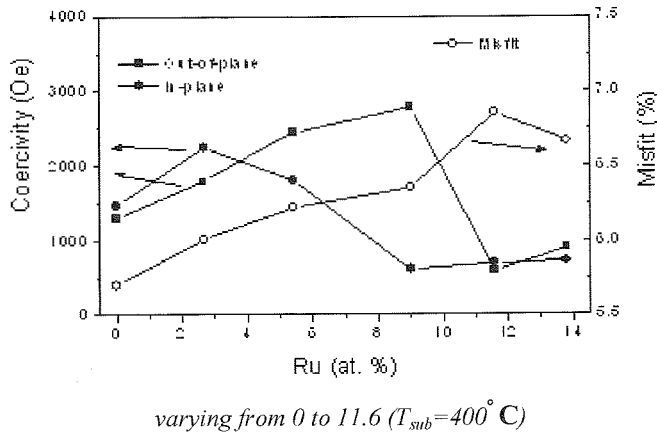


Figure 7 shows the variation of the out-of-plane and in-plane coercivities with the Ru content in the Cr underlayer for these samples. The change in the corresponding lattice misfit between the CrRu underlayer and FePt films is also shown in Figure 7. With the increase in Ru content in the Cr underlayer, the lattice misfit increased linearly with increasing Ru, reached a maximum at 11.6 at.% Ru, and subsequently decreased.

On the other hand, the out-of-plane coercivity increased with Ru content and reached a maximum at 9.0 at.%, then significantly decreased with increasing Ru in the Cr underlayer. The in-plane coercivity increased first and then decreased, reaching the lowest value at 9.0 at.% Ru. Note that as the lattice mismatch was 6.3% (9 vol.% Ru), out-of-plane coercivity attained the largest value, consistent with that of FePt films on MgO (001) substrate with different intermediate layers as discussed in Section 2.2.

Figure 7 Out-of-plane coercivity, in-plane coercivity, and lattice misfit between CrRu and FePt as a function of Ru content



For magnetic recording media, the interface roughness between the magnetic layer and underlayer is very important since the rough interface may result in thick magnetic dead layer that deteriorates magnetic properties. The sharpness of the interface is controlled by interdiffusion and chemical reaction. The interface between Cr underlayer and FePt magnetic layer is very rough due to the diffusion, as shown in Figure 9(a). A buffer layer to block the underlayer diffusion is therefore required. The choice of the buffer layer must meet two requirements:

- low diffusion to FePt
- small lattice mismatch with FePt (001) plane.

Pt has a high melting point with a low diffusion constant in Fe (Landolt and Börnstein, 1992). The lattice mismatch between FePt and Pt is 2%. Pt as buffer layer between Cr underlayer and FePt magnetic layer was reported (Chen et al., 2003). Figure 8 shows the XRD spectra of thin films with the structure of Glass/Cr₉₁Ru₉ (30 nm)/Pt (0–6 nm)/Fe₅₀Pt₅₀ (20 nm)/Cr (2 nm). With 4 nm Pt buffer layer, a good FePt (001) texture with the full-width-half-maximum of the rocking curve of about 7° was obtained. The X-ray Photoelectron Spectroscopy (XPS) spectra of samples, shown in Figure 9, indicated that Cr diffusion from CrRu underlayer occurred for the sample with no buffer layer. On the other hand, Cr diffusion was effectively suppressed for the sample with 4 nm buffer layer. The out-of-plane and in-plane hysteresis loops of FePt film with 4 nm Pt buffer layer are shown in Figure 10. The out-of-plane loop showed a coercivity of 3.7 kOe with remanent magnetisation squareness of 0.97, nucleation field of –2.5 kOe and coercivity slope of 4.0. The in-plane coercivity was 190 Oe and much smaller than

the out-of-plane coercivity. These indicated that good $L1_0$ FePt (001) texture with good perpendicular properties have been achieved at low deposition temperature.

Figure 8 XRD spectra of Glass/Cr₉₁Ru₉ (80 nm)/Pt (0–6 nm)/Fe₅₀Pt₅₀(20 nm) films with various Pt layer thickness (Substrate temperature 400°C)

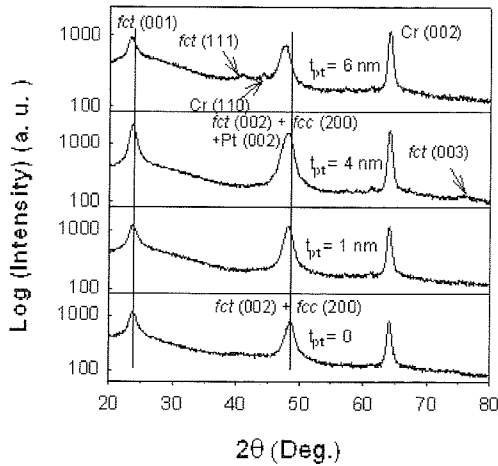


Figure 9 Depth profiles of FePt films: (a) without the Pt buffer layer and (b) with 4 nm Pt buffer layer thickness. A 2 nm Cr cap layer was deposited to protect FePt from oxidation

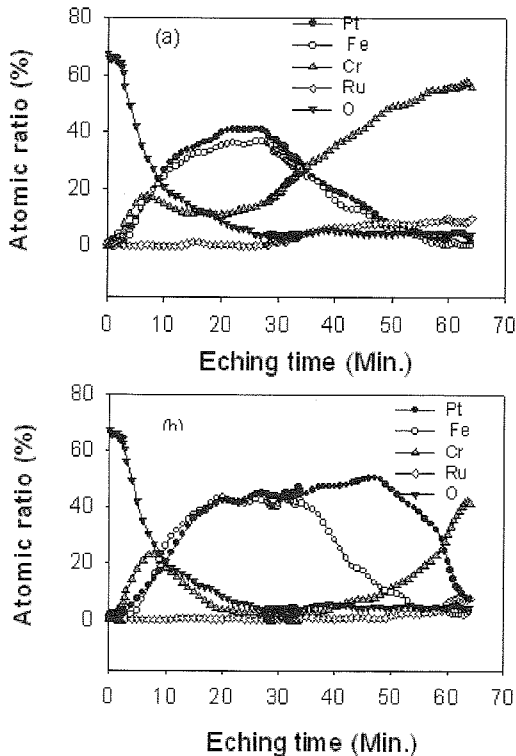
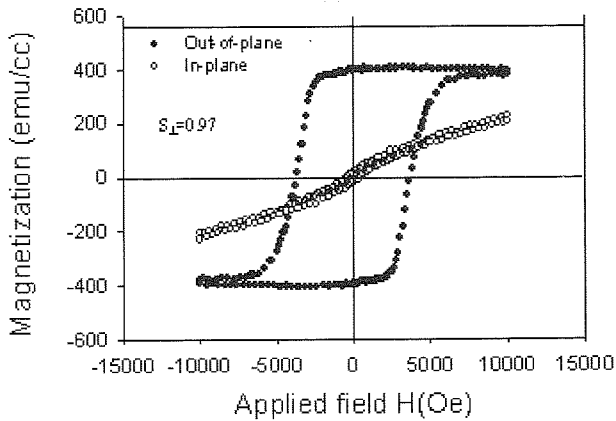


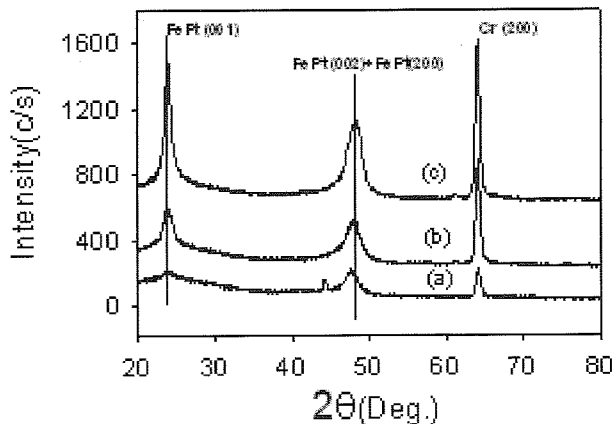
Figure 10 Out-of-plane and in-plane hysteresis loops of Cr₉₁Ru₉ (80 nm)/Pt (4 nm)/FePt (20 nm) film deposited at 400°C



The base pressure of the vacuum is a very important factor affecting the texture of both CrRu underlayer and FePt magnetic layers (Chen et al., 2002). The $L1_0$ FePt films exhibited (200) preferred orientation and had longitudinal anisotropy at the base pressure of 4×10^{-6} Torr. As the base pressure was improved (below 9×10^{-7} Torr), the $L1_0$ FePt films showed the (001) preferred orientation with perpendicular anisotropy. The XRD spectra of FePt films deposited at various base pressures are shown in Figure 11.

The epitaxial growth method requires a thick underlayer to optimise the FePt (001) texture (Ding et al., 2005d). In double-layered perpendicular recording media, if the soft magnetic layer is below the underlayer, the recording resolution will be drastically deteriorated owing to the increase in head field-gradients. If a soft magnetic layer is above the underlayer, the lattice match with underlayer such as FeSi or FeCo with (100) orientation is needed, limiting the choice of the soft magnetic layer with the best magnetic properties.

Figure 11 XRD spectra of Glass/CrRu (80 nm)/Pt(4 nm)/Fe₅₂Pt₄₈(20 nm) films deposited at base pressure of (a) 4×10^{-6} Torr (b) 9×10^{-7} Torr (c) 5×10^{-9} Torr (substrate temperature 400°C)



3.2 Non-epitaxial growth

In Sellmyer's group, non-epitaxial growth method was developed to fabricate FePt (001) textured films (Luo and Sellmyer, 1999; Luo et al., 2000; Zeng et al., 2002). In this method, $(\text{Fe/Pt})_n$ multilayer films were deposited on glass substrate or thermally oxidised Si substrate and subsequently post-annealed in forming gas ($\text{Ar} + 4\% \text{H}_2$) by Rapid Thermal Annealing (RTA). There were a few key experimental conditions affecting the orientation (Yan et al., 2003). Among the experimental conditions, annealing time, temperature and the thickness of each Fe or Pt layer were the most important factors. At temperatures below 350°C , only (111) peak was observed. With increasing temperature, the (111) peak tended to decrease and FePt (001) peak increased. When 550°C was exceeded, good $L1_0$ FePt (001) textured films were obtained. However, with further increase in the temperature to above 750°C , the films reverted to (111) preferred orientation. When the annealing time was too short (2 s) or too long (30 min) (Yan et al., 2002), strong FePt (111) peak appeared. For moderate annealing times, FePt (001) texture was preferred. When each Fe and Pt layer was thicker than 1.38 nm and 1.2 nm, respectively, FePt (111) texture predominated. The mechanisms of the non-epitaxial growth can be understood by combining the kinetics and thermodynamics of film growth with the initial nucleation of FePt (001) grain owing to the stress resulted from the difference in the thermal expansion coefficient between the substrate and FePt films (Rasmussen et al., 2005). From the thermodynamics point of view, FePt (111) is preferred since (111) plane is closest packed with the lowest energy. Therefore, films deposited at low temperature has (111) texture since the thermal stress is not sufficient for nucleation of (001) grains. Films deposited at high temperature or post-annealed for a long time favoured the (111) preferred orientation due to predominant thermodynamics. At moderate temperatures or moderate annealing times, FePt (001) textured films were obtained possibly because the thermal stress sufficiently causes the nucleation of (001) grain with favourable kinetics for diffusion to occur. For the thicker Fe and Pt layers, the (111) preferred orientation could be ascribed to that the diffusion length at that temperature and annealing time was insufficient.

The advantage of non-epitaxial growth is the use of a thinner layer between soft underlayer and magnetic recording layer in the double-layered perpendicular media, where the efficiency of the writing field and the writing field gradient can be dramatically enhanced compared with that with a thick spacing layer. On the other hand, in the industry production line, high productivity (several seconds per disk) is the most important factor affecting the practical application of a technology. The multilayer process and long-time thermal annealing are the main disadvantages of the non-epitaxial growth method.

4 Media noise reduction

For perpendicular recording media, the media noise mainly originates from transition noise, which is closely related to magnetic domain size. Usually, the reduction in the media noise is achieved by reducing the magnetic grain size and decreasing the exchange coupling between the grains. For FePt media, the elemental doping to reduce the grain size and decrease the exchange coupling also result in the decrease in ordering of FePt due to the decrease in surface diffusion, thus deteriorating the magnetic properties

(Chen et al., 2005b). Recently, Suzuki et al. (2003) proposed a pinning type FePt perpendicular media. Because of the large magnetic anisotropy of $L1_0$ FePt film, the domain wall width was quite small and comparable with the size of structure defects, e.g., crystal defects. The pinning was proportional to the density of the pinning sites such as the crystal imperfections and inhomogeneities and was most pronounced when the size of pinning sites was comparable with the domain wall width (Skomski and Coey, 1999). The structural defects induced in FePt recording layer will provide a number of pinning sites for suppression of the domain wall propagation and decrease in the domain size and thus decrease in the media noise. The idea had also been demonstrated by a two-step method deposited FePt media (Suzuki and Ouchi, 2002). However, the *fcc* FePt nucleation layer deteriorated the magnetic properties such as coercivity and squareness.

In this part, we discuss a method to induce the pinning sites and decrease the domain size (Chen et al., 2005c). In Section 2.1, it has been discussed that the Ag may promote the phase transformation of FePt. Moreover, Ag (100) plane has similar atomic configuration with that of FePt (001) plane and the lattice mismatch between the two planes is 7.1%. It is expected when a thin Ag layer is inserted into FePt layers, the Ag itself and structure defects of FePt layers caused by inserted Ag layer may pin the domain wall and decrease the domain size and media noise, while maintaining the magnetic properties of FePt layer and the FePt (001) texture.

The FePt single-layered perpendicular media were deposited on a 2.5 in glass disk made by Hoya Corp. with the structure of substrate/Cr₉₀Ru₁₀(30 nm)/Pt (4 nm)/FePt(6 nm)/Ag(*t* nm)/FePt(6 nm), where the total FePt thickness was maintained at 12 nm and *t* = 0, 0.5, 1, 2 (Chen et al., 2005c). The FePt (001) texture was retained regardless of Ag layer thickness. The out-of-plane hysteresis loops of FePt films with one Ag layer insertion are shown in Figure 12. The coercivity increased linearly from 1.93 kOe to 3.2 kOe with increasing Ag thickness from 0 nm to 2 nm. The slope of the hysteresis loop at coercivity – (dM/dH) decreased monotonically, indicating that the exchange coupling was reduced. To understand the magnetisation reversal mechanism and thus the change in coercivity after inserting the Ag layer with different thicknesses, the angular variation of coercivity was investigated, as shown in Figure 13. Without Ag insertion, the magnetic reversal mechanism was close to the domain wall motion mode. With increasing Ag thickness, the magnetic reversal mechanism approached the Stoner–Wohlfarth rotation mode, which is favourable for reducing the media noise. The Magnetic Force Microscopy (MFM) images of ac-demagnetised FePt films with different thicknesses of inserted Ag layer are shown in Figure 14. The domain size decreased with increasing Ag pinning layer thickness, indicating domain wall pinning by Ag. Corresponding to the decrease in the slope of M–H loops with the increase of the Ag layer thickness, the domain size also decreased, further indicating the decrease in lateral exchange coupling. The read/write test was performed on a Guzik spin-stand (1701B) using a 30 Gb/in² commercial ring head. The media noise and SNR of the FePt media with different thicknesses of Ag are shown in Figures 15 and 16, respectively. With increasing Ag thickness up to 2 nm, media noise was effectively reduced and the Signal-to-Noise Ratio (SNR) was remarkably enhanced. The reduction in media noise was mainly due to the pinning of the domain wall by Ag and structural defects in FePt layer caused by Ag insertion.

Figure 12 Out-of-plane hysteresis loops of 12 nm FePt films deposited at 350°C without Ag layer and with one Ag layer of different thickness

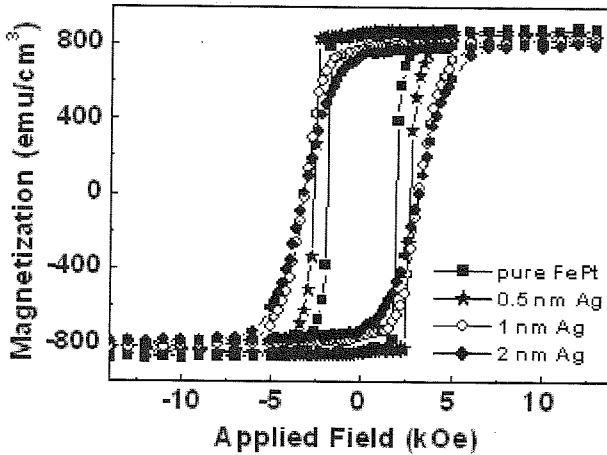
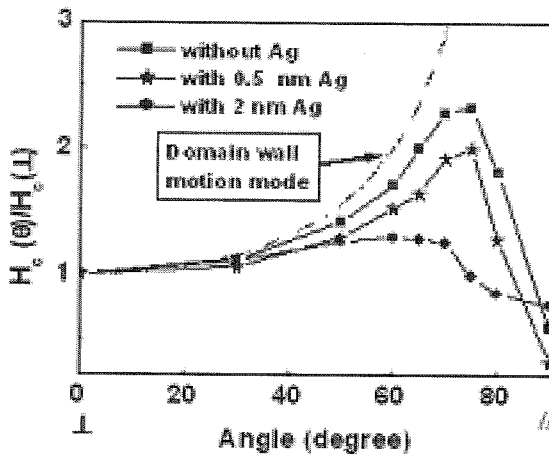


Figure 13 Angular dependence of coercivity of samples with varied thickness of one-layer Ag insertion



The media noise can be decreased by introducing pinning sites and reducing domain size. Yet, the challenge to obtain uniform pinning sites using this approach remains. In addition, the domain size is proportional to the pinning sites caused by crystalline defects. The crystalline defects in FePt crystals will, however, decrease the anisotropy and deteriorate the magnetic properties. Therefore, when the areal density is 1 Tbits/in² and above, the domain wall pinning-based method results in thermal instability of recording bits because of the deterioration of magnetocrystalline anisotropy caused by crystalline defects.

Figure 14 MFM images of 10 nm FePt films with one-layer inserted Ag thickness of (a) 0 nm; (b) 1 nm and (c) 2 nm anisotropy caused by crystalline defects

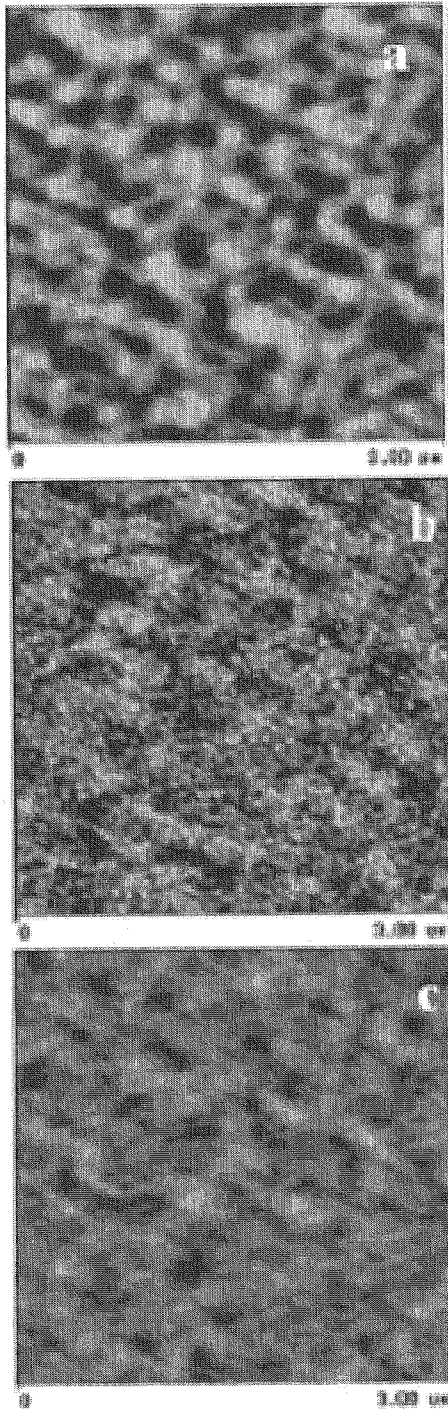


Figure 15 Noise as a function of linear density for FePt samples with different one-layer Ag thickness

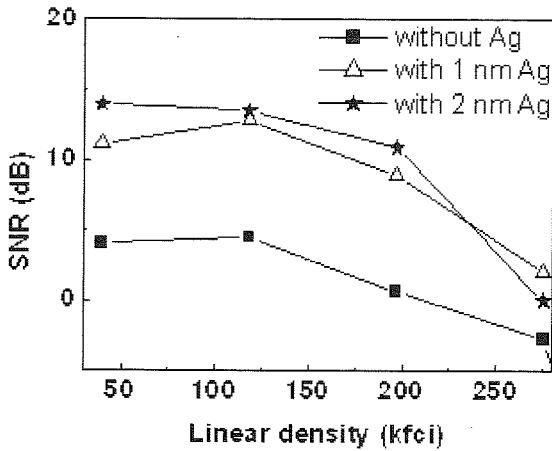
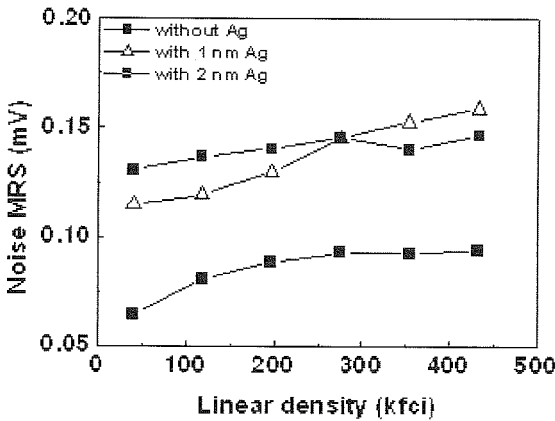


Figure 16 Signal-to-noise (SNR) as a function of linear density for FePt samples with different one-layer Ag thickness



5 Summary

In this paper, the developments in $L1_0$ FePt chemical ordering at low temperature, control of FePt (001) texture, and media noise reduction were reviewed. Some key technical issues in applications of FePt film for ultra-high-density magnetic recording media have been solved independently from each other. For practical applications, solutions that address not only a single issue, but also the composite of issues, must be sought. In this aspect, the materials ‘engineering’ problems associated with the requirements of ultra-high-density recording remain considerable and challenging.

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