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Magnetic Anisotropy**

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Vacuum Annealed FePt/Ag Nano-multilayers with Perpendicular Magnetic Anisotropy

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Abstract

(FePt/Ag)_n nano-multilayers were deposited on MgO(100) single crystal with laser ablation and then subjected to annealing. FePt L1₀ grains with (001) texture and thus a large perpendicular magnetic anisotropy constant K_u of the order of 10^7 erg/cm³ were formed. A thick Ag layer is found to be favorable for decreasing the dispersion of the easy axis for magnetization. The measurement of time decay of magnetization gave rise to a small activation volume of the order of 10^{-19} cm³, showing the promising of being the recording medium for future high density perpendicular recording.

1. Introduction

It is known that FePt alloy thin films in the ordered L1₀ phase exhibits a perpendicular magnetic anisotropy constant K_u of the order of 10^7 erg/cm³ at room temperature [1,2] and is very attractive for future high density magnetic recording. In the FePt L1₀ phase, Fe and Pt atomic planes stack alternatively along c axis, which is the easy axis for magnetization. Usually as-deposited FePt alloy thin films are disordered fcc phase, and thus have very small K_u values. In order to obtain the ordered L1₀ phase, as-deposited films need to be annealed [3,4]. One of the side effects of annealing is the grain growth. In addition, there also exists strong exchange coupling between grains in the FePt L1₀ film. Both can result in a big activation volume for magnetic switching and thus are the sources of recording noise, which must be minimized.

In order to obtain small size- and magnetically decoupled- grains in FePt L1₀ thin films,

nanocomposite FePt films with various matrix [5,6] were studied. In most of the reports, the orientation of the magnetic easy axis is random, which would lead to a very low resultant magnetic anisotropy in the film. Therefore, it is very important to engineer the crystallographic orientation of $L1_0$ ordered thin film so that the easy axis can be established in the desired direction, e.g. along the film normal for perpendicular magnetic recording.

Nanocomposite films are usually fabricated by annealing the nano-multilayers or co-deposited film of FePt and the matrix materials. In this study, FePt/Ag multilayers were deposited on MgO(100) substrates and annealed to fabricate FePt-Ag nanocomposite films with decoupled magnetic grains and perpendicular magnetic anisotropy. There are two reasons for choosing Ag as the matrix. One is the similar crystallographic structure to each other and close lattice parameters between FePt, Ag and MgO, which is favorable for controlling the growth orientation of the film. The other reason is to keep the FePt phase unmixed with the matrix phase.

2. Experimental Procedure

$(\text{FePt/Ag})_n$ multilayers were deposited onto MgO(100) substrates using a laser ablation system. The background and deposition pressures were 2×10^{-7} Torr and 5×10^{-7} Torr, respectively. The substrates were kept at ambient temperature during deposition. As-deposited multilayers were then annealed in a rapid thermal annealing furnace in a vacuum of 3×10^{-6} Torr. Structure was characterized by x-ray diffraction with $\text{Cu-K}\alpha$ irradiation in a conventional θ - 2θ scanning mode. Magnetic properties were measured using vibrating sample magnetometer, Alternating Gradient Force Magnetometer and torque magnetometer.

3. Results and discussion

To obtain the desired crystallographic orientation of FePt, MgO substrate and MBE technique are often used. In most cases, the substrate is heated to high temperature both before and during deposition [1,7]. In this study, the FePt/Ag multilayers were deposited on unheated MgO(100) substrates with laser ablation. However, the multilayers with a FePt bottom layer also present (100) orientation, which should be resulted from the hetero-epitaxial growth because of the same crystallographic structure and the close lattice parameters between Ag, FePt layers and MgO(100) substrate. In the case that the Ag layer is the bottom layer, no apparent preferential orientation could be observed.

To fabricate the FePt-Ag nanocomposite film, the as-deposited multilayers were subjected to vacuum annealing. For all the annealed films, a peak at about 24 degree appears in the x-ray diffraction patterns, corresponding to the (001) plane of FePt $L1_0$ phase, indicating the formation of FePt $L1_0$ phase in the film. Only diffraction peaks from FePt ($L1_0$), Ag and MgO can be observed, showing that FePt ($L1_0$) and Ag phases are separated from each other in the annealed film.

A series of $[\text{FePt}(2\text{nm})/\text{Ag}(d)]_{10}$ multilayers with FePt bottom layer were annealed at 600°C for 15 minutes, d varying from 0 to 5 nm while FePt layer was kept at 2 nm. As shown in Fig.1, in addition to weak (001) and (002) peaks, the x-ray diffraction pattern for $d=0$ nm, i.e, the annealed FePt single layer, shows strong (111) and (200) diffractions, indicating that the crystalline grains are mainly oriented with both (111) and (200) planes parallel to the film plane. With increasing the Ag layer thickness, (001) and (002) peaks from FePt and (002) peak from Ag become stronger and stronger while other peaks become weaker and weaker, implying the development of the (001) preferential orientation in the film. However, except for the strong diffractions from (001) and (002) planes, weak peaks from (111) planes still remain for a Ag layer thickness $d < 4\text{nm}$. As the Ag layer thickness was further increased, only the (001) and (002) peaks from FePt($L1_0$) and Ag could be clearly observed, showing that the annealed FePt/Ag films on the MgO(100) substrate have completely the same crystallographic orientation as the substrate. It is shown that a thick Ag layer is in favor of the (001) epitaxial growth.

For all the as-deposited FePt/Ag multilayers, the periodic layered structures along thickness direction were evidenced with low angle x-ray diffraction. However, with increasing the annealing temperature, the low angle diffraction peaks disappears. The evolution of the low angle diffraction suggests the morphology change of the FePt grains in the FePt/Ag film with annealing, most likely from discontinuous layers to spherical or cubic shape, and thus the deteriorating of the layered structure. X-ray diffraction results also show that the FWHM (full width at half maximum) of the FePt($L1_0$) (001) and (002) peaks are rather big, indicating small FePt($L1_0$) grains. On the other hand, the Ag peaks in all the x-ray diffraction patterns are rather sharp, showing a large coherent length along thickness direction. It seems that in the annealed films, FePt grains are dispersed in the Ag matrix.

Since FePt($L1_0$) phase is fct structure with $a > c$, the (001) orientation of FePt($L1_0$) grains should be

attributed to the larger Ag lattice parameter and the multilayer structure, which help keeping the c-axis of the FePt(L1₀) phase along the film normal during the phase transition from fcc to fct, so that the mismatch between FePt(L1₀) and Ag lattices could be smaller. Apparently, a thicker Ag layer is more helpful for keeping this orientation.

The *M-H* loops of the annealed FePt-Ag films were measured with a VSM at a maximum applied field of 15 kOe in both perpendicular and in-plane directions. Due to the shape anisotropy, all the as-deposited multilayers are found to possess the in-plane easy axis for magnetization. For multilayers with a FePt layer of 2nm, it is shown that with increasing the Ag layer thickness, the easy axis for annealed film rotates to the perpendicular direction. For a Ag layer thicker than 3 nm, the film normal is apparently the easy axis after annealing. The remanence ratio M_r of the M-H loop measured along the perpendicular direction also increases to nearly 1 when Ag layer thickness increases to 5nm, at which the in-plane hysteresis is nearly 0, typical for magnetization along hard axis. This means that there is almost no in-plane component for the easy axis and an almost perfect perpendicular anisotropy is realized.

Considering that the large magnetic anisotropy in the FePt L1₀ phase is mainly from the magnetocrystalline anisotropy, for which the [001] direction is the easy axis for magnetization, the orientation change of the easy axis in the annealed FePt/Ag films is in accordance with the development of the (001) preferential orientation with increasing the Ag layer thickness. With the improvement of the (001) preferential orientation in the annealed FePt/Ag films, the easy axis accordingly rotates to the perpendicular direction.

The dependence of the remanence ratio M_r and coercivity H_c of the perpendicular *M-H* loops on annealing temperature T_a is shown in Fig.2. When the annealing temperature is 540 °C, M_r is only 0.32 while the H_c is 250 Oe. After raising T_a to above 570 °C, M_r increases to almost 1. At the same time, H_c also increases with increasing the annealing temperature. The ordering degree of the L1₀ phase was calculated[1] according to the ratio between the integrated intensities of (001) and (002) peaks and found also increases as the annealing temperature increases. The increment of both M_r and the H_c should be partly related to the increased S . Another possible reason for the H_c enhancement may be the growth

of the FePt(L1₀) grains, which is well below the critical size for single domain. X-ray diffraction results show that the FWHM (full width at half maximum) of the FePt(L1₀) (001) and (002) peaks decrease with raising the annealing temperature, indicating the growth of the FePt(L1₀) grains.

The anisotropy constant was measured with a torque magnetometer at a maximum field of 15 kOe. Since the applied field is much lower than the anisotropy field, for those films with the easy axis well perpendicular to the film plane, the initial slope method was used to estimate the anisotropy constant [8]. An anisotropy constant about $2.5 \times 10^7 \text{ erg/cm}^3$ was obtained for an annealing temperature above 600°C. Figure 2 also shows the relationship between K_u and annealing temperature. The increment of K_u should be mainly related to the increased S .

For a recording medium, activation volume is very important. It is the switching unit during magnetic reversing. Usually, a small activation volume corresponds to a sharp transition between recorded bits, and thus a high signal to noise ratio. A small activation volume is favorable for a high recording density. Activation volume can be estimated by measuring the time decay of magnetization at various reversing fields [9]. For the Co-alloy media, V_a is usually the order of 10^{-18} cm^3 . [10]. In the present annealed FePt/Ag films, smaller activation volume was observed. For the [FePt(2nm)/Ag(5nm)]₁₀ multilayers annealed at 630 °C for 15 minutes, V_a was measured to be $6 \times 10^{-19} \text{ cm}^3$, as shown in Fig.3. In combination with the ΔM measurement, which shows decoupled FePt grains, the grain size (diameter) is roughly estimated to be 10 nm under the assumption of spherical grain.

4. Summary,

Perfect epitaxial growth of FePt/Ag nanocomposite film and accordingly high perpendicular magnetic anisotropy were realized on MgO(100) substrate by carefully choosing the underlayer, layer thickness and annealing conditions. A thick Ag layer is a key factor to improve the (001) orientation and thus decrease the dispersion of the easy axis for magnetization. A small activation volume of the order of 10^{-19} cm^3 was observed. These results show that the FePt/Ag nanocomposite film is promising for future high density perpendicular magnetic recording medium.

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Figure captions

Figure 1. XRD patterns for $(\text{FePt}2\text{nm}/\text{Ag}t\text{nm})_{10}$ multilayers with a FePt bottom layer annealed at 600°C for 15 minutes. (a) $d=0\text{nm}$, (b) $d=3\text{nm}$, and (c) $d=5\text{nm}$.

Figure 2. Dependence of H_c , M_r , K_u and S on annealing temperatures for $(\text{FePt}2\text{nm}/\text{Ag}5\text{nm})_{10}$ multilayers (FePt bottom layer) annealed for 15 minutes.

Figure 3. Activation volume for $(\text{FePt}2\text{nm}/\text{Ag}5\text{nm})_{10}$ multilayers (FePt bottom layer) annealed at 630°C for 15 minutes. ($\Delta H=500\text{e}$)

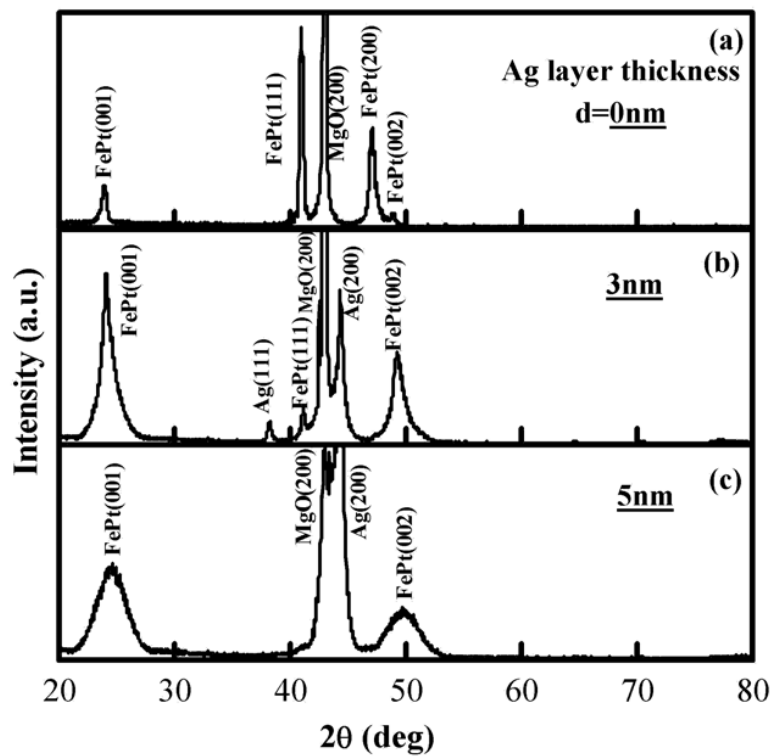


Fig.1 by T.Yang et al

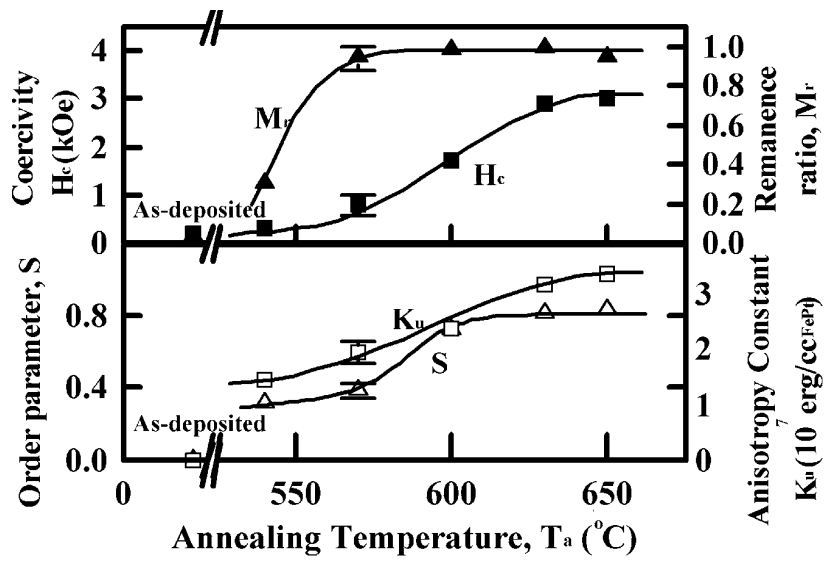


Fig.2 by T.Yang et al

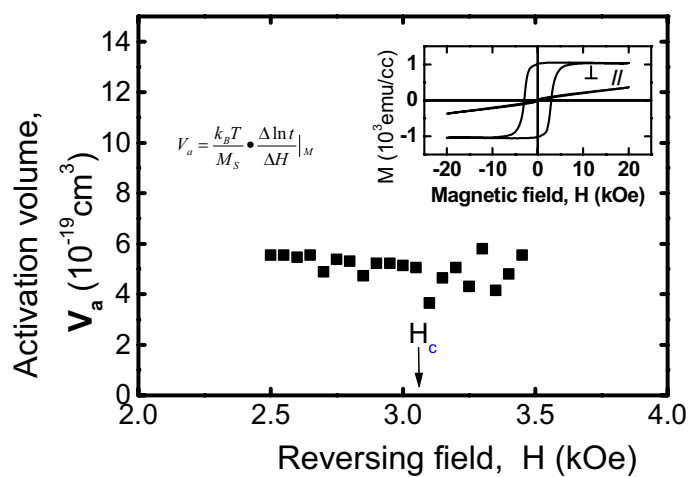


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