L1$_0$ Ordered FePt:C Composite Films With (001) Texture

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L1$_0$ Ordered FePt:C Composite Films With (001) Texture

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Abstract—Highly textured (001) FePt:C nanocomposite thin films, deposited directly on thermally oxidized Si wafers, are obtained by multilayer deposition plus subsequent thermal annealing. Nanostructures, crystalline orientations, interactions, and magnetic properties are investigated by transmission electron microscopy (TEM), X-ray diffraction (XRD), magnetic force microscopy, and magnetic measurements. The formation of the ordered L1$_0$ phase is confirmed by XRD, and only visible $(00l)$ peaks indicate a high degree of the (001) texture. TEM observation reveals that FePt grains are embedded in the C matrix and appear to be well isolated. The FePt grains are very uniform with average sizes about 5 nm.

Index Terms—FePt thin films, L1$_0$, magnetic recording.

Fig. 1. XRD patterns of 16-nm FePt:C film annealed at 550 °C for 300-s 32% volume percentage C.

I. INTRODUCTION

FEPT-BASED nanocomposite films prepared by sputtering are attracting considerable attention for extremely high density media because of the high magnetic-anisotropy L1$_0$ phase [1], [2]. For perpendicular recording, the easy axis of the FePt grains should be aligned normally with the film plane. This means that the (001) texture is required for the FePt grains. However, sputtered FePt-based nanocomposite films have a tendency to grow with (111) texture, so the easy axis of the FePt grains is at some angle from the film's normal direction. Recently, (001) texture has been obtained in FePt-based nanocomposited films with epitaxially grown [3], [4] and nonepitaxially grown [5]–[8] methods. For practical applications, the latter method is more convenient than the former. Thus, the nonepitaxially grown method is paid more and more attention. In this paper, we report nonepitaxially grown FePt:C nanocomposite films, and their magnetic, microstructure, and magnetic interactions properties. We present a micromagnetic analysis of the magnetization reversal in these films.

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II. RESULTS AND DISCUSSION

The samples were magnetron sputtered on thermally oxidized Si substrates with a multilayer structure of $[\text{Fe/Pt/C}]_n$. The composition of Fe, Pt, and C was well controlled by adjusting the thickness ratio of Fe, Pt, and C layers. The initial layer thicknesses ranged from 3–10 nm. The total film thickness was 16 nm. The purpose of C was to serve as a nonmagnetic matrix, reducing the degree of magnetic exchange coupling between FePt grains. Four concentrations of 10, 19, 26, and 32 of carbon volume fraction were used in this study. The as-deposited films were annealed in a rapid thermal annealer (RTA) at 550 °C for 300 s. Structural properties were analyzed by X-ray diffraction (XRD) and transmission electron microscopy (TEM). The magnetic measurements were made on an SQUID magnetometer with the magnetic field applied perpendicular to the film plane. Magnetic correlation lengths were determined by magnetic force microscopy (MFM).

XRD shows that the as-deposited film is a disordered face-centered cubic (fcc) phase. This phase has very low anisotropy energy because of the high symmetry of the crystal structure. Therefore, magnetic measurements show the film is magnetically soft with the coercivity less than 10 Oe. After annealing, The FePt undergoes a phase change from the disordered fcc phase to ordered face-centered tetragonal (fct) phase. At the same time, FePt layers were broken up, and a nanocomposite film was formed with FePt grains embedded in the C matrix. Fig. 1 shows XRD patterns of the FePt:C films annealed at 550 °C for 300 s with thickness 16 nm, i.e., 32% of carbon. Superlattice peaks (001), (002) appeared on the XRD pattern, indicating FePt change of phase from fcc to fct after annealing. Only $(00l)$ diffraction peaks appear on the XRD pattern, which means that the film has (001) texture after annealing. The quality of the film is best when there is slight excess of Pt over Fe in the sputtered films. The full-width at
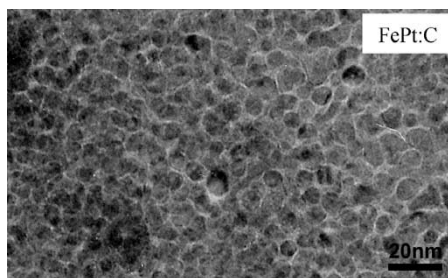
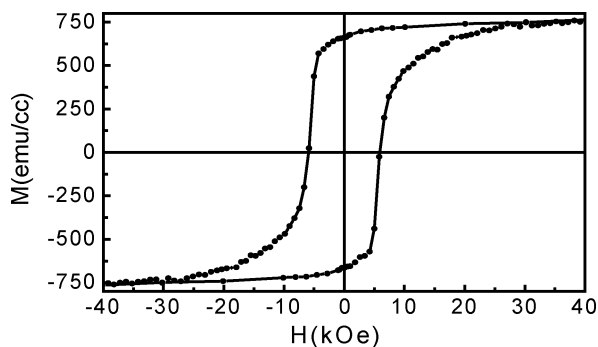Fig. 2. Plan-view TEM image of the 16-nm FePt:C film annealed at 550 °C for 300-s 32% volume percentage C.

Fig. 3. Hysteresis loop of 16-nm FePt:C film annealed at 550 °C for 300-s 32% volume percentage C.

Fig. 4. MFM images for FePt:C films with different C content.

half-maximum (FWHM), obtained from the rocking curve of (001) peak, is 1.68°, confirming a high degree of (001) texturing. This result indicates that the high-quality (001)-oriented nanocomposite film was obtained by nonepitaxial growth plus subsequent annealing.

TEM experiments were carried out on a JEOL JEM2010 TEM. The TEM specimens were thinned by mechanical polishing and followed by ion-mill polishing. Fig. 2 shows the plan-view TEM image of the FePt:C film. TEM observation reveals that FePt grains with uniform size less than 5 nm are embedded in the carbon matrix and appear to be well isolated. A more detailed investigation of the degree of ordering and orientation mechanism of the FePt:C films will be published in another paper.

A hysteresis loop for this FePt:C film is shown in Fig. 3. The film was measured by SQUID with the applied field perpendicular to the plane. Although the saturation field is rather high, it is clear that the loop shows perpendicular anisotropy with square shape direction due to the enhanced preferential FePt L1$_0$ (001) texture. The perpendicular loop shows large coercivity (H$_c$ = 6.2 kOe) and high remanence ratio (S = 0.9). These better magnetic properties are similar to those needed for extremely high-density perpendicular recording media.

The correlation length was analyzed by MFM in order to study exchange coupling between magnetic grains. Fig. 4 shows the MFM images for FePt:C films with different C content. The images were obtained using a high-coercivity CoPt MFM tip magnetized along the z direction (perpendicular to the sample surface), and samples were in the thermally demagnetized state. The MFM tip has a CoPt particle of around 50 nm at the end of tip. Magnetic features as small as 30 nm can be distinguished. Grain-size-analysis software was used to determine the tran-
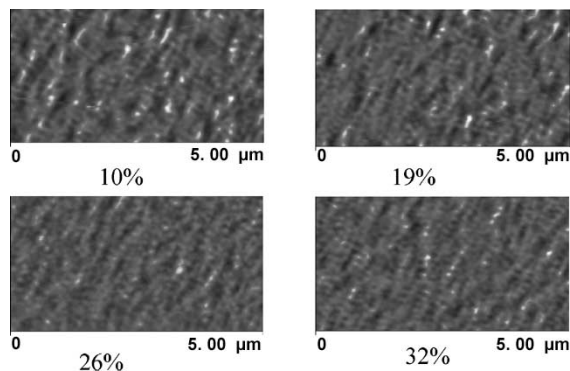
sition width of the magnetization. A threshold at 50% of the largest frequency shift in the image was used to estimate the correlation length. The results clearly show that the correlation length decreases with the increase of C content. The correlation length is around 190 nm when C content is 10% volume fraction and decreases to less than 100 nm when C content increases to 40% volume fraction. The relatively short magnetic correlation length for high C content film indicates weak intergranular coupling between FePt magnetic grains [9].

In order to analyze the experimental results, we performed micromagnetic simulations of granular media mimicking the experimental situation. The magnetic grain size is considered to be between 6–7 nm with random variation of diameter to obtain $\Delta d/d = 0.2$. To model realistic films some random deviations of the direction of uniaxial anisotropy axis were assumed. They did not exceed 2° from the z direction. The magnetization of the FePt grains is taken as 1000 emu/cm^3, the anisotropy constant is 3×10^7 erg/cm^3, and the exchange A(bulk) is 2×10^{-6} erg/cm. The system was modeled as bilayer of almost spherical hard magnetic particles with randomly varied size (with the restriction of $\Delta d/d = 0.2$). The C matrix is assumed to cover the grains and reduce intergrain coupling. The exchange coupling between grains is treated as a parameter A/A(bulk). We use Landau–Lifshitz–Ginsburg approach developed by the NIST group [10].

There are two limiting regimes of the magnetization reversal. When exchange between grains is of the same value as an exchange in the hard magnetic media itself, the switching occurs by means of the domain-wall motion with pinning on the imperfections of the composite structure. We performed two types of calculations in this case. One starting from uniform magnetization, and the other calculation starting with four grains reversed. The latter simulates the case of the domain wall already present in the system. At higher exchange the pinning fields are smaller than the nucleation fields. However, below A/A(bulk) = 0.15 (i.e., A = 0.3×10^{-6} erg/cm) the presence of the initial wall does not change the switching field substantially, and it coincides with the nucleation curve (no initial domain wall). As expected, the coercivity is reduced significantly in the pinning case as compared with the nucleation case. Nevertheless, our calculations overestimate the coercivity because no temperature effects are taken into account.

When the exchange interaction between grains is equal to zero (uncoupled grains), almost all of the grains switch individually by a localized nucleation on quasi-coherent rotation
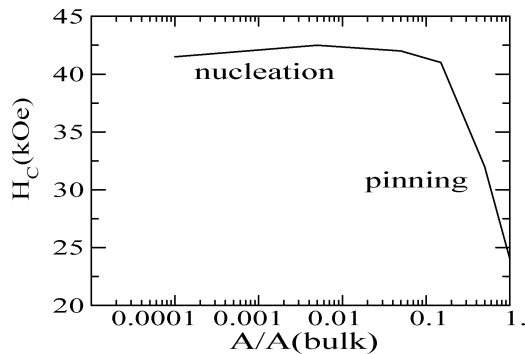
Fig. 5. Coercivity of the nanocomposite film as a function of intergranular exchange coupling.
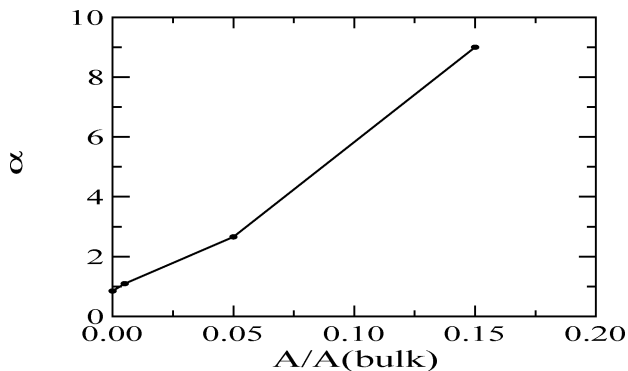

Fig. 6. Slope of the hysteresis loop as a function of the intergranular exchange coupling.

mode. This case shows the largest coercivity. Fig. 5 shows the coercivity as function of the intergrain exchange coupling. We can see noticeable decrease in coercivity with increase of the exchange coupling between grains. This occurs because at elevated exchange between particles the mechanism changes to "domain-wall"-motion-like.

Fig. 6 shows the slope of the magnetization α at the coercive field as a function of the exchange. The slope increases as the intergranular exchange increases. The experimentally observed α is close to 3. This suggests that there is a moderate intergranular exchange in our films. Regarding the correlation of α with exchange, there are extensive discussions in [11] and [12].

Because TEM pictures show well-isolated grains, the exchange coupling apparently occurs through the nonmagnetic metallic matrix (e.g., see the discussion in [13]). Our films have a packing fraction close to 0.7. When the packing fraction is higher, the intergranular distance is small. In [13], we have shown that intergranular exchange can be quite large at short intergranular distances. This exchange is reduced at larger intergranular separation. Thus, the strength of the intergranular exchange can be extracted from the experiment if coercivity as

function of the packing fraction is analyzed. If there is a strong variation of coercivity with packing fraction, the grains have substantial coupling. Comparison of our experimental results with the results of LLG model shows, that at the larger carbon content, we can obtain only moderately coupled grains and possibility for independent grain switching.

III. CONCLUSION

In summary, highly textured (001) FePt:C nanocomposite thin films are obtained by multilayer deposition directly on thermally oxidized Si wafers and subsequent thermal annealing. The medium consists of well-isolated 5-nm FePt grains of $L1_0$ phase embedded in carbon matrix. The analysis of correlation length and micromagnetic simulations shows that intergranular exchange can be moderately small. These nanocomposite films have promising properties as a media for high-density perpendicular magnetic recording.

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