Electrochemical fabrication and magnetization properties of CoCrPt nanowires and nanotubes

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(Received 8 December 2008; accepted 28 April 2009; published online 18 May 2009)

Magnetization properties of CoCrPt alloy nanocylinders (nanowires and nanotubes) fabricated by low cost electrodeposition method have been investigated. Angular dependence of coercivity depicts curling mode of magnetization reversal process for CoCrPt nanowires (NWs) while for nanotubes (NTs) there is a transition from curling to coherent mode as a function of field angle. The effective anisotropy during reversal process is determined from a competition between the magnetostatic interactions, surface effects, and shape anisotropy in NTs while in NWs shape anisotropy is the dominant anisotropy. Furthermore, magnetization and remanence curves describe that the surface effects and dipolar coupling are increased in NTs as compared to the NWs due to their geometry. These results depict that the magnetization properties are influenced by the geometry of nanocylinders, which can become good candidate for ultrahigh density magnetic recording media. © 2009 American Institute of Physics. [DOI: 10.1063/1.3139059]

CoCrPt is a promising candidate for various applications especially for magnetic recording media.1–3 As the recording density is approaching to 1 T bit/in.2, interest in perpendicular magnetic recording systems with CoCrPt medium is increasing due to the limitations of current longitudinal recording technology.3 An ideal ultrahigh density recording medium would have a nanostructure with magnetically isolated small grains.3 The ultrahigh density magnetic recording with 1 bit down to nanosize is touching the superparamagnetic limit. To overcome this limitation, the possible method with 1 bit down to nanosize is touching the superparamagnetism limit. To overcome this limitation, the possible method with 1 bit down to nanosize is touching the superparamagnetic limit. To overcome this limitation, the possible method

FIG. 1. (Color online) [(a) and (b)] FESEM image of CoCrPt: (a) NWs embedded in AAO template and (b) NTs separated from AAO template. [(c) and (e)] Two initial orientation of magnetic moments in NTs, [(d) and (f)] magnetization reversal modes, (d) curling mode, and (f) coherent mode.

0003-6951/2009/94(20)/203101/3/$25.00

94, 203101-1 © 2009 American Institute of Physics

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solution. Average external diameter \( D \) of NWs and NTs is \( \sim 200 \) nm and NTs have average internal diameter \( d \) \( \sim 80 \) nm and \( t_r \sim 60 \) nm. The averaged aspect ratio \( \beta = d/D \) for NWs is \( =0 \), and NT samples is \( =0.4 \). Figures 1(c)–1(f) illustrate magnetic moment orientations in NTs, [c] and [e] two initial saturated states, and [d] and [f] during the reversal process via (d) curling and (f) coherent RM.

Figure 2(a) describes angular dependence of \( SQ \) for CoCrPt NW and NT samples. Shapes of \( SQ(\theta) \) curves determine the easy axis of nanocylinders.\(^5\) \( SQ \) values for NWs and NTs increase with the increase in angle having highest value at \( \theta = \pm 90^\circ \) which is the easy axis of present samples, however, the increase is larger for NWs as compared to that of NTs. Figure 2(b) shows angular dependence of \( H_c \) at room temperature for CoCrPt NWs and NTs. Two possible RM, coherent and curling, give different angular dependences of coercivity. Since \( D \sim 200 \) nm of our samples is much greater than critical diameter \( D_c \) (Refs. 6 and 10) for coherent rotation, therefore, RM is expected to occur through curling rotation. The curling mode of RM for nanocylinders predicts that

\[
H_c = [a(1+a)/a^2 + (1+2a)\cos^2 \theta]H_k, \tag{1}
\]

where \( a = -1.08(D_c/D)^2 \).\(^5\) Equation (1) describes that \( H_c \) increases as angle \( \theta \) increases, whereas coherent rotation mode predicts that \( H_c \) decreases as angle increases.\(^5,6\) For CoCrPt NWs, \( H_c \) increases with increasing angle \( \theta \) from \( 0^\circ \) to \( \pm 90^\circ \) representing curling mode of RM. \( H_c \) of NTs initially increases with increasing angle up to \( \theta = \pm 70^\circ \), in good agreement with the curling model, however, above this critical angle, \( H_c \) decreases abruptly expressing an \( M \)-type variation. \( M \)-type curves for NTs [Fig. 2(b)] reveal that at large angles, coherent rotation is dominant, while curling happens only for small angles \( (\theta \approx \pm 70^\circ ) \). The distinct geometry of NTs presents two dynamic configurations of magnetic moments with the applied field. When the field angle is small, the magnetic moments will align preferably parallel to the tube axis [Fig. 1(c)] and reversal will take place by curling rotation [Fig. 1(d)]. At large field angles, the moments will align perpendicular to tube axis [Fig. 1(e)] and coherent RM will be observed [Fig. 1(f)]. Different alignment of moments and surface effects due to \( t_r \) in NTs are causes of transition from curling to coherent RM for higher angles. The transition angle \( (\theta_t) \) depends on \( D \) and \( t_r \) of NTs as previously proved theoretically for other NTs.\(^9\) Using the analytical method given in Ref. 9, we have found that the transition of magnetization reversal process from curling to coherent for CoCrPt NT arrays occurs at \( \theta_t > 70^\circ \) in agreement with our measured angular dependence of \( H_c \). At finite temperatures, the process of RM can be viewed as overcoming of a single energy barrier \( (E_B) \). Thermal fluctuations can allow the magnetization of a sample to surmount the \( E_B \) and switch from one stable direction to the other. A reversing field aligned in opposite direction from magnetization direction acts to lower the \( E_B \), thereby increasing the probability of switching.

To peruse the contribution of thermal fluctuations in RM,\(^10\) magnetic hysteresis loops for CoCrPt \( Cr_{13}Pt_{12} \) NWs and NTs are measured in temperature range of 5–300 K. \( H_c \) and magnetization \( (M) \) as function of \( T_p \) are determined from the loops [Figs. 2(c) and 2(d)]. The values of \( H_c \) decrease with an increase in \( T_p \), the variation being more rapid for NTs (from 50 mT at 5 K to 13 mT at 300 K) as compared to the NWs (from 35 mT at 5 K to 23 mT at 300 K). This is to be expected, since as the geometry of nanocylinders changes from NW to NT, surface effects become dominant. Figure 2(c) also reports the \( T_p \) dependence of NT1 at angle \( 70^\circ \) and \( 90^\circ \). The trend of \( H_c \) decrease with increase in \( T_p \) is same at both angles, however decrease is fast at angle \( 70^\circ \) (from 90 mT at 5 K to 28 mT at 300 K). The \( T_p \) dependence of intrinsic properties, which determines the anisotropy field, could only account for a small portion of the \( H_c \) change. Therefore, main characteristics of this \( T_p \) dependence must originate from thermal fluctuations. Figure 2(d) shows that \( M \) at 300 K of NWs and NTs are about 14% and 45% smaller than the respective values at 5 K. Decrease in the value of \( M \) is smaller in case of NWs as compared to that of NTs. At low \( T_p \), magnetcocrystalline anisotropy becomes dominant toward the effective anisotropy caused by the spin-orbit interactions.\(^10\) This \( T_p \) dependent anisotropy decreases with an increase in \( T_p \), while dipolar magnetostatic interactions and surface effects in case of NTs become dominant with an increase in \( T_p \) due to their geometry. Comparatively small \( T_p \) dependence for NWs is due to their strong shape anisotropy which remains dominant even at low \( T_p \). The magnetostatic interactions among NWs and NTs are often characterized by delta \( M(\Delta M) \) plots.\(^8,12\) \( \Delta M(H) = M(H) - [1 - 2M_s(H)] \), where \( M_s(H) = M(H) + M(H) \) are demagnetization (DCD) and isothermal remanent magnetization (IRM) values of remanence, normalized to the saturation remanence \( M_s(\infty) \). \( \Delta M \) plots for CoCrPt \( Cr_{13}Pt_{12} \) NWs and NTs in Fig. 3(a) render negative peaks describing the dipolar interactions among NWs and NTs. However, CoCrPt NTs exhibit stronger dipolar interactions than NWs due to the comparatively large surface effects in tube geometry.
recording density to be ascertained. In general, a logarithmic or quasi-logarithmic decay of $M$ is observed.\(^{13}\)

$$M_t = M^0[1 - S(H,T)\ln t],$$

(2)

where $S(H,T)$ is magnetic viscosity coefficient which can be obtained by fitting the above equation.\(^{15}\) Figure 3(b) illustrates the time dependence of $M$ for Co$_{75}$Cr$_{13}$Pt$_{12}$ NWs and NTs. $M$ for both NWs and NTs has logarithmic time dependence, represented by Eq. (2), exhibiting a typical relaxation behavior. This behavior is due to occurrence of broad range of $E_g$ that arises from a wide distribution of nanocylinder size or anisotropy constants in the system.\(^{13}\)

Irreversible changes of magnetization during the reversal process can be determined by measuring the remanence (IRM and DCD) curves.\(^{15}\) The coercive point on these curves, i.e., remanent coercivity ($H_c$) at which remanence falls to zero, is more appropriate for characterization of media rather than magnetization coercivity. The remanence curves are contributed by the moments, which are unable to overcome the $E_g$ for RM and magnetization component recorded in such case is due only to irreversible changes.\(^{13}\)

Figures 3(c) and 3(d) show irreversible susceptibility ($\chi_{irr}$) curves of Co$_{75}$Cr$_{13}$Pt$_{12}$ nanocylinders, which are derivatives of remanence curves with respect to field and give switching field distribution of systems. Results in Figs. 3(c) and 3(d) depict a change in position of maxima related to the value of $H_c$ from both IRM and DCD curves $\sim 0.26$ mT for NWs and $\sim 0.78$ mT for NTs. The $H_c$ value for NTs is $\sim 3$ times larger than that of NWs. The reason for large $H_c$ value for NTs must lie in the manifestation of a strong anisotropy which occurs due to the spins in NT surface. Another interesting result is the fact that the $\chi_{irr}$ curves become wider for NTs, possibly due to an increased dispersion of anisotropy as the surface effects and dipolar coupling\(^{16}\) is increased in case of NTs due to their distinct geometry. These effects are due to surface anisotropies which may be nonuniform across the size distribution. The comparison of magnetization properties for NWs and NTs reveals that the geometry of nanocylinders play an important role to determine the effective anisotropy during the magnetization reversal process. Desired geometry of nanocylinders with a wide range of diameter, thickness, and length can be adopted for potential applications such as quite short NWs (nanoparticles) and NTs (nanorings) for patterned recording media,\(^{3}\) perpendicular spin transfer torque-magnetic random access memory (STT-MRAM), and nanoring MRAM.\(^{17}\)

A comprehensive comparative study of magnetization properties for CoCrPt alloy NWs and NTs has been presented. Curling mode of magnetization reversal mechanism for CoCrPt NWs is perceived on the basis of angular dependence of coercivity. For NTs, a transition from curling to coherent reversal process is observed as a function of angle for applied magnetic field. This transition is due to the broad dispersion of anisotropy as the surface effects and dipolar coupling is increased in case of NTs due to their distinct geometry. Time, temperature, and field dependent magnetization properties reveal that the geometry of nanocylinders strongly affects the effective anisotropy to overcome the energy barrier during the reversal process. The results are in accordance with theoretical predictions and indicate that the magnetization properties of NTs is determined by magnetostatic interactions, dipolar coupling, and surface effects in NTs whereas in case of NWs shape anisotropy is the dominant anisotropy. These CoCrPt nanocylinders are potential candidates for various applications in high density recording media and lower dimension devices.

The project was supported by the State Key Project of Fundamental Research, Ministry of Sci. and Tech. (MOST Grant No.2006CB932200) and National Natural Science Foundation (NSFC Grant Nos.10874225 and 50721001) and Microfabrication Center of IOP.