Continuously graded anisotropy in single $(Fe_{53}Pt_{47})_{100-x}Cu_x$ films

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We report on continuously graded anisotropy. During deposition, a compositional gradient is achieved by varying the Cu concentration from Cu-rich $(Fe_{53}Pt_{47})_{70}Cu_{30}$ to Cu-free $Fe_{53}Pt_{47}$. The anisotropy gradient is then realized after annealing using the composition dependence of the low-anisotropy (A1) to high-anisotropy ($L1_0$) ordering temperature. The critical role of the annealing temperature on the resultant anisotropy gradient is investigated. Magnetic measurements support the creation of an anisotropy gradient in properly annealed films which exhibit both a reduced coercivity and moderate thermal stability. These results demonstrate that an anisotropy gradient can be realized, and tailored, in *single* continuous films without the need for multilayers.
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The roadmap to magnetic recording media with areal bit densities beyond 1 Tbit/in.^{2} is plagued by the so-called magnetic recording "trilemma" where the thermal stability and signal-to-noise ratio (SNR) must be *simultaneously* balanced with the writabilty of a given bit.[1,2] To maintain both a sufficient SNR and high bit density, the volume of the individual grains that constitute a given bit must approach the superparamagnetic limit. While high anisotropy (K_u) materials, such as $L1_0$ FePt alloys,[3] would dramatically improve thermal stability, the magnetic fields required for switching such a high K_u bit far exceed the capabilities of the write head. Tilted,[4,5] and exchange coupled composite (ECC) media,[6] as well as heat-assisted magnetic recording,[7] and microwave-assisted magnetic recording techniques,[8] have been proposed to lower the necessary writing field. An extension of ECC media is termed graded media where the anisotropy is varied, either discretely or continuously,[9] over many layers and is predicted to provide additional gains in writabilty over conventional bi-layer hard/soft ECC media. In graded media, the low K_u layers act to reduce the switching field while the high K_u layers preserve thermal stability.

Graded K_u materials are also potentially useful in devices which rely on spin transfer torque (STT) phenomena, such as spin torque oscillators and STT magnetoresistive random access memory.[10,11] Recent work has shown a considerable reduction in the critical current densities necessary for the switching of a composite hard/soft free layer.[12,13] A free layer with a graded K_u is the next step in further reducing the current density. Fabrication of graded media, in particular the realization of a continuous gradient, is challenging and has, until now, been based on multilayered structures.[14–18]

In this letter, we report on a simple approach to fabricate continuously graded-K_u *single* films based on the strong dependence of the A1 (low K_u) $\rightarrow L1_0$ (high K_u) ordering temperature on the Cu content in $(Fe_{53}Pt_{47})_{100-x}Cu_x$ $(x=0-30)$ films.[19] First, a compositional gradient is achieved by varying the Cu concentration from Cu-rich $(Fe_{53}Pt_{47})_{70}Cu_{30}$ at the bottom to Cu-free $Fe_{53}Pt_{47}$ at the top during film deposition, as schematically represented in Fig. 1 (left panel). The K_u gradient is then realized after proper annealing. The Cu-rich regions transform from the as-deposited low K_u cubic A1 phase into the high K_u tetragonal $L1_0$ phase at a lower annealing temperature than the Cu-poor regions, thus establishing an K_u gradient through the thickness of the film. Magnetic measurements support the creation of an K_u gradient with reduced coercivity and moderate thermal stability.

The $(Fe_{53}Pt_{47})_{100-x}Cu_x$ $(x=0-30)$ (called graded FePtCu hereafter) films (20 and 50 nm thick) were deposited at room temperature on thermally oxidized Si substrates by magnetron sputtering in a chamber with a base pressure of better than 5×10^{-8} Torr. During the co-sputtering of high purity Fe, Pt, and Cu targets the compositionally graded films were realized by gradually decreasing the sputtering power of the Cu gun from 35 to 0 W. Therefore, the bottom of the film is Cu-rich $(Fe_{53}Pt_{47})_{70}Cu_{30}$ while the top is Cu-free $Fe_{53}Pt_{47}$. A compositionally uniform sample with the same total Cu content as the graded sample, $(Fe_{53}Pt_{47})_{85}Cu_{15}$ (called uniform FePtCu hereafter), was deposited as a reference. To improve surface roughness, (111)-texture, and lower the chemical ordering temperature of the $L1_0$ phase, the FePtCu films were

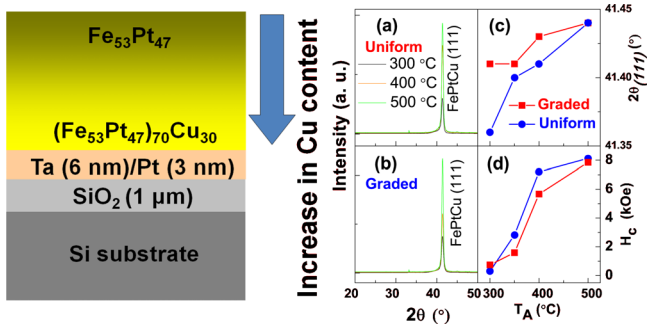

FIG. 1. (Color online) Left panel: schematic of the Cu content depth profile in a graded FePtCu film. Right panel: XRD patterns of (a) uniform and (b) graded FePtCu (20 nm) films annealed at 300, 400, 500 °C. (c) (111) peak position and (d) in-plane coercivity of the uniform (blue circles) and graded (red squares) samples as a function of annealing temperature T_A.

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deposited on Ta(6 nm)/Pt(3 nm).[20] A capping layer of Ta (5 nm) was deposited to prevent oxidation. The as-deposited uniform and graded samples were simultaneously annealed at T_A=300, 400, and 500 °C for 35 min in vacuum. The composition of the films was determined by energy dispersive x-ray spectrometry and the crystallographic structure was investigated by x-ray diffraction (XRD) with Cu K_α radiation. Magnetization measurements were performed at room temperature with in-plane fields on an alternating-gradient magnetometer (AGM) and a home-built longitudinal magneto-optical Kerr effect (MOKE) setup.

The structural properties of the uniform and graded FePtCu samples are shown in Fig. 1(a)–1(c) for T_A=300, 400, and 500 °C. We clearly observe a strong (111) texturing for all annealing temperatures [Figs. 1(a) and 1(b)]. For both the uniform and graded samples, as the annealing temperature is raised, the intensity of the (111) diffraction peak progressively increases, indicating an improvement in the (111)-textured crystallization. Importantly, for both uniform and graded samples the (111) peak shifts to higher angles, Fig. 1(c), with increasing annealing temperature. This, in turn, implies an enhancement of the chemical ordering degree of the $L1_0$ phase for higher annealing temperatures.[21] Note that the (111) peak is shifted to angles higher than that of fully ordered FePt (41.08°) due to the Cu dopant which has been shown to decrease the c lattice parameter.[19] While an increase in $L1_0$ order is found with increasing annealing temperature, how the structural A1-$L1_0$ ordering gradient (and thus the magnetic K_u gradient) is manifested through the thickness of the film is not readily accessible from the XRD measurements.

Magnetic measurements, on the other hand, not only show enhanced $L1_0$ chemical ordering with T_A but also provide unambiguous evidence of the graded nature of the properly annealed films. First, the major loop coercivity (H_C), Fig. 1(d), is found to increase with T_A, consistent with the XRD data and the improved high K_u $L1_0$ order. Additional insight into the graded nature of the samples is found by analysis of the major hysteresis loops. Major loops measured using an AGM, Figs. 2(a), 2(c), and 2(e), along with the derivatives of the descending branches of the major loops, Figs. 2(b), 2(d), and 2(f), highlight the important role of proper T_A in establishing the K_u gradient.

At a low T_A of 300 °C, Figs. 2(a) and 2(b), both the uniform and graded samples remain relatively soft (note the field scale), consistent with the as-deposited, low K_u A1 phase. The graded sample shows a small increase in H_C compared to the uniform sample annealed at the same temperature indicating the onset of $L1_0$ ordering of the Cu-rich fractions of the film. The loop derivative is also significantly broader for the graded sample, which is also in agreement with the existence of a high K_u phase and the incipient K_u gradient in this film.

At an intermediate T_A of 400 °C, Figs. 2(c) and 2(d), the H_C of both the graded and uniform films dramatically increases as a larger fraction of the films transforms into the high K_u $L1_0$ phase. Interestingly, after annealing at 400 °C, the graded film exhibits a fundamentally different reversal path compared to the uniform film. As we can clearly see from the derivatives, Fig. 2(d), the graded sample exhibits an asymmetric peak with an extended switching shoulder. This shoulder corresponds to the softer portions of the film beginning to reverse first. In fact, the overall shape of the loop is

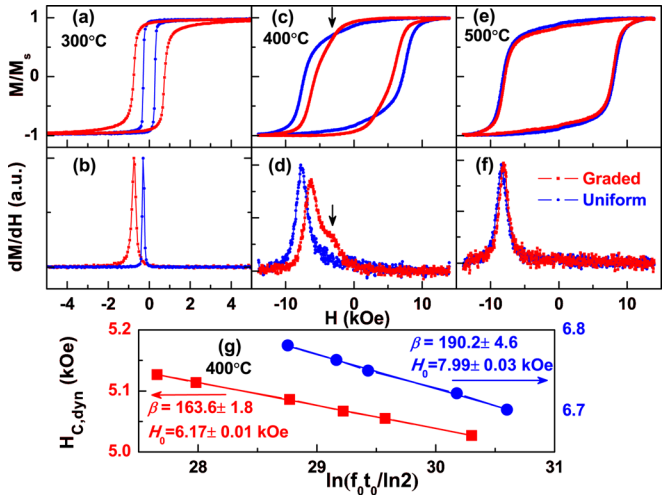

FIG. 2. (Color online) In-plane AGM hysteresis loops (top row) and their derivatives (middle row) for uniform (blue circles) and graded (red squares) FePtCu (20 nm) films annealed at 300 °C [(a) and (b)], 400 °C [(c) and (d)], and 500 °C [(e) and (f)]. The derivatives are of the descending branch only and smoothed. The vertical arrow in (c) and (d) indicates the initial linear decrease in the magnetization switching. (g) Dynamic coercivity, $H_{C,dyn}$, as a function of decay time, t_o, for the uniform (blue circles) and graded (red squares) samples annealed at 400 °C. The thermal stability factor, β, and intrinsic coercivity, H_o, are extracted from a fit to Sharrock's equation.

reminiscent of simulated hysteresis curves of films with a graded K_u that show an initial linear decrease in the magnetization [see arrow in Fig. 2(c)].[22] The initial linear decay of the magnetization can be associated with the formation of a partial domain wall through the film thickness that precedes switching. Actually the plateau in the major loop derivative [see arrow in Fig. 2(d)] directly indicates this initial linear decrease in the magnetization. Most importantly, the coercivity of the compositionally graded film, H_C=5.67 kOe, is smaller than the uniform film, H_C=7.21 kOe, which is also consistent with the existence of an K_u gradient. Additionally, the remanence (M_r/M_s, where M_r and M_s are the remnant and saturation magnetizations, respectively) of the graded sample, M_r/M_s=0.91, is larger than the uniform sample, $M_{r/}M_s$=0.79. This implies that the graded sample has a substantial fraction of soft phase.

Finally, after annealing at 500 °C, Figs. 2(e) and 2(f), the uniform and graded samples essentially become identical. We find that the H_C, the location of the (111) peak, the loop derivatives, and even the overall shape of the loops become nearly indistinguishable for the uniform and graded samples. We, therefore, conclude that a significant amount of interdiffusion occurs at this elevated T_A. It is also not surprising that the compositionally uniform and graded samples become virtually identical in that they both contain the same total Cu concentration.

To assess the thermal stability of our graded samples we have carried out dynamic H_C measurements. The dynamic H_C, $H_{C,dyn}$, is the field required to bring the magnetization to zero after a characteristic time, t_o, and functionally obeys Sharrock's equation.[23] In our calculations, an attempt frequency $f_o=5\times10^9$ Hz is used and we can presume n=1.[22,24,25] From this analysis, the thermal stability factor, defined as $\beta\equiv\Delta E_o/k_BT$, and time independent intrinsic H_C, H_o, can then be extracted. Here ΔE_o is the energy barrier and k_BT is the thermal activation energy. The $H_{C,dyn}$ measure-

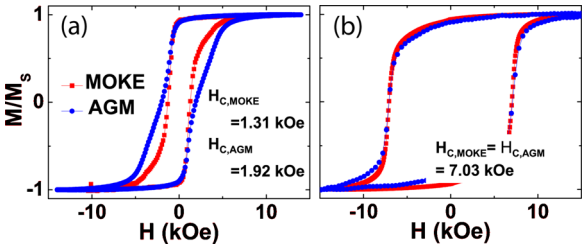

FIG. 3. (Color online) MOKE (red squares) and AGM (blue circles) hysteresis loops for a graded FePtCu (50 nm) film annealed at (a) 300 °C and (b) 400 °C, respectively.

ments for the uniform and graded films annealed at 400 °C are shown in Fig. 2(g) where we find $H_o = 7.99 \pm 0.03$ kOe, $\beta = 190.2 \pm 4.6$ and $H_o = 6.17 \pm 0.01$ kOe, $\beta = 163.6 \pm 1.8$, for the uniform and graded samples, respectively. Although the graded sample shows a small, 14%, decrease in thermal stability, it also shows a significantly larger, 23%, decrease in H_o.

The AGM, which measures the total magnetic moment, is not able to directly determine how the K_u varies through the thickness of the film. To probe the graded K_u we have measured *surface* magnetic properties of a 50 nm thick graded FePtCu film using the MOKE setup where the finite penetration depth of light (~30 nm in FePt) can be exploited. The MOKE and AGM in-plane loops are shown in Fig. 3(a) for a sample annealed at 300 °C. Clearly the MOKE loop has a smaller coercivity, $H_{C,\mathrm{MOKE}} = 1.31$ kOe, than the AGM loop, $H_{C,\mathrm{AGM}} = 1.92$ kOe and exhibits a different reversal path. As expected, the MOKE loop, which only probes the upper portions of the film, is significantly softer because the Cu-poor regions near the top of the film have not fully transformed into the high K_u $L1_0$ phase at this particular T_A. These depth sensitive results, along with the observed in-plane easy axis (induced by the thin film shape anisotropy), confirm that the anisotropy varies through the film thickness instead of forming, e.g., random $L1_0$ clusters embedded in an A1 matrix. However, after annealing at 400 °C both the AGM and MOKE loops, Fig. 3(b), have the same H_C, $H_{C,\mathrm{AGM}} = H_{C,\mathrm{MOKE}} = 7.03$ kOe, and nearly identical loop shape. This indicates that after annealing at 400 °C the 50 nm graded FePtCu film has achieved a uniform K_u distribution, similar to the 20 nm thick sample annealed at 500 °C. As reported for uniform FePtCu films,[26] the $L1_0$ chemical ordering process also depends on film thickness and is actually promoted in thicker films.

In summary, we propose and demonstrate a simple procedure to establish a continuous K_u gradient through the thickness of FePtCu films. The K_u gradient is realized after proper annealing of compositionally graded films. In addition, similar $L1_0$ FePtCu (111) films have been reported to have tilted anisotropies.[27,28] This fact, combined with the advantages of graded K_u may result in a very versatile magnetic structure, which may not only be appealing for magnetic recording but also for STT applications.[29,30] We anticipate that the experimental procedure presented here can be further improved and extended to other, e.g., perpendicular and/or granular, material systems where a graded anisotropy is desired.

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