Reducing the Writing Field of $L1_0$-FePt by Graded Order Parameter

G. Mankey – University of Alabama

et al.

Citation of published version:

Lu, Z., et al. (2013): Reducing the Writing Field of $L1_0$-FePt by Graded Order Parameter. *Journal of Applied Physics*, 113(7). DOI: https://doi.org/10.1063/1.4791583

Journal of Applied Physics

Reducing the writing field of $L1_0$-FePt by graded order parameter

Cite as: J. Appl. Phys. **113**, 073912 (2013); https://doi.org/10.1063/1.4791583
Submitted: 24 November 2012 . Accepted: 28 January 2013 . Published Online: 21 February 2013

Zhihong Lu, Junbo Guo, Zhanghua Gan, Yong Liu, Rui Xiong, G. J. Mankey, and W. H. Butler

JOURNAL OF APPLIED PHYSICS **113**, 073912 (2013)

Reducing the writing field of $L1_0$-FePt by graded order parameter

Zhihong Lu,[1,a)] Junbo Guo,[1] Zhanghua Gan,[1] Yong Liu,[2] Rui Xiong,[2] G. J. Mankey,[3] and W. H. Butler[3]
[1]*School of Materials and Metallurgy, Wuhan University of Science and Technology, Wuhan, Hubei 430081, People's Republic of China*
[2]*School of Physics and Technology, Wuhan University, Wuhan, Hubei 430072, People's Republic of China*
[3]*MINT Center, University of Alabama, Tuscaloosa, Alabama 35401, USA*

(Received 24 November 2012; accepted 28 January 2013; published online 21 February 2013; corrected 26 February 2013)

The dependence of the magnetic properties of epitaxial $Fe_{50}Pt_{50}$ films on order parameter (S) was investigated. It was demonstrated that the magnetic anisotropy could be tuned by controlling S which can be controlled by the growth temperature. Based on this result, two kinds of multilayered structures, each with a 13 nm fully ordered $Fe_{50}Pt_{50}$ layer as the bottom layer, were built: (1) 4-layered structure with S decreasing layer by layer from bottom to top; (2) graded structure with S changing more continuously along the thickness. The magnetic properties of the films were characterized using vibrating sample magnetometry. It was found that both structures have their easy axis perpendicular to the film; the anisotropy fields of the 4-layered film and the graded film are 53 kOe and 37 kOe, respectively. These values are much lower than that of the fully ordered uniform $Fe_{50}Pt_{50}$ film (about 73 kOe). The results suggest that it may be possible to reduce the writing field of $Fe_{50}Pt_{50}$ by gradually changing the order parameter. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4791583]

INTRODUCTION

Fully ordered $L1_0$ phase FePt alloys have extremely large crystalline anisotropy up to $7 \times 10^6\,J/m^3$ with the anisotropy direction along [001] direction. If FePt films with [001] orientation can be applied in fabricating perpendicular magnetic recording media, the grain size can be reduced to several nanometers without losing acceptable thermal stability. With this kind of small grain size, the areal density can approach to 10 Tb/in^2.[1] Therefore, $L1_0$ phase FePt alloy is believed to be one of the most promising candidates for ultrahigh density magnetic recording. However, in the past decade, although $L1_0$ phase FePt alloy films were widely studied,[2–7] challenges remain that prevent them from being applied in the fabrication of magnetic recording media. One of the largest challenges is the so called writability problem—the write-head cannot provide a field high enough to write such hard material.

According to the theoretical studies,[8–10] the writing field of fully ordered equiatomic FePt can be drastically decreased if we can use it as the hardest end of a multilayered structure whose anisotropy decreases gradually along the thickness. A recording medium based on this kind of structure is called grade medium. It was also found that a graded medium can possess acceptable thermal stability and much lower writing field.[11] A big technical challenge for enabling this concept is to develop the ability to control the magnetic anisotropy of each magnetic layer so that the anisotropy profile of the multilayered structure can be designed.

Previous studies[12,13] showed that the anisotropy of $Fe_{50}Pt_{50}$ alloy depends on its chemical order parameter. It is possible to build a multilayered structure stacked with $Fe_{50}Pt_{50}$ films with different order parameters.

In the present study, we investigated the dependence of the magnetic properties of epitaxial FePt films on order parameter S and demonstrated that the magnetic anisotropy can be tuned by controlling the chemical order parameter S. Based on this result, we built multilayered structures with anisotropy monotonically changing along the thickness. By studying the magnetic properties of these structures, we found that the anisotropy field of $Fe_{50}Pt_{50}$ could be efficiently reduced by gradually changing the order parameter, which suggests that the writing field of $Fe_{50}Pt_{50}$ can also be reduced in this way.

EXPERIMENT

The samples used in this study are single-layered and multilayered $Fe_{50}Pt_{50}$ films deposited on the single crystalline MgO (001) substrates by using the DC sputtering method. An equiatomic $Fe_{50}Pt_{50}$ alloy target was used for the deposition of $Fe_{50}Pt_{50}$ films. The base pressure is about 4×10^{-8} Torr. Before deposition, MgO substrates were first degassed at 750 °C for half an hour. To get better epitaxial $Fe_{50}Pt_{50}$ films, a 4 nm Cr layer and a 12 nm Pt buffer layer were deposited on each MgO substrate as a seed layer and buffer layer, respectively. The $Fe_{50}Pt_{50}$ films were then deposited on the Pt buffer layers at a sputtering rate of 0.64 Å/s, followed by the deposition of a 5 nm Pt layer as the capping layer to prevent the $Fe_{50}Pt_{50}$ film from being oxidized.

A home-made heater was used to heat the sample. The heater is made of 6 filaments from halogen light bulbs with a maximum designed power of about 1500 W. The heater holder is made of a Ta sheet with a thermocouple mounted on it. To obtain the temperature of substrate during

a)Electronic mail: zludavid@live.com.

sputtering, the relation between the temperatures of heater holder and the substrate was first calibrated. To do this, a bare substrate was put on the heater and a thermocouple was mounted onto the substrate. At each applied voltage, the temperatures of the heater holder and the substrate were measured at the same time so that the substrate temperature as a function of the temperature of heater holder was obtained. During the sputtering, the temperature was controlled by varying the applied voltage and was monitored by the reading of the thermocouple on the heater holder. The growth temperature was figured out by using the calibration curve.

For single-layered $Fe_{50}Pt_{50}$ films, the thickness of $Fe_{50}Pt_{50}$ was kept at 13 nm and the growth temperature was varied from 300 to 700 °C. The different $Fe_{50}Pt_{50}$ films are expected to have different order parameters S because the order parameter is determined by the growth temperature.

Two kinds of multilayered $Fe_{50}Pt_{50}$ film structures were built (as shown in Fig. 1): (1) 4-layered structure with the layers deposited at different temperature; (2) graded structure with the growth temperature decreasing more continuously along the thickness after deposition of the bottom layer. In both kinds of multilayered structure, a 12 nm fully ordered $Fe_{50}Pt_{50}$ layer (deposited at 700 °C) was taken as the bottom layer. When building the 4-layered $Fe_{50}Pt_{50}$, before depositing each layer, the shutter was closed until the temperature reached the designed value to make sure that each layer was grown at constant temperature. For the graded structure, after the deposition of the 12 nm $Fe_{50}Pt_{50}$ bottom layer was completed at 700 °C, the temperature was manually decreased from 700 °C to 350 °C by changing the applied voltage of the heater. During this period, the sputtering process of $Fe_{50}Pt_{50}$ was not interrupted. When depositing the graded layers, it is hard to decrease the temperature uniformly. However, by manually adjusting the applied voltage, the change of temperature can be controlled to some extent. The control process was in the following way: at beginning, the applied voltage was decreased slowly to prevent the temperature from dropping too fast; as the temperature became lower, the applied voltage was decreased faster; below 420 °C, the power supply was turned off and the sample was naturally cooled. It was found that the temperature was about 350 °C when the deposition finished.

The crystal structures of the films were characterized by x-ray diffractometry (XRD) and the order parameters were then calculated according to the ratio of diffraction intensities of (001) and (002). The magnetic properties of the films were measured at room temperature using vibrating sample magnetometry (VSM) in a physical property measurement system (PPMS) by Quantum Design. The magnetic field was applied in two directions: perpendicular to the sample surface and parallel to the sample surface.

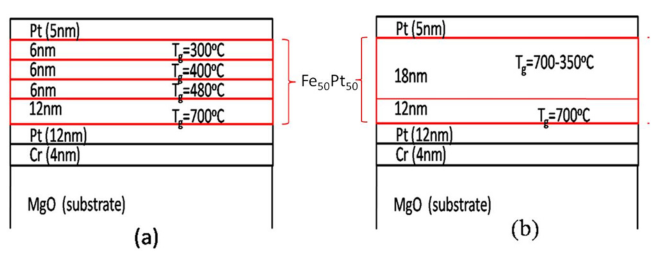

FIG. 1. The sample structures: (a) 4-layered $Fe_{50}Pt_{50}$ Film; (b) graded $Fe_{50}Pt_{50}$ film.

RESULTS AND DISCUSSION

By analyzing the XRD spectra of the single-layered $Fe_{50}Pt_{50}$ thin films deposited at different temperatures, the order parameters of the films were evaluated. The dependence of order parameter on growth temperature (T_g) is shown in Fig. 2. It was found that the order parameter of $Fe_{50}Pt_{50}$ increases with the T_g. When deposited at 700 °C, $Fe_{50}Pt_{50}$ film is almost fully ordered (S = 0.9), while, as T_g goes to 300 °C, the order parameter goes to zero and the $Fe_{50}Pt_{50}$ film becomes completely disordered.

The hysteresis loops of the single-layered $Fe_{50}Pt_{50}$ thin films were measured by VSM with the field applied in two directions: perpendicular and parallel to the film plane. The saturated magnetizations (M_s) of the films were found to be similar which indicates that M_s of $Fe_{50}Pt_{50}$ does not depend significantly on S. $Fe_{50}Pt_{50}$ thin films were found to have easy axis perpendicular to the film plane even when S goes down to 0.3. As S becomes smaller, the easy axis lies in the film plane. The anisotropy field, H_k, under which the saturation of magnetization along hard axis first reaches, was obtained directly from the hard axis M-H loop. The dependence of anisotropy field H_k on order parameter is shown in Fig. 3. It can be seen that for uniform $Fe_{50}Pt_{50}$ thin films, H_k monotonically increases with order parameter—the larger the order parameter, the higher the H_k. For completely disordered $Fe_{50}Pt_{50}$ thin film, the easy axis is in the film plane, H_k (~12.4 kOe), derived from the out-of plane loop is almost equal to the demagnetizing field (~13.0 kOe).

Assuming that, when the magnetic field is applied along the hard axis, the magnetic moment rotates coherently, the crystalline anisotropy of each film with perpendicular easy axis can be estimated using following equation:

$$K_u = \frac{1}{2} M_s (H_k + 4\pi M_s), \qquad (1)$$

where K_u, M_s, and H_k represent anisotropy energy, saturated magnetization and anisotropy field, respectively. The dependence of K_u on order parameter is also shown in Fig. 3. It is

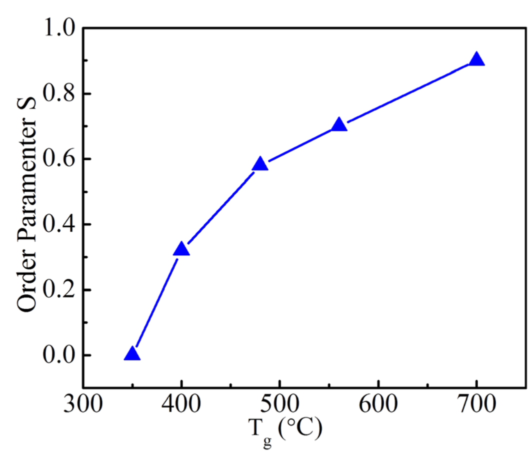

FIG. 2. Dependence of order parameter S on growth temperature.

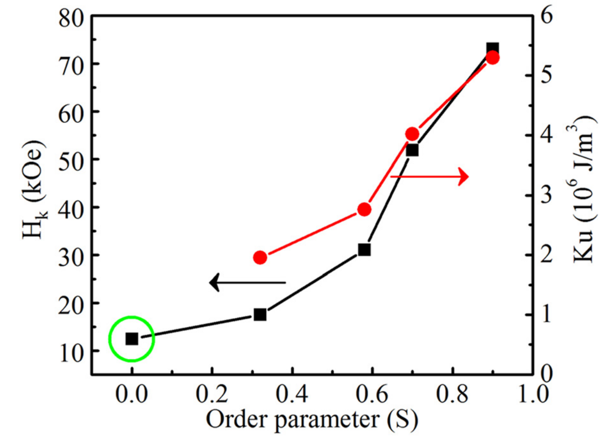

FIG. 3. Dependence of anisotropy field (H_k) and magnetic anisotropy on order parameter (the green circled point represents the anisotropy field of disordered $Fe_{50}Pt_{50}$ Film whose easy axis lies in the film plane).

found that K_u increases with order parameter. For the fully ordered $Fe_{50}Pt_{50}$ (S = 0.9) thin film, K_u is about 5.3×10^6 J/m^3 as S reaches 0.9.

The X-ray diffraction spectra of the 4-layered $Fe_{50}Pt_{50}$ thin film and the graded $Fe_{50}Pt_{50}$ film with growth temperature continuously decreasing from 700 to 350 °C are shown in Fig. 4.

In the spectrum of 4-layered $Fe_{50}Pt_{50}$ thin film (Fig. 4(a)), the (002) peak of $Fe_{50}Pt_{50}$, and the (200) peaks of Pt, Cr (200), and MgO were severely overlapped. To accurately determine the order parameters, we need to separate these peaks. This can be achieved by fitting them with Lorentz functions. The fits (red) and the deconvolved peaks (green) are also shown in Fig. 4. The order parameter determined by the intensity ratio of the (001) and (002) peaks is 0.58. Since the sample was stacked with four $Fe_{50}Pt_{50}$ layers with different order parameters, the order parameter determined from X-ray diffraction is actually an average of the order parameters of all these four layers. According to our results, the order parameters for $Fe_{50}Pt_{50}$ films deposited at 300 °C, 400 °C, 480 °C, and 700 °C are 0, 0.32, 0.56, and 0.9 respectively. The average order parameter can be calculated by the following equation:

$$S = t^{-1} \sum_i t_i \cdot S_i, \tag{2}$$

where t is the total $Fe_{50}Pt_{50}$ thickness and t_i and S_i are the thickness and order parameter of i layer, respectively.

The order parameter directly calculated by using Eq. (2) is 0.55. This value is very close to what we obtained by X-ray diffraction (S = 0.58), which indicates the order parameter of each $Fe_{50}Pt_{50}$ layer is similar to that of a uniform film deposited at the same temperature.

As shown in Fig. 4(b), in the diffraction pattern of the graded $Fe_{50}Pt_{50}$ film, the peaks are much better defined than the 4-layered film. The average order parameter S derived from XRD data is about 0.7 which is higher than that of the 4-layered $Fe_{50}Pt_{50}$ film. Since it is difficult to control the decrease rate of the temperature precisely, the thickness of $Fe_{50}Pt_{50}$ deposited at each temperature is not known.

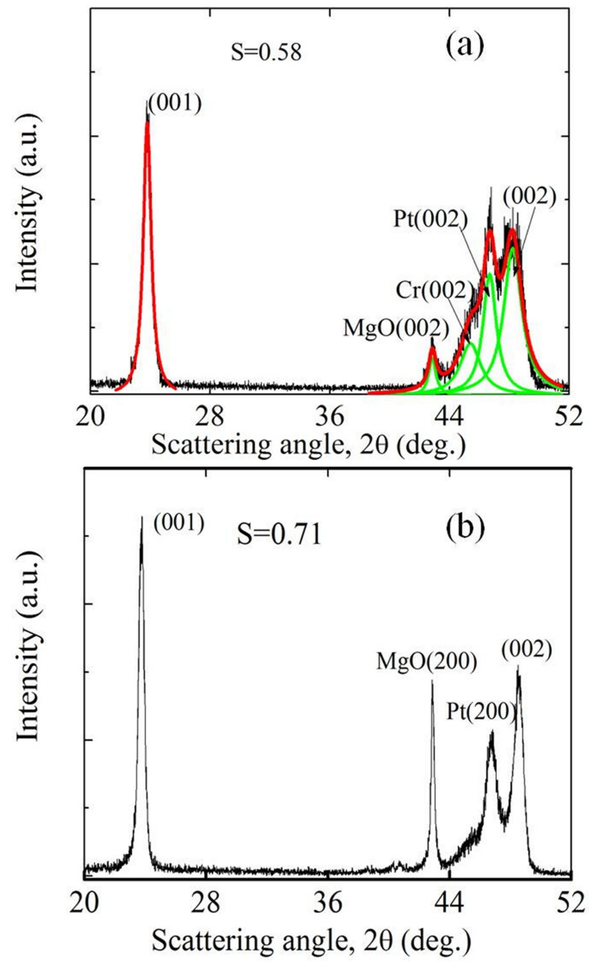

FIG. 4. X-ray diffraction spectra of 4-layered $Fe_{50}Pt_{50}$ film (a) and graded $Fe_{50}Pt_{50}$ film (b).

However, it is clear that the average order parameter and hence the average anisotropy energy density in the graded film are significantly higher than those in the 4-layered film.

Figs. 5(a) and 5(b) shows the room temperature hysteresis loops of the layered $Fe_{50}Pt_{50}$ sample and the graded $Fe_{50}Pt_{50}$ sample, respectively. The saturation magnetization of the samples is still about 1200 emu/cc, almost the same as that of a uniform $Fe_{50}Pt_{50}$ film, which confirms that the saturation magnetization of $Fe_{50}Pt_{50}$ does not depend significantly on order parameter S. By comparing the hysteresis loops in two directions, it is found that the easy axis is perpendicular to the film plane for both of the samples. It can be seen from the easy axis loops that the coercivities of the samples are quite small. The reason is that the films studied are continuous films and their easy axis switching involves lateral domain wall motion. The low field parts of the easy and hard axis loops show apparently that, in both films, there are some components with anisotropy in the film plane. Comparatively, in the graded sample, the amount of in-plane component is less than that in layered sample. Ordered $Fe_{50}Pt_{50}$ has perpendicular anisotropy, while disordered $Fe_{50}Pt_{50}$ has in-plane anisotropy. The anisotropy in-plane part in the films comes from the contribution of disordered $Fe_{50}Pt_{50}$. According to the XRD analysis, the disordered part comprises a lower proportion in the graded sample than in

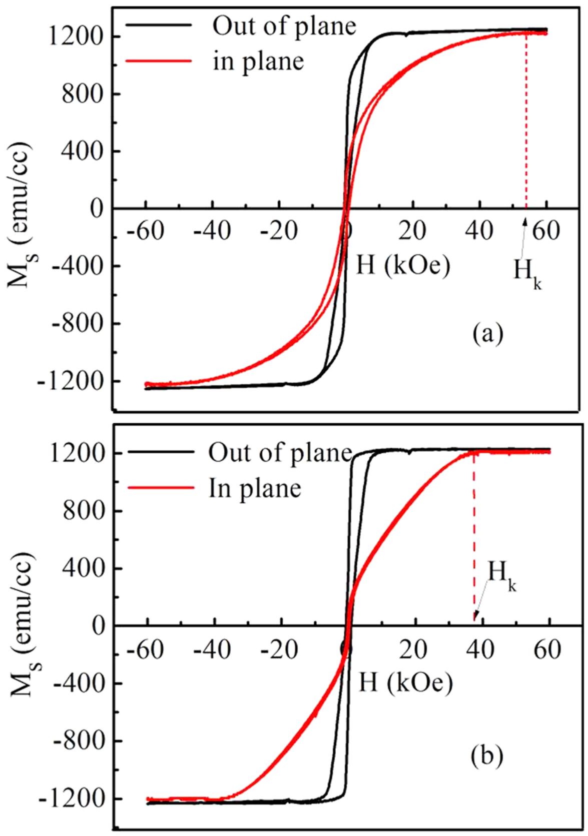

FIG. 5. Magnetic properties of 4-layered $Fe_{50}Pt_{50}$ film (a) and graded $Fe_{50}Pt_{50}$ film (b).

the 4-layered sample. Therefore, it is not surprising that the graded sample has less in-plane component that the 4-layered sample. From Fig. 5, it is found that the anisotropy field of the 4-layered $Fe_{50}Pt_{50}$ is about 53 kOe. This value is much lower than that of the uniform film deposited at 700 °C, which has an anisotropy field about 73 kOe. For the graded sample, the anisotropy field obtained from the hard axis loop is about 37 kOe. This value is even smaller than that of the 4-layered $Fe_{50}Pt_{50}$ film.

The results shown above suggest that although for a single-layered $Fe_{50}Pt_{50}$ film, the magnetic properties become harder with the increase of the order parameter, the condition is quite different for multilayered $Fe_{50}Pt_{50}$. The 4-layered $Fe_{50}Pt_{50}$ film has lower average order parameter but has higher anisotropy field than graded $Fe_{50}Pt_{50}$ film, which indicates that the anisotropy field of a multilayered $Fe_{50}Pt_{50}$ film depends strongly on how the film is built—how the anisotropy varies along the thickness. Due to the gradual change of the growth temperature during deposition, the order parameter in graded $Fe_{50}Pt_{50}$ film changes more continuously along the thickness, which corresponds to a more continuous change of magnetic anisotropy along the thickness. The gradual variation of magnetic anisotropy along the thickness in the graded $Fe_{50}Pt_{50}$ film is the main reason for lower anisotropy field. According to our theoretical results,[14] the anisotropy field may also depend on the coupling strength. In the layered sample, the interruption of deposition during fabrication may introduce an extra interface between layers and reduce the coupling strength between adjacent layers. The relatively lower coupling strength between layers may also account for the larger anisotropy field in the sample. In a real perpendicular medium, each bit consists of many grains. The writing field of the medium is actually determined by the coercivity instead of the anisotropy field of grains. It should be mentioned here that the easy axis switching of a grain is completely different from that of a continuous film which involves lateral domain wall motion. The coercivity of a continuous film does not give any information about the writing field. Without patterning the media, the technologically important writing field cannot be directly and exactly evaluated. However, some important information about the writing field can be obtained by analyzing the anisotropy field. In a uniform medium, the grains are Stoner-Wohlfarth like particles, the coercivity or writing field is almost the same as the anisotropy field. In a medium made of multilayered magnetic film, although coercivity is different from anisotropy field due to the vertical domain wall motion in grains,[15,16] grains with lower anisotropy field may also have lower coercivity.[14] Since the multilayered $Fe_{50}Pt_{50}$ films have much lower anisotropy field than uniform ordered $Fe_{50}Pt_{50}$ film, both of them are expected to have much lower writing field. Compared with the 4-layered $Fe_{50}Pt_{50}$ film, the graded $Fe_{50}Pt_{50}$ film is expected to have even lower writing field.

According to theoretical predictions,[11,17] if the anisotropy of a graded medium can be made to change quadratically along the thickness, the writing field will be lowest. This goal is difficult to reach due to the difficulty in achieving precise control of the anisotropy of each layer. However, to some extent, it is still possible to better arrange the anisotropy distribution in the graded $Fe_{50}Pt_{50}$ film if the change of growth temperature can be more efficiently controlled without interrupting the deposition process. Therefore, we expect that the writing field can be further decreased by improving the fabrication process.

CONCLUSION

In summary, by studying the magnetic properties of single-layered $Fe_{50}Pt_{50}$ films, we demonstrated that the magnetic anisotropy could be tuned by controlling S which can be controlled by the growth temperature. Based on this, we built two kinds of multilayered $Fe_{50}Pt_{50}$ films whose order parameter decreases layer by layer. It is found that both films have much smaller anisotropy field than ordered uniform $Fe_{50}Pt_{50}$ film, the one with S changing more gradually has even smaller anisotropy field. The results suggest that the writing field of $Fe_{50}Pt_{50}$ could be efficiently reduced by gradually changing the order parameter.

ACKNOWLEDGMENTS

The study was supported in part by Chinese National Foundation of Natural Science (Grant Nos. 51001083 and 61106005) and National Science Foundation MRSEC Grant Nos. DMR-0213985.

[1]D. Suess, T. Schrefl, R. Dittrich, M. Kirschner, F. Dorfbauer, G. Hrkac, and J. Fidler, J. Magn. Magn. Mater. **290–291**(Part 1), 551 (2005).

[2]L. Zhang Y. K. Takahashi, A. Perumal, and K. Hono, J. Magn. Magn. Mater **322**, 2658 (2010).
[3]S. Sun, C. B. Murray, D. Weller, L. Folks, and A. Moser, Science **287**, 1989 (2000).
[4]M. L. Yan, X. Z. Li, L. Gao, S. H. Liou, D. J. Sellmyer, R. J. M. van de Veerdonk, and K. W. Wierman, Appl. Phys. Lett. **83**, 3332 (2003).
[5]J. S. Chen, J. F. Hu, B. C. Lim, Y. K. Lim, B. Liu, G. M. Chow, and G. Ju, J. Appl. Phys. **103**, 07F517 (2008).
[6]J. S. Chen, B. C. Lim, J. F. Hu, Y. K. Kim, B. Liu, and G. M. Chow, Appl. Phys. Lett. **90**, 042508 (2007).
[7]A. Perumal, Y. K. Takahashi, T. O. Seki, and K. Hono, Appl. Phys. Lett. **92**, 132508 (2008).
[8]R. Skomski, T. A. George, and D. J. Sellmyer, J. Appl. Phys. **103**, 07F531 (2008).
[9]D. Suess, J. Lee, J. Fidler, and T. Schrefl, J. Magn. Magn. Mater. **321**, 545 (2009)
[10]D. Suess, J. Fidler, G. Zimanyi, T. Schrefl, and P. Visscher, Appl. Phys. Lett. **92**, 173111 (2008).
[11]Z. Lu, P. B. Visscher, and W. H. Butler, IEEE Trans. Magn. **43**, 2941 (2007).
[12]S. Okamoto, N. Kikuchi, O. Kitakami, T. Miyazaki, Y. Shimada, and K. Fukamichi, Phys. Rev. B **66**, 024413 (2002).
[13]R. F. C. Farrow, D. Weller, R. F. Marks, M. F. Toney, S. Hom, G. R. Harp, and A. Cebollada, Appl. Phys. Lett. **69**, 1166 (1996).
[14]Z. Lu, P. B. Visscher, and J. W. Harrell, J. Appl. Phys. **103**, 07F507 (2008).
[15]A. Yu. Dobin and H. J. Richter, Appl. Phys. Lett. **89**, 062512 (2006).
[16]H. Kronmüller and D. Goll, Physica B **319**, 122 (2002).
[17]D. Suess, J. Magn. Magn. Mater. **308**, 183 (2007).