Microstructure and magnetic properties of $\text{Fe}_{100-x}\text{Pt}_x$ alloy films

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Polycrystalline $\text{Fe}_{100-x}\text{Pt}_x$ alloy thin films with Pt composition $x = 25\text{--}67$ at. % were prepared by dc magnetron sputtering on natural-oxidized silicon wafer substrates, then postannealed in vacuum at various temperatures and over different periods. The effects of film composition, magnetic layer thickness, annealing temperature, and annealing time on the magnetic properties parallel and normal to the film plane were investigated. Films with high in-plane coercivity could be obtained by annealing the films in the temperature range between 400 and 650 °C. Optimum in-plane squareness and coercivity of the film occurred at a film composition of $\text{Fe}_{50}\text{Pt}_{50}$ with thickness of about 200 nm after annealing at 600 °C for 30 min. The analyses of transmission electron microscopy diffraction patterns indicated that this annealed $\text{Fe}_{50}\text{Pt}_{50}$ film was nearly entirely in the fct γ_1 -FePt phase. The average grain size of this $\text{Fe}_{50}\text{Pt}_{50}$ film was about 85 nm. The grain size was almost independent of the cooling rate after annealing, but the magnetic hardening mechanism and coercivity of the annealed film was largely dependent on the cooling rate. © 1999 American Institute of Physics. [S0021-8979(99)01404-8]

I. INTRODUCTION

FePt compound alloy has received significant attention because it has very high magnetocrystalline anisotropy energy ($K_u \cong 7 \times 10^7$ erg/cm³), high coercivity, good corrosion resistance, and large energy products $(\text{BH})_{\text{max}}$.¹ It suits for applying in magnetic recording media, permanent magnets such as magnetic bias films of magnetoresistive elements, microelectronic mechanics, and magnetic tips of magnetic force microscopy. Yung *et al.*² and Aboaf *et al.*³ have investigated large in-plane coercivity FePt thin films prepared by dc and rf sputtering. Early investigations have shown that the magnetic properties of FePt alloy are sensitive to process parameters.¹⁻⁴

In this article, the FePt film is deposited on natural-oxidized silicon wafer substrate at room temperature. The effects of magnetic layer thickness, annealing temperature and annealing time on the magnetic properties parallel and normal to the $\text{Fe}_{100-x}\text{Pt}_x$ film plane are investigated. The as-deposited film is fcc γ -FePt phase. A $\text{Fe}_{50}\text{Pt}_{50}$ film with high in-plane coercivity and squareness (i.e., M_r/M_s) is produced after annealing at 600 °C for 30 min in vacuum. This film is nearly single phase of fct γ_1 -FePt phase which is precipitated from fcc γ -FePt phase. No antiphase boundaries (APBs) and twins⁴⁻⁶ are observed in this film. Coercivities of the films with different cooling rates after annealing are compared to clarify the origin mechanism of the coercivity.

II. EXPERIMENT

$\text{Fe}_{100-x}\text{Pt}_x$ ($x = 25\text{--}67$) alloy thin films were produced by dc magnetron sputtering system onto natural-oxidized silicon wafer substrates at room temperature. The substrate was rotated in order to get uniform composition. Rotating rate of the substrate was 75 rpm. A mosaic target consisting

of high purity iron disk (99.99%) overlaid with high purity platinum pieces (99.99%) was used. This arrangement provides a wide range of effective target compositions and therefore film compositions. The deposition rate was about 0.3 nm/s.

With 2 in. diameter sputtering gun, applied dc power source was set at 40 W. The base pressure in the sputter chamber was 5×10^{-7} Torr, and after the high purity argon gas was introduced, sputter pressure was fixed at 5 mTorr. Film thickness was varied from 10 to 700 nm. The as-deposited film was sealed in quartz capsule then postannealed in vacuum of 1×10^{-6} Torr.

The magnetic properties of the films were measured with vibrating sample magnetometer (VSM) and superconducting quantum interference device (SQUID) at room temperature and their maximum applied fields were 12 and 50 kOe, respectively. The microstructure of the film was characterized by JOEL 100CX transmission electron microscopy (TEM), and phases of the film were examined by x-ray diffractometer with $\text{Cu } K\alpha$ radiation. The average grain size of the film was measured by the TEM bright field image. The composition and homogeneity of the films were determined by energy disperse x-ray diffractometer (EDX). The thicknesses of the films were measured by a α step.

III. RESULTS AND DISCUSSION

Here, we change FePt composition, film thickness, annealing temperature, and annealing time to examine the variation of magnetic properties parallel and normal to the film plane.

A. As-deposited films

Figure 1 shows the relationship between saturation magnetization M_s , in-plane coercivity $H_{c\parallel}$, perpendicular coercivity $H_{c\perp}$ and Pt content of the as-deposited FePt film at

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FIG. 1. Variations of M_s and H_c with Pt content of as-deposited $\text{Fe}_{100-x}\text{Pt}_x$ films at room temperature. Pt content of the film is varied from 25 to 67 at. % and the film thickness is 200 nm.

room temperature. The film thickness δ is 200 nm. It can be seen that the M_s value decreases with increasing Pt content. As Pt content of the film equals to 25 at. %, M_s value of the film is about 940 emu/cm³. When Pt content is increased to 67 at. %, M_s value of the film decreases to about 610 emu/cm³. The decrease of M_s with increasing Pt content is due to that M_s value of the film is diluted by Pt atoms.² The variations of $H_{c\parallel}$ and $H_{c\perp}$ with Pt content are small, and $H_{c\parallel}$ is always lower than $H_{c\perp}$ for the same Pt content. $H_{c\parallel}$ is lower than 175 Oe and $H_{c\perp}$ is lower than 625 Oe for the Pt content between 25 and 67 at. %. Although these as-deposited films are soft magnetic γ -FePt phase,⁴ large internal stresses contribute to their coercivity. These internal stresses will make the as-deposited film with high Pt content produces some microcracks,² but we find that these microcracks disappeared after annealing.

Typical TEM bright field image and diffraction pattern of as-deposited FePt film are shown in Fig. 2. Figure 2(a) is the TEM photograph of as-deposited $\text{Fe}_{50}\text{Pt}_{50}$ film. We can see that it is polycrystalline. If we examine it in detail, average grain size is very small and it is about 5 nm. The bright curve lines in the photograph are microcracks. The diffraction pattern of Fig. 2(b) indicates that this film is fcc γ -FePt phase.

B. Post-annealed films

Figure 3(a) shows the relationships among M_s , $H_{c\parallel}$, Pt content and annealing temperature T_{an} of annealed $\text{Fe}_{100-x}\text{Pt}_x$ ($x = 25, 38, 50$, and 67) films. The annealing time t_{an} is 30 min and the film thickness is 200 nm. We can see that the maximum $H_{c\parallel}$ is lower than 2.5 kOe when Pt contents of the films are 25, 38, and 67 at. %. However, the $H_{c\parallel}$ of $\text{Fe}_{50}\text{Pt}_{50}$ film is higher than 7 kOe as T_{an} is in the range of 550 and 600 °C. The maximum $H_{c\parallel}$ of the $\text{Fe}_{50}\text{Pt}_{50}$ film is about 10 kOe which occurs at annealing temperature of 600 °C. M_s values of the films always decrease with increasing T_{an} except the $\text{Fe}_{75}\text{Pt}_{25}$ film. For the $\text{Fe}_{75}\text{Pt}_{25}$ film, the M_s value is decreased with increasing T_{an} as $T_{\text{an}} < 550$ °C and increased with increasing T_{an} as $T_{\text{an}} > 550$ °C. Its M_s value is about 910 emu/cm³ when $T_{\text{an}} = 650$ °C. From x-ray diffraction patterns of the $\text{Fe}_{75}\text{Pt}_{25}$ films, we find that the increase of M_s with T_{an} as $T_{\text{an}} > 550$ °C is due to that the presence of

FIG. 2. TEM micrograph and electron diffraction pattern of the as-deposited $\text{Fe}_{50}\text{Pt}_{50}$ film. (a) is the TEM microstructure and (b) its electron diffraction pattern. The film thickness is 200 nm.

α -Fe phase in the film.² By the observation of x-ray diffraction patterns, Fe_3Pt phase and FePt_3 phase are not found in the low Pt and high Pt content films, respectively. From Fig. 3(b), we can see that the relationship between $H_{c\perp}$ and T_{an} is

FIG. 3. (a) Variations of M_s and $H_{c\parallel}$ with annealing temperature. Pt contents of the films are 25, 38, 50, and 67 at. %, respectively. (b) Variations of $H_{c\perp}$ with annealing temperature. The film thickness is 200 nm and the annealing time is 30 min.

FIG. 4. Variations of H_c , M_s , and average grain size with annealing time of $\text{Fe}_{50}\text{Pt}_{50}$ films. Average grain size is obtained from TEM photograph. Solid lines are the magnetic properties and dash line is the mean grain size. The film thickness is 200 nm and the annealing temperature is 600 °C.

similar to the relationship between $H_{c\parallel}$ and T_{an} of Fig. 3(a), but $H_{c\perp}$ of the film is always lower than its $H_{c\parallel}$. This indicates that these films all have in-plane magnetic anisotropy. Maximum $H_{c\perp}$ is occurred at $T_{\text{an}}=550$ °C for the $\text{Fe}_{50}\text{Pt}_{50}$ film, it is about 6 kOe. The increase of $H_{c\parallel}$ and $H_{c\perp}$ with T_{an} as $T_{\text{an}}>400$ °C is due to the increase of the amount of fct γ_1 -FePt phase which is transformed from the fcc γ -FePt phase in the film.^{2,7} The fct γ_1 -FePt phase has a high magnetocrystalline anisotropy constant. As $T_{\text{an}}>600$ °C, the decrease of $H_{c\parallel}$ with T_{an} is due to the growth of grain size and the chemical interaction of FePt layer with Si substrate. The depth profiles of the films with different annealing temperatures examined by Auger electron spectrometer (AES) confirm that the chemical interaction of FePt layer with Si substrate is heavily as T_{an} is higher than 600 °C. The results of AES analysis will be published elsewhere.

Figure 4 shows the relationships among the magnetic properties, average grain size, and annealing time t_{an} of the $\text{Fe}_{50}\text{Pt}_{50}$ film which annealed at 600 °C. The average grain size is achieved by TEM observation. It indicates that $H_{c\parallel}$ increases gradually with t_{an} from 8.4 kOe for $t_{\text{an}}=5$ min to 10 kOe for $t_{\text{an}}=30$ min then decreases quickly with increasing t_{an} . As t_{an} longer than 60 min, $H_{c\parallel}$ decreases to about 600 Oe. However, grain size D of the annealed film always increases with t_{an} . It can be seen that $D=85$ nm for $t_{\text{an}}=30$ min and $D=103$ nm as $t_{\text{an}}=120$ min. Saturation magnetization M_s always decreases with increasing t_{an} .

The relationship between $H_{c\perp}$ and t_{an} is similar to that of $H_{c\parallel}$, but $H_{c\perp}$ is always lower than $H_{c\parallel}$. $H_{c\perp}$ is close to $H_{c\parallel}$ as t_{an} longer than 40 min. This indicates that the in-plane magnetic anisotropy of the $\text{Fe}_{50}\text{Pt}_{50}$ film is gradually destroyed by increasing t_{an} . Yung *et al.*² and Watanabe⁸ reported that origin of the high coercivity of FePt alloy is related to the degree of the imperfection of fct γ_1 -FePt phase. Because imperfection fcc γ_1 -FePt phase will cause the pinning of magnetic domain wall motion. Lower T_{an} and shorter t_{an} cannot transform fcc γ -FePt phase to fct γ_1 -FePt phase. However, higher T_{an} and longer t_{an} will make the fct γ_1 -FePt phase more perfect and grain growth. Only suitable heat-treatment conditions can get large amount of imperfect fct γ_1 -FePt phase, single-domain grain size, and maximum

FIG. 5. TEM micrograph and electron diffraction pattern of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ film. The annealing temperature is 600 °C and annealing time is 30 min. (a) TEM microstructure and (b) its electron diffraction pattern.

coercivity. The grain size of the fct γ_1 -FePt phase is increased with increasing T_{an} and t_{an} . As grain size is larger than single-domain size, coercivity of the film decreases rapidly. From Fig. 4, we can see that the coercivity of the film is decreased rapidly as grain size is larger than 90 nm. Watanabe *et al.*⁴ predicted that the critical diameter of single-domain particle of fct $\text{Fe}_{50}\text{Pt}_{50}$ phase was 600 nm, and the diameter limit of superparamagnetic behavior was 3 nm. However, from the relationship between the coercivity and the grain size of Fig. 4, we speculate that the critical diameter of single-domain particle of the fct $\text{Fe}_{50}\text{Pt}_{50}$ phase may be about 90 nm.

Figures 5(a) and 5(b) are TEM bright field image and electron diffraction pattern of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ film. It reveals that this film is fct γ_1 -FePt phase and its grain shape is spherical. Comparing Figs. 5(a) and 2(a) we can see the growth of grains after postannealing. The grain size of the as-deposited film is about 5 nm and it increases to about 85 nm after 600 °C, 30 min annealing. The superlattice reflections in the electron diffraction pattern of Fig. 5(b) indicate the formation of $L1_0$ ordered γ_1 -FePt phase.

According to Tanaka *et al.*,⁶ single-domain size grains, APBs in the grain, and the interfaces between different orientation variants will effectively work as pinning sites against magnetic domain wall motion for bulk FePt alloy. Although APBs is not observed in our annealed $\text{Fe}_{50}\text{Pt}_{50}$ film [see Fig. 5(a)], the grain boundaries and interfaces of fcc/fct phases in the film may act as a role of pinning sites of APBs. It is well known that the fcc γ -FePt phase of as-deposited film is nucleation site of the fct γ_1 -FePt phase. It is difficult to transform the fcc γ -FePt phase in the film to fct γ_1 -FePt phase completely by heat treatment.

Figure 6(a) shows the variation of the in-plane and out-plane coercivities with the film thickness δ of annealed

FIG. 6. (a) Variations of H_c with film thickness of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ films, (b) variations of M_s and the in-plane squareness (M_r/M_s) with film thickness of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ films, the annealing temperature is 600°C and the annealing time is 30 min.

$\text{Fe}_{50}\text{Pt}_{50}$ films. $H_{c||}$ is increased with the film thickness from 1 kOe for $\delta=16.5$ nm to 10 kOe for $\delta\approx 200$ nm then keeps small variation with further increasing δ to 700 nm. $H_{c\perp}$ is below 800 Oe when the film thickness is lower than 60 nm, and it increases rapidly with δ to 6.8 kOe for $\delta\approx 200$ nm then keeps small variation with increasing δ . The variation of $H_{c\perp}$ with δ has similar tendency to that of $H_{c||}$ with δ .

Figure 6(b) shows the relationships among the saturation magnetization M_s , in-plane squareness S (i.e., M_r/M_s) and thickness δ of the post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ films, where M_r is the remnant magnetization. For these films, the M_s value is about 680 emu/cm^3 and it almost keeps constant with the variation of δ . The S value of the film is also not affected by the film thickness, it is about 0.8.

For bulk FePt alloys, Tanaka *et al.*⁶ thought that very high transition temperature (1570 K) of disorder fcc γ -FePt phase to order fct γ_1 -FePt phase and short transition time make the control of this transformation by heat treatment difficult. However, it is easier to get nearly single γ_1 -FePt phase by thin film process. Tsoukatos *et al.*⁹ had investigated the effects of film thickness on the magnetic hysteresis of CoPt films with film thickness lower than 200 nm, they found that average grain size and coercivity of the film were increased with film thickness. In Fig. 6(a), it has similar tendency as the film thickness is lower than about 200 nm. However, as film thickness is larger than 200 nm, coercivity of the film only keeps small variation with further increasing film thickness. From TEM observation, we find that the grain size of the $\text{Fe}_{50}\text{Pt}_{50}$ film ($D\approx 90$ nm) is not increased with

FIG. 7. Variations of M_s and H_c with Pt content of post-annealed $\text{Fe}_{100-x}\text{Pt}_x$ films. Pt content of the film is varied from 25 to 67 at. % and the film thickness is 200 nm, the annealing temperature is 600°C and the annealing time is 30 min.

increasing δ again as it is thicker than 200 nm. This might be owing to that the film has not enough thermal energy for grain growth under constant T_{an} and t_{an} . So, H_c of the film almost keeps constant with further increasing δ because grain size is still in the single-domain size range.

Comparing Fig. 6(a) with Fig. 6(b), we select Pt content as 50 at. %, $\delta=200$ nm, $T_{\text{an}}=600^\circ\text{C}$, and $t_{\text{an}}=30$ min to examine the in-plane magnetic properties of the films.

Figure 7 shows the relationships of M_s and coercivities of post-annealed $\text{Fe}_{100-x}\text{Pt}_x$ films ($x=25-67$) with Pt content. The film thickness is 200 nm, T_{an} is 600°C , and t_{an} is 30 min. We can see that maximum $H_{c||}$ and $H_{c\perp}$ all occur at Pt=50 at. %. Tanaka *et al.*⁶ indicated that the magnetic properties of FePt alloy strongly depend on the composition as well as the heat-treatment conditions. From the composition point of view, maximum coercivity of the FePt film can be obtained after heat treating the film so as to obtain the highest ratio of ordered fct γ_1 -FePt phase to disordered fcc γ -FePt phase because γ -FePt phase is magnetically soft but γ_1 -FePt phase has very high magnetocrystalline anisotropy constant. From Fig. 7, we suspect that the highest [fct phase/fcc phase] ratio may be occurred at about Pt=50 at. % for our films. In general, M_s value of the FePt film is decreased with increasing Pt content for as-deposited γ -FePt phase. However, this tendency is changed after the film is annealed. The reason is still not understood.

Figure 8(a) shows the $M-H$ loops of VSM and SQUID, they are all measured at room temperature. Dash line is VSM loop and solid line is SQUID loop. From these loops we find that the M_s value of dash loop is much smaller than that of solid loop. This is due to that the maximum applied field of VSM (i.e., 12 kOe) is not large enough to saturate the sample. In the past, it is recognized that annealed $\text{Fe}_{50}\text{Pt}_{50}$ film is fct γ_1 -FePt phase and its M_s value is about 450 emu/cm^3 .⁵ From the $M-H$ loop of SQUID (it's maximum applied field is 50 kOe) in Fig. 8(a), we find that M_s value of the fct γ_1 -FePt phase is much larger than 450 emu/cm^3 . We can see that the $(BH)_{\text{max}}$ value of this film is about 14 MG Oe as shown in Fig. 8(b). This magnetic property is suitable for many permanent film applications. The "two shoulder" shape of SQUID $M-H$ loop in Fig. 8(a) shows

FIG. 8. (a) M - H loops of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ film, they are all measured along the film plane. Dash loop is achieved by VSM and solid loop is obtained from SQUID. (b) B - H loop of this film, it is measured by SQUID. The film thickness is 200 nm, the annealing temperature is 600 °C and the annealing time is 30 min.

the evidence of exchange coupling between magnetically hard fct γ_1 -FePt phase and soft fcc γ -FePt phase.¹⁰ It also indicates that there have little amount of magnetically soft fcc γ -FePt phase remained in this annealed film.

Figure 9 shows $H_{c\parallel}$ versus applied field H_a of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ film. Solid line is the $H_{c\parallel}$ of the film which is quenched by ice water, and dash line is the $H_{c\parallel}$ of the film which is slowly cooled in furnace. These $H_{c\parallel}$ are obtained from VSM minor loops with H_a varied from 600 to 12 000 Oe. Figure 9 shows that the film which quenched by ice water exhibits domain wall pinning mechanism; and the film which slowly cooling in furnace (cooling rate is about 4 °C/min) exhibits domain nucleation mechanism.¹¹ The coercivity of furnace-cooled film measured by SQUID is equal to 1.5 kOe for $T_{\text{an}}=550$ °C and 2 kOe for $T_{\text{an}}=600$ °C. These coercivities are only a fifth of the coercivities of ice-water-quenched films as shown in Fig. 6. However, from the observation of TEM bright field images, we find that average grain size of furnace-cooled film is about equal to that of ice-water-quenched film. For example, the average grain size of furnace-cooled $\text{Fe}_{50}\text{Pt}_{50}$ film after annealed at 600 °C for 30 min is about 90 nm and it is about 85 nm for ice-water-

FIG. 9. $H_{c\parallel}$ vs H_a of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ film. Solid line is the $H_{c\parallel}$ of the film which is quenched by ice water and dash line is the $H_{c\parallel}$ of the film which is slowly cooled in furnace. These $H_{c\parallel}$ are obtained by VSM minor loops. The film thickness is 200 nm, the annealing temperature is 600 °C, and the annealing time is 30 min.

quenched film. Figure 10 shows the x-ray diffraction patterns of furnace-cooled and ice-water-quenched $\text{Fe}_{50}\text{Pt}_{50}$ films. Comparing the intensities and nonsymmetry of the fct (001) and (110) peaks of Figs. 10(a) and 10(b), it reveals that the high coercivity of ice-water-quenched film is come from large amount of imperfect fct γ_1 -FePt phase, which trans-

FIG. 10. X-ray diffraction patterns of post-annealed $\text{Fe}_{50}\text{Pt}_{50}$ films. (a) Furnace-cooled film, and (b) ice-water-quenched film.

formed from fcc γ -FePt matrix. This result indicates that the high coercivity of ice-water-quenched film is not only due to the small grain size but also the increase of the amount of imperfect fct γ_1 -FePt phase.

IV. CONCLUSIONS

We have investigated the sputtered FePt films over a wide composition range and for various annealing temperatures and annealing times. The Fe₅₀Pt₅₀ film which annealed at 600 °C for 30 min in vacuum exhibits a high in-plane coercivity of 10 kOe, as film thickness is about 200 nm. The analysis of TEM electron diffraction pattern indicates that this film is nearly single phase of fct γ_1 -FePt phase. From the observation of bright field TEM image, its average grain size is about 85 nm. The film's M_s value is about 680 emu/cm³ and $(BH)_{\max}$ value is about 14 MG Oe, Fe₃Pt and FePt₃ phases are not found in our low Pt content films and high Pt content films, respectively.

Comparing the coercivities of the minor loops of furnace-cooled film and ice-water-quenched film, it indicates that origin of the coercivity is domain wall pinning type for ice-water-quenched film and domain nucleation type for furnace-cooled film. The grain size of furnace-cooled film is similar to that of ice-water-quenched film, much higher co-

ercivity of ice-water-quenched film is caused by the larger amount of imperfect fct γ_1 -FePt phase that transformed from fcc γ -FePt matrix. We also find that the M_s value of fct γ_1 -FePt phase is much larger than past experimental data.

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- ¹B. Zhang and W. A. Soffa, IEEE Trans. Magn. **MAG-26**, 1388 (1990).
- ²S. W. Yung, Y. H. Chang, T. J. Lin, and M. H. Hung, J. Magn. Magn. Mater. **116**, 411 (1992).
- ³J. A. Aboaf, T. R. McGuire, S. R. Herd, and E. Klokholm, IEEE Trans. Magn. **MAG-20**, 1642 (1984).
- ⁴M. Watanabe, T. Nakayama, K. Watanabe, T. Hirayama, and A. Tonomura, Mater. Trans., JIM **37**, 489 (1996).
- ⁵B. Zhang and W. A. Soffa, Scr. Metall. Mater. **30**, 683 (1994).
- ⁶Y. Tanaka, N. Kimura, K. Hono, K. Yasuda, and T. Sakurai, J. Magn. Magn. Mater. **170**, 289 (1997).
- ⁷K. Watanabe and H. Masumoto, Mater. Trans., JIM **24**, 627 (1983).
- ⁸K. Watanabe, Mater. Trans., JIM **29**, 80 (1988).
- ⁹A. Tsoukatos, H. Wan, G. C. Hadjipanayis, Y. J. Zhang, M. Waite, and S. I. Shah, J. Magn. Magn. Mater. **118**, 387 (1993).
- ¹⁰J. P. Liu, C. P. Luo, Y. Liu, and D. J. Sellmyer, Appl. Phys. Lett. **72**, 483 (1998).
- ¹¹G. C. Hadjipanayis and A. Kim, J. Appl. Phys. **63**, 3310 (1988).