Prospects of Hybrid Recording Materials

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Thermally assisted or hybrid magnetic recording system is expected to be a data storage device with high areal density beyond 1 Tb/in². Several features of the hybrid recording are treated, such as high resolution recording capability by sharp thermal gradient, and pico-second order high-speed magnetization reversal. Since the hybrid recording solves the head field limit problem, the high magnetic anisotropy (K_u) materials with order of 10^7 erg/cm³ are used for the hybrid recording media. We discuss the candidates of the high K_u materials, FePt and CoPt L1₀ ordered alloy, Tb-Fe-Co amorphous, and Co/Pd multilayer thin films.

Key words: thermally assisted magnetic recording, hybrid recording, L1₀ ordered alloy, FePt, CoPt, Tb-Fe-Co, Co/Pd, Co/Pt multilayer thin film, magneto anisotropy

1. Introduction

Magnetic recording system has been required with high areal density and high data rate recording. Commercial hard disk drives with areal densities around 60 Gb/in² are available today, and areal densities beyond 100 Gb/in² have been demonstrated at a laboratory level. Moreover, the feasibility of perpendicular magnetic recording system at a density of 1 Tb/in² has been studied by various authors¹⁾⁻⁵⁾. With increasing the areal density, the medium noise should be decreased in order to maintain the sufficient signal-to-noise-ratio (SNR) to replay. Since the medium noise depends on a switching volume for magnetization reversal in the media, the increase of the recording density has been traditionally approached by reducing a medium grain size and enhancing the isolation of the magnetic grains in order to break exchange coupling. This approach, however, leads to the thermal stability problem of the recorded bits, when the magnetic anisotropy energy per switching volume K_uV become comparable with the thermal energy $k_B T$. Under such conditions, the medium starts to exhibit the superparamagnetic behavior. To preserve the recorded bits for a period of ten years without the thermal decay, the stability ratio $K_uV / k_B T$ is required to be more than 50⁶⁾⁻⁸⁾. Here, K_u is the magnetic anisotropy constant, V is magnetic switching volume, k_B is the Boltzmann constant, and T is the absolute temperature, respectively. As the grain volume is reduced with higher areal density, the higher K_u materials are needed to maintain the stability.

Recently, various extremely high K_u materials, such as FePt ordered alloy with the L1₀ phase structure⁹⁾, have been investigated as the high density recording media with

the thermal stability. These materials have the K_u values of the order of 10^7 erg/cm³, which are more than 10 times as large as those of the conventional Co-Cr-Pt media¹⁰⁾. Increasing K_u , however, also increases the dynamic coercivity or the medium switching field H_0 at writing frequency (≈ 1 GHz), since the H_0 is proportional to the ratio K_u/M_s (M_s = saturation magnetization). The high K_u media would consequently have very high H_0 greater than 20 kOe, which is far in excess of available write field capability of the head (≈ 18 kOe)¹¹⁾. The head field capability limits the solution of the thermal stability problem by increasing the anisotropy energy, and probably limits the potential areal density of the conventional magnetic recording system, as shown in Fig. 1 (a).

One approach to solving the above problems in the conventional magnetic recording system is a thermally assisted magnetic recording, or a hybrid magnetic recording. Recently, the theoretical and the experimental researches¹²⁾⁻¹⁷⁾ have been reported. This paper attempts to provide an overview of the hybrid recording system. Specially, we will discuss the high K_u material candidates for the hybrid recording media.

Fig.1 Principle of hybrid recording. (a) conventional magnetic recording, (b) hybrid recording.

2. Characteristics of hybrid recording system

2.1 Merits of hybrid recording

The hybrid recording is the combined technology of the magnetic and the optical magnetic recording, and its concept is very simple as shown in Fig. 1 (b). The high coercivity media are heated locally during the writing process. Heating reduces the switching field, so that data can be recorded by the available writing head fields. After writing, the media should cool down quickly to room temperature. The recorded data is archived at room temperature, where the coercivity is much larger than the head field. The data is played back by a high sensitive

magneto flux detector, such as a giant magneto-resistive (GMR) head

In the magnetic recording system, the bit transitions are determined by the magnetic field from the writing head, while the transitions are determined by the characteristics of the thermal profile in the magneto optical recording media. The hybrid recording process has both the thermal profile in the media and the writing head field. Because of this, the hybrid recording methods can be classified roughly into three ways¹²⁾ to record the bits: (i) track width of writing head (T_w) < heating spot size (D_{hs}), (ii) $T_w > D_{hs}$, and (iii) $T_w \approx D_{hs}$. The first type method ($T_w < D_{hs}$) is very similar to conventional magnetic recording because the transitions and the track width are determined by the magnetic field of the writing head and the medium is only heated to reduce the coercivity. The sharpness of the transitions depends on the field gradient from the head. The second type method ($T_w > D_{hs}$) is similar to the magneto optical recording since the transitions and track width are determined by the characteristics of the thermal profile. In the third type method ($T_w \approx D_{hs}$), the bits are determined by both the magnetic field profile and the thermal profile. The sharpness of the transitions probably depends on the field gradient from the head, the medium temperature profile during the writing process, and the medium characteristics during the cooling process to room temperature after recording.

The track width and the thickness of the main pole for the 1 Tb/in² single pole type (SPT) write head are estimated to be 38 nm and 50 nm, respectively¹¹⁾. The spot size of the focused blue laser light ($\lambda = 405$ nm) is about 500 nm, which is about 10 times larger than the pole size of the 1Tb/in² SPT head. The spot size is larger than the track width of the present commercial hard disk drives (≈ 300 nm). So, the first type method is probably one approach to realize the hybrid recording. This method needs the low noise media with the exchange-decoupled magnetic grains, since small bit patterns are written by the sharp head field gradient and the heating process is only used for reducing the medium coercivity.

There is a possibility of recording tiny bits by the sharp thermal gradient. Figure 2 shows the magnetic force microscope (MFM) images of the domains recorded on the Tb-Fe-Co specimen by the magnetic recording and the second type hybrid recording methods¹⁸⁾. The specimen is the perpendicular magnetic recording medium with the coercivity H_c of 3 kOe at room temperature. When the 100 kFCI bit patterns (bit length : 250 nm) were written using a conventional thin film head (head field $\gg H_c$) without heating, the clear domain patterns could not be observed, as shown in Fig. 2 (a). On the other hand, as shown in Fig. 2 (b), the 250 kFCI bit patterns (bit length : 100 nm) could be recorded, when the focused pulse laser was irradiated to the medium locally among an uniform magnetic field of 200 Oe. The 20 nm-length tiny magnetic domains in a Tb-Fe-Co MO recording media, as mentioned later, can be recorded by the sharp thermal gradient²⁴⁾. These results suggest that the bit transitions of the strong exchange

coupling media can be determined by the thermal profile. When a tiny heat source is developed and an areal density of the pinning sites in the media is increased, the smaller bit patterns will be able to be recorded by the sharp thermal gradient.

Fig.2 Magnetic force microscope images of domain patterns recorded by (a) magnetic recording method, and (b) hybrid recording method¹⁸⁾.

2.2 Possibility of high speed recording

The data storage system is required with the high speed recording as well as the high areal density recording. Switching time of magnetization reversal in the media is important factor affecting the high speed recording, or the high frequency recording. When the magnetic field is applied with the frequency range over 10^9 Hz, every magnetic material faces the switching speed limit caused by natural resonance. The switching time strongly depends on Gilbert's damping constant α for the material¹⁹⁾. The switching time of the conventional magnetic recording media is estimated to be larger than 1 ns by numerical micromagnetic simulation^{20,21)}, since the α for the Co-Cr alloy medium materials are indicated to have small values around 0.01 by the ferromagnetic resonance experiments²²⁾. The recording process of the hybrid recording system might spend longer switching time than that of the conventional magnetic recording, since the increase of the medium temperature by heating is due to the phonon oscillation.

Fig.3 Pico-second order magnetization reversal induced by 100 femto-second laser irradiation²³⁾.

As shown in Fig. 3, a pico-second order magnetization reversal is observed in the Gd-Fe-Co perpendicular thin film, when a 100 femto-second laser is irradiated on the

film²³⁾. This switching speed is much faster than the ferromagnetic resonance frequency. The high speed spin reversal of the Gd-Fe-Co induced by femto-second laser pulse is due to the direct photon-electron interaction. This result suggests that the hybrid recording system will overcome the ferromagnetic resonance limit as well as the paramagnetic limit.

3. Material candidates for hybrid recording media

3.1 High K_u materials

The bit size of the 1 Tb/in² is roughly 15×40 nm². In order to keep medium noise within acceptable bounds, each bit contains only 20-30 magnetic grains with grain sizes on the order of 5 nm, which is about one-half that of conventional media. When the thermal stability factor of the grain should be more than 50 at room temperature, the anisotropy energy of the grain is required to be more than 2×10^7 erg/cm³.

Typical high K_u materials are plotted in the schematic picture of Fig. 4 in order to demonstrate the characteristics of the materials. The horizontal direction shows the intensity of the exchange coupling, while the vertical axis shows the crystallized structure. The contour lines show the intensity of the anisotropy energy. The typical permanent magneto materials, such as FePt and CoPt L1₀ ordered alloy, Nd-Fe-B, and SmCo₅, have high K_u values more than 10^7 erg/cm³. The Co/Pd multilayer thin films and the Tb-Fe-Co amorphous thin films have also the high perpendicular anisotropy energy, and these materials are convenient to the magneto optical recording media. Those high K_u materials shown in Fig. 4, however, take strong exchange coupling, which is the origin of the medium noise in the conventional magnetic recording. So, the exchange coupling is a important factor to use these high K_u materials for the high density recording media.

Fig.4 Candidates of hybrid recording materials.

3.2 Tb-Fe-Co amorphous materials

Tb-Fe-Co thin films are perpendicular anisotropy amorphous films with strong exchange coupling, which are typically used for the magneto optical recording media. The exchange coupling is disadvantage to the conventional magnetic recording media, since it is difficult to reduce the

cluster size of the magnetization reversal. On the other hand, as mentioned above, the bits can be written in the Te-Fe-Co media by the thermally assisted recording. Figure 5 shows the MO signals for the isolated domains recorded with the length of 20 nm²⁴⁾. The signals were read out by using a magnetic amplifying MO system. This result suggested that the high linear density over 1000 kFCI can be recorded in the Tb-Fe-Co media by using thermally assisted recording. Kojima et al²⁵⁾ reported that the possibility of the high track density of 100 kTPI was demonstrated by using the thermal gradient of the heating spot, and also the recorded bit size depended strongly on the underlayer structure. In order to write a small bit in the Tb-Fe-Co media with the strong exchange coupling, it is important to increase the areal density of the wall pinning sites and the wall coercivity.

Fig.5 Magneto optical signals from isolated patterns with 20 nm bit length recorded by thermally assisted recording²⁴⁾.

3.3 Co/Pt and Co/Pd multi-layer thin films

Co/Pt and Co/Pd multilayer thin films have large perpendicular magnetic anisotropy K_p and large polar Kerr effect, which are convenient for magneto-optical recording media. Recently, these films have been also actively investigated for the perpendicular magnetic recording media because of their high K_p . Curie temperature T_c as well as the K_p is important factor to apply the multilayer films to the hybrid recording media.

Magnetic properties of the multilayer films depend on the thickness of the Co, Pt, and Pd layers. The K_p values depend on both the Co layer and the Pt (or Pd) layer thickness, since the K_p is induced by the lattice strain at the interface between the Co and the Pt (or Pd) layers. The T_c depends strongly on the Co layer thickness²⁶⁾, and weakly on the Pt (or Pd) layer thickness²⁷⁾. Co/Pd multilayer specimens with different Co layer thickness were prepared by a dc magnetron sputtering deposition with a low Ar gas pressure of 0.3 Pa. The Co layer thickness t_{Co} was changed from 0.2 nm to 0.5 nm, while the Pd layer thickness was constant (0.8 nm). With increasing the Co layer thickness, the M_s increases linearly from 510 emu/cc to 710 emu/cc, while the K_p has a maximum value of 6×10^6 erg/cc around $t_{Co} = 0.3 \sim 0.4$ nm. The M_s of these specimens

decrease monotonically with increasing temperature, as shown in Fig. 6. The decreasing rate of the M_s is larger, when the t_{Co} become thinner. The K_p values also decrease monotonically with increasing the temperature. The K_p of the thinner Co-layer specimen decreases rapidly. For instance, the K_p value of the 0.2nm-thick specimen disappears at a temperature around 500 K, where the M_s value vanishes. These results suggest that the T_c of the Co/Pd multilayer films decreases with decreasing the Co layer thickness.

Fig.6 Temperature dependence of saturation magnetization M_s for Co/Pd multilayer specimens.

Fig.7 Plan-view transmission electron microscope (TEM) images of Co/Pd multilayer specimens deposited with different Ar pressure conditions. (a) low pressure (0.3 Pa), (b) high pressure(11 Pa).

The magnetic properties of the multilayer films depend on the film structure as well as the Co, Pd (or Pt) layer thickness. Figure 7 shows the plan-view transmission electron microscope (TEM) images of the multilayer films deposited in the different Ar pressure conditions. The specimen with a low pressure (0.3 Pa) deposition is a continuous medium with the strong exchange coupling,

while the high pressure (11 Pa) specimen become an exchange-decoupled medium with the isolated magnetic grains, Figure 8 shows the temperature dependence of M_s for these two specimens. The M_s values of the high pressure specimen decreases quickly with increasing the temperature, though the Co layer thickness is the same value of 0.4 nm. These results suggest that the Curie temperature decreases with isolating the magnetic grains in the media.

Since the writing process in the hybrid recording system will be probably carried out at the temperature range around 500 K $\square$ 600 K, the Co/Pd multilayer films with $t_{Co} = 0.3 \square 0.4$ nm deposited under the low Ar pressure condition are convenient for the hybrid recording media. These media have the strong exchange coupling between the magnetic grains. So, the wall pinning site density in the media must be increased in order to obtain a low noise media with a small domain size. The data will be probably recorded in the decoupled media at the lower temperature than that of the media with the strong exchange coupling.

Fig.8 Temperature dependence of M_s for Co/Pd specimens prepared by low Ar pressure deposition (0.3 Pa) and high pressure deposition (11 Pa).

3.4 FePt and CoPt $L1_0$ ordered alloys

FePt and CoPt ordered alloy thin films with the $L1_0$ phase structure have been actively investigated for the perpendicular magnetic recording media with enhanced thermal stability. However, these media need very strong head field for magnetization reversal. Figure 9 shows the relationship between the remanent coercivity H_r of the CoPt ordered thin film in addition of B element and the pulse width of applying magnetic field. The specimen was deposited at room temperature by an electron cyclotron resonance sputtering method, and heat treatment carried out at a temperature of 600 $^{\circ}$ C after deposition. The H_r was measured by the custom-made vibrating sample magnetometer system equipped with a conventional electromagnet (maximum field = 18 kOe) and a pulse magnetic field generator (pulse width = 1 μ s $\square$ 1 s, magnetic field = 0 $\square$ 7.5 kOe). The H_0 is roughly estimated to be 20 kOe by fitting of the data points to the Sharrock's equation²⁸⁾. So, this result indicates that strong head field more than 20 kOe is necessary to write in this medium at room temperature. As shown in Fig. 10, the coercivity of this specimen decreases with increasing the

temperature. With heating up to 530 K, the coercivity decreases to 1.2 kOe, which is only one-fifth of the coercivity at 300 K, and the H_0 is supposed to be about 4 kOe. The data can be recorded on the CoPt ordered media by the conventional write head, when the media is heated. So, the $L1_0$ ordered alloys are useful for the thermal assisted media.

Fig.9 Relationship between remanent coercivity H_r of the Co-Pt-B ordered thin film and the pulse width of applying magnetic field.

Fig.10 Temperature dependence of coercivity H_c for Co-Pt-B ordered thin film.

However, there are many problems which should be solved before practical application of the $L1_0$ ordered alloys. The major problems are

- i) decrease of ordering temperature,
- ii) reduction of medium noise.

The FePt and CoPt thin films need a heat treatment at a high temperature around 900 K during deposition and/or post-deposition annealing, in order to obtain the $L1_0$ ordered phase. The heat treatment temperature is about 300 K higher than the substrate temperature during the deposition of the conventional Co-Cr-Pt media on glass substrates. Since the glass transition temperature of the glass substrates is lower than the heat treatment temperature, the reduction of the ordering temperature is required for the development of the $L1_0$ ordered media. Some approaches have been proposed to reduce the ordering temperature of the $L1_0$ ordered alloys: e.g. the addition of a third elements such as Cu, B, and Sb⁽²⁸⁾⁻⁽³⁰⁾,

employment of a multilayered Fe/Pt films⁽³¹⁾, and sputter-deposition under an extremely high gas pressure condition⁽³²⁾. Figure 11 shows the relationship between the annealing temperature after deposition and the coercivity of the FePt specimens prepared by the above-mentioned three methods. The coercivity of those three specimens increase at the annealing temperature between 600 K and 700 K, that means the ordering temperature of those specimens is decreased by about 200 K. This result suggests that the FePt and the CoPt ordered alloy media can be deposited on the glass substrates.

Fig.11 Relationship between annealing temperature after deposition and H_c of FePt specimens^{(28),(31),(32)}.

Fig.12 Transmission electron microscope (TEM) image of chemically synthesized FePt $L1_0$ ordered particles⁽³⁵⁾.

The other problem is the reduction of the medium noise. In order to decrease the medium noise, the magnetic switching volume of the FePt media must be reduced by breaking the exchange coupling between the FePt grains. Granular media and film formed by chemical reaction have been studied for reducing the exchange interaction. The granular media are FePt composite films with a non-magnetic matrix such as SiO_2 ⁽³⁶⁾, MgO ⁽³⁷⁾, Al_2O_3 , ZrO_2 ⁽⁹⁾, B_2O_3 ⁽³⁸⁾, TaN, Si_3N_4 , Ag, B⁽³⁹⁾, and C⁽⁴⁰⁾. The switching volume is decreased with adding the matrix up to 30 vol.%, since the non-magnetic matrix isolate the FePt crystal grains. The granular media are effective to the reduction of

the medium noise, however it is difficult to decrease the ordering temperature of the FePt crystal grains. Chemically synthesized FePt fine particles with the L1₀ ordered structure have been also studied for the high density recording media with the low medium noise³⁴⁾. Figure 12 shows the TEM image of the L1₀ ordered FePt particles synthesized with the reduction method by using an ethylene glycol³⁵⁾. The coercivity of the particles is more than 9 kOe, though the grain size is only about 5 nm.

4. Conclusions

Increase of medium switching field and head field limit put the limit on the use of high K_u materials for high areal density magnetic recording. Since the hybrid recording solve the head field limit problem, the hybrid recording media will be able to use extremely high K_u materials, such as FePt and CoPt L1₀ ordered alloy permanent magnet materials, Co/Pt and Co/Pd multilayer thin films, and Tb-Fe-Co magneto optical recording media, whose K_u values are more than 10⁷ erg/cc. The bit transitions are determined by the heating profile of the media as well as the head field gradient. Therefore, tiny bit patterns will be probably recorded in the strong exchange coupling media. The hybrid recording media have "huge" alternative of not only high K_u materials but also the film structure.

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References

- 1) R. Wood: *IEEE Trans. Magn.*, **36**, 36 (2000).
- 2) R. Wood, J. Miles, and T. Olson: *IEEE Trans. Magn.*, **38**, 1711 (2002).
- 3) Z. Jin, H. Bertram, B. Wilson, and R. Wood: *IEEE Trans. Magn.*, **38**, 1429 (2002).
- 4) J. Miles, D. McKirdy, R. Chantrell, and R. Wood: *IEEE Trans. Magn.*, **39**, 1876 (2003).
- 5) M. Mallary, A. Torabi, and M. Benakli: *IEEE Trans. Magn.*, **38**, 1615 (2002).
- 6) H. Bertram, H. Zhu, and R. Gustafson: *IEEE Trans. Magn.*, **34**, 1845 (1998).
- 7) S. Charap, P. Lu, and Y. He: *IEEE Trans. Magn.*, **33**, 978 (1997).
- 8) D. Weller and A. Moser: *IEEE Trans. Magn.*, **35**, 4423 (1999).
- 9) K. Coffey, M. Parker, and J. Howard: *IEEE Trans. Magn.*, **31**, 2737 (1995).
- 10) N. Inaba, Y. Uesaka, and M. Futamoto: *IEEE Trans. Magn.*, **36**, 54 (2000).
- 11) Y. Kanai, R. Matsubara, H. Watanabe, H. Muraoka, and Y. Nakamura: *IEEE Trans. Magn.*, **39**, 1955 (2003).
- 12) T. Rausch, P. Herget, J. Bain, J. Zhu, D. Stancil and T. Schlesinger: *Proceeding of SPIE*, **4342**, 502 (2002).
- 13) M. Alex, A. Tselikov, T. McDaniel, N. Deeman, T. Valet, and D. Chen: *IEEE Trans. Magn.*, **37**, 1244 (2001).
- 14) J. Ruigrok: *J. Magn. Soc. Japan*, **25**, 313 (2001).
- 15) M. Alex, T. Valet, T. McDaniel, and C. Brucker: *J. Magn. Soc. Japan*, **25**, 328 (2001).
- 16) T. McDaniel, W. Challener, and K. Sendur: *IEEE Trans. Magn.*, **39**, 1972 (2003).
- 17) K. Kojima, M. Hamamoto, J. Sato, K. Watanabe, and H. Katayama: *IEEE Trans. Magn.*, **37**, 1406 (2001).
- 18) T. Takeuchi (unpublished).
- 19) R. Kikuchi: *J. Appl. Phys.*, **27**, 1352 (1956).
- 20) Q. Peng and H. Bertram: *IEEE Trans. Magn.*, **33**, 2677 (1997).
- 21) M. Benakli, A. Torabi, M. Mallary, H. Zhou, and H. Bertram: *IEEE Trans. Magn.*, **37**, 1564 (2001).
- 22) N. Inaba, Y. Uesaka, A. Nakamura, M. Futamoto, Y. Sugita, and S. Narishige: *IEEE Trans. Magn.*, **33**, 2989 (1997).
- 23) J. Hohlfield, Th. Gerrits, M. Bilderbeek, Th. Rasing, H. Awano, and N. Ota: *Phys. Rev. B*, **65**, 012413 (2001).
- 24) H. Awano, S. Imai, M. Sekine, M. Tani, N. Ota, K. Mitani, N. Takagi, H. Noguchi, and M. Kume: *IEEE Trans. Magn.*, **36**, 2261 (2000).
- 25) K. Kojima, M. Hamamoto, J. Sato, K. Watanabe, and H. Katayama: *IEEE Trans. Magn.*, **37**, 1406 (2001).
- 26) H. Kerseren and W. Zeper: *J. Magn. Magn. Mats.*, **120**, 271 (1993).
- 27) W. Zeper, F. Greidanus, and P. Carcia: *IEEE Trans. Magn.*, **25**, 3764 (1989).
- 28) M. Sharrock: *J. Appl. Phys.*, **76**, 6314 (1994).
- 29) O. Kitakami, S. Okamoto, N. Kikuchi, T. Miyazaki, and Y. Shimada: *J. Magn. Soc. Japan*, **26**, 1047 (2002).
- 30) O. Kitakami, Y. Shimada, K. Oikawa, H. Daimon, and K. Fukamichi: *Appl. Phys. Lett.*, **78**, 1104 (2001).
- 31) T. Maeda, A. Kikitsu, T. Kai, T. Nagase, H. Aikawa, and J. Akiyama: *IEEE Trans. Magn.*, **38**, 2796 (2002).
- 32) Y. Endo, N. Kikuchi, O. Kitakami, and Y. Shimada: *J. Appl. Phys.*, **89**, 7065 (2001).
- 33) T. Suzuki: *Materials Trans.*, **44**, 1535 (2003).
- 34) S. Sun, C. Murray, D. Weller, L. Folks, and A. Moser: *Nature*, **287**, 1989 (2000).
- 35) Y. Kurobe, H. Daimon, N. Ota, and N. Toshima: *The Bulletin of the Nano Science and Technology*, **1**, 15 (2003). (in Japanese)
- 36) C. Luo and D. Sellmyer: *Appl. Phys. Lett.*, **75**, 3162 (1999).
- 37) T. Suzuki and K. Ouchi: *IEEE Trans. Magn.*, **37**, 1283 (2001).
- 38) C. Luo, S. Liou, L. Gao, Y. Liu, and D. Sellmyer: *Appl. Phys. Lett.*, **7**, 2225 (2000).
- 39) N. Li and B. Lairson: *IEEE Trans. Magn.*, **35**, 1077 (1999).
- 40) M. Yu, Y. Liu, and D. Sellmyer: *J. Appl. Phys.*, **87**, 6959 (2000).

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