The enhanced negative magnetoresistance of Fe/Tb multilayer at multiextreme conditions

Masashi Ohashi,[1,a)] Gendo Oomi,[2] Eiji Ohmichi,[3,b)] Toshihito Osada,[3] Katsuyoshi Takano,[4] Hiroshi Sakurai,[5] and Fumitake Itoh[6]
[1]*Faculty of Environmental Design, Kanazawa University, Kakuma-machi, Kanazawa 920-1192, Japan*
[2]*Department of Physics, Kyushu University, Ropponmatsu 4-2-1, Fukuoka 810-8560, Japan*
[3]*ISSP, University of Tokyo, Kashiwanoha 5-1-5, Kashiwa, Chiba 277-8581, Japan*
[4]*Satellite Venture Business Laboratory, Gunma University, Tenjin-cho 1-5-1, Kiryu, Gunma 376-8515, Japan*
[5]*Department of Electronic Engineering, Gunma University, Tenjin-cho 1-5-1, Kiryuu, Gunma 376-8515, Japan*
[6]*Research Institute of Electromagnetic Devices, Hishi-machi 2506-8, Kiryu, Gunma 376-0001, Japan*

(Received 13 June 2008; accepted 29 July 2008; published online 1 October 2008)

Magnetoresistance (MR) in Fe/Tb magnetic multilayer is studied under multiextreme conditions, i.e., high magnetic field, low temperature, and high pressure. The negative MR is observed to be 24.6% in $[Fe(12\ nm)/Tb(15\ nm)]_{25}$ at 4.2 K, and MR is not saturated completely even up to 30 T. With increasing pressure, the magnitude of MR tends to be suppressed, indicating that magnetic order in the Tb layers is suppressed by applying pressure. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2986150]

I. INTRODUCTION

Magnetic multilayer systems including a heavy rare earth metal are known to have various magnetic properties, such as antiferromagnetic, spiral magnetic, or twisted magnetic structure. Such magnetic structure can be realized in the magnetic exchange spring multilayers. The magnetic exchange springs can tailor artificial domain wall. It has been argued that domain wall in a ferromagnet should give rise to the magnetoresistance (MR).[1] Mibu *et al.*[2] studied the effect of exchange springs in the SmCo/NiFe system. However the MR is small (1.5%) and dominated by anisotropic magnetoresistance (AMR). Gordeev *et al.*[3] demonstrated that the formation of short exchange springs in the $YFe_2/TbFe_2$ superlattice results in a large magnitude of MR as high as 32%. In general, the directions of magnetization in consecutive layers can be switched when a magnetic field is applied, and MR changes dramatically as a whole.

In the Fe/Gd and Fe/Dy multilayer systems, on the other hand, twisted magnetic structures have been inferred experimentally[4–6] and theoretically.[7–12] The Fe/Tb multilayer system, lying between the Fe/Gd and Fe/Dy systems in the Periodic Table, is expected to have some kind of twisted magnetic structure, caused by the competition among the exchange coupling, the Zeeman energy, and the anisotropic energy. The magnetic properties of the Fe/Tb multilayer were studied not only by superconducting quantum interference device magnetometory but also by x-ray magnetic circular dichroism., The magnetic properties of Fe and Tb layers were discussed selectively.[13] The magnetization increases with increasing magnetic field and does not easily saturate up to 5 T at 5 K; it is explained that the direction of Tb magnetic moment of the inner Tb layer turns to the applied magnetic field. Moreover, it was found that the Tb magnetic moments become twisted with increasing applied magnetic field as follows: (1) When the applied field H is less than the coercive force H_C, Fe and Tb magnetic moments align antiparallel, Fe moments being parallel to the magnetic field. This would be due to the ordinary exchange coupling between Fe and Tb magnetic moments. (2) For $H > H_C$, a twisted magnetic structure appears at low temperature.

In the present work, we have examined the MR of Fe/Tb multilayer under high magnetic field up to 30 T at 4.2 K. The result will be discussed by considering a large magnetic anisotropy of Tb layers. Furthermore, the pressure dependence of MR is extracted from the present results. It is well known that the magnitude of MR can be controlled by the pressure on the magnetic multilayer systems.[14–19] For example, Suenaga *et al.*[14] reported the pressure induced enhancement of the giant MR in Fe/Cr multilayers. In this paper we also discuss the effect of pressure on the electrical resistance and MR in an Fe/Tb multilayer.

II. EXPERIMENTAL

We fabricated the multilayer sample Ag(15 nm)/$[Fe(12\ nm)/Tb(15\ nm)]_{25}$/Fe(12 nm)/substrate, with dual-type radio frequency (rf) sputtering method, using 99.9% Fe and 99.9% Tb targets of 50 mm diameter.[13] The base pressure was less than 0.8×10^{-6} Torr. The sputtering was carried out in an atmosphere of argon gas with 1.0 Pa by applying 150 W rf power. The distance between the target and substrate was 60 mm. The substrates were water cooled, which were alternately rotated by 180° to deposit each element. The deposition rates of Fe and Tb were 0.11 and 0.13 nm/s, respectively. The thicknesses of the layers were controlled by a given time interval (Fe: 111 s/layer; Tb: 116 s/layer). A silver capping layer was deposited to avoid the

a)Electronic mail: ohashi@t.kanazawa-u.ac.jp.
b)Present address: Department of Physics, Kobe University, 1-1 Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan.

oxidation. The thickness of each layer was confirmed by x-ray absorption analysis. The Fe and Tb atomic density distributions and their ratio in the sample were also characterized with Rutherford backscattering spectrometry.

The x-ray diffraction pattern has been observed to correspond to that of hcp Tb (PDF 02-0899) and bcc Fe (PDF 06-0696). The Tb layers tend to have (001) texture (*c*-plane) and the Fe layers have polycrystalline texture. The thickness of the each layer, the atomic ratio, and the designed period were identified from the small angle diffraction pattern. Some unclear small angle diffraction peaks have also been observed, indicating that interface diffusion exists between Fe and Tb layers. The magnetization measurement at low temperature (25 K) has shown that the *M*-*H* curve has a large coercive field (0.18 T) and the magnetization does not saturate up to 5 T. The details of sample fabrication and characterization are described in a previous paper.[13]

The electrical resistance was measured by the usual four-probe dc method with the current direction on the film plane. At the ambient pressure, high-field measurements of up to 30 T were carried out with the use of a pulse magnet at the Institute for Solid State Physics, University of Tokyo. Pulsed magnetic fields were generated by capacitor discharge. A long pulse duration of 60 ms enabled us to obtain low-noise data. The direction of the magnetic field was on the film plane and perpendicular to the direction of the current. High-pressure measurements were carried out by using a tungsten carbide piston and a Ni–Cr–Mo–Co alloy (MP35N) cylinder. The pressure was always kept constant in the temperature range between 2 and 300 K by controlling the load within $\pm 1\%$. A mixture of fluorinerts FC70 and FC77 in ratio of 1:1 was used as a pressure transmitting medium. A high field of up to 9 T was generated by using superconducting magnet. The details of the present high-pressure apparatus were reported previously.[20,21]

III. RESULTS AND DISCUSSION

A. The magnetoresistance of Fe/Tb at high magnetic field up to 30 T

Figure 1(a) shows the MR curve of Tb monolayer at 4.2 K. Here the magnitude of MR ratio is defined as

$$\mathrm{MR}(H) = \frac{R(0) - R(H)}{R(0)}. \quad (1)$$

The slope $d\mathrm{MR}(H)/dH$ is negative in the region of high magnetic field of up to 30 T, and no anomaly is observed in the $\mathrm{MR}(H)$ curve.

The magnitude of the negative MR ratio is MR(30 T) =9.9%. Such a large MR of a heavy rare earth metal was reviewed by McGuire and Potter in Ref. 22, in which the giant magnitude of MR was obtained in Ho metal to be 32% at 4.2 K. Taking into account that Tb metal has phenomenally high magnetic anisotropy, the negative MR of Tb can also be explained as due to a kind of AMR effect. It is supported by the fact that the slope $|d\mathrm{MR}(H)/dH|$ of Tb decreases slightly with increasing magnetic field. As shown in Fig. 1(a), the MR curve tends to saturate above 10 T but has a long tail at high magnetic field.

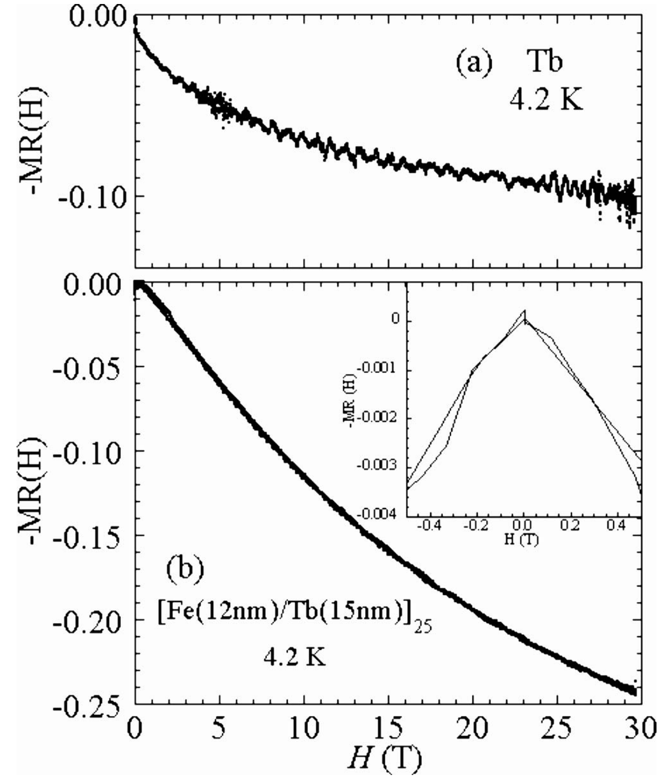

FIG. 1. The MR curves of (a) Tb at 4.2 K and (b) [Fe(12 nm)/Tb(15 nm)]$_{25}$ as a function of the magnetic field applied parallel on the plane. Inset shows the MR curve of Fe/Tb from −0.5 to 0.5 T.

As for the Fe/Tb multilayer, MR is symmetrical against the magnetic field $\pm H$, while the *M*-*H* curve shows a hysteresis loop.[13] Figure 1(b) shows the MR curve of [Fe(12 nm)/Tb(15 nm)]$_{25}$ at 4.2 K. In the present result, the giant negative MR is obtained to be MR(30 T)=24.6%. Such a large negative MR has never been reported in multilayer systems consisting of a transition metal and a rare earth metal. Moreover, it is found that MR is not saturated completely even at 30 T. Apparently the MR of the Fe/Tb multilayer has been enhanced compared with that of the Tb monolayer film. Since the AMR effect is enhanced by spin polarization and spin-orbit interaction,[23] it is reasonable to assume that the AMR effects on the Tb layer is enhanced by spin polarization of the Fe layers.

B. The electrical resistance of Fe/Tb under high pressure

In this section, we show the temperature dependence of the electrical resistance *R* of Fe/Tb multilayer at several pressures. At room temperature, *R* is almost independent of pressure. The pressure coefficient $|R^{-1}\partial R/\partial P|$ is less than 10^{-3} GPa^{-1}, which is one order smaller than those of Fe/Cr (Refs. 14 and 15) and Co/Cu (Refs. 15–17) multilayers. Figure 2 shows the electrical resistance *R* of [Fe(12 nm)/Tb(15 nm)]$_{25}$ as a function of the temperature at several pressures. At 0.1 GPa, *R* decreases with decreasing temperature, showing a good linearity from room temperature down to ~220 K, but $R(T)$ deviates from linearity at low temperature. The slope $\partial R/\partial T$ tends to increase with decreasing temperature slightly from ~220 K down to

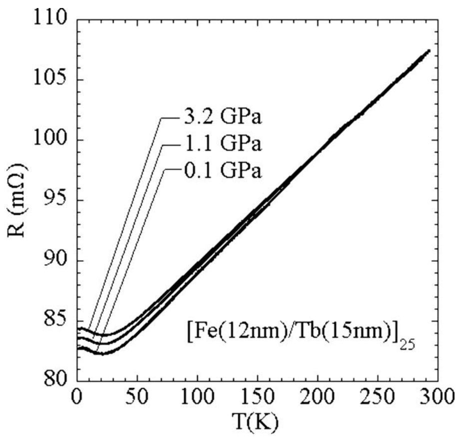

FIG. 2. The electrical resistance of $[Fe(12\ nm)/Tb(15\ nm)]_{25}$ as a function of the temperature at several pressures.

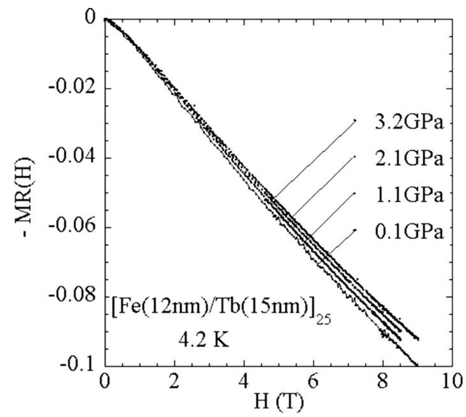

FIG. 3. MR curve of $[Fe(12\ nm)/Tb(15\ nm)]_{25}$ at 4.2 K as a function of the magnetic field applied parallel on the plane. The value of MR is obtained by using Eq. (1).

$\sim$50 K. It is caused by the ferromagnetic order of Tb at $T_C \sim 219$ K.[24,25] Colvin *et al.*[25] reported the sharp change in the slope of the resistivity curve on Tb at 229 K for a weak antiferromagnetic state and at 219 K for a ferromagnetic one.

$R(T)$ is almost independent of pressure above T_C, indicating that the scattering process between conduction electron and phonon is not changed by pressure up to 3.2 GPa. Below T_C, on the other hand, we note a general increase in the total resistance of Tb with increasing pressure. It means that the spin dependent scattering is enhanced with increasing pressure since the ferromagnetic order of the Tb layer is suppressed. Indeed, the residual resistivity ratio $R(280\ K)/R(4.2\ K)$ decreases with increasing pressure. The ratio $R(280\ K)/R(4.2\ K)$ is obtained to be 1.28 at ambient pressure and that at 3.2 GPa is 1.26. This suggestion is consistent with the previous report that the spontaneous magnetization of Tb is suppressed by applying pressure.[26]

It is found that $R(T)$ curves show a minimum around $T_{min} \sim 21$ K and a maximum around $T_{max} \sim 4$ K, which is not observed in that of multilayer made by 3*d* transition metals such as Fe/Cr and Co/Cu. Some of magnetic phase boundary may exist near T_{max} and T_{min}, but the reason is unknown in detail. Both T_{max} and T_{min} are independent of pressure.

C. The magnetoresistance of Fe/Tb under high pressure

The effect of pressure on the MR of the Fe/Tb multilayer has been reported previously.[27] Figure 3 shows MR ratios up to 8.5 T at 4.2 K under several pressures. It is already shown in Fig. 1(b) that MR is not saturated completely even at 30 T. Furthermore, the magnitude of MR decreases with increasing pressure. Here we discuss the effect of pressure on the magnitude of MR ratio, MR(8.5 T), which is estimated by substituting $H=8.5$ T in Eq. (1). Figure 4(a) shows the magnitude of MR ratio at 8.5 T, MR(8.5 T), as a function of pressure. MR(8.5 T) decreases in proportion to applying pressure. The pressure coefficient is obtained to be $(1/\mathrm{MR})d(\mathrm{MR})/dP \sim -0.025\ \mathrm{GPa}^{-1}$. In order to explain this result, we defined the magnitude of MR as $\Delta R = R(0) - R(8.5\ T)$. By substituting ΔR into Eq. (1) at the magnetic field of 8.5 T, the MR ratio is obtained as $\mathrm{MR}(8.5\ T) = \Delta R/R(0)$. By differentiating the equation with respect to pressure, we obtain

$$\frac{1}{(\mathrm{MR})}\frac{\partial(\mathrm{MR})}{\partial P} = \frac{1}{\Delta R}\frac{\partial \Delta R}{\partial P} - \frac{1}{R(0)}\frac{\partial R(0)}{\partial P}. \quad (2)$$

It means that the effect of pressure on MR consists of two terms; one is the effect of pressure on ΔR and the other is that on $R(0)$.

We show $R(0)$ at 4.2 K as a function of pressure in Fig. 4(b). $R(0)$ increases at a rate of $[1/R(0)][dR(0)/dP] = 6.0 \times 10^{-3}\ \mathrm{GPa}^{-1}$. Qualitatively, this result is consistent with the suggestion, as discussed in Sec. III B, that the spin dependent scattering is enhanced because of the suppression of the ferromagnetic order of the Tb layer. Indeed, as shown in Fig. 2, the $R(T)$ curve increases with increasing pressure below T_C.

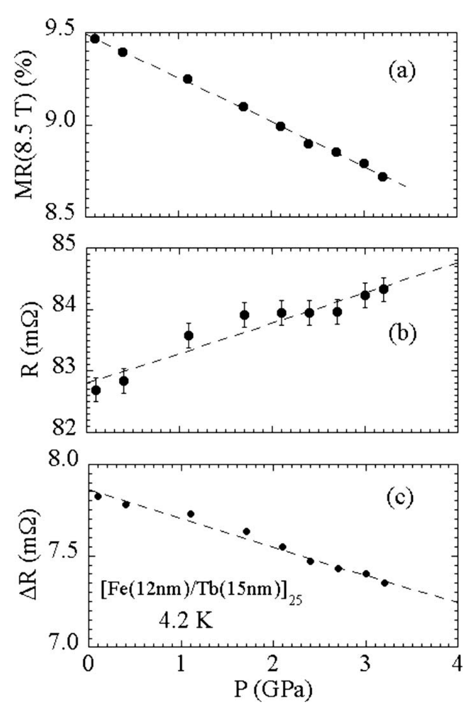

FIG. 4. Pressure dependences of (a) MR(8.5 T), (b) the electrical resistance at 0 T, and (c) the MR ΔR at 8.5 T of $[Fe(12\ nm)/Tb(15\ nm)]_{25}$ at 4.2 K.

Furthermore, as shown in Fig. 4(c), ΔR decreases at a rate of $(1/\Delta R)(d\Delta R)/dP = -0.020\ \text{GPa}^{-1}$ at 4.2 K. Since the pressure suppresses the ferromagnetic order of the Tb layer, AMR effects can also be suppressed. Then ΔR decreases with increasing pressure. By substituting the values of $[1/R(0)][dR(0)/dP]$ and $(1/\Delta R)(d\Delta R/dP)$ into Eq. (2), $(1/\text{MR})(d\text{MR}/dP)$ is estimated to be $-0.026\ \text{GPa}^{-1}$, which is almost the same as $-0.025\ \text{GPa}^{-1}$ obtained by using the experimental results in Fig. 4(a). It means that the suppression of MR is caused by both terms: the effects of pressure on ΔR and $R(0)$. Both effects are caused by same origin. The change in magnetic states in the Tb layers is strongly related to the suppression of the magnitude of MR by applying pressure.

IV. CONCLUSIONS

We found that the Fe layer enhances the MR of the Tb layer in the Fe/Tb magnetic multilayer. The giant magnitude of negative MR is obtained to be 24.6% in $[\text{Fe}(12\ \text{nm})/\text{Tb}(15\ \text{nm})]_{25}$ at 4.2 K. Moreover, MR is not saturated completely even at a high magnetic field of 30 T. The magnitude of MR is suppressed by applying pressure because of the suppression of magnetic order in the Tb layers.

ACKNOWLEDGMENTS

This work was supported in part by grants from the Ministry of Education, Science, Sports and Culture of Japan, the Murata Science Foundation, and Shibutani Incorporated Foundation of Academic, Culture and Sports Development.

[1] P. M. Levy and S. Zhang, Phys. Rev. Lett. **79**, 5110 (1997).
[2] K. Mibu, T. Ngahama, T. Shinjo, and T. Ono, Phys. Rev. B **58**, 6442 (1998).
[3] S. N. Gordeev, J.-M. L. Beaujour, G. J. Bowden, B. D. Rainford, P. A. J. de Groot, R. C. C. Ward, M. R. Wells, and A. G. M. Jansen, Phys. Rev. Lett. **87**, 186808 (2001).
[4] F. Itoh, M. Nakamura, H. Sakurai, H. Kiriake, M. Nawate, S. Honda, and H. Kawata, Jpn. J. Appl. Phys., Suppl. 32-2, **32**, 326 (1993).
[5] N. Ishimatsu, H. Hashizume, S. Hamada, N. Hosoito, C. S. Nelson, C. T. Venkataraman, G. Srajer, and J. C. Lang, Phys. Rev. B **60**, 9596 (1999).
[6] A. Koizumi, M. Takagaki, M. Suzuki, N. Kawamura, and N. Sakai, Phys. Rev. B **61**, R14909 (2000).
[7] R. E. Camley, Phys. Rev. B **35**, 3608 (1987).
[8] R. E. Camley and D. R. Tilley, Phys. Rev. B **37**, 3413 (1988).
[9] R. E. Camley, Phys. Rev. B **39**, 12316 (1989).
[10] M. Motokawa, Prog. Theor. Phys. **101**, 537 (1990).
[11] M. Motokawa and H. Dohnomae, J. Phys. Soc. Jpn. **60**, 1355 (1991).
[12] K. Takanashi, Y. Kamiguchi, H. Fujimori, and M. Motokawa, J. Phys. Soc. Jpn. **61**, 3721 (1992).
[13] K. Takanod, K. Ikeuchi, H. Sakurai, H. Oike, and F. Itoh, J. Phys. Chem. Solids **65**, 1985 (2004).
[14] K. Suenaga, S. Higashihara, M. Ohashi, G. Oomi, M. Hedo, Y. Uwatoko, K. Saito, S. Mitani, and K. Takanashi, Phys. Rev. Lett. **98**, 207202 (2007).
[15] G. Oomi, T. Sakai, Y. Uwatoko, K. Takanashi, and H. Fujimori, Physica B (Amsterdam) **239**, 19 (1997).
[16] T. Sakai, H. Miyagawa, G. Oomi, K. Saito, K. Takanashi, and H. Fujimori, J. Phys. Soc. Jpn. **67**, 3349 (1998).
[17] G. Oomi, H. Miyagawa, T. Sakai, K. Saito, K. Takanashi, and H. Fujimori, Physica B (Amsterdam) **284–288**, 1245 (2000).
[18] K. Suenaga, G. Oomi, T. Sakai, K. Saito, K. Takanashi, and H. Fujimori, J. Phys. Soc. Jpn. **75**, 024702 (2006).
[19] K. Suenaga, S. Higashihara, G. Oomi, T. Sakai, K. Saito, S. Mitani, and K. Takanashi, IEEE Trans. Magn. **42**, 1499 (2006).
[20] F. Honda, S. Kaji, I. Minamitake, M. Ohashi, G. Oomi, T. Eto, and T. Kagayama, J. Phys.: Condens. Matter **14**, 11501 (2002).
[21] M. Ohashi, G. Oomi, S. Koiwai, M. Hedo, and Y. Uwatoko, Phys. Rev. B **68**, 144428 (2003).
[22] T. R. McGuire and R. I. Potter, IEEE Trans. Magn. **11**, 1018 (1975).
[23] I. A. Campbell, A. Fert, and O. Jaoul, J. Phys. C **3**, S95 (1970).
[24] *Ferromagnetic Materials*, edited by E. P. Wohlfarth (North-Holland, Amsterdam, 1999), Vol. 1, p. 189.
[25] R. V. Colvin, S. Legvold, and F. H. Spedding, Phys. Rev. **120**, 741 (1960).
[26] D. Bloch and R. Pauthenet, Proceedings of the International Conference on Magnetism, Nottingham, 1964 (unpublished), p. 255.
[27] M. Ohashi, G. Oomi, and H. Sakurai, J. Phys.: Conf. Ser. **51**, 119 (2006).