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journal or publication title	Journal of Physics: Conference Series
volume	150
number	4
page range	42149
year	2009-01-01
URL	http://hdl.handle.net/2297/24314

doi: 10.1088/1742-6596/150/4/042149

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Abstract. Magnetic twist driven magnetoresistance in Fe/Tb magnetic multilayer is studied. The negative MR ratio is observed to be 24.6 % on $[Fe(12\ nm)/Tb(15\ nm)]_{25}$ at 4.2 K, which is much larger than that of Tb monolayer film, 9.9 %. Such large MR has never reported in multilayer systems including rare earth metal. Assuming that the MR of Tb can also be explained by the AMR effect, it means that the MR effects of the Tb layer is enhanced by spin polarization of the Fe layers.

1. Introduction

Magnetic multilayer systems including 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.* have studied the effect of exchange springs in SmCo/NiFe system. However MR is small (1.5%) and dominated by anisotropic magnetoresistance (AMR)[2]. S. N. Gordeev et. al. have demonstrated that the formation of short exchange springs in $YFe_2/TbFe_2$ superlattice results in a large magnitude of MR as high as 32 %[3]. 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 Fe/Re (Re: rare earth) multilayer system, on the other hand, twisted magnetic structures have been inferred experimentally[4, 5, 6] and theoretically[7, 8, 9, 10, 11, 12]. We have been studied about Fe/Tb multilayer system[13, 14, 15], which 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 magnetization of Fe/Tb multilayer increases as increasing magnetic field and does not easily saturate up to 5 T at 5 K. Moreover, it was found that the

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Tb magnetic moments become to twist with increasing the applied magnetic field H, as follows. (1) When H is less than the coercive force H_C, Fe and Tb magnetic moments align anti-parallel, Fe moments being parallel to the direction of H. 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.

2. 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 (R.F.) sputtering method, using 99.9 % Fe and 99.9 % Tb targets of 50 mm diameter. The thickness of layer were controlled by a given time interval (Fe: 111 s/layers, Tb: 116 s/layers). A silver capping-layer was deposited to avoid the oxidation. The thickness of each layer was confirmed by X-ray absorption analysis. The Fe and Tb atomic density distributions and the ratio in the sample were also characterized with Rutherford Backscattering Spectrometry.

An X-ray diffraction measurement has shown 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. Small angle diffraction signals have been observed and it is consistent with the thickness of the each layer, atomic ratio and the designed period. The detail of sample fabrication and characterization are described in the previous paper[13].

The electrical resistance was measured by the usual four-probe DC method with the current direction in the film plane. High field measurements up to 30 T were carried out with the use of a pulse magnet at the Institute for Solid State Physics, the 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. A direction of magnetic field was in the film plane and perpendicular to the direction of the current.

3. Result and discussion

Figure 1 shows the electrical resistivity of Tb monolayer ρ as a function of the temperature. ρ decreases with decreasing temperature and shows a sudden decrease near 220∼240 K. From the anomaly on the $d\rho/dT - T$ curve as seen in the inset of figure 1, two characteristic temperatures are estimated to be 219.5 K and 235.3 K, respectively. It is consistent with the previous report that the sharp change was observed in the slope of the resistivity curve on Tb at 229 K for a weak antifferomagnetic state and at 219 K for a ferromagnetic one[16].

Figure 2 shows MR curve of Tb monolayer at 4.2 K. The slope $dMR(H)/dH$ is negative in the region of high magnetic field up to 30 T, and no anomaly is observed in $MR(H)$ curve. Here the magnitude of MR ratio is defined as,

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

At the field of 30 T, MR is obtained to be $MR(30\text{ T}) = 9.9$ %. Such large MR of rare earth metal has been reviewed by T. R. McGuire and R. I. Potter [17], in which the large magnitude of MR is obtained to be in Ho metal 32 % at 4.2 K. Taking account that the hard axis (b-axis) align in the film plane by the (100) texture Tb film, the negative MR of Tb can also be explained by a kind of the AMR effect. It is supported by the fact that the slope $|dMR(H)/dH|$ of Tb decreases slightly as increasing magnetic field; as shown in figure 2, MR curve tends to saturate above 10 T but has a long tail at high magnetic field. We approximately estimated H_s as the intersection of the line extrapolated from the linear part of the steepest MR curve at low field

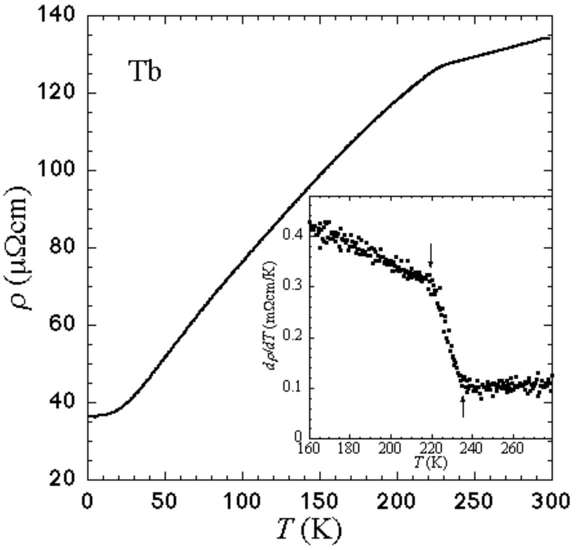

Figure 1. The electrical resistivity of Tb monolayer as a function of the temperature. Inset shows temperature derivative of the resistivity.

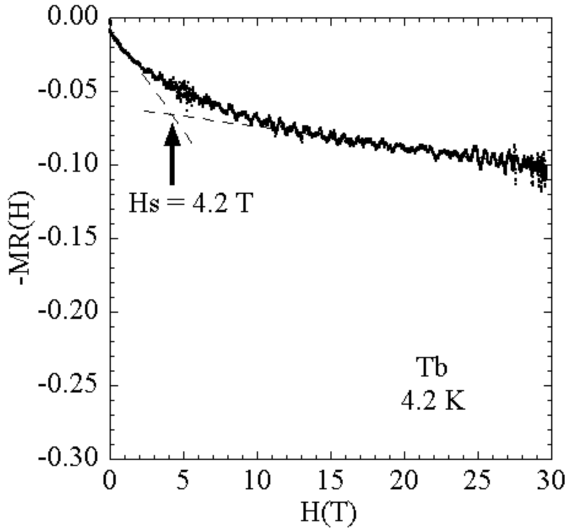

Figure 2. The magnetoresistance (MR) curve of Tb monolater as a function of the magnetic field applied parallel in the plane.

with the line extrapolated from high field. As seen in the result of figure 2, H_s is obtained to be 4.2 T.

Figure 3 shows the electrical resistivity ρ of [Fe(12 nm)/Tb(15 nm)]$_{25}$ as a function of the temperature. ρ decreases with decreasing temperature showing a good linearity from room temperature down to ~220 K, but $\rho(T)$ deviates from a linearity at low temperature; the slope $\partial\rho/\partial T$ tends to increase as decreasing temperature slightly from ~220 K down to ~50 K. It may be caused by the ferromagnetic order of Tb layer.

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

As for Fe/Tb multilayer, MR is symmetrical against the magnetic field $\pm H$ while $M - H$ curve shows hysteresis loop[13]. Figure 4 shows MR curve of [Fe(12 nm)/Tb(15 nm)]$_{25}$ at 4.2 K. In the present result, the negative MR is obtained to be MR(30 T)= 24.6 %, which is much larger than that of Tb monolayer. Moreover, such large negative MR has never reported in multilayer systems consisting of a transition metal and a rare earth metal. It means that MR of Fe/Tb multilayer comes not only from the interaction between the conduction electron and Tb magnetic moment, but also from some of the other effect such as the magnetic interaction between the moment of Tb layer and that of Fe one. Since the AMR effect is enhanced by spin polarization and spin-orbit interaction [18], it is reasonable to assume that the AMR effects of the Tb layer is enhanced by spin polarization of the Fe layers.

The saturation field is also estimated approximately to be H_s= 13.4 T, which is much larger than that of Tb monolayer, H_s= 4.2 T. It is consistent with the fact that magnetization also does not easily saturate up to 5 T[13], suggesting that some parts of Fe and Tb moments are not aligned parallel. Indeed, MR is not saturated completely even at 30 T.

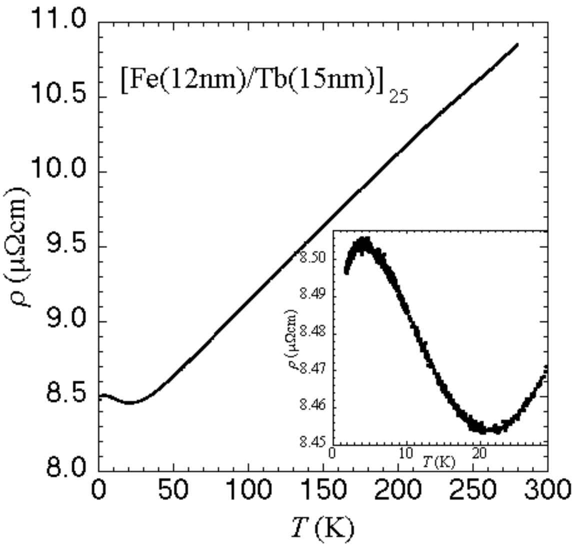

Figure 3. The electrical resistivity of [Fe(12 nm)/Tb(15 nm)]$_{25}$ multilayer as a function of the temperature.

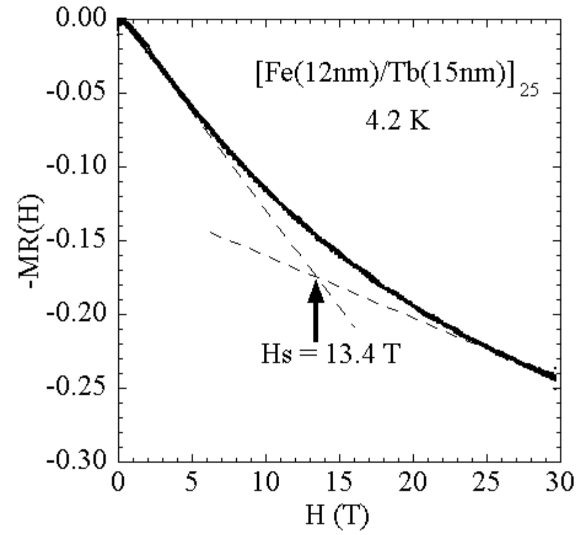

Figure 4. The magnetoresistance (MR) curve of [Fe(12 nm)/Tb(15 nm)]$_{25}$ multilayer as a function of the magnetic field.

4. Summary

We found the Fe layer enhances the MR of Tb layer in the Fe/Tb magnetic multilayer. The large magnitude of negative MR is obtained to be 24.6 % in [Fe(12 nm)/Tb(15 nm)]$_{25}$ at 4.2 K. Moreover, MR is not saturated completely even at high magnetic field of 30 T. Apparently the MR of the Fe/Tb multilayer has been enhanced compared with Tb monolayer film, indicating that the AMR effect of the Tb layer is enhanced by spin polarization of the Fe layers.

Acknowledgments

This work was supported in part by grants from the Japanese Ministry of Education, Science and Culture, the Murata Science Foundation, Kansai Research Foundation for technology promotion and Shibutani Incorporated Foundation of Academic, Culture and Sports Development.

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