Effect of pressure on the giant magneto-resistance of Fe/Tb multilayer

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Abstract. Magnetic twist driven giant magneto-resistance in Fe/Tb multilayer system is studied under high pressure up to 3.2 GPa. The $R(H) - H$ ($R(H)$: magneto-resistance) curve is described in [Fe(12 nm)/Tb(15 nm)]$_{25}$ multilayer as a function of magnetic field at various pressures. It is found that $R(H)$ does not saturate but keep an enhancement by applied magnetic field up to 9 T at 4.2 K. It is consistent with the fact that the magnetization does not have saturated but enhance, that is, the direction of Tb magnetic moment by inner of Tb layer turn to applied magnetic field. The MR ratio, which is defined as $MR = \Delta R / R(0)$, where $\Delta R = R(8.5 \text{ T}) - R(0)$, is obtained to be 9.5 % at 4.2 K at ambient pressure, and decreases as increasing pressure. It is suggested that the pressure effect on $MR$ is mainly due to a change in $\Delta R$ by applying pressure, that is, spin-dependent part of the electrical resistivity is suppressed by applying pressure.

1. Introduction

Multilayer systems consisting of a transition metal and a heavy rare earth metal are known to have various magnetic properties, such as anti-ferromagnetic, spiral magnetic or twisted magnetic structure. In Fe/Gd, Fe/Dy system, for example, twisted magnetic structures have been inferred experimentally and theoretically.

In this study we choose a Fe/Tb multilayer system. Fe/Tb system lying between Fe/Gd and Fe/Dy system in the periodic table is expected to have some kind of twisted magnetic structure. Magnetic properties of the Fe/Tb multilayer were studied not only by SQUID magnetometry but also by X-ray Magnetic Circular Dicroism (XMCD), and was discussed about magnetic properties of Fe and Tb layer, selectively[1]. It was found that the Tb magnetic moments become to twist with increasing the 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 anti-parallel, 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 when the sample temperature is low, particularly lower than 150 K. This magnetic phase could come from the competition among the exchange coupling, the Zeeman energy and the anisotropic energy.

In general, the value of layer thickness is one of the most important factors dominating the magnitudes of the giant magnetoresistance (GMR) of the magnetic multilayer systems, and can be controlled by applying pressure. In the present work, we have examined the GMR of Fe/Tb
at 4.2 K and at high magnetic field up to 9 T, and the pressure dependence of GMR is extracted from the present results.

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 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 R.F. power. The distance between the target and substrate was 60 mm. The substrates were water-cooled, which was alternately rotated by 180 degree to deposit each element. Deposition rates of Fe and Tb were 0.11 nm/s and 0.13 nm/s, respectively. 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.

The electrical resistance for the current was measured by the usual four-probe DC method with the current direction in the film plane. High field up to 9 T was generated by using superconducting magnet and a direction of magnetic field was in the film plane and perpendicular to the direction of the current. High pressure was generated up to 3.2 GPa by using a tungsten carbide piston and a Ni-Cr-Mo-Co alloy (MP35N) cylinder [2]. The pressure was always kept constant in the temperature range between 2 K and 300 K by controlling the load within ±1 %. A mixture of Fluorinerts of FC70 and FC77 in ratio 1:1 was used as a pressure transmitting medium. The details of the present high-pressure apparatus were reported previously [3].

3. Results
The magnetoresistance $R(H)$ is symmetrical against ±H and hysteresis in the $R(H)$ - $H$ curve is very small. In figure 1, $R(H)$ - $H$ curves at 4.2 K under high pressures are shown. Although it is expected that two magnetic phase transitions exist at 4.2 K [1], no anomaly is observed in $R(H)$ - $H$ curve. It is found that $R(H)$ does not have a saturated but keep an enhancement up to 9 T applied magnetic field at 4.2 K. Similar behavior has been observed in the recent results, in which the magnetization increases as increasing magnetic field and does not easily saturate up to 5 T at 5 K [1]. This is explained that the direction of Tb magnetic moment by inner of Tb layer turn to applied magnetic field.

It is unusual that $R(H)$ - $H$ curves show such good linearity up to high magnetic field as Figure 1. It suggests that the saturation field $H_S$ is much higher than 9.0 T. Indeed, $R(H)$ tends to saturate at high magnetic field; the slope $dR(H)/dH$ decreases slightly as increasing magnetic field. Here we defined the magnitude of MR as $\Delta R = R(8.5T) - R(0)$, and the MR ratio as $MR = \Delta R/R(0)$. At ambient pressure, $MR$ is obtained to be 9.5 % at 8.5 T. It is expected that an extremely large MR ratio will be developed by applying higher magnetic field than 10 T. Further studies above 10 T are in progress.

As increasing pressure, the value of $R(0)$ is found to increase at 4.2 K while the pressure coefficient of $R(0)$ at room temperature is almost zero. It means that the residual resistivity ratio $R(280 K)/R(4.2 K)$ decreases as increasing pressure; the ratio of $R(280 K)/R(4.2 K)$ are obtained to be 1.28 at ambient pressure and that at 4.2 GPa to be 1.26, respectively. It is difficult to estimate the effect of pressure on the saturation field $H_S$ since MR curve does not saturate up to 9 T in the pressure region up to 3.2 GPa. More systematic works may be desired to settle this point. Figure 2 shows the magnitude of MR ratio, $MR$, as a function of pressure. $MR$ decreases in proportion to applying pressure. The pressure coefficient is obtained to be $(1/MR)d(MR)/dP \sim -0.025 \text{ GPa}^{-1}$. 

4. Discussion

In order to explain the effect of pressure of MR as shown in Fig. 2, we differentiate the equation, \[ MR = \Delta R / R(0) \], with respect to pressure,

\[ \frac{1}{MR} \frac{\partial (MR)}{\partial P} = \frac{1}{\Delta R} \frac{\partial \Delta R}{\partial P} - \frac{1}{R(0)} \frac{\partial R(0)}{\partial P}. \]  

It means that the effect of pressure of MR consists of two terms; one is the effect of pressure of \( \Delta R \) and another is that of \( R(0) \).

Here we show \( R(0) \) and the \( \Delta R \) as a function of pressure in Figures 3 and 4, respectively. When pressure is applied, \( R(0) \) increases, which is opposite to the effect of pressure on \( \Delta R \). It is found that the magnitude of \( (1/R(0))(dR(0)/dP) \) and \( (1/(MR))d(MR)/dP \) are obtained to be \( 6.0 \times 10^{-3} \) GPa\(^{-1}\) and \( -0.025 \) GPa\(^{-1}\). By substituting them to the equation (1), \( (1/\Delta R)(d\Delta R/dP) \) is estimated to be \( -0.031 \) GPa\(^{-1}\).

On the other hand, the magnitude of \( (1/\Delta R)(d\Delta R/dP) \) is also obtained from the experimental results to be \( -0.020 \) GPa\(^{-1}\), which is same sign and order as that estimated from the equation (1). It means that \( (1/(MR))d(MR)/dP \) is same order as \( (1/\Delta R)(d\Delta R/dP) \), implying that the pressure effect on MR is mainly due to a change in \( \Delta R \) by applying pressure.

In general, the effect of pressure on the magnitude of MR ratio is divided into two parts; the first is the effect of pressure on the magnetoresistivity (nearly spin-dependent resistivity) and the second is that on the resistivity above \( H_s \), i.e., the saturation resistivity \( R(H > H_s) \). By assuming that \( \Delta R \) is related to the magnetoresistivity in Fe/Tb multilayer, it is suggested that spin-dependent part of the electrical resistivity is suppressed by applying pressure. Similar behavior is observed in Fe/Cr antiferromagnetic multilayer, in which \( H_s \) and the MR ratio has been observed at high magnetic field above \( H_s \) under high pressure, and it was found that the spin-dependent scattering plays an important role in the pressure dependence of MR ratio[4].
5. Conclusion
In [Fe(12 nm)/Tb(15 nm)]$_{25}$ multilayer, which has some kind of twisted magnetic structure, we observed the MR ratio at 4.2 K under high pressure. The spin-dependent scattering was estimated by assuming that $\Delta R$ is related to the magnetoresitivity. By using the equation (1) to the present results, it was suggested that the pressure effect on $MR$ is mainly due to a change in $\Delta R$ by applying pressure, that is, spin-dependent part of the electrical resistivity is suppressed by applying pressure. To make it more clearly, the result of $R(H > H_s)$ is needed as a function of pressure. This work was supported by a Grant in Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture.

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