Effect of Pressure on the Giant Magnetoresistance for Co/Cu with Different Cu-Layer Thicknesses

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Effects of pressure on the giant magnetoresistance (GMR) at various temperatures are studied for $[\text{Co}(10.8\text{\AA})/\text{Cu}(t_{\text{Cu}}\text{\AA})]_{15}$ magnetic multilayers (MMLs) with t_{Cu} near the first peak ($t_{\text{Cu}} \approx 10$) of MR ratio. A significant difference is found that the pressure effect on the magnitude of MR ratio of Co/Cu for $t_{\text{Cu}}=9.8$ decreases with increasing pressure, while that for $t_{\text{Cu}}=11.7$ increases. This enhancement of GMR in Co/Cu with $t_{\text{Cu}}=11.7$ caused by applying pressure, at 5 K, 77 K and room temperature, is the first observation in Co/Cu MMLs.

Key words: Co/Cu magnetic multilayer, high pressure, giant magnetoresistance, spin-dependent scattering

1. Introduction

Extensive studies on the giant magnetoresistance (GMR) of a wide variety of materials such as magnetic multilayers (MMLs),^{1,2)} granular alloys,³⁾ spin valves,⁴⁾ *etc.*, have been performed by a huge amount of experimental and theoretical investigations to clarify the origin of GMR. The magnitude of GMR in MMLs is attributed to the spin-dependent scattering of conduction electrons, which is dominated by several factors, the alignment of magnetization in ferromagnetic (FM) layers, random potential at interfaces (so-called the interface roughness),⁵⁾ compositional mixing due to interdiffusion,⁶⁾ and so forth. In addition, it has been revealed that the magnitude of MR oscillates as a function of non-ferromagnetic (NM) layer thickness, t_{NM} .²⁾ By applying pressure, we can change the values of t_{NM} and the interface roughness dominating the magnitude of GMR. Thus, a drastic change in the electronic or magnetic state of MML is expected by application of pressure on MMLs, which show GMR effect. In this sense, high pressure study on GMR is considered to be one of the useful methods to investigate the detailed mechanism of GMR phenomena in MML.

We reported until now that pressure effects of GMR on the first peaks as functions of t_{NM} in Fe/Cr, Co/Cu and Fe/Cu MMLs, and the magnitude of GMR decreased by applying pressure in all cases.⁷⁾ In this paper, we have found that pressure enhances GMR of Co/Cu with t_{Cu} on the halfway up the right-hand side of the first peak.

2. Experimental

The Co/Cu samples were prepared by means of multi-target-type ion beam sputtering technique.⁸⁾ Fe 50 Å was first deposited as a buffer layer on a Si(100) substrate placed on a rotating table. Co (99.9 % in purity) and Cu (99.9 % in purity) were alternately deposited on the buffer layer. The layer thickness of Co was kept at 10.8 Å and the Cu layer thickness t_{Cu} was varied. The Co/Cu samples in the present work were $[\text{Co}(10.8\text{\AA})/\text{Cu}(t_{\text{Cu}}\text{\AA})]_{15}$ with $t_{\text{Cu}}=9.8$ and 11.7. The samples with $t_{\text{Cu}}=9.8$ and 11.7 are on the first peak and on the halfway up the right-hand side of the first peak in the oscillation curve of MR ratio as a function of t_{Cu} (hereafter, we abbreviate these as Co/Cu(9.8) and Co/Cu(11.7)). The repetition number of stacking layers was 15.

High pressure up to 2.2 GPa was generated by a piston-cylinder apparatus utilizing the conventional Teflon-cell technique. The pressure inside the cell was kept constant by controlling the load of hydraulic press within ± 5 % throughout the experiment. The temperature inside the cell was measured by a calibrated Cu(Fe)-chromel thermocouple and RuO₂ resistor embedded into the Cu-Be cylinder. The electrical resistance was measured by means of the standard four probe method. Magnetic field and current were applied parallel to the film plane of the sample (so-called CIP-MR). The details of the present high pressure apparatus were reported elsewhere.⁹⁾

3. Results

Figure 1 shows the maximum values of MR ratio, $(\Delta\rho/\rho_s)_{\text{max}}$, obtained at room temperature and at 4.2 K. The MR ratio is defined as $\Delta\rho/\rho_s = [\rho(H) - \rho_s]/\rho_s$, where ρ_s and $\rho(H)$ are the electrical resistivity above and below the saturation field H_s . The values of $(\Delta\rho/\rho_s)_{\text{max}}$ at 4.2 K are 39.2 %, 31.3 % for Co/Cu(9.8) and Co/Cu(11.7), respectively. In this case, the period of the oscillation is about 12 Å.

For Co/Cu(9.8) and Co/Cu(11.7), $\Delta\rho/\rho_s$ curves at 4.2 K under high pressure are shown in Fig. 2 as a function of magnetic field H ranging from -0.2 to 0.2 T. Most interesting features in Fig. 2 are that the shape of a hysteretic curve of $\Delta\rho/\rho_s$ changes in the way that for

Fig. 1 The maximum values of $\Delta\rho/\rho_s$, $(\Delta\rho/\rho_s)_{\max}$, at 4.2 K and room temperature as a function of t_{Cu} .

thicker Cu layers the $\Delta\rho/\rho_s$ curve shows sharp peaks, and different sign of pressure effect on $(\Delta\rho/\rho_s)_{\max}$ at 4.2 K is observed between Co/Cu (9.8) and Co/Cu(11.7): $(\Delta\rho/\rho_s)_{\max}$ for Co/Cu(9.8) is decreased by applying pressure; 39.2 % at 0 GPa and 37.7 % at 2.2 GPa, while about 20% increase of $(\Delta\rho/\rho_s)_{\max}$ at 0 GPa is observed at 2.2 GPa for Co/Cu(11.7).

Fig. 2 MR ratio, $\Delta\rho/\rho_s$, at 4.2 K of Co/Cu(9.8) and Co/Cu(11.7) under high pressure as a function of magnetic field H .

This discovery of the enhancement of the GMR by applying pressure is the first observation in MML systems studied

until now by the present authors.⁷ The coercive force of Co layers, H_c , where the resistance curve shows peaks decreases with increasing pressure for both samples, the decreasing rate of H_c , $\partial H_c/\partial P$, is about -2×10^{-3} T/GPa for Co/Cu(9.8) and -7×10^{-3} T/GPa for Co/Cu(11.7). The magnitude of GMR and H_c in Co/Cu (11.7) are strongly affected by applying pressure compared with those of Co/Cu(9.8). In other words, the effect of pressure on the several factors dominating the magnitude of GMR such as the alignment of magnetization in FM layers, the interface roughness, compositional mixing may be more sensitive in Co/Cu(11.7) than that of Co/Cu(9.8).

Fig. 3 The pressure dependence of the maximum values of MR ratio, $(\Delta\rho/\rho_s)_{\max}$, at 4.2 K, 77 K and room temperature as a function of pressure P .

The values of $(\Delta\rho/\rho_s)_{\max}$ at 4.2 K, 77 K and room temperature for Co/Cu(9.8) and Co/Cu(11.7) are shown in Fig. 3 as a function of pressure. As was mentioned in the preceding paragraph, remarkable differences in the pressure dependent $(\Delta\rho/\rho_s)_{\max}$ at 4.2 K are observed among Co/Cu MMLs with different t_{Cu} : the value of $(\Delta\rho/\rho_s)_{\max}$ for Co/Cu(9.8) decreases smoothly with increasing pressure. However, Co/Cu(11.7) shows a large increase of $(\Delta\rho/\rho_s)_{\max}$ at high pressure. It should be noted that the significant increase of $(\Delta\rho/\rho_s)_{\max}$ by applying pressure for Co/Cu(11.7) is also observed both at 77 K and room temperature, however, pressure dependence of $(\Delta\rho/\rho_s)_{\max}$ becomes less prominent as temperature increases.

The pressure effect on $\Delta\rho/\rho_s$ is divided into two parts, the first is the effect of pressure on $\Delta\rho$ and the second is

Fig. 4 (a) Pressure dependence of spin-independent resistivity $\rho_s(H > H_c)$ and (b) pressure dependence of spin-dependent resistivity $\Delta\rho$, of Co/Cu(9.8) and Co/Cu(11.7) at 4.2 K.

that on ρ_s . The first part corresponds to the pressure change of spin-dependent resistivity but the second is that of spin-independent (bulk) resistivity. The values of ρ_s of Co/Cu(9.8) and Co/Cu(11.7) at 4.2 K are shown in Fig. 4(a) as a function of pressure. ρ_s for Co/Cu(9.8) decreases gradually with increasing pressure; about 2.6 % decrease at 2.2 GPa. However, that for Co/Cu(11.7) is almost constant up to 2.2 GPa within experimental error. As shown in Fig. 4(b), $\Delta\rho$ for Co/Cu(9.8) decreases linearly with pressure having a rate $\partial \ln \Delta\rho / \partial P = -2.6 \times 10^{-2} \text{ GPa}^{-1}$; about 6.2 % decrease at 2.2 GPa. On the other hand, the enhancement of $\Delta\rho$ by applying pressure is seen for Co/Cu(11.7). The pressure coefficient of $\Delta\rho$ is $9.3 \times 10^{-2} \text{ GPa}^{-1}$. By applying 2.2 GPa, $\Delta\rho$ increases by about 21 %, which is larger than that of Co/Cu(9.8) with different sign. It has been suggested that GMR is strongly dependent on the interface state such as magnetic and structural roughnesses. The relationship between surface roughness and the magnitude of GMR has recently investigated extensively by many authors.¹⁰⁾⁻¹²⁾ It has been found that in the case of Fe/Cr MML ($\Delta\rho/\rho_s$)_{max} is enhanced by increasing interfacial roughness up to an optimum as long as the magnetization of Fe-layer is coupled antiferromagnetically, reaches a maximum, and then decreases with a further increase of the roughness.¹²⁾ Assuming that ρ_s is dominated mainly by the roughness in bulk sample and $\Delta\rho$ mainly by that of roughness at interface,¹²⁾ the present result indicates that the pressure

effect on $\Delta\rho$ is more significant than that of ρ_s . Thus, the effect of pressure on the magnitude of GMR is mainly dominated by a change in the interfacial roughness by applying pressure.

Finally, we consider about the enhancement of GMR in Co/Cu(11.7) by applying pressure. The present result would be explained qualitatively by taking account of the change in the interatomic distance perpendicular to the layer plane in MML. If we assume the bulk modulus of Cu layer is the same as that of the bulk Cu, 137 GPa, the change in the value of t_{Cu} , δt_{Cu} , at 2.2 GPa is about 0.5 % ($\approx 0.06 \text{ \AA}$) for Co/Cu(11.7), while the increase of $(\Delta\rho/\rho_s)_{\text{max}}$, $\delta(\Delta\rho/\rho_s)_{\text{max}}$, at 2.2 GPa corresponds to about 6 % decrease in t_{Cu} , $\delta t_{\text{Cu}} \approx 0.7 \text{ \AA}$ for Co/Cu(11.7), which is almost one order of magnitude larger than that estimated from the bulk modulus of Cu. Thus, it is difficult to explain quantitatively the change in $(\Delta\rho/\rho_s)_{\text{max}}$ only by considering the pressure change in t_{Cu} at high pressure. On the other hand, we may consider that the first peak of $(\Delta\rho/\rho_s)_{\text{max}}$ ($t_{\text{Cu}} \sim 10 \text{ \AA}$ at 0 GPa) shifts to a larger value of t_{Cu} at high pressure, indicating that the oscillation period of $(\Delta\rho/\rho_s)_{\text{max}}$ as shown in Fig. 1 is changed by applying pressure. From the theoretical model, Bruno *et al.*¹³⁾ suggested that the oscillation period is crucially related with the vector q_s linking the two points of the "dog's bone" orbits around the Fermi surface, indicating that the pressure enhancement of GMR in Co/Cu(11.7) is due to the change in the oscillation period caused by the modification of the Fermi surface under pressure. To settle this point more experimental data of GMR at high pressure for Co/Cu samples with different t_{Cu} together with other microscopic measurements are required.

References

- 1) M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, J. Chazelas: *Phys. Rev. Lett.*, **61**, 2472 (1988).
- 2) S. S. P. Parkin, N. More, K. P. Roche: *Phys. Rev. Lett.*, **64**, 2304 (1990).
- 3) J.Q. Xiao, J.S. Jian, C.L. Chien: *Phys. Rev. Lett.*, **68**, 3749 (1992).
- 4) A. Encinas, F. Nguyen Van Dau, M. Sussiau, A. Schuhl, P. Galtier: *Appl. Phys. Lett.*, **71**, 3299 (1997).
- 5) J. Inoue, A. Oguri and S. Maekawa: *J. Phys. Soc. Jpn.*, **60**, 376 (1991).
- 6) F. Petroff, A. Barthélemy, A. Hamzic, A. Fert, P. Etienne, S. Lequien and G. Creuzet: *J. Magn. Magn. Mat.*, **93**, 95 (1991).
- 7) G. Oomi, T. Sakai, Y. Uwatoko, K. Takanashi and H. Fujimori: *Physica B*, **239**, 19 (1997).
- 8) N. Kataoka, K. Saito and H. Fujimori: *J. Magn. Magn. Mat.*, **121**, 385 (1993).
- 9) G. Oomi, T. Kagayama: *Physica B*, **239**, 191 (1997).
- 10) E.E. Fullerton, D.M. Kelley, J. Guimpel, I.V. Schuller, Y. Bruynseraede: *Phys. Rev. Lett.*, **68**, 859 (1992).
- 11) K. Takanashi, Y. Obi, Y. Mitani, H. Fujimori: *J. Phys. Soc. Jpn.*, **61**, 1169 (1992).
- 12) V. Korenivski, K.V. Rao, D.M. Kelly, I.K. Schuller, K.K. Larsen, J. Böttiger: *J. Magn. Magn. Mat.*, **140-144**, 549 (1995).
- 13) P. Bruno and C. Chappert: *Phys. Rev. B*, **46**, 261 (1991).