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Giant magnetoresistance and interlayer exchange coupling in Ni–Co/Cu multilayer films

H. Kubota [a], S. Ishio [a,1], T. Miyazaki [a,*] and Z.M. Stadnik [b]

[a] *Department of Applied Physics, Tohoku University, Sendai 980, Japan*
[b] *Department of Physics, University of Ottawa, Ottawa, Ontario KIN 6N5, Canada*

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Abstract

The oscillation of giant magnetoresistance and interlayer exchange coupling as a function of Cu thickness was studied for Ni–Co/Cu multilayer films prepared by magnetron sputtering onto a glass substrate. They had a fcc (111) preferred orientation parallel to the growth direction. Both the value of magnetoresistance ratio and interlayer exchange coupling strength increased with increasing Co content, which were in qualitative agreement with theoretical calculations. The strength of exchange coupling was proportional to the square of the saturation magnetization.

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1. Introduction

The origin of giant magnetoresistance (GMR) and interlayer exchange coupling (ILEC) have attracted much attention since their discovery in Fe/Cr [1–3] and Co/Cu [4] systems. GMR and ILEC depend sensitively on the film structure such as the interface mixing [5–8], preferred orientation of the samples [9,10], and the total thickness of multilayer films [11]. In addition to this dependence on film structure GMR and ILEC are closely related to each other [12]. Theoretical studies [13,14] indicate an importance of the spin dependent scattering by the magnetic atoms at the interface for GMR, and that of the magnetic polarization of magnetic atoms at the interface for ILEC. A further experimental study may be required in order to obtain a sufficient understanding of the origin of GMR. The study of the compositional dependence of magnetoresistance is very interesting because it enables us to compare the experimental results with the available calculations [14].

Therefore, we chose a Ni–Co alloy as magnetic layers because Ni–Co alloy system has a single fcc structure in the whole composition range and its lattice constant is almost the same as that of Cu. By using Ni–Co alloys of different composition as a magnetic layer we can change the value of the magnetic moment without remarkably changing the film structure. In this report we investigate the composition dependence of GMR and ILEC in Ni–Co/Cu multilayer systems and discuss the role of magnetic atoms at the interface for GMR and ILEC.

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* Corresponding author.

[1] Present address: Department of Material Engineering and Applied Chemistry, Akita University, Akita 010, Japan.

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2. Experimental procedure

We have chosen Ni_xCo_{100-x} ($x = 0$, 30, 50, 70, 80, 90 and 100) and Cu as magnetic and nonmagnetic layers, respectively. Samples were prepared by magnetron sputtering (rf for Ni–Co and dc for Cu) at an argon pressure of 15 mTorr on a water cooled glass substrate. The deposition rates were 1 and 2 Å/s for Ni–Co alloy and Cu, respectively. The thickness of a Ni–Co layer was fixed to 15 Å, while that of Cu was varied from 5 to 40 Å. The structure of samples was studied by X-ray diffraction (Cu-Kα) at both low and middle angle regions. The magnetization curves were measured by VSM with magnetic fields ranging up to 16 kOe. The magnetoresistance measurement was performed by the dc four terminal method at room temperature with magnetic fields ranging up to 20 kOe applied parallel and perpendicular to the direction of a current in the film plane. The MR ratio was measured in a parallel configuration. The value was a few percent smaller than that measured in the perpendicular configuration due to an anisotropic magnetoresistance.

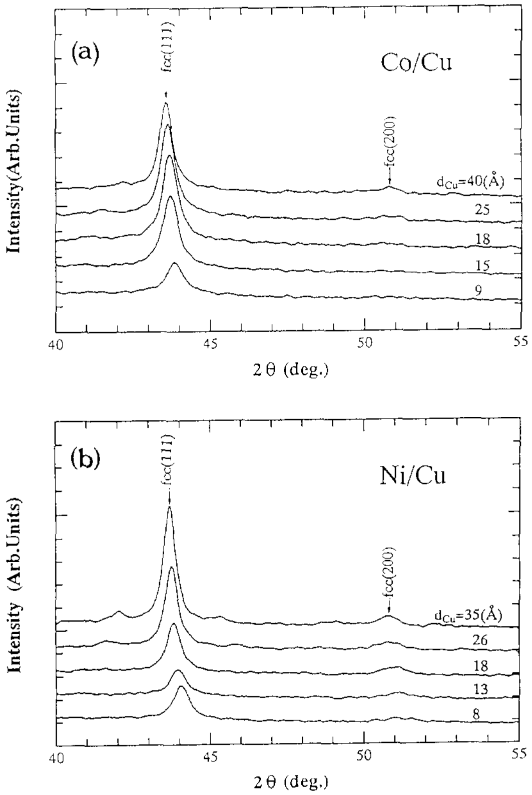

Fig. 1. X-ray diffraction patterns of Co/Cu and Ni/Cu multilayers. The thickness of magnetic layers is 15 Å and bilayer number is 30 in every sample. The thickness of Cu layers (d_{Cu}) is noted in the figure.

3. Results and discussion

3.1. Film structure

Fig. 1 shows the middle angle X-ray diffraction patterns of Co/Cu (a) and Ni/Cu (b) multilayer systems. As seen in the figure the fcc (111) peak lies between the peak position of bulk Cu (43.3°) and that of bulk Ni (44.5°) or fcc Co (44.3°), and we can not distinguish individual peaks for bulk Cu and Ni or Co. With increasing Cu thickness the peak position shifts to lower angle. For example in Co/Cu systems the peak position is 43.9° for 9 Å Cu thickness and 43.5° for 40 Å Cu thickness. The intensity ratio $I(200)/I(111)$ is almost independent of Cu thickness, and there are not any oscillation as reported for $Ni_{80}Fe_{20}$/Cu multilayers [14]. The diffraction patterns of other Ni–Co/Cu multilayers were nearly the same as those shown in Fig. 1.

In the low angle X-ray diffraction, the first and the second peaks due to the superlattice were observed for higher Co concentrations. However, with increasing Ni concentration the intensity of the first peak became weak and the second peak disappeared. This is because an atomic form factor of Ni is almost the same as that of Cu [16], and also that Ni has a better solubility than Co in a Cu matrix [17]. However the interface roughness may also reduce the intensity; a more detailed analysis of interface structure has to be made.

3.2. Composition dependence of GMR

Fig. 2 shows the MR ratio ($\Delta\rho/\rho_s$) as a function of Cu thickness for all the Ni–Co/Cu multilayer films. Here $\Delta\rho$ is the resistivity change with applied magnetic field and ρ_s is the saturated resistivity. Three peaks are clearly observed in most of the multilayers with Co/Cu being an exception. The variation of the MR ratio as a function of Cu thickness in all the compositions is very similar to the results obtained for Co/Cu by Mosca [3] or by Parkin [18]. We also measured the magnetic hysteresis loops for these multilayer films. The samples corresponding to the large MR ratio in every composition exhibited a small remanent magnetization, while those corresponding to the small MR ratio a large remanent magnetization. The ratio of M_r/M_s (M_r: remanent magnetization, M_s: saturation magnetization) for the former and the latter samples were about 0.2 and 1.0, respectively. Therefore, the magnetization of adjacent magnetic layers of the samples corresponding to the MR peaks were considered to be coupled antiferromagnetically.

Fig. 3 shows the value of MR ratio at three peaks as a function of Ni–Co composition. The data reported by other groups are also plotted in the figure [18–20]. The MR ratio increase with increasing Co content of magnetic layers. The values are 54 and 5.8% for Co/Cu and Ni/Cu, respectively. ρ_s of multilayer films exhibited a maximum at $Ni_{70}Co_{30}$ and the values were 20, 30 and 25 (μΩ · cm) for Co/Cu, $Ni_{70}Co_{30}$/Cu and Ni/Cu, respectively at the Cu thickness being about 9 Å. The composition dependence of ρ_s for multilayer films is very similar to that of Ni–Co bulk alloys [21], where resistivity exhibited a maximum at 90 at% Ni. On the other hand, the $\Delta\rho$ exhibited a maximum at $Ni_{30}Co_{70}$ and the values were 10, 13 and 1.5 (μΩ · cm) for Co/Cu, $Ni_{30}Co_{70}$/Cu and Ni/Cu, respectively. These aspects result in a rapid decreasing of MR ratio with increasing Ni concentration.

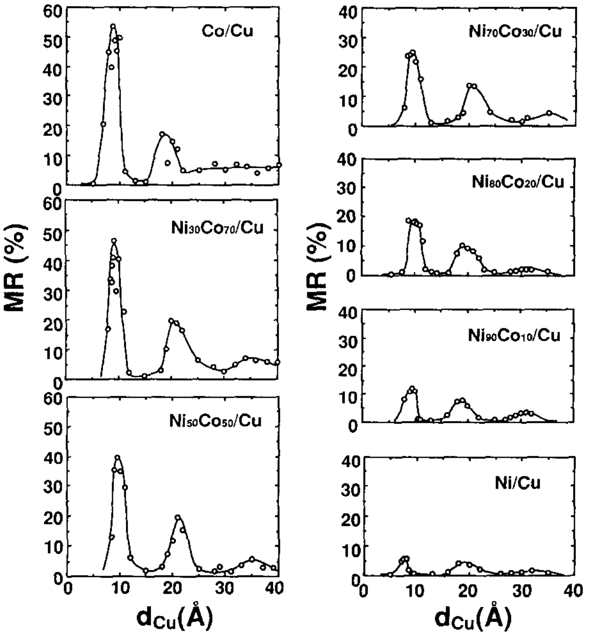

Fig. 2. The oscillation of the MR ratio as a function of Cu thickness for all the Ni–Co/Cu multilayers.

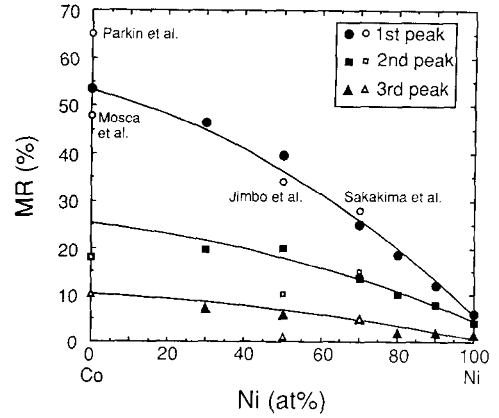

Fig. 3. The composition dependence of the MR ratio for Ni–Co/Cu multilayers. The closed symbols represent our data and the open ones represent those of other groups.

Fig. 4 shows the MR ratio at the first peak as a function of the electron number of the magnetic alloys. In this case it should be noted that the value of the MR ratio is defined as $\Delta\rho/\rho_0$, where ρ_0 is the resistivity at zero magnetic field. Other experimental results [18–20,22–24] and a theoretical prediction [14] are also plotted for comparison. The MR ratio exhibits a maximum at an electron number of about 27, which agrees qualitatively with theory. Therefore, the spin dependent scattering of conduction electron by the magnetic atoms at the interface can be considered as the origin of GMR in Ni–Co/Cu multilayer films [14]. The discrepancy of the absolute value of the MR ratio between experiment and theory is due to the experiment being carried out at room temperature, and ρ_0 contained the resis-

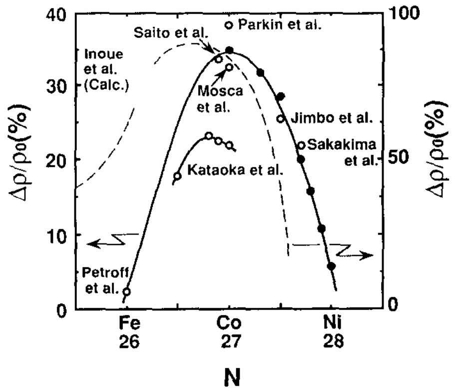

Fig. 4. The variation of $\Delta\rho/\rho_0$ as a function of the electron number of the magnetic layer. The solid line is a guide for the eyes and the dashed line is the calculated result from Ref. [13].

tivity due to phonon and magnon scattering. Furthermore, the calculation only considered interface scattering and neglected the bulk scatterings due to phonon, magnon and lattice defects which exist in actual multilayer films.

3.3. Composition dependence of interlayer exchange coupling

Fig. 5 shows the saturation magnetic field H_s as a function of Cu thickness. Here H_s is evaluated from the MR vs. magnetic field curve. As seen in the figure, H_s oscillates with increasing Cu thickness for the samples of $x = 70$–100, and three peaks are observed clearly. On the other hand, for the samples of $x \leqslant 50$ only the first peak is observable and H_s increases slightly with increasing Cu thickness of more than 20 Å. This result is consistent with the Cu thickness dependence of the MR ratio shown in Fig. 2. In the case of the MR ratio the oscillation is clearly observed for the samples of $x = 70$–100. However, for the samples of $x \leqslant 50$, the background value increases with increasing Cu thickness in addition to the oscillation value. The reason for the increase of background of MR and H_s may be considered as follows. When the magnetic properties of each magnetic layers are different, a difference of coercivity gives rise to an antiparallel state of magnetization for adjacent magnetic layers in the magnetization process. With increasing Cu thickness both ferro- and antiferromagnetic interlayer coupling decrease. The magnetization of each magnetic layers behave independently. Therefore, the magnetoresistance was induced at coercive field [25–27] and the MR ratio increases gradually with increasing Cu thickness. The reason why the magnetic properties of the layers differ only for the samples of $x \leqslant 50$ is not clear at present.

Fig. 6 shows the saturation magnetic field H_s at two peaks as a function of Ni–Co composition. The values at the first peak increase with increasing Co content and they are 4.5 and 0.8 kOe for Co/Cu and Ni/Cu, respectively. On the other hand, the values at the second peak are almost constant in the whole composition range and are about 0.2 kOe.

From H_s and the saturation magnetization of magnetic layers, we can evaluate the strength of interlayer exchange coupling J by using the following equation:

$$J = M_s \cdot H_s \cdot d/4, \tag{1}$$

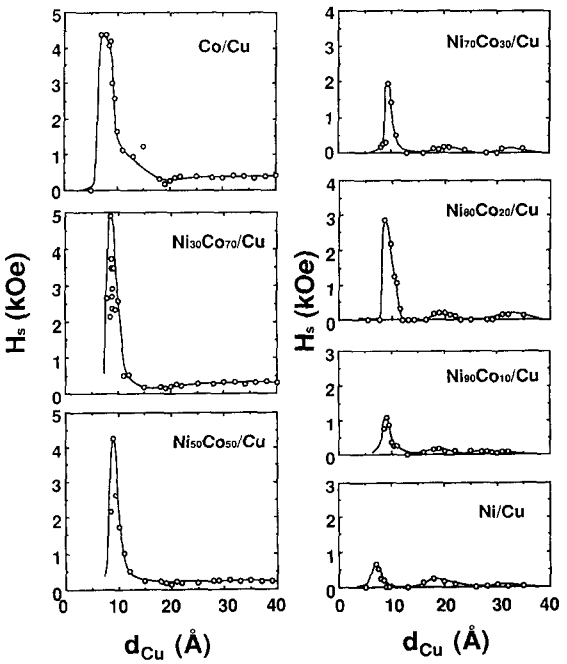

Fig. 5. The oscillation of saturation field as a function of Cu thickness for all the Ni–Co/Cu multilayers.

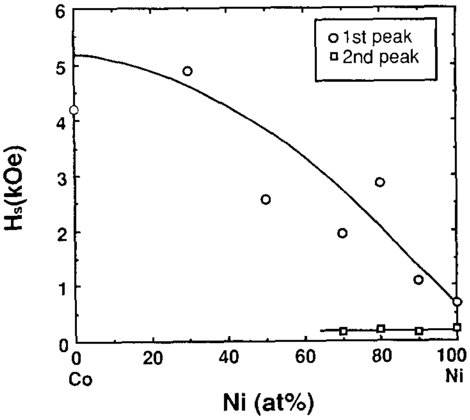

Fig. 6. The composition dependence of saturation fields for Ni–Co/Cu multilayers.

where d is the thickness of the magnetic layer [1]. The J value at the first peak increased significantly with increasing Co content and the values were 0.23 and 0.02 erg/cm^2 for Co/Cu and Ni/Cu, respectively. For Co/Cu multilayer the present J value was as large as the one reported for a sputtered sample [4] but much smaller than the one reported for a MBE grown sample [9,28]. The coupling strength is strongly affected by the method of preparation because the mixing at the interface reduces the coupling strength [29].

In the present study, samples were prepared under the same sputtering condition, and the preferred crystal orientation of the films are almost the same. Therefore, the magnetization of a magnetic layer can be assumed as one of the most important parameters in defining the strength of ILEC in this case. Fig. 7 shows the J value as a function of magnetization of the magnetic layer. Data reported by other groups are also plotted for comparison [4,11,23,24]. The values are roughly proportional to the square of magnetization in Ni–Co/Cu multilayer system. The fact does not contradict the theoretical prediction which is based on RKKY theory [29]. A more detailed study must be performed if we are to clarify the relationship between ILEC and interface mixing. The crystal orientation and the interface structure of multilayers will have to be controlled more precisely.

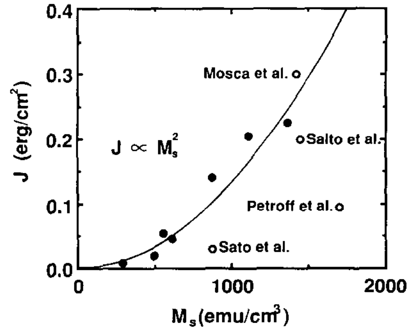

Fig. 7. The variation of the J value as a function of saturation magnetization of magnetic layers in the multilayer. The solid line represents the square of the magnetization of magnetic layers.

4. Summary

The Ni–Co/Cu multilayer films were prepared by sputtering and the giant magnetoresistance and the interlayer exchange coupling were investigated as a function of composition of magnetic layers. The results can be summarized as follows. (1) Samples had a weakly preferred fcc(111) orientation. (2) The oscillation of the MR ratio was observed as a function of Cu thickness and three peaks were observed in almost every composition. The MR ratio reached 54 and 5.8% for Co/Cu and Ni/Cu, respectively. The composition dependence of MR ratio agrees qualitatively with the theoretical prediction. (3) An oscillation of the saturation field was also observed as a function of Cu thickness especially in higher Ni concentration. The antiferromagnetic coupling strength J at the first peak was proportional to the square of the saturation magnetization of magnetic layers.

5. Acknowledgements

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