Magnetic properties and magnetoresistance effect in Co/Au, Ag nano-structure films produced by pulse electrodeposition

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We have investigated the relationship between the magnetism and the magnetoresistance effect in the Co/Au, Ag multilayer films with layers produced in the atomic level by pulse electrodeposition method. The magnetoresistance effect is dependent on both the thickness of Co ferromagnetic layer and Ag, Au non-magnetic layers. The magnetization of these films shows the minimum value against the Ag and Au layer thickness. The Ag and Au layer thickness showing the maximum of MR ratio is not of necessary in agreement with the Ag and Au layer thickness showing the minimum of magnetization. Antiparallel alignment of magnetic spin is a necessary but not sufficient condition in order to generate the GMR of multilayer films. For the Co/Au multilayer films, the Au layer thickness showing the minimum of the magnetization shifts to higher side of the Au layer thickness.

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1 Introduction
The studies on the physical properties of the nano-ordered multilayer films have attracted much attention not only in the fundamental physics, but also in electronic engineering. The productions of multilayered films have been attempted actively by the several methods. Though the electrodeposition is not by no means easy to find a suitable condition for deposition, it has a significance as a useful means to prepare the nano-ordered thin films, even if the suitable deposition condition could be established successfully. Furthermore, it becomes a very useful method for the development of the research in nano-ordered multilayered films with the combination of ferromagnetic and non-magnetic layers, which shows the giant magnetoresistance effect [1–3]. It is possible to control the film composition, thickness of multilayer and grain size in an atomic order by regulating the pulse amplitude and width [4–7]. If the pulse width of deposition time to produce multilayers is reduced to very small values, the multilayer film with layers of two different atomic compositions eventually results in a binary alloy of solid solution type mixed in the atomic level.

In this present work, we have investigated the relationship between magnetism and magnetoresistance effect in the Co/Au, Ag films with layers produced in the atomic level by pulse electrodeposition method.

2 Experiments
The electrolytic bath for Co/Ag multilayer film deposition was composed of CoSO₄ ⋅ 7H₂O, AgI, KI and that for Co/Au multilayer film deposition was composed of CoSO₄ ⋅ 7H₂O, K₂Au(CN)₄₂⁻, Na₃C₆H₅O₇ ⋅ 2H₂O, NaCl. The substrates were 150 Å copper thin films vapor deposited on glass plates. The multilayer films were deposited using a square pulse wave of current density range 0.1–25 mA/cm². The composition of the deposited films was determined by atomic absorption spectroscopy.

The ferromagnetic layer was Co-rich, which composition in Co/Ag and Co/Au multilayer films was 92 at%Co–8 at%Ag and 95 at%Co–5 at%Au, respectively. The MR ratio using a dc four probe method

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was measured under magnetic field up to 21 kOe. The magnetic properties were investigated using a VSM (Vibrating Sample Magnetometer).

3 Results and discussion Figure 1(a) shows the Ag layer thickness dependence of MR ratio at the magnetic field of 21 kOe for the Co/Ag multilayer films. The MR ratio shows the maximum value against the Ag layer thickness, and the layer thickness of Ag shifts slightly to higher thickness of Ag layer with increasing Co layer thickness. The experimental results, shown, are the average of more than two measurements. The similar tendency is observed in the Co/Au multilayer films as shown in Fig. 2(a).

Figure 1(b) shows the Co layer thickness dependence of MR ratio rearranged from these results of Ag dependence of Fig. 1(a). The additional experimental data have been included in the figure. The MR ratio shows the maximum value against the Co layer thickness, and the maximum MR ratio and the Co layer thickness showing the maximum MR ratio increases with increasing the Co and Ag layer thickness up to Ag layer thickness of 15 Å. The experimental results observed in Co/Au multilayer films have similar tendencies as shown in Fig. 2(b).

For the Ag layer thickness of 20 Å or higher than 15 Å, the value of the maximum MR ratio decreases and the Co layer thickness showing the maximum shifts very slightly toward the lower side of Co thickness. The reason for shifting toward lower side of Co thickness showing the maximum of MR for the
higher thickness of non-magnetic layer (Ag, Au: 20 Å) is seemed to be as follows. Since the antiferromagnetic coupling interaction, i.e., the interaction of antiparallel alignment of the spin between the ferromagnetic layers adjacent to non-magnetic layer reduces for the higher thickness of non-magnetic layer, the weak ferromagnetic coupling interaction corresponding with the lower thickness of Co layer in the ferromagnetic layer satisfies the condition in order to produce the antiparallel alignment of the spin.

The reason for the shifting of lower side in Co layer thickness showing the maximum of MR ratio for the lower thickness of the non-magnetic layer (Ag, Au: 5 Å) is seemed to be the following.

a) Since the ferromagnetic layer adjacent to non-magnetic layer becomes to be continuous for the lower thickness in an atomic scale of non-magnetic layer and higher thickness of ferromagnetic Co layer, the MR ratio decreases due to increase in the ferromagnetic region not showing antiparallel alignment of the spin.

b) On the other hand, as the ferromagnetic layer adjacent to non-magnetic layer becomes to be discontinuous for the lower Co and non-magnetic layer thickness in an atomic scale, the MR ratio increases due to the increase in the region of antiparallel alignment. Therefore the layer thickness shifts toward lower side of Co layer thickness.

Figures 3 and 4 show the magnetization of Co per weight of Co contained in the Co-rich ferromagnetic layers plotted as a function of Ag and Au layer thickness for the constant layer thickness of Co at the magnetic field of 1 kOe. If the magnetization of Co ferromagnetic layer is independent on the non-magnetic layer, the magnetization of Co per weight should be same value even the variation of the Ag or Au thickness. The width of decrease in the magnetization against the layer thickness of Au for the higher layer thickness of Co 20 Å shows small value as expected, since there is weak interaction between the ferromagnetic layers as shown in Fig. 4. The magnetization has a tendency to show the minimum with decreasing the Co layer thickness. The minimum of magnetization is near the non-magnetic layer thickness of 20 Å for the Co thickness of 10 Å in Co/Ag films and Co thickness of 15 Å in Co/Au films. The magnetization becomes to decrease remarkably with decrease in Co layer thickness, and the layer thickness showing the minimum shifts toward the lower side of Au layer thickness for the Co/Au films. The fluctuation of magnetization in the region of larger Au layer thickness for the thinner Co films is larger than those of higher thickness of Co. The reason of the remarkable decrease in the magnetization with decrease in the Co layer thickness is seemed to be that the magnetism of the Co layer liable to be influenced greatly by the surrounding Au atom, as Co layer thickness decrease further. The layer thickness showing the decrease of the magnetization is in good agreement with the non-magnetic layer thickness showing the maximum of MR ratio, for the [Co10Å/Ag], and [Co15Å/Au] films. (This tendency is further described later in Fig. 5).
The non-magnetic layer thickness showing the minimum of the magnetization has a tendency to be not of necessary in agreement with the larger thickness showing the maximum of the MR ratio with decrease in Co layer thickness. Where, the arrow mark shown in Fig. 3 and Fig. 4 corresponds with the thickness showing the maximum of MR ratio in Fig. 1(a) and Fig. 2(a). Such a tendency is almost in agreement with our previous result measured for the Co/Cu multilayer films [7]. The reason seems to be that the origin to give the large MR ratio is different with the origin for the decrease in the magnetization. The MR ratio strongly depends on the antiparallel alignment of the magnetic spin between the Co ferromagnetic layers, however, the magnitude of the magnetization is apt to be influenced greatly by the crystal structure of Co, particle size and the surrounding effect due to the presence of Au atoms in the neighbourhood.

Figures 5(a) and (b) shows the correlation of the magnetization and the MR ratio for the [Co10Å/Ag]50 and [Co15Å/Au]50 multilayer films, that is, it seems to be that the magnetization is closely related to the MR ratio for these Co/Au and Co/Ag multilayer films. The results shown in this figure suggests that the antiparallel alignment of the magnetic spin between the adjacent ferromagnetic layers is very important in order to produce the large MR ratio.

![Fig. 5](image_url)  
*Fig. 5* The relationship between the magnetization (in Fig. 3 and Fig. 4) and the MR ratio (in Fig. 1 and Fig. 2) for (a) the [Co10Å/Ag] and (b) the [Co15Å/Au] films.

**References**