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# Periodic Structure and Magnetic Properties of Multiple-structure Multilayered Co/Au Films

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Multiple-structure multilayered Co/Au films (MSM Co/Au films) were fabricated in order to improve the magnetic properties of Co/Au films further. MSM Co/Au films has the structure which inserted a Au thin film layers in the uniformly space of Co/Au films, and the layered structure will be shown as following; $[(Co/Au)_n/Au]_m$. It was analyzed by X-ray diffraction (XRD), vibrating sample magnetometer (VSM), and extended 3-step model profile fittings to understand structure and magnetic property changes of MSM Co/Au films. The annealing effect of MSM Co/Au films was also examined. Coercivity and squareness ratio of MSM Co/Au films increased, while the Au thin film layers thickened. The perpendicular magnetic anisotropy of MSM Co/Au films showed the value that was higher than Co/Au films, and it increased with the annealing. This time, the mixed layer in the interface was decreased from the result of extended 3-step model profile fittings, since Co-Au is a eutectic system. These improvement of the magnetic properties observed in MSM Co/Au films seems to be the underlayer effect with the Au thin film layers.

**Key words:** multiple-structure multilayered Co/Au film, magnetic property, perpendicular magnetization

## 1. INTRODUCTION

Co/Au films have new functions such as perpendicular magnetization and GMR, and the application to high-density magnetic recording medium in the next generation is expected [1]. Though Co/Au films have the magnetic properties that the conventional material does not contain, and it has also remained on improving point. Then, MSM Co/Au films were newly fabricated by multiplexing Co/Au films for improving the magnetic properties. In our study by the present, it has been confirmed that the magnetic property is improved by obtaining the multistage shape magnetization curve on MSM Co/Pd films [2]. Therefore, it is predicted that the magnetic properties will similarly improved even in MSM Co/Au films with MSM Co/Pd films.

In this paper, the relevance to periodic structure and magnetic properties of MSM Co/Au films is reported. The annealing effect of MSM Co/Au films is also reported.

## 2. EXPERIMENTAL

MSM Co/Au films were fabricated by the dual source RF magnetron sputtering equipment. It was sputtered in $1\times10^{-4}$ Pa vacuum. Ar was used for the sputtering gas, and the gas pressure was 0.4 Pa. Table I shows the layered structure of MSM Co/Au. In table 1, the stacking number is equal for MSM-1 and MSM-2, and it is the sample in which only the Co layer thickness changed. MSM-3 is the sample in which stacking number (X, Y) changed. MSM-4 fixed the stacking number of Co/Au with 3 times, and it is the sample in which Au thin film layers and whole stacking number (Au, Z) changed. The magnetization curve was measured by VSM, and the structure analyses were carried out by XRD. Using the Cu target, XRD was measured between the scanning field of 1.3-15 deg (low angle region) and 30-50 deg (high angle region). The profile fitting method was used in the analysis of the interfacial structure. In the low angle region, the optical thin film model was used, and in the high angle region, extended 3-step model was used.

**Table I.** Layered structure of MSM Co/Au films.

| Sample | Layered Structure/nm $[(Co/Au)_n/Au]_m$ |
|---|---|
| MSM-1 | $[(0.8/5.4)_3/1.0]_{20}$ |
| MSM-2 | $[(1.4/5.4)_3/1.0]_{20}$ |
| MSM-3 | $[(0.8/5.4)_X/1.0]_Y$ |
| MSM-4 | $[(0.8/5.4)_3/\mathbf{Au}]_Z$ |

## 3. RESULTS AND DISCUSSION

### 3.1 Periodic structure and magnetic property

MSM Co/Au films has the structure which inserted a Au thin film layers in the uniformly space of Co/Au films, and the layered structure will be shown as following; $[(Co/Au)_n/Au]_m$. The multiple structure contains two periodic thickness $\Lambda_M$ and $\Lambda_T$. $\Lambda_M$ is the periodic thickness of multilayered Co/Au films part in multiple structure, that is, $\Lambda_M$=[Co/Au]. $\Lambda_T$ is the periodic thickness of multiple structure, and it contains a Au thin film layer, that is, $\Lambda_T$=[(Co/Au)$_n$/Au]. MSM Co/Au films showed the perpendicular magnetization that was strong as well as Co/Au films.

MSM-3 is the samples that only the stacking number X and Y changed by fixing of each layer thickness. Regardless of the stacking number, all samples of MSM-3 showed the strong perpendicular magnetization. Fig 1 showed the magnetization curve of MSM-1 and MSM-2. Fig 1-(a) showed the magnetization curve as Co layer thickness was 0.8 nm, and the perpendicular magnetization was observed. Fig 1-(b) showed the magnetization curve as Co layer thickness was 1.4 nm, and the in-plane magnetization was observed.

Therefore, the perpendicular magnetization of MSM Co/Au was dependent only on Co Layer thickness regardless of the stacking number. Though the perpendicular magnetization was shown, when Co layer thickness kept to some extent thinness, it tended to lose the perpendicular magnetization, when Co layer thickness thickened.

### 3.2 Magnetic properties with Au thin film layer

Structural features of MSM Co/Au films are to pile Au thin film layers between multilayered Co/Au films. MSM-4 is the samples in which only Au thin film layers and stacking number Z changed by the fixation of multilayered Co/Au films. The change of the coercivity with film thickness of Au thin film layers was shown in Fig 2. It is usual Co/Au films that the value of Au thin film layer thickness show 0 nm. The coercivity increased, when Au thin film layers thickened.

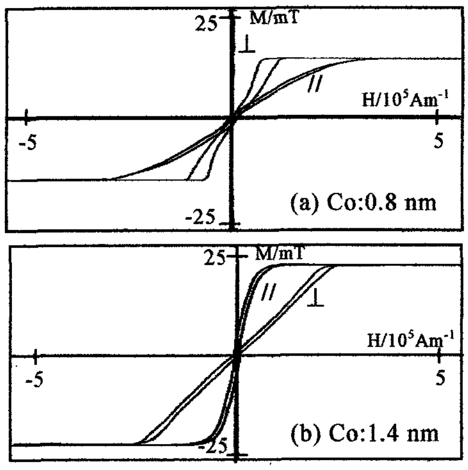


**Fig 1.** Magnetization curve with Co layer thickness.

The existence of Au thin film layers was made to increase coercivity. It seemed to generate the increase of coercivity, since the underlayer for multilayered Co/Au films increased as Au thin film layers thickened. These underlayer effect was observed in the study of MSM Co/Pd films [2]. From the study of MSM Co/Pd films, the result which the coercivity increased with that underlayer is thick was obtained. The effect similar to MSM Co/Pd films seemed to occur on MSM Co/Au films. The change of the squareness ratio with film thickness of Au thin film layers was shown in Fig 3. The squareness ratio is a ratio of residual magnetization to saturated magnetization. It is usual Co/Au films that the value of Au thin film layer thickness show 0 nm. The squareness ratio increased, when Au thin film layers thickened, and finally showed the maximum value. Generally, the squareness ratio increases in the thin multilayered films. However, the squareness ratio increased in the sufficiently thick film thickness on MSM Co/Au films. It seems to occur the increase of the squareness ratio as the result that held and stabilized multilayered Co/Au films by Au thin film layers.

### 3.3 Annealing effect and interfacial structure

Figure 4 shows the perpendicular magnetic anisotropy with annealing. In MSM Co/Au films, the perpendicular magnetic anisotropy once increased with annealing, and it decreased afterwards. The perpendicular magnetic anisotropy in which MSM Co/Au films higher than Co/Au films was obtained. The profile fittings were performed in order to examine the interfacial structure with the increase in the perpendicular magnetic anisotropy. The profile fitting method is a means for analyzing the behavior of atomic layers from the comparison of XRD measured peaks and calculated peaks of the calculation model. To begin with, the periodic thickness was decided from the profile fittings in the low angle region by the optical thin film model considering the multiple scattering [3].

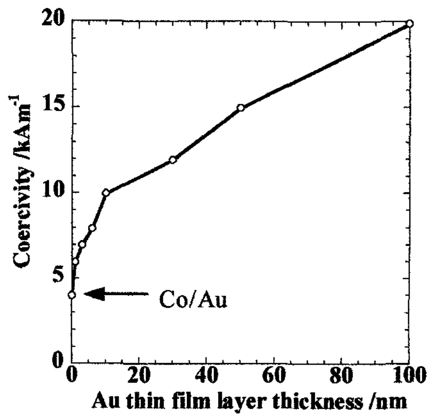


**Fig 2.** Coercivity with the Au thin film layers.

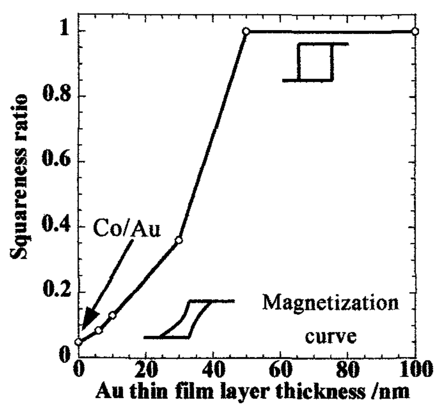


**Fig 3.** Squareness ratio with the Au thin film layers.

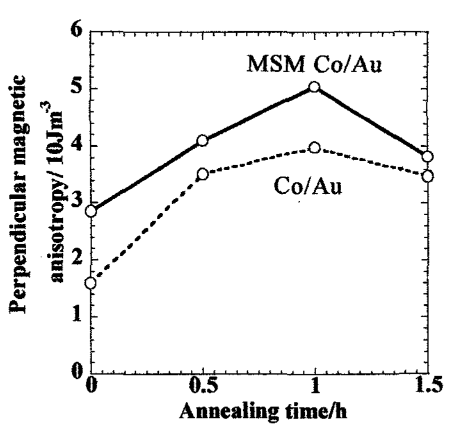


**Fig 4.** Perpendicular magnetic anisotropy with annealing.

Using the value of this periodic thickness, the interfacial structure was analyzed from the profile fittings in the high angle region. In this study, the extended 3-step model considering two fluctuations was used in the high angle region. Fig 5 shows the schematic view of the extended 3-step model. The first fluctuation was generated from the lattice spacing of mixed layers, and it was assumed $\Delta\Lambda_M$ of the periodic thickness $\Lambda_M$. The second fluctuation was generated with $\Delta\Lambda_M$, and it was assumed $\Delta\Lambda_T$ of the periodic thickness $\Lambda_T$. It was also assumed that the Au thin film layers do not fluctuate. The XRD intensity I(Q) is expressed as the following equation by using Laue function $L_T(Q)$ and layer structure factor $F_T(Q)$, since $F_T(Q)$ contains two fluctuations.

$$I(Q)=L_T(Q)\ \langle F_T(Q)F_T^*(Q)\rangle \tag{1}$$

It has been reported that the Laue function is given by the following equation when the periodic thickness $\Lambda_T$ fluctuates around the average $\Lambda'_T$ with a Gaussian distribution function $\exp[-(\Lambda_T - \Lambda'_T)/\sigma_T^2]$ [4].

$$\langle L_T(Q)\rangle = \frac{1+\exp[-N_T\sigma_T^2Q^2/2]-2\exp[-N_T\sigma_T^2Q^2/4]\cos[N_T\Lambda'_TQ]}{1+\exp[-\sigma_T^2Q^2/2]-2\exp[-\sigma_T^2Q^2/4]\cos[\Lambda'_TQ]} \tag{2}$$

The layer structure factor $\langle F_T(Q)\rangle$ is expressed as the following equation, since the layer structure factor of multilayered Co/Au films $F_M(Q)$ contains fluctuation $\Delta\Lambda_M$ while the layer structure factor of Au thin film layers $F_{Buf.}(Q)$ do not fluctuate [5].

$$\langle F_T(Q)\rangle = F_{Buf.}(Q) + \langle F_M(Q)\rangle \tag{3}$$

Here, $F_{Buf.}(Q)$ and $\langle F_M(Q)\rangle$ is expressed as the following equation respectively.

$$F_{Buf.}(Q) = f_{Buf.}(Q)\exp\left[i\frac{n_{Buf.}d_{Buf.}}{2}Q\right]L^{\frac{1}{2}}_{Buf.}(Q) \tag{4}$$

$$\begin{aligned}\langle F_M(Q)\rangle = \exp(i\Lambda_BQ)L_M(Q)\Big\{ & f_A(Q)\exp\left[i\frac{n_Ad_A}{2}Q\right]L^{\frac{1}{2}}_A(Q) \\ & + f_C(Q)\exp\left[i(n_Ad_A+\frac{n_Cd_C}{2})Q\right]L^{\frac{1}{2}}_C(Q) \\ & + f_B(Q)\exp\left[i(n_Ad_A+n_Cd_C+\frac{n_Bd_B}{2})Q\right]L^{\frac{1}{2}}_B(Q) \\ & + f_C(Q)\exp\left[i(n_Ad_A+n_Cd_C+n_Bd_B+\frac{n_Cd_C}{2})Q\right]L^{\frac{1}{2}}_C(Q)\Big\}\end{aligned} \tag{5}$$

where

$$Lx(Q) = \frac{\sin^2(n_xd_xQ/2)}{\sin^2(d_xQ/2)} \qquad (x = A, B, C, \text{and Buf.}) \tag{6}$$

$$\langle L_M(Q)\rangle = \frac{1+\exp[-N_M\sigma_M{}^2Q^2/2]-2\exp[-N_M\sigma_M{}^2Q^2/4]\cos[N_M\Lambda'_MQ]}{1+\exp[-\sigma_M{}^2Q^2/2]-2\exp[-\sigma_M{}^2Q^2/4]\cos[\Lambda'_MQ]} \tag{7}$$

The atomic scattering factor, lattice spacing, and number of atoms is expressed by $f_X$, $d_X$, and $c_X$ respectively, where X= Buf., A, B and C.

The profile fitting in the low angle region decided the periodic thickness $\Lambda_M$:29, and $\Lambda_T$:33 [6]. The profile fitting in the high angle region decided the each atomic plane as follows; Co layers:2, Au layers:23, and mixed layers:2. Fig 6 shows the profile fittings after annealing in the high angle region. The mixed layers became 1 atomic plane, and it decreased further than the condition before the annealing. It is because mixed layers in the interface decreased with annealing, as Co and Au are a eutectic system. The annealing eased the disorder, and the layer structure was made to be an ideal condition. Therefore the perpendicular magnetic anisotropy increased. However, the separation of Co and Au was promoted after long annealing, and the perpendicular magnetic anisotropy was reversely decreased.

## 4. CONCLUSION

MSM Co/Au films showed the perpendicular magnetic anisotropy that was higher than Co/Au films.

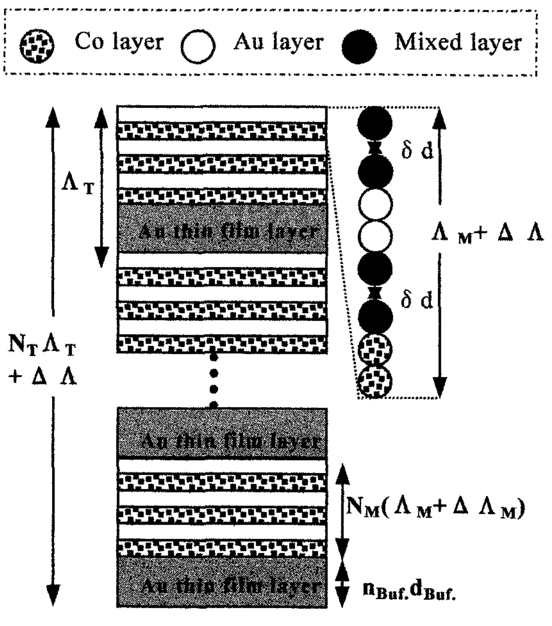


**Fig 5.** Schematic view of the extended 3-step model.

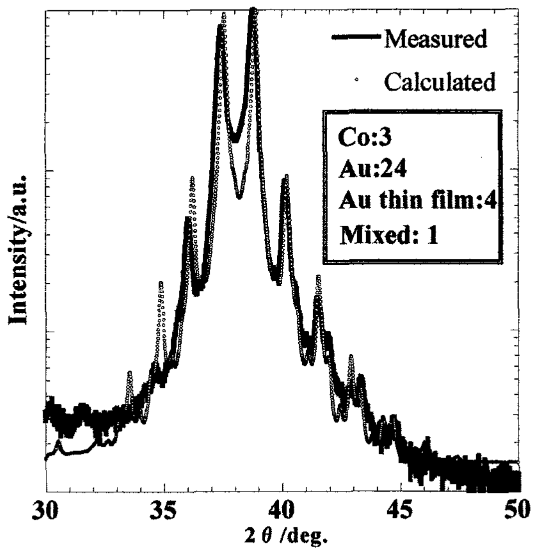


**Fig 6.** Profile fitting by the extended 3-step model in the high angle region. (473 K, 1 h-annealing)

Au thin film layers made to increase both coercivity and squareness ratio. The underlayer for multilayered Co/Au films part in multiple structure increased with that the Au thin film layers thickened, and the coercivity increased. The squareness ratio also increased when the Au thin film layer thickened. As a result of holding multilayered Co/Au films by the Au thin film layers, the structure was stabilized, and the squareness ratio increased. The perpendicular magnetic anisotropy increased with annealing. The annealing eased the disorder, and the layer structure was made to be an ideal condition, since Co-Au is a eutectic system.

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