Changes in Angular Distribution of Incident Sputtered Particles in Sputter Deposition of Iron Films

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Abstract—Changes in angular distribution of incident sputtered particles on a substrate were investigated experimentally and by computer simulation. The angular distribution changes significantly with substrate position, sputtering gas pressure, and type of sputtering apparatus. The angular distribution agrees well with the results calculated by computer simulation. The change in angular distribution leads to a change in the film structure. For example, growth of elongated grains was observed in the deposition of iron films by facing target sputtering. This was qualitatively explained by computer simulation to be caused by the oblique incidence of the sputtered particles on the substrate. In addition, computer simulation indicates that an increase in the number of incident particles with high incidence angle results in the formation of porous films with columnar structure so that the control of the distribution of the incidence angle is important to obtain a magnetic thin film with desired microstructure.

I. INTRODUCTION

Control of the incident angle of deposition particles on the substrate is very important for obtaining films with desired structure and magnetic properties[1]. It is well known that the distribution of the incident angle changes with substrate position, sputtering gas pressure, type of sputtering source, etc. However, it is not clear how the distribution of the incident angle changes with the sputtering conditions and how the changes in the distribution affect the structure of the deposited films.

In this study, we investigated the changes in the film structure and angular distribution of incident particles with substrate position and sputtering gas pressure in the sputter deposition of iron films by using two types of sputtering systems (planar magnetron and facing target sputtering system). Computer simulation by the Monte Carlo method was also carried out to clarify the differences in the angular distribution of incident sputtered particles between the two sputtering systems and show how the differences in angular distribution lead to structural differences in the films.

II. EXPERIMENTAL

Figure 1 shows the sputtering systems used in this study. Planar magnetron sputtering system and facing target sputtering system with a 10 cm diameter target were used for the film deposition. Iron films were deposited on a glass slide substrate at various argon gas pressures.

In order to measure the angular distribution of the incident sputtered particles on the substrate, films were deposited on the glass slide substrate through a small aperture as shown in Fig. 2. The angular distribution of the sputtered particles was estimated from the distribution of the film thickness on the substrate as follows:

\[ D(\theta) = t \cos(\theta) \times \tan^{-1}(x/d), \]

where, \( D(\theta) \) is the amount of the incident particles on the substrate with angle \( \theta \), \( t \) is the film thickness at the position \( x \), and \( d \) is the distance between aperture and substrate.

III. SIMULATION MODEL

The process of depositing thin film by sputtering is consists of 3 steps: sputter emission, sputtered particle transport, and deposition on the substrate. Computer simulation of sputtered particle transport has been reported by several researchers [2-7]. They calculated the energy distribution and angular distribution of incident particles on the substrate along with the film thickness distribution over the substrate.

On the other hand, the effect of oblique incidence of atoms on the film structure was investigated by D. Henderson et al. [8], and A.G. Dirks et al. [9] using computer simulation. They deposited atoms on a substrate assuming the atoms to be hard spheres and to be incident...
on the substrate at a fixed angle.

In this study, Motohiro’s model [2] was used to calculate the angular distribution of incident particles on the substrate. Thompson’s energy distribution[10] and the cosine law were used to determine the energy and emission angle of each iron atom ejected from the target, respectively. In the scattering due to collision with argon gas atoms, the energy dependent collision cross section adopted by Motohiro in his calculation was used. In other words, Abrahamson’s inter-atomic potential [11] was used to calculate the collision cross section.

In order to investigate the effect of the angular distribution of incident particles on film structure, atoms were deposited on a substrate (500 x 500 x 500) in size, a: atomic diameter) assuming the atom to be hard spheres and to be incident on the substrate with the same angular distribution as calculated by the above mentioned method. In this calculation, the incident atoms are assumed to be allowed to relax to the extent that each move to the nearest position where it makes contact with two other additional atoms deposited earlier.

IV. RESULTS AND DISCUSSIONS

A. Experimental results

Figures 3 and 4 show the changes in the distribution of incident angles of deposited particles with sputtering gas pressure and position on substrate in magnetron sputtering and facing target sputtering, respectively. It is clear from the figures that the angular distribution changes significantly with sputtering gas pressure. It should be also noted that the angular distribution changes significantly with position on substrate, which may degrade the uniformity of the films over the substrate.

Besides, a comparison of the angular distributions of magnetron sputtering and facing target sputtering shows that there are many more particles which have large incidence angles above 45° in facing target sputtering.

On the other hand, the iron film deposited at an argon gas pressure around 5 mTorr by a facing target sputtering system has a unique structure as shown in Fig.5. Specifically, growth of elongated grains in the direction normal to the incident direction of the deposited particles is observed in the films. This seems to be caused by the incidence of particles with large angles as shown in Fig.4.

The film structure also changes significantly with sputtering gas pressure. The elongated grains are only observed in the films deposited at a sputtering gas pressure around 5 mTorr. This suggests that the film structure depends significantly on both the incidence angle and...
kinetic energy of the deposited particles, since the
distribution of the incidence angles and the energy of the
deposited particles should change with sputtering gas
pressure owing to collision of the particles with argon gas
atoms.

B. Simulated results

Figure 6 shows examples of the trajectories of
sputtered particles ejected from the target in (a) magnetron
sputtering and (b) facing target sputtering at various
sputtering gas pressures. As the sputtering gas pressure
increases, the trajectories of the sputtered particles become
complex because of the scattering by collision with gas
atoms.

Figures 7 and 8 show examples of the calculated
angular distribution of the incident angles of deposited
particles in the magnetron sputtering and facing target
sputtering, respectively. These results agree well with the
experimental results shown in Figs. 3 and 4. This suggests
that computer simulation is useful for obtaining the
angular distribution of the incident particles on the
substrate.

Figure 9 shows a simulated inplane atomic layer
(13th atomic layer from the bottom of the film) and a cross
section of the film in magnetron sputtering. In the

(a) magnetron sputtering
(b) facing target sputtering

Fig. 6 Calculated trajectories of sputtered particles ejected
from the target.
simulation, atoms were deposited with the angular distribution of the incident particles for a gas pressure of 1 mTorr in the magnetron sputtering. Compared with the film deposited by normal incidence of particles, the film was more porous and had a columnar structure. This is due to the presence of a large amount of particles which were incident on the substrate with large angles.

Figure 10 shows the simulated inplane atomic layer and cross section of the film deposited by facing target sputtering. In the simulation, the angular distribution of the incident particles on the substrate for the gas pressure of 2 mTorr was used. Grains elongated in the direction transverse to the incident direction are observed in the simulated layer, although the size of the grains is much smaller than that of the grains observed in the actual films shown in Fig.5. Besides, the film has a more porous structure than the film deposited by magnetron sputtering. This result indicates that the formation of the elongated grains which results in an inplane uniaxial magnetic anisotropy is mainly due to the oblique incidence of sputtered particles in facing target sputtering.

In this simulation, surface migration of the deposited atom was not taken into consideration. As a result, the self shadowing effect became more prominent. However, the change in microstructure with sputtering gas pressure and with the type of sputtering system can be qualitatively explained by the changes in the angular distributions of the incident particles on the substrate. Therefore, this computer simulation is useful for investigating how to control the microstructure of the thin film magnetic recording media and angular distribution of the deposited particles and how the angular distribution affects the film structure.

V. CONCLUSIONS

Changes in angular distribution of incident sputtered particles on the substrate was investigated experimentally and by computer simulation. The results obtained in this study can be summarized as follows:

(1) The angular distribution changes significantly with substrate position, sputtering gas pressure and type of sputtering system. This angular distribution agrees well with the results calculated by computer simulation.

(2) Computer simulation shows that growth of elongated grains observed in the iron films deposited by facing target sputtering is mainly caused by oblique incidence of sputtered particles on the substrate. It further suggests that an increase in the amount of the particles incident on the substrate with large angles results in formation of a porous film with columnar structure.

REFERENCES