Ion Implantation Effects on CoFeB Magnetic Thin Films

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Abstract - Magnetic thin film materials are used in various electronic device fields. We simulated the change of physical properties of magnetic thin film material by ion implantation and conducted experimental verification. From the simulation results, it was possible to predict the etching by ion beam, which showed a decrease in the saturation magnetization. In addition, the simulation results confirmed that atomic diffusion may occur at the interface between the magnetic thin film material and the substrate, and vacancies may occur inside the thin film material. This was shown to decrease the coercivity due to the decrease of the grain size of the magnetic thin film. As a result, the decrease in saturation magnetization was minimal due to the ion implantation, but the coercivity was reduced by more than 2 times, which may contribute to the development of low power electronic devices.

Key words : Ion implantation, Magnetic thin film, Simulation

INTRODUCTION

Soft magnetic thin film materials have been applied to various magnetoelectronic devices such as magnetic random access memory (Iwata-Harms *et al*. 2018; Zhang *et al*. 2018), data storage device (Maat *et al*. 2016), spin logic based devices (Fuji *et al*. 2018; Oh *et al*. 2019), etc. The magnetic thin film material is generally manufactured by sputtering system and its physical properties are determined by process conditions such as gas atmosphere and input power and composition of the target. Many materials having compositions such as CoFeB, FeTaN, CoNbZr and FeAlO have been studied (Fergen *et al*. 2002), and are used in a single layer or multi-layers to form a circuit together with an insulating film and an electrode (Baek *et al*. 2018; Correa *et al*. 2019). Soft magnetic thin films applied to electronic devices require high saturation magnetization, low coercivity, and high permeability. The saturation magnetization is determined by the composition of the ferromagnetic materials and the coercivity is known to depend on the grain size (Alben *et al*. 1978; Lavrijsen *et al*. 2011). In order to induce a high permeability, it is necessary to control magnetic anisotropy, which includes crystal magnetic anisotropy, shape magnetic anisotropy, and induced magnetic anisotropy.

Although the deposition method using sputtering is excellent in terms of productivity, it is limited in grain control because it is deposited in a cluster form. Radiation technologies are used in modification of thin film technologies (Oh *et al*. 2019). Ion implantation is used to strengthen the mechanical properties (Shanaghi *et al*. 2019) and control the doping concentration of semiconductors while maintaining the main properties of the material (Chen *et al*. 2018; Wong *et al*. 2019). The purpose of studying the application of ion implantation process to magnetic thin film materials is to improve the partial characteristics such as coercivity and permeability while maintaining the main characteristics such as saturation magnetization. If the physical properties of the magnetic thin film is improved through such modification, it is considered that the loss of the electronic device can be reduced and further contribute to the improvement of the physical properties through the improvement of the

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resonance frequency. Therefore, this study simulates the physical changes that occur when nitrogen ion implantation into CoFeB magnetic thin film material and analyzes the effect on magnetic properties.

EXPERIMENTAL PROCEDURE

1. Thin film deposition

Magnetic thin films with thickness of 20 nm were deposited on to a oxidized silicon wafer substrate (1.25 × 1.25 cm) using a DC magnetron sputtering system. Deposition condition was Ar atmosphere of 2 mTorr at a input power of 100 W and background pressure was less than 5×10^{-7} Torr. The composition of target was $Co_{32}Fe_{48}B_{20}$ (at%). The thickness of the thin films was controlled by deposition time and measured by an alpha step.

2. Ion implantation and simulation

Nitrogen ion implantation was carried out on magnetic thin film deposited wafer using ion implanter in Korea Atomic Energy Research Institute (KAERI). The fluence was varying from 10^{14} to 10^{16} ions·cm^{-2} with 20 keV acceleration voltage.

The effects of ion implantation were simulated using "The Stopping and Range of Ions in Matter" (SRIM) code (Ziegler *et al*. 2010). Simulation conditions were set with sample structure, top layer $Co_{32}Fe_{48}B_{20}$ (at%) with 20 nm, middle layer SiO_2 with 100 nm and bottom layer Si. Density of top and middle layer was automatically calculated, 7.09 g·cm^{-3} and 1.72 g·cm^{-3} . The effects was calculated with 99,999 ions on only in 30 nm thickness with TRIM calculation, "Damage calculation with full Damage Cascades option".

3. Magnetic properties

The magnetic properties were measured using a vibrating sample magnetometer with an applied magnetic fields, varying from −100 to 100 Oe parallel to the film plane. The saturation magnetization was calculated by magnetization (emu) values at maximum applied field dividing the sample volumes and coercivity was obtained at the inversion points of magnetization. These samples have uniaxial anisotropy characteristic in plane, easy and hard axis.

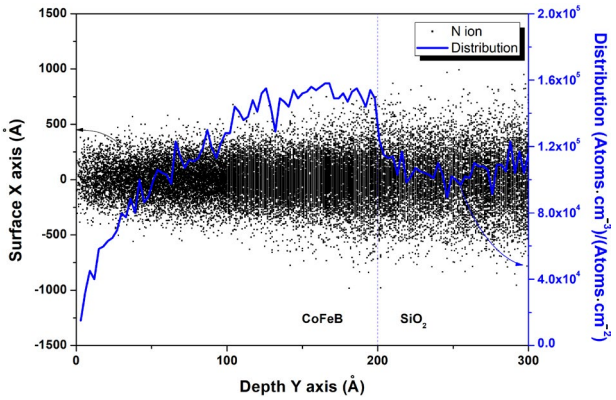

Fig. 1. Ion distribution as a function of the depth in CoFeB/SiO_2 layer.

RESULTS AND DISCUSSION

1. Ion distribution

The simulation was conducted by simulating the conditions as the ion implantation of the prepared specimen. The nitrogen ions distribution inside the specimen is shown in Fig. 1. Ion implantation proceeded in the depth direction from the 0 position of the surface. The gray dots in the figure correspond to the last positions of the ions. As it enters from the magnetic layer surface, the concentration of ions increases to saturate around 10 nm and have a constant distribution up to 20 nm as an interface. It is thought that scattering at the interface is such that the concentration of ions in the interface layer drops sharply. Although not shown in this figure, the average penetration depth of ions is 42.7 nm and can reach up to 138 nm. Thus, most of the ions are distributed in the CoFeB and SiO_2 layers and hardly reach the Si substrate.

2. Recoil atom distribution

The ion implantation causes the movement of target atoms. Recoil atoms can move into voids that can penetrate the surroundings and form vacancies, or replacement can occur by exchanging positions with surrounding atoms. This phenomenon contributes to the diffusion of atoms as shown in Fig. 2. In the simulation results, it was observed that each atom of the magnetic layer diffused into the SiO_2 layer over the interface. The penetration depth reaches approximately 2 nm and decreases exponentially. Conversely, atoms in the SiO_2 layer also diffuse toward the magnetic layer. This diffusion is considered to be due to the driving

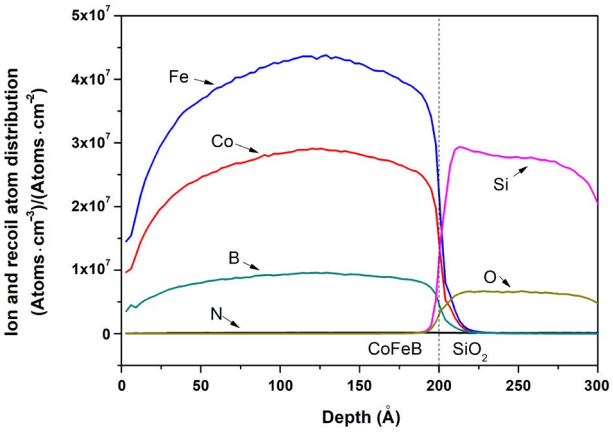

Fig. 2. Ion and recoil atom distribution as a function of the depth of CoFeB/SiO_2 layer.

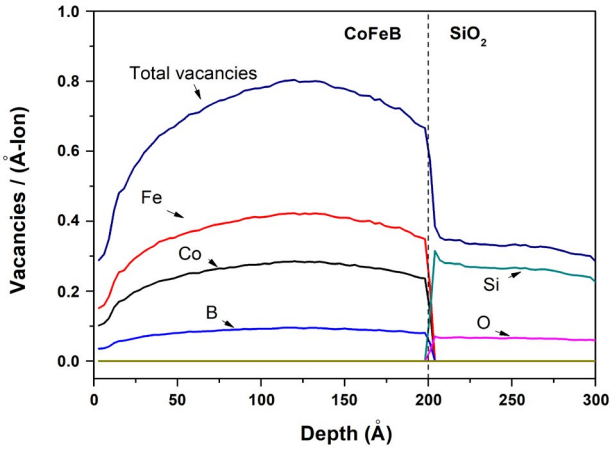

Fig. 3. Vacancy distribution of CoFeB/SiO_2 layers as a function of the depth.

force of the scattered ions in the SiO_2 layer. Therefore, the diffusion distance in the reverse direction is about 1 nm, about half that of the forward direction. At the interface, materials of complex composition will be produced by bidirectional diffusion. An oxide may be formed by diffusion of Co and Fe ions in the SiO_2 layer, and an amorphous oxide will increase around the CoFe phase in magnetic layer.

The distribution of recoil atoms in each layer shows a similar tendency to the distribution of nitrogen ions in Fig. 1. Since the power of nitrogen ions distribution is 5 in Fig. 1 and recoil atoms are 7, it can be seen that collisions with hundreds of atoms occur before the nitrogen ion stop. These results indicate that the main factor contributing to the change in physical properties of the thin film is due to the atomic diffusion rather than the effect of ion distribution.

3. Vacancy distribution

Fig. 3 shows the vacancy concentration for each element over depth. The distribution of vacancy shows similar results as the distribution of ions and the results of recoil atoms. The sum of vacancies and replacement collision is 188/ion (which is not shown in figure, identified in simulation monitoring program). Unfortunately, the simulation results do not confirm the type of vacancy such as Schottky and Fenkel defect or the formation of dislocations. It is assumed that only a number of defect concentration increases can affect grain size. As will be explained in the next section, grain size is related to the coercivity of the magnetic properties of the thin film.

4. Magnetic properties

The saturation magnetization of thin film decreases with increasing ion implantation. This is considered as a result by the surface etching of a thin film. In the simulation, the etching rate of each element of the magnetic thin film is Co: 0.43, Fe: 0.65 and B: 0.12 atoms·ion^{-1}. Considering that the composition of the magnetic thin film, the etching rate of Co and Fe depends on the composition. However, B has a lower etching rate than the other two elements. As a result, the composition of B may be relatively increased on the surface. This change in composition is a very small difference that is not enough to affect the magnetic properties. Removal of CoFe from the surface leads to lower saturation magnetization as shown in Fig. 4. Numerically, the magnetization value 13,400 emu·cm^{-3} of the pristine sample is reduced by 3.4% to 12,950 emu·cm^{-3} by 10^{16} ion·cm^{-2} ion implantation. This is expected to cause a thickness reduction approximately 0.67 nm, but this is not a measurable value at the level of several atom layers. Nevertheless, one of the important information from the simulation results is that it can explain the decrease in saturation magnetization and create uneven surface composition changes between CoFe and B.

Fig. 5 shows the coercivity obtained from the magnetic hysteresis curve according to the ion implantation. The coercivitiy decreased by ion implantation up to 10^{15} ion·cm^{-2}, which is thought to be the result of the increase in vacancies described above. The effect of grain size on the coercivity of the magnetic thin film is explained by the random anisotropy model (Alben *et al*. 1978). In the proposed model, the

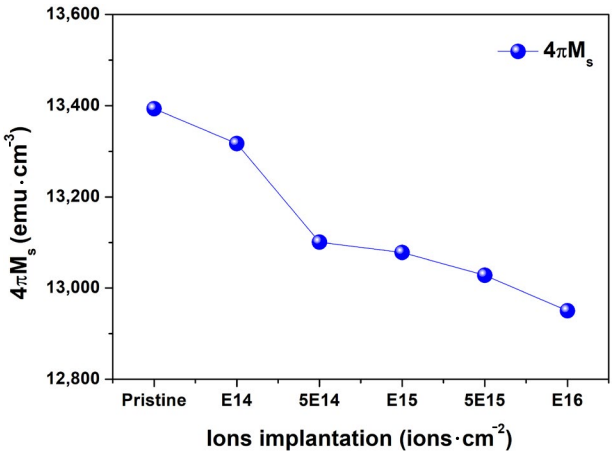

Fig. 4. Saturation magnetization of CoFeB thin films as a function of ions implantation.

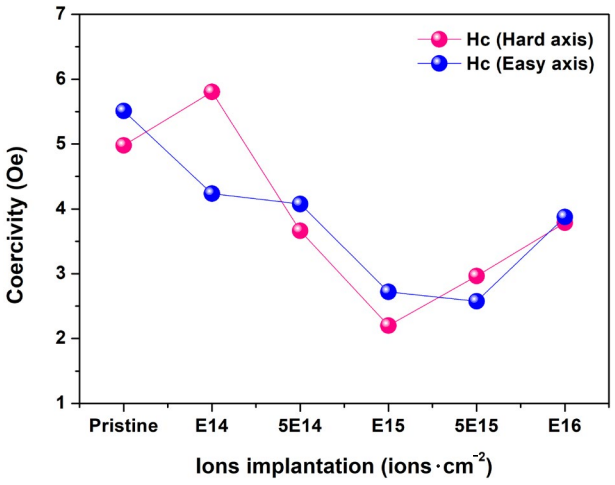

Fig. 5. Magnetic coercivity of CoFeB thin film as a function of the ion implantation.

coercivity decreases when the grain size is smaller than the magnetic exchange length. An increase in defects caused by ion beam irradiation causes an increase in dislocations, thereby reducing grain size, which may explain the decrease in coercivity. The increase in coercivity is believed to be due to an increase in compositional heterogeneity. As described above, the composition change is a result of the complex effect of the difference between the composition of CoFe phase and B on the surface, the composition change at the interface due to diffusion, and the change of the composition and the movement of recoil atoms in the entire region of the thin film.

The reduction of coercivity is important for the industrial application of the materials. In the power conversion function in which a soft magnetic material is used, the power loss can be reduced by reducing the area of the magnetic hysteresis curve corresponding to the magnetic loss. It also has a great advantage in the implementation of network devices and equipment using ferromagnetic resonance.

CONCLUSION

The physical properties of CoFeB thin films with soft magnetic properties by ion implantation were simulated and the magnetic properties were studied. Simulation using SRIM code was able to estimate the atom diffusion and vacancy distribution in the magnetic thin film. It was found that the etching effect predicted in the simulation could cause a decrease in the saturation magnetization. In addition, the expectation that the grain size would change due to the generation of dislocation caused by the increase of the vacancy appeared to be the change of the characteristics of the coercivity. The reduction of magnetic loss by ion implantation is expected to lead to the expansion of industrial applications through the improvement of soft magnetic thin film properties.

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