Self-assembled strontium ferrite on Au nano-dot arrays using rapid thermal annealing

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Abstract. The self-assembled SrM dot array on Au nano-dots has been prepared by using DC magnetron sputtering system without any substrate heating. Then, flash annealing was carried out to crystallize the SrM film. C-axis oriented SrM perpendicular to the films can be observed only at annealing temperature of 800 °C for annealing time of 7 min. The coercivity and remanent squareness ratio in perpendicular direction are 2.8 kOe and 0.72, respectively. The reversal magnetization of SrM on patterned Au nano-dots is closer the Stoner-Wohlfarth model compared to continuous films. The peak of $\Delta M$ of SrM film deposited on patterned Au nano-dots is lower compared to SrM deposited on continued Au films.

1. Introduction

To extend data storage capabilities beyond superparamagnetic limit of conventional granular media, patterned media [1,2], in which each bit is stored in a single domain islands, have been considered as one of prominent candidates for high density magnetic recording media. Several varieties of patterned films fabrication e.g. lithography [3], irradiation through a mask [4], milling with focused ion beam [5] and imprint technology [6] were reported. However, these four techniques are unsuitable for large scale, low throughput and expensive method. Another method for preparation of patterned film is self-assembling method. In this work, self-assembly prepared by sputtering deposited method is used because it has the potential for making very fine-scale structures over large areas in a rapid process and no chemical used in process.

The Co-alloys, L₁₀ phases, rare-earth transition metals and ferrites are the candidate magnetic materials for high density recording. In this work, we choose hexagonal strontium ferrite (SrFe₁₂O₁₉ or SrM in short) because it has fairly large magnetocrystalline anisotropy, excellent chemical stability, magnetic moment aligned along the c-axis and minimum stable grain size about 8.8 nm which is computed using the media stability criterion of $KV > 60k_B T$. Due to these characteristics, SrM is an attractive material for high density magnetic recording application.

In the previous works, self-assembled strontium ferrite (SrM) on random distribution of Au islands structures that are prepared by sputtering method at high substrate temperature was studied [7,8]. In this study, an attempt to prepare the patterned SrM thin films on Au nano-dots with an approximately uniform distribution has been carried out by rapid thermal annealing (RTA) process.

2. Experiments

The SrM film was deposited on Au underlayer using a magnetron sputtering apparatus. The Au film is expected to be used as the underlayer for promotion of c-axis orientation of hexagonal ferrite layer.
The misfit ratio between (111) plane of fcc Au and c-plane of hcp SrM is 2.1%. The self-assembled Au nano-dots are prepared by chemical process. Au dot arrays were deposited onto the substrate by sputtering at an elevated substrate temperature. The average Au dot size is about 15 nm in diameter and uniform distribution. The thickness of SrM layer was kept at 35 nm. A sintered ferrite disk with stoichiometric composition of M-type, i.e. Sr:Fe = 1:12, was used as the target for SrM film. After evacuating the chamber to a pressure below $2 \times 10^{-6}$ Torr, the mixture gas of Ar and O$_2$ with gas pressure of 1.98 and 0.02 mTorr, respectively, was used as sputtering gas. The samples were prepared without any substrate heating. An infrared image furnace was used for flash annealing. The as-deposited SrM films were put in the closed chamber of the annealing furnace, and then annealing was carried out within at temperature of 800 °C for annealing time of 3-10 min in atmospheric pressure without applying any vacuum. The crystallographic properties of the films were characterized by an x-ray diffractometer (XRD) with Cu $K_{\alpha}$ radiation. The magnetic properties were measured by vibrating sample magnetometer (VSM) with maximum field strength of 24 kOe. The surface morphologies of the films were observed by using scanning electron microscope (SEM) and atomic force microscope (AFM). The magnetic domain structures of the films were evaluated by using magnetic force microscope (MFM).

3. Results and Discussion

In Fig. 1, the SrM thin films with and without Au underlayer deposited on Corning glass can be crystallized for annealing time, $t$, over 5 and 10 min, respectively. It means that the underlayer can be used to enhance the crystallization degree of SrM. For SrM/Au/SiO$_2$/Si thin films, the crystallization of SrM/Au deposited on SiO$_2$/Si is lower than that for Corning glass. It is related to the nature of the SiO$_2$/Si substrate which can absorb the heat energy but it penetrates the Corning glass substrate. So, the temperature of Au islands for SiO$_2$/Si substrate is higher than that for glass substrate. From these results, an attempt to prepare the isolated SrM patterned films has been carried out by using Au underlayer [7,8].

![Figure 1](image1.png)

**Figure 1.** Saturation magnetization, $M_s$, of SrM thin films at $T_a$ of 800 °C for various annealing times, $t$.

![Figure 2](image2.png)

**Figure 2.** XRD patterns of SrM/Au/Pyrex glass at as deposited state and annealed sample at $T_a$ of 800 °C for 7 min.
Figure 2 shows XRD diagrams for SrM films prepared on Au nano-dots at as-deposited and annealed state. The preferred orientation of (111) fcc lattice of Au underlayer can be observed for all of the films. As-deposited SrM/Au/Pyrex glass thin films are completely amorphous with the saturation magnetization, $M_s$, value of zero and no diffraction line from SrM planes was observed. Upon annealing at $T_a$ of 800 °C for 7 min, the Au grains may act as nucleation sites for the formation of SrM crystallites in the SrM/Au/Pyrex glass thin films. The presence of diffraction lines from SrM (00$l$) planes can be observed in Fig. 2. These results indicate that the annealing process can be used to promote the crystallized SrM thin films and the (111) orientation of Au underlayer promotes c-axis oriented SrM.

Magnetic properties are also in a good agreement with the XRD patterns. As shown in Fig. 3, the coercivity in perpendicular direction, $H_{c\perp}$, is higher than that for in-plane direction, $H_{c//}$. It means that all of the films exhibit perpendicular anisotropy. The perpendicular coercivity, $H_{c\perp}$, and perpendicular squareness ratio, $S_{\perp}$, are 2.8 kOe and 0.72, respectively. The saturation magnetization, $M_s$, is about 90 emu/cm$^3$. This value of $M_s$ is lower than that of the theoretical value of standard SrM film (360 emu/cm$^3$). It might be due to partially crystallization of SrM thin films.

Figure 4 shows the angular dependence of $H_c/H_c(0^\circ)$ for SrM thin films prepared on Au nano-dots compared to the continuous SrM thin films that are SrM/Au/SiO$_2$/Si, SrM/Au/Corning glass and SrM/SiO$_2$/Si. In comparison, the results of Stoner – Wohlfarth (S – W) and domain wall motion (DWM) modes are included. Apparently, the angular dependence does not agree with those of S – W and DWM modes. The magnetization reversal process is accompanied by the combination of DWM and S – W rotation. However, the magnetization reversal process of SrM thin films prepared on Au nano-dots is nearly the S – W model than the others.

The interactions between magnetic particles of the thin films have been evaluated with the $\Delta M$ method [9]. Following this method, the presence and strength of interactions is described as this equation: $\Delta M(H) = I_d(H) - I_r(\infty) - 2 I_r(H) - I_r(\infty)$, where $I_d(H)$ is the dc demagnetization remanence (DCD), $I_r(H)$ is the isothermal remanent magnetization (IRM) and $I_r(\infty)$ is the isothermal remanent magnetization at saturation. The finite negative and positive values of $\Delta M$ indicate the magnetostatic and exchange coupling, respectively.

As shown in Fig. 5, the $\Delta M(H)$ deviations of the SrM thin films prepared on Au nano-dots compared to the continuous SrM thin films that are SrM/Au/SiO$_2$/Si, SrM/Au/Corning glass and SrM/SiO$_2$/Si are reported. It indicates magnetostatic interactions in the films. The peak of $\Delta M$ of
SrM/Au/Pyrex glass thin films is lower compared to SrM/Au/SiO$_2$/Si, SrM/Au/Corning glass and SrM/SiO$_2$/Si. The weaker interaction might be contributed from non-magnetic phase existed in the space between the magnetic particles and hence the intergranular interactions are reduced.

Figure 6 shows surface of the SrM thin films prepared on Au nano-dots and its magnetic domain structure. The average size of domain structure is 200 – 500 nm larger than Au dot size because of reformation of Au underlayer to be island structure when annealing the sample.

**Figure 5.** The $\Delta M$ deviation of the SrM/Au thin films on various substrates.

**Figure 6.** (a) Surface morphology and (b) magnetic domain structure of SrM/Au/Pyrex glass annealed at 800 °C for 7 min.

4. Conclusions
The $c$-axis oriented SrM thin films can be prepared on patterned Au nano-dots with an approximately uniform distribution by rapid thermal annealing process. The magnetization reversal process of SrM on patterned Au thin film is accompanied by the combination of domain wall motion and S – W rotation. However, it is closer the S – W model compared to continuous films. The magnetic interaction of SrM grains on Au nano-dots is reduced in compare with SrM films deposited on continuous Au thin films.

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