AFM study of combinatorial Ga^+ implanted Co_7Ag_{93} film and its Kerr effect

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Abstract *In this paper, a magnetooptic chip was prepared on Si wafer by combinatorial Ga^+ implantation into ion sputtered Co_7Ag_{93} film. The surface morphology of each unit of the chip was detected by AFM, while their Kerr effect was measured by MOKE equipment. It is observed that the maximum Kerr rotation (MKR) occurs when the incident photon energy is around 3.8–3.9 eV. Summarization of MKR versus implanted Ga^+ dose shows that the MKR enhancement by Ga^+ implantation can be characterized as incubation, enhancement and saturation regions. Considering the mutual solubility and surface morphology transition after annealing, it is suggested that Ga^+ tends to form CoGa and/or $CoGa_3$ intermetallic compounds. Before the formation of $CoGa_3$ compounds, no apparent MKR enhancement could be observed. While when the surface is half occupied by forest-like $CoGa_3$ compounds, MKR enhancement will be saturated. By comparison of the maximum Kerr rotation with the cone areal density, it can be induced that not only the bulk concentration and structure, but also the surface morphology plays an important role in magnetooptic Kerr effect.*

Keywords Combinatorial ion implantation, AFM, MOKE, Surface morphology
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1 INTRODUCTION

Giant magnetic resistance (GMR) has been widely applied in hard disk readout heads. To investigate the origin of room temperature GMR, Co_xAg_{1-x} is an ideal proto system since Co and Ag can be thoroughly separated under proper preparation condition.[1–3] Therefore, massive studies on the structures and magnetic properties of Co_xAg_{1-x} have been done in the last decade.[4–9] On the other hand, it is seldom noticed that Co_xAg_{1-x} also exhibits notable magnetooptic properties. Considering that the magnetooptic materials are widely used in information storage and optical communication,[10]

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also that the present magnetooptic theory is mainly phenomenal,[11] it is interesting to explore the origin of magnetooptic effect on an atomic scale.

AFM is a convenient and powerful tool to investigate the surface morphology of thin solid films. Some achievements have been reported in magneto resistance films studied by AFM.[5,6] Nevertheless, to the author's knowledge, the correlation between surface morphology and magnetooptic Kerr effect (MOKE) has not yet been reported so far. In this paper, we apply AFM to detect the surface morphology of combinatorial Ga^+ implanted into CoAg film prepared by ion sputtering.

2 EXPERIMENTAL

The CoAg film was deposited on [100] Si wafer with a composition of 7 at.% Co and a thickness about 200nm. The concentration of Co was measured by energy dissipative x-ray spectroscopy (EDXS). Ga^+ was implanted by an isotope separator into the film with an area of 2 cm×2 cm and energy of 50 keV. The dose of implanted Ga^+ was set to 0.5×10^{16}, 0.9×10^{16}, 1.3×10^{16}, 1.7×10^{16} atm/cm^2. The combinatorial implantation was realized by applying a binary mask scheme.[12] Using this kind of mask scheme, we can accelerate the synthesis process by obtaining 2^n sample units through n steps. Another advantage of this mask scheme is, the sample units thus obtained on the chip construct a complete combination of n compositions or elements. In our experiments, we obtain a magnetooptic chip which has an array of 4×4 circular units with a diameter of 3 mm.

This chip was observed by AFM as sputtered and after annealing in sequence at 150°C and 300°C under hydrogen atmosphere for 30 minutes respectively. The magnetooptic properties of the 16 units were detected by use of MOKE with an accuracy of ±0.01°. The 3-D surface morphology of Co_7Ag_{93} film without Ga^+ implantation, with 0.5×10^{16}/cm^2 Ga^+ implantation, and with 4.4×10^{16}/cm^2 Ga^+ implantation as implanted, after annealing at 150°C and 300°C are shown in Fig.1 to Fig.3 respectively.

The Kerr spectrum of each unit was detected by use of MOKE under a constant magnetic field of 1 T. The maximum Kerr rotation (MKR) of every units all occurs at 3.8–3.9 eV and is plotted in Fig.4.

3 RESULTS AND DISCUSSION

Assuming an FCC Ag film surface, we can calculate the areal density of Ag, which is 1.79×10^{15}/cm^2. Since the Co concentration is not high, we can simply estimate the density of Co treating Co as substitution atoms, which gives 1×10^{14}/cm^2. Using Trim program, we can obtain the incident range of 50 keV Ga^+ into Co_7Ag_{93}, which is 167 nm with a straggling of 94 nm. Thus the areal density of Ga^+ is about 1×10^{14}/cm^2.

By comparison of Fig.1 to Fig.3, the following surface topography can be observed. For low dose Ga^+ implantation (LDI), the film surface as implanted is smoother than the film without ion implantation (NI). While for high dose Ga^+ implantation (HDI), the film surface is much rougher which is characterized by dense and sharp forest-like cones. After annealing at 150°C, LDI film surface undergoes a similar roughening transition as NI film, which is characterized by sharp forest-like cones. After annealing at 300°C, LDI film forms a less denser but larger sharp conic forest, whereas the surface of NI film seems to be remelted which is characterized by flat and rounded islands. However, the annealing effect on HDI film appears to be quite different. High dose Ga^+ implantation induced inhomogeneous sharp cones with an average height not larger than 50 nm. After annealing at 150°C, all cones grow higher and thicken, densely occupy the film surface. After annealing at 300°C, however, these cones become distinct shaped, the average height of the cones is lowered to 20–30 nm, and the tips become rounded.

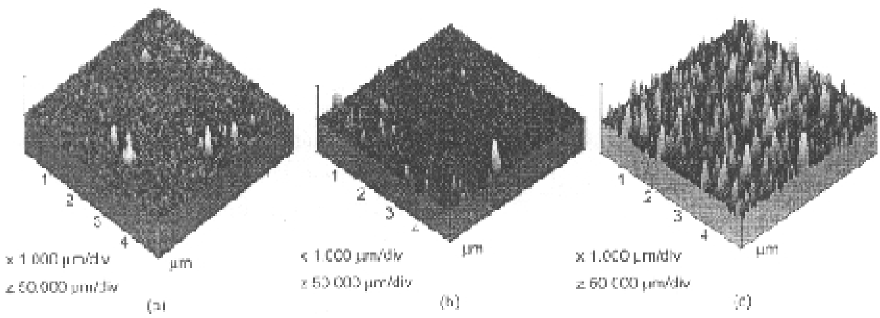

Fig.1 Surface morphology observed by AFM of CoAg film with different dose of Ga^+ implantation without annealing

(a) As sputtered CoAg film, (b) Implanted by 5×10^{15} at./cm^2 Ga^+, (c) Implanted by 4.4×10^{16} at./cm^2 Ga^+

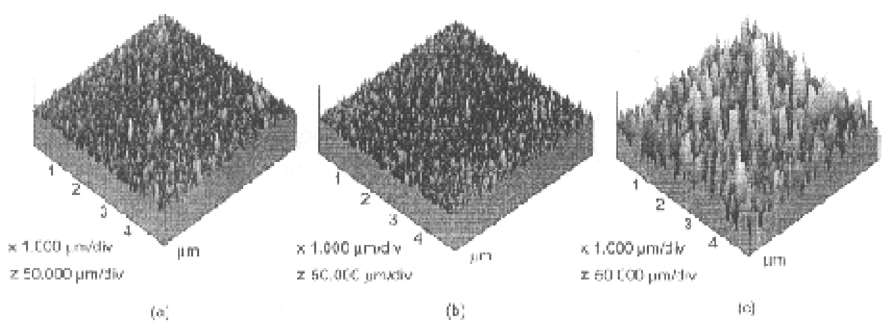

Fig.2 Surface morphology observed by AFM of CoAg film with different dose of Ga^+ implantation after annealing at 150°C under hydrogen atmosphere for 30 min

(a) As sputtered CoAg film, (b) Implanted by 5×10^{15} at./cm^2 Ga^+, (c) Implanted by 4.4×10^{16} at./cm^2 Ga^+

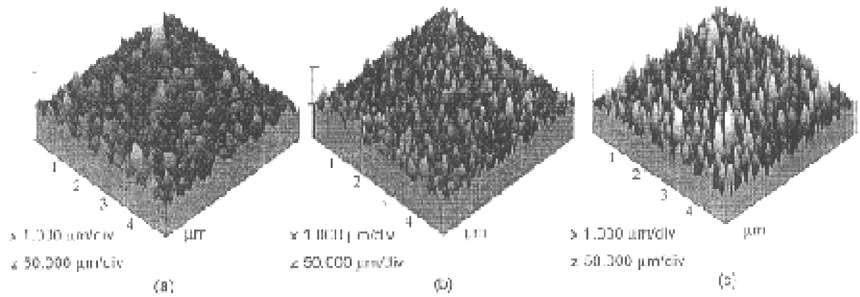

Fig.3 Surface morphology observed by AFM of CoAg film with different dose of Ga^+ implantation after annealing at 300°C under hydrogen atmosphere for 30 min
(a) As sputtered CoAg film, (b) Implanted by 5×10^{15} at./cm^2 Ga^+, (c) Implanted by 4.4×10^{16} at./cm^2 Ga^+

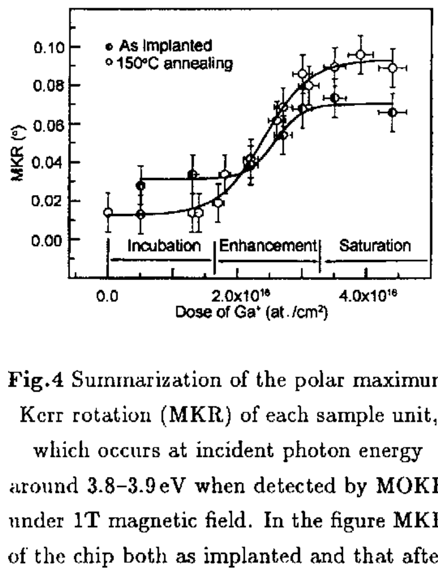

Fig.4 Summarization of the polar maximum Kerr rotation (MKR) of each sample unit, which occurs at incident photon energy around 3.8–3.9 eV when detected by MOKE under 1T magnetic field. In the figure MKR of the chip both as implanted and that after annealing at 150°C for 30 min are shown. The two curves only serve to guide the eyes

By measuring the Kerr effect of the magnetooptic chip, it is noted that MOKE of different sample units is almost the same except that the difference in maximum Kerr rotation, which occurs at 3.8–3.9 eV. Looking at the MKR transition with Ga^+ implantation dose and annealing temperature shown in Fig.4, it is clear that for LDI, MKR increases little below a critical implantation dose (C_L). For HDI, MKR also increases little above an upper critical implantation dose (C_U). Apparent enhancement of MKR only appears for Ga^+ implantation dose (C_I) higher than C_L but lower than C_U. We termed these three regions as incubation region ($C_I < C_L$), enhancement region ($C_L < C_I < C_U$), and saturation region ($C_I > C_U$) respectively.

C_L and C_U vary with the annealing temperature. C_L is around $1\times10^{14}Ga^+/cm^2$, which agrees with the Co areal density. C_U is about $2\times10^{14}Ga^+/cm^2$, which is double of the Co areal density. Referring to the binary phase diagrams,[12] it is known that Co can not dissolve in Ag, Ga has a solubility from 12 at.% to 35 at.% in Ag (when ζ' phase forms), though Ga is almost immiscible in Co, they can form CoGa or $CoGa_3$ intermetallic compounds. The atomic radius of Co, Ag and Ga is 1.25, 1.44 and 1.41

angstroms respectively. It is clear that for LDI, sputtering effect makes the surface smoother. If Ga^+ only substitutes Co position and dissolves in Ag, then LDI film and NI film will follow similar surface roughening process when annealed under 300°C, since they shows quite similar surface topography when annealed under 150°C. In fact, the conic forest of LDI film is stabilized due to Ga^+ implantation rather than remelted by annealing, the latter occurs in NI film. On the other hand, the conic forest induced by Ga^+ implantation for HDI film is quite stable, no dramatic roughening shows up. For this reason, it can be deduced that at least some Ga^+ tends to form intermetallic compounds but not dissolve in Ag. Considering that C_L roughly equals to the areal density of Co, while C_U doubles that, it might be inferred that before Co atoms completely forms CoGa compounds, MKR enhancement is not obvious, on the other hand, when half of the surface Co atoms form $CoGa_3$ compounds, MKR enhancement will be saturated. This conclusion here still remains an open question for further structural detection, and the electronic mechanism for MKR enhancement needs to be given.

It is interesting to observe that for LDI films, when the dose of Ga^+ implantation is lower than 1.3×10^{14} at./cm^2, MKR decreases at elevated annealing temperature. This is contradictory to that reported for binary CoAg system.[13,14] Regarding this dose lies nearby C_L, it is possible that CoGa compounds has a weaker Kerr rotation compared with binary CoAg and $CoGa_3$ compounds. Concrete interpretation can be made if detailed MOKE of pure CoGa and $CoGa_3$ compounds is detected.

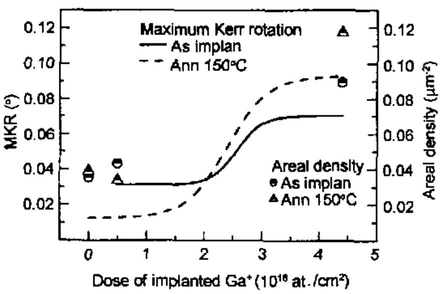

Fig.5 Comparison of MKR with surface cone areal density in μm^{-2}

Previous studies all ascribe MOKE to the effect of bulk microstructure transition.[7,13–15] In fact, MOKE is a surface sensitive effect, the SMOKE technique has now become a powerful tool to detect the surface magnetization.[10] In Fig.5 the surface characteristics of implanted CoAg films are given by the areal density of surface conic islands for comparison with the maximum Kerr rotation. It can be seen that the cone areal density has an agreeable tendency with the maximum Kerr rotation, except that after annealing and for high dose Ga^+ implantation in which intermetallic compounds form, the two have a large deviation. Therefore it can be concluded that the Kerr rotation is not only determined by the surface concentration, structure, but also the surface morphology.

4 CONCLUSION

In this paper, a binary mask scheme was applied to prepare a magnetooptic materials chip with 4×4 units based upon sputtered CoAg film on (100) Si. The surface morphology of Ga^+ implantation and their Kerr effect after different annealing were studied by applying AFM and MOKE. It was observed that for low dose Ga^+ implantation, the film surface is smoother than that as sputtered. While for high dose Ga^+ implantation, the film surface is much rougher. After annealing, both as-sputtered CoAg film and that with low dose Ga^+ implantation undergo an apparent roughening process. For as-sputtered CoAg film, conic islands form after 150°C annealing, and then become flatten after 300°C annealing, but the film with low dose Ga^+ implantation forms much denser and sharper Co islands. Nevertheless, no apparent roughening behavior can be observed for the film with high dose Ca^+ implantation.

Maximum Kerr rotation of Ga^+ implanted CoAg film always occurs at 3.8–3.9 eV, with the increase of the dose of implanted Ga^+, the maximum Kerr rotation is enhanced. By comparison of the maximum Kerr rotation with the cone areal density, it can be induced that not only the bulk concentration and structure, but also the surface morphology plays an important role in magnetooptic Kerr effect.

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