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Microstructure, magnetic and magneto-optical properties of Fe-doped $SmCo_5$ thin films

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Abstrat. The SmCo/Cu, SmCo/Cu/Cr and Fe-doped SmCo films on glass and Si (100) substrates are synthesized by pulsed laser deposition (PLD) technique. The microstructure, magnetism and magneto-optical Kerr effect (MOKE) of Fe-doped SmCo films are studied systematically. The results show that the corcivity and saturation magnetization of films deposited on Si substrates are better than that of on glass subatrates. It is also found that the surface morphology and magnetic properties of Fe:SmCo films are influenced by the annealing temperature. Meanwhile, the X-ray diffraction peaks of $SmCo_5$ phase are enhanced, especially for $SmCo_5$ (001), (002) and (003) peaks after annealing due to the enhancement of Cu (111) peak in the films with Cu buffer layer. Moreover, the MOKE of the samples on both glass and Si substrates are enhanced after Fe doping and the MOKE of samples is controlled by the Fe content, which provides a new way for optimizing the property of SmCo film as the magneto optical storages.

1. Introduction

Since the 1960's, SmCo alloys have been extensively studied. SmCo alloys have the high magnetic anisotropy properties (K_u), and the high Curie temperature (T_C), as well as the excellent corrosion resistance, high thermal stability and high magnetic energy product, which shows a good application prospect of SmCo alloys in high temperature environments and many fileds [1-6]. In 1989, Coehoorn *et al*. proposed the concept of nano-composite magnets based on the $Nd_2Fe_{14}B/Fe_3B$ phase [2], causing a wide attention of the academic community. In 1991, Kneller and Hawig proposed the concepts of exchange spring elasticity in the nano-composite model system [3]. They found that the magnetic energy product of nano-composite magnet can be greatly improved by the soft magnetic phase and hard magnetic phase in nano-composite materials. The reversible exchange interaction of the soft magnetic phase, Fe, is found in the low magnetic field and an irreversible exchange interaction of the hard magnetic phase, SmCo, occurs in the high magnetic field. The first-order reversal curve is usually used to distinguish the magnetization process of reversible and irreversible exchange interaction. For Fe:SmCo thin film, the current research focuses on how to enhance the magnetic properties and establish the exchange coupling model [4-7]. The study of Choi *et al*. shows that the interface effect of Fe:SmCo can be controlled by changing the thickness ratio of SmCo and Fe layers which increases anisotropy and maximum magnetic energy product [8,9]. MOKE technique is a fast and easy analysis way in micro-size arrange for magnet, recently, which has been widely used in the analysis of magnetic properties and MOKE [10,11].

We studied the characteristics of Fe:SmCo multilayer films with Cr and Cu as buffer layer, which prepared on the single crystal Si (100) and SiO_2 substrate by PLD. The magnetic properties and MOKE as a function of Fe concentration are studied under different substrates and annealing conditions.

2. Experiment

Fe-doped SmCo/Cu (Cr) films are prepared on glass and Si (100) substrates by PLD using a KrF excimer laser with a frequency of 8 Hz. The deposition chamber is pumped down to a base

pressure of 2.0×10^{-4} Pa and the substrate temperature is 400°C. The film thicknesses are controlled by deposition time. The film thickness is about 40 nm when the deposition time 40 min. The deposition time of Fe is set as 3, 5, 8 and 10 min, respectively, and corresponding samples deposited on Si or SiO_2 substrates are labeled as S1~S4 and G1~G4, respectively. The samples are annealed at the pressure of 5.0×10^{-5} Pa for 30 min. The annealing temperature of sample G4 and S4 are set as 650 °C and denoted as G4-650 and S4- 650, respectively.
The crystal structure is characterized by X-ray diffraction (XRD) with Cu K_α radiation. Surface morphology of the films is measured by scanning electron microscopy (SEM). MOKE curve is obtained using a high resolution magneto optical Kerr measurement system at room temperature.

3. Results and discussions

3.1. Effect of Cu and Cr buffer layer on the SmCo thin film

Figure 1 is the XRD spectra of SmCo (30 nm) /Cu (100 nm) and SmCo (100 nm) /Cr (30 nm) /Cu (3 nm) with different buffer layers of Cr and Cu on Si (100) substrates. In the range from 20° to 80°in Figure 1, the magnetic phase $SmCo_5$ (002) peak and Cu (111) peak are found. The stronger peaks of Cu (111) show that the Cu buffer layer has good texture, which is beneficial to the formation of the magnetic SmCo (001) layer because the high quality Cu (111) texture can promote the growth of $SmCo_5$ crystal structure. Sayama Junichi *et al*. [12] found that the coercive force of magnetic layer increased with the enhancement of Cu (111) texture and the studies of Ohtake and Nukaga *et al*. [13] have also given the same conclusion. In contrast to Figure 1(a) and 1(b), the diffraction peaks of the Cu buffer layer and the $SmCo_5$ layer are obviously enhanced when added 3 nm Cr layer on Cu buffer layer. Thus, the Cr buffer layer has promoted the growth of Cu (111) texture and the good crystallinity of $SmCo_5$. which agrees with Morisako's suggestions [14].

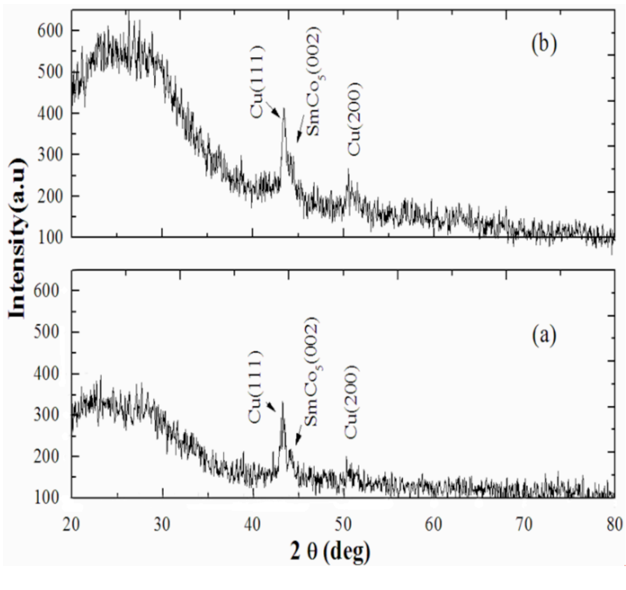

Figure 1. XRD measurements of (a) SmCo (30 nm)/Cu (100 nm); (b) SmCo (30 nm)/Cu (100 nm)/Cr (3 nm) thin film on Si (100) substrates

3.2. Magnetic properties and MOKE

The magneto-optic Kerr curves (or the MOKE magnetic hysteresis loop) of samples with different substrates as shown in Figure 2. For all samples, the MOKE curves dose not show "the wasp-waisted hysteresis loop", which indicates that the samples produced a magnetic exchange coupling with the Fe phase and SmCo phase. According to the exchange elastic model of Kneller and Hawig [3], a soft magnetic layer has a critical thickness

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$$t_{cs} = 2\pi\left(A_s / 2K_u\right)^{1/2} \quad (1)$$

where A_s and K_u are a exchange energy of the soft magnetic phase and a magnetic anisotropy constant of the hard magnetic phase, respectively. If the soft magnetic layer thickness $t_s \leq t_{cs}$, the loop curve has a double phase behavior, while $t_s \geq t_{cs}$, the coupling of the soft magnetic layer and hard magnetic layer appears which result in a single hysteresis loop. For FeSmCo, A_s and K_h are 2.5×10^{-11} J/m and 1.71×10^{7} J/m^3, respectively, the critical thickness t_{cs} is 5.4 nm [15]. In our experiment, the maximum thickness of Fe layer is about 5 nm, obviously $t_s \leq t_{cs}$, hence, it satisfies the exchange coupling condition. We suggested that the exchange coupling of a soft magnetic phase Fe and a hard phase SmCo was formed in our samples.

Furthermore, the magnetic properties of the Si substrate samples are superior to the SiO_2 substrate as shown in Figure 2. For the eight samples, the coercivity values of SmCo films on Si (100) substrates are greater than that of on SiO_2 substrates. The coercivity values of SiO_2 (G1 ~ G4) are 48 Oe, 135 Oe, 241 Oe, 208 Oe, respectively, while that of Si (S1□S4) are 143 Oe, 176 Oe, 333 Oe, 351 Oe respectively. Obviously, the coercivity with Si substrate is greater than that of SiO_2 substrates for the same Fe content. In addition, for the same substrate the coercivity of samples increased with the increase of Fe content. Zhang *et al.* studied the effect of Fe on the coercivity of $SmCo_5$ as well as its formation mechanism to the $SmCo_5$ doped α-Fe with 0, 20, 30 and 35 wt% [7], which found that the coercivity can be controlled by domain wall pinning mechanism. Similar results are also shown in our measurements. We found that the increase of Fe content leads to the enhancement of the magnetic wall-pinning effect and promoted the increase of coercivity.

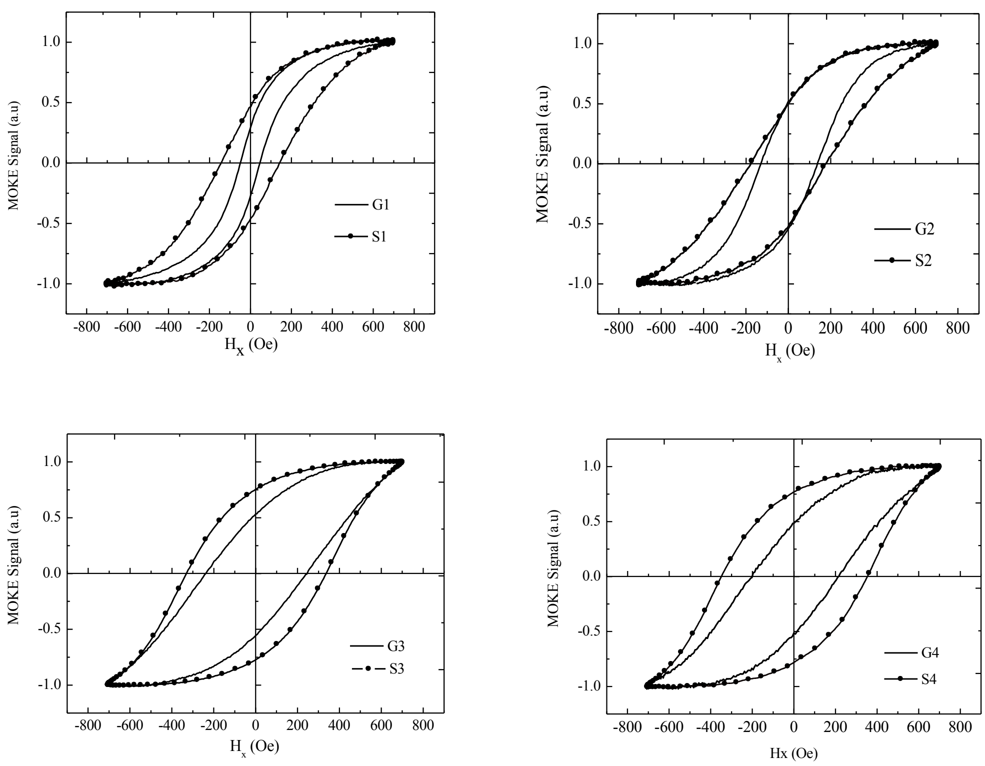

Figure 2. The MOKE curves of Fe: SmCo thin films with S1～S4 and G1~G4.

Figure 3 is the MOKE curves of the different samples deposited on Si (S1～S4) and SiO_2 (G1~G4) substrates. Fang *et al.* found that the Kerr rotation angle (θ_k), is proportional to the saturation magnetization [16]. The Kerr rotation angle is enhanced with the increase of Fe content, indicating that the addition of Fe is beneficial to enhance the Kerr effect in SmCo film. It means that the MOKE of samples can be controlled by the Fe content, which provides a new way for optimizing the performance of SmCo-based thin films as a magneto optical storage medium.

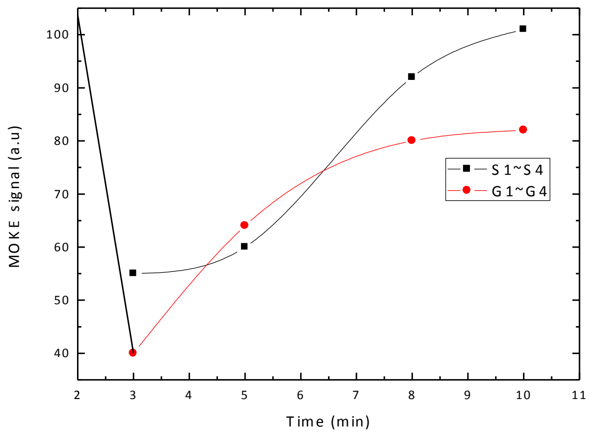

Figure 3. the change of Kerr effect with Fe content for the different substrate samples

3.3. Effect of annealing on the structure and magnetic properties

Figure 4 is the XRD spectra of the samples G4-650 and S4-650. The diffraction peaks of $SmCo_5$ (002) and $SmCo_5$ (200) appeared in sample G4-650, while $SmCo_5$ (002) and $SmCo_5$ (003) diffraction peaks appeared in sample S4-650. $SmCo_5$ (001), $SmCo_5$ (210), Sm_2Co_7 (008), Sm_2Co_7 (214) and Sm_2Co_{17} (304) diffraction peaks can be also seen (the highest peak corresponding to the Si substrate). Moreover, additional Cu (200) and Fe (111) diffraction peaks are seen comparing to the non annealed samples.

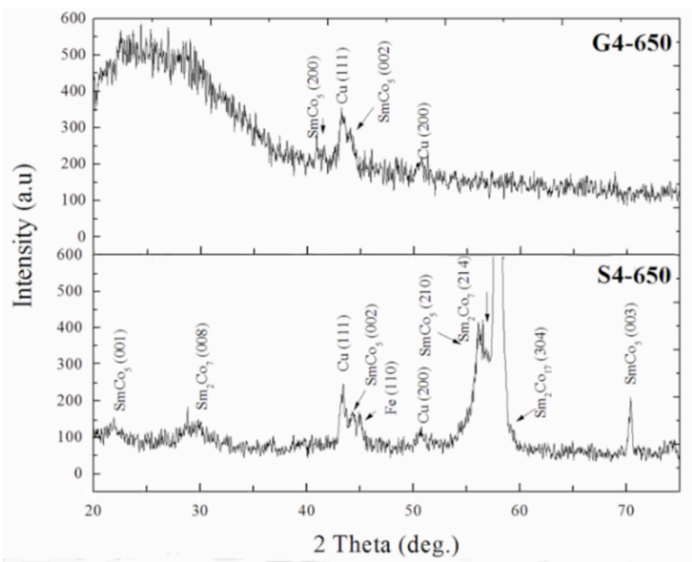

Figure 4. XRD patterns of samples (a) G4 and (b) S4 after annealing

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Figure 5 gives the SEM pictures of the annealed sample G4-650 and S4-650. The average crystalline grain size of the sample G4-650 is less than that of sample S4-650. After annealing, the thin film surface is more uniform and without the large crystalline grain. It also shows that the sample surface is still relatively flat after 650 K annealing.

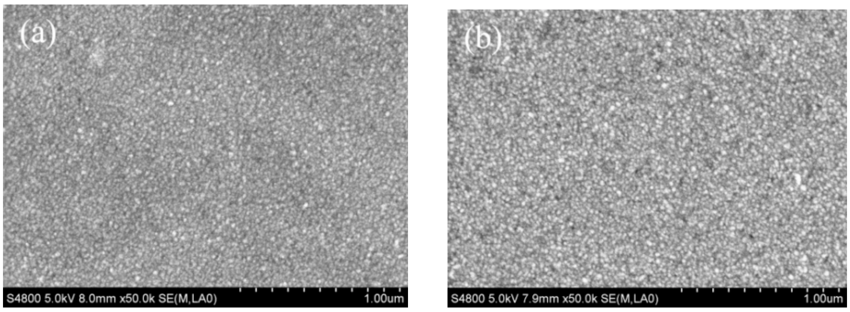

Figure 5. SEM spectra of samples (a) G4-650 and (b) S4-650.

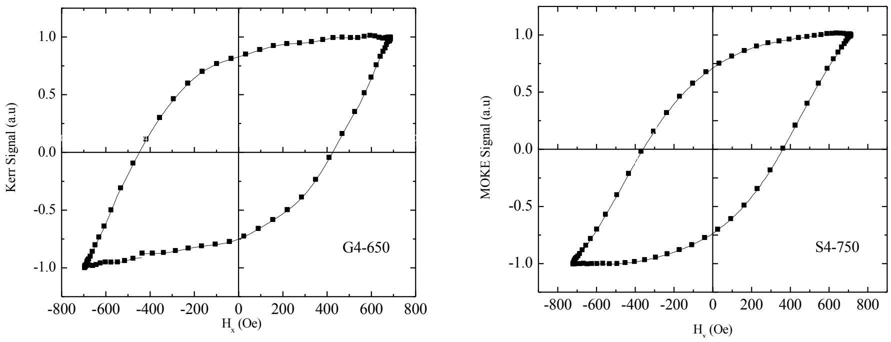

Figure 6. Magneto optic Kerr curve of sample after annealing (a) G4-650 and (b)S4-650

Figure 6 is the MOKE curves of sample G4-650 and S4-650. Contrast to Figure 2, the coercivity properties of G4-650 and S4-650 samples are significantly improved, and the coercivity values of S4 increase from 351 Oe to 370 Oe and from 208 Oe to 450 Oe after 650 K annealing, respectively. We suggested that the increase of coercivity after 650 K annealing is mainly due to the grain refine of samples, which is agreement with the reports of Zhang *et al.* [17].

4. conclusions

The magnetism, MOKE and the structure of Fe doped SmCo films were studied. It was found that the magnetism and MOKE of $SmCo_5$ phase increase with increasing Fe content. For the samples with different substrates, the magnetic properties of the samples on Si substrate are superior to that of on SiO_2 substrate, and after high temperature annealing, the increase of coercivity for both samples, of which the coercivity of SiO_2 substrate is better than the one of Si substrate. The experiment found that the crystalline grains of films were refine after the annealing, which makes the increase of coercivity. Moreover, the MOKE of the samples on glass and Si substrates are enhanced by the Fe content, which provides a new way for optimizing the MOKE of SmCo film as the magneto optical storages.

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