Rare Metal Materials and Engineering
Volume 43, Issue 10, October 2014
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com

ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2014, 43(10): 2335-2338.

ARTICLE

Magnetic Properties of $SmCo_7$ Permanent Magnetic Films for High Temperature Applications

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Abstract: High temperature magnetic properties of the $SmCo_7$ films deposited on Si(100) substrate with Mo underlayer were investigated. The results show that the effects of high temperature aging treatment on the crystal structure and the magnetic properties of the films are not obvious. According to the law of approach to the saturation and high temperature magnetization curves of the films, the temperature dependence of magnetic anisotropy constant K_1 can be obtained, which clearly suggests that the preferred orientation of SmCo crystalline will be destroyed at a certain extent by elevated temperatures. Moreover, the proper temperature dependence of magnetic properties for the films, is suitable for applications in microelectromechanical system (MEMS).

Key words: rare earth permanent magnets; SmCo films; high temperature applications; MEMS

Samarium cobalt (SmCo) permanent magnetic films have many potential applications in microelectromechanical system (MEMS), and many efforts have been put into the research about these films, mainly including $SmCo_5$ and Sm_2Co_{17} systems [1-3]. The development of MEMS requires collecting the information about temperature dependence of magnetic behavior for the SmCo films, which is attributed to that the thermal stability of these films is one of the fundamental aspects to take into account when they are fabricated for a certain "IC" technical application [4-6]. Recently, the $SmCo_7$ phase is proved to be the most promising candidates for high temperature applications [7-9]. However, the high temperature magnetic behavior of the $SmCo_7$ films is still unclear.

In our previous works, the SmCo-based films with varied composition were deposited on Si substrate, indicating that the magnetic phase transformation (Sm_2Co_{17}→$SmCo_7$→$SmCo_5$) took place with increasing of Sm concentration [10]. The $SmCo_7$ films were obtained, which exhibited enhanced magnetic properties with improved annealing method [11]. Moreover, it was found that the crystal structure and the magnetic properties of the $SmCo_7$ films were improved when Mo or Cr films were served as underlayer [12]. In this paper, the $SmCo_7$ films were prepared on Si substrate with Mo underlayer, and the high temperature magnetic properties were investigated.

1 Experiment

The Mo film was deposited on Si(100) substrate as underlayer for the SmCo films by magnetron sputtering process under the base pressure of 8.0×10^{-6} Pa. Subsequently, the SmCo films with additives of Fe, Cu, and Zr were prepared by sputtering from a 2:17-type $Sm(Co_{0.62}Fe_{0.25}Cu_{0.1}Zr_{0.03})_{7.5}$ composite target, and a protective layer was prepared too. The Ar (99.999%) gas pressure, sputtering power density and substrate temperature were 0.9 Pa, 5.1 W/cm^2, and 650 °C, respectively. The film thickness was determined via a scanning electron microscopy (SEM, JSM-6409) by observing the film cross-section. The crystal structure was studied by a X-ray diffraction (XRD, Bede TM-2000) with Cu Kα radiation. The magnetization curves and the magnetic hysteresis loops were measured from 25 °C to 300 °C by a vibrating sample magnetometer (VSM, BHV-525).

2 Results and Discussion

Received date: October 2, 2013
Foundation item: Scientific Research Foundation of CUIT (KYTZ201112); Young and Middle-Aged Academic Leaders of Scientific Research Funds of CUIT (J201222)
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The thickness of SmCo films can be mediated by the sputtering time. According to the film cross-section, the average deposition rate of 7.4 nm/min has been obtained. The surface and the cross-section of the 3.0 μm thick SmCo films without subsequent annealing treatment are shown in Fig.1. Notable surface defect is not found for the films such as holes and flaws, and a perfect surface structure is observed. The atactic column structure is observed in the films cross-section, which agrees well with one-dimensional column growth mechanism [13]. It is suggested that the inner-stress of the film deposited on hot Si substrate without any annealing process decreases, which is responsible for the improved growth, and the films with larger thickness can be observed.

High temperature aging at 300 °C for 8 h was carried out for the SmCo films with 3.0 μm thickness. Crystal structure and magnetic properties of the films were measured at room temperature subsequently. Fig.2a gives the XRD patterns of the films treated under different aging conditions. It is found that the crystal structure of the films treated in air or vacuum with base pressure of 2.0×10^{-3} Pa have no change compared with the films without heat treatment. These films still exhibit $TbCu_7$-type structure with a strong (110) orientation. Fig.2b shows the in-plane magnetic hysteresis loops of the films treated under different aging conditions. No remarkable difference is observed for the magnetic hysteresis loops, meaning that the magnetic behavior is independent on the aging treatment. The above XRD and VSM results strongly suggest that the irreversible changes of the crystal structure, the distribution of easy magnetization axis, and the microstructure do not take place for the $SmCo_7$ films treated at 300 °C for 8 h. It provides an important opportunity to the $SmCo_7$ films for use in MEMS.

Under strong external magnetic field, the law of the approach to saturation (LATS) for magnetic materials can be given as:

$$M = M_s\left(1-\frac{a}{H}-\frac{b}{H^2}-\frac{c}{H^3}-\cdots\right)+\chi_p H \tag{1}$$

where M is the magnetization, H is the external magnetic field, M_s is the saturation magnetization, χ_p is the paramagnetic susceptibility, while a, b, and c denote different magnetic resistance, during the magnetization process.

The terms of $1/H^2$ and $1/H^3$ produce a negligible contribution to the magnetization M in presence of a large external

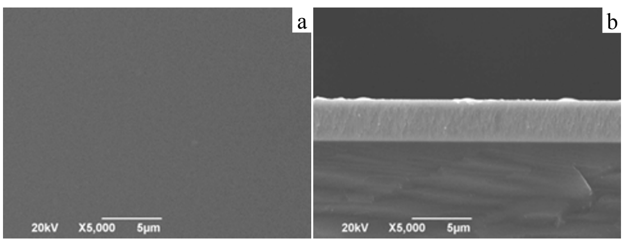

Fig.1 SEM images of surface (a) and cross-section (b) of the SmCo films

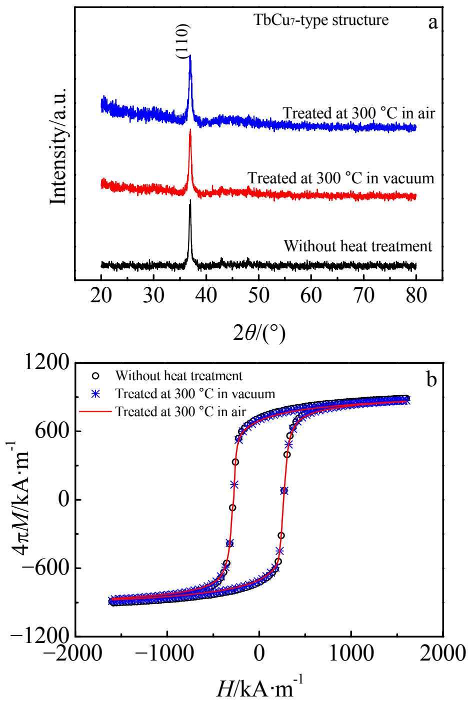

Fig.2 XRD patterns (a) and VSM results (b) of the SmCo films

magnetic field H, where the saturated state is observed without respect to the paramagnetic susceptibility χ_p. The Eq. (1) can be represented as:

$$\frac{M}{H}=\frac{M}{M_s}\frac{M_s-M}{a} \tag{2}$$

In moderate external magnetic field region, the dependence of M/H on M accords with a straight linear relation. The saturation magnetization M_s can be obtained by extrapolating the straight linear relation of the M/H-M to zero M/H.

For polycrystalline permanent magnetic materials, the magnetic anisotropy constant K_1 can be obtained according to the LATS, which is a significant intrinsic magnetic parameter for the SmCo films. Based on the LATS, the differential susceptibility χ_d (dM/dH) can be given as:

$$\chi_d = M_s\left(aH+2b+\frac{3c}{H}\cdots\right)\frac{1}{H^3}+\chi_p \tag{3}$$

The coefficient b can be obtained from the slope (k=2bM_s) of a straight linear relation between dM/dH and $1/H^3$ under moderate external magnetic field.

Moreover, the coefficient b is found to be correlated with the magnetization process, which can be calculated by solving the equilibrium state of magnetization process as follow:

$$b=\frac{1}{2\mu_0^2 M_s^2}\left(\frac{\partial F_k}{\partial\theta}\right)^2 \tag{4}$$

where, θ is an angle between the M_s and H directions in a grain, and F_k is the magnetic anisotropy energy. It is clear that the coefficient b originates in the magnetic resistance from the magnetic anisotropy to the changed magnetization vector.

The $SmCo_7$ films exhibit polycrystalline structure constituted by lots of grains with different easy magnetization axis directions. So, the coefficient b can be calculated by seeking the average value of $\partial F_k/\partial\theta$. If the uniaxial anisotropy of the hexagonal $SmCo_7$ film is given, the coefficient b is easily calculated in spherical coordinates system as following:

$$b = \frac{4}{15}\frac{K_1^{\,2}}{\mu_0^{\,2} M_s^{\,2}} \tag{5}$$

At present, the magnetic anisotropy constant K_1 can be calculated based on the dM/dH-$1/H^3$ relationship.

Fig.3 gives the magnetic properties of the $SmCo_7$ films at different temperatures. When the temperature increases from 25 °C to 300 °C, the magnetic anisotropy K_1 decreases from 1.25×10^5 J/m^3 to 0.91×10^5 J/m^3 gradually. Magnetic anisotropy originates in the correlation between electronic orbit and crystal structure. The preferred orientation of an electron spin along special axis direction is forced by the spin-orbit coupling interaction. Nevertheless, it is destroyed by elevated temperatures at a certain extent, which is reasonable for the decreased K_1. The $SmCo_7$ films exhibit a lower K_1 compared with that of the SmCo alloy (about 5×10^6 J/m^3) at room temperature.

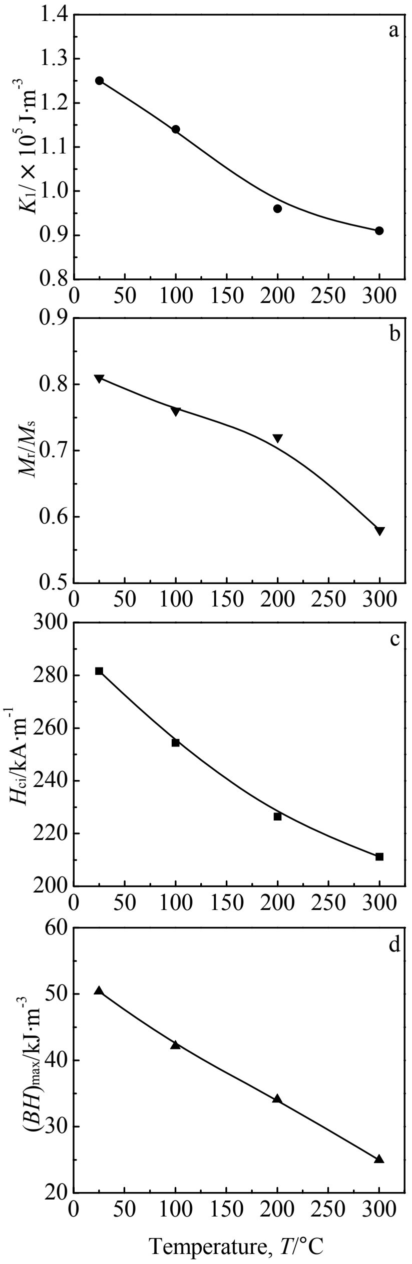

Fig.3 Magnetic properties of the $SmCo_7$ films at high temperatures: (a) K_1 vs T, (b) M_r/M_s vs T, (c), H_{ci} vs T , and (d) $(BH)_{max}$ vs T

This is suggested to be correlated with the crystal lattice defect in the $SmCo_7$ films, because the incomplete crystal structure decreases the preferred orientation of the electron spin. This is well agreement with the decreased remanence ratio M_r/M_s from 0.81 to 0.58, which results in deteriorated magnetic properties. Intrinsic coercivity H_{ci} and maximum magnetic energy product $(BH)_{max}$ of the films decrease gradually with the increase of temperature, which accords with the first order linear relation. It is worthwhile to note that the temperature coefficient of H_{ci} is calculated to be –0.091%/°C from 25 °C to 300 °C, exhibiting a good temperature stability. These results suggest that the $SmCo_7$ films provide a good temperature stability and a proper temperature dependence of magnetic properties, which is suitable for use in MEMS.

3 Conclusions

1) The irreversible changes of the crystal structure, the distribution of easy magnetization axis, and the microstructure do not take place for the $SmCo_7$ films treated at 300 °C for 8 h under different aging conditions.

2) When the temperature increases from 25 °C to 300 °C, the magnetic anisotropy K_1 of the $SmCo_7$ films decreases from 1.25×10^5 J/m^3 to 0.91×10^5 J/m^3 gradually, which is suggested to be correlated with the crystal lattice defect in the films.

3) The intrinsic coercivity H_{ci} and the maximum magnetic energy product $(BH)_{max}$ of the $SmCo_7$ films decrease gradually with the increase of temperature.

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