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Anomalous Hall effect and perpendicular magnetic anisotropy in $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ thin films

K. Kamala Bharathi [a,*], S. Venkatesh [b], G. Markandeyulu [c], C.V. Ramana [a]

[a] Department of Mechanical Engineering, University of Texas at El Paso, El Paso, TX 79968, USA
[b] Department of Condensed Matter Physics and Material Sciences, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
[c] Advanced Magnetic Materials Laboratory (AMMLa), Department of Physics, Indian Institute of Technology Madras, Chennai 600 036, India

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ABSTRACT

$Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films of 100 nm thickness were grown using DC magnetron sputter deposition and their structure, magnetization, electrical and Hall resistance characteristics were investigated. An increase in electrical resistivity from $4.75\times10^{-6}\,\Omega\,m$ to $5.62\times10^{-6}\,\Omega\,m$ and from 2.26×10^{-6} to $2.84\times10^{-6}\,\Omega\,m$ for $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films, respectively, with decrease in temperature from 300 to 40 K is attributed to the strain induced anisotropy that dominates at lower temperatures. The positive extraordinary Hall coefficients (R_S) are observed for both films at 300 and 80 K. The existence of hysteresis indicates that $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films possess perpendicular anisotropy at 300 K. Hysteresis loop becomes narrow at 80 K for both $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films. Magnetization measurements at 300 K exhibiting small coercive field values of 31 and 49 Oe for $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films, respectively, confirm the existence of perpendicular anisotropy at 300 K.

1. Introduction

Rare-earth transition metal (R-TM) alloys received significant attention recently due to their potential applications in actuators and microsystems [1–4]. R-TM thin films find applications in magneto-optic recording devices, actuators, motors and acoustic wave generators [1–4]. In general, the rare-earth iron-based alloys offer the best possibility of developing giant magnetostriction at room temperature or above, since the highly aspherical 4f orbitals of the rare earths remain in an oriented state, owing to the strong coupling between the rare-earth and the iron moments [5]. R-TM films are known to exhibit significant Hall effect [6–8] at very low magnetic field and perpendicular magnetic anisotropy at room temperature [6–8].

The total Hall resistivity (ρ_H) of spontaneously magnetized materials consists of two components [9]: the ordinary (ρ_0) and the anomalous (or extraordinary; ρ_s) components. Therefore, the total Hall resistivity is expressed as [9]

$$\rho_H = R_o H + R_S 4\pi M_S \tag{1}$$

where R_o and R_S are the ordinary and the extraordinary Hall coefficients, respectively, and M_S is the saturation magnetization. The ordinary Hall effect arises from the Lorentz force acting on the moving electrons, and the extraordinary Hall effect results from asymmetric scattering of the conduction electrons (skew scattering [10] or side jump [11]) by magnetic atoms. Since, in a magnetic material, the magnitude of R_o is known to be much smaller than that of R_S, the Hall resistivity of a magnetic material is essentially given by $R_S 4\pi M_S$. Investigating the Hall effect is, therefore, of great theoretical and practical importance since it provides a detailed understanding of the electronic transport in these R-TM alloys. Based on such measurements, Tb–Fe thin films are reported to exhibit perpendicular magnetic anisotropy [12,13]. Harris and Pokhil [14] and Harris et al. [15] proposed the “random magnetic anisotropy” model in amorphous $TbFe_2$ alloys, according to which each Tb moment is in a local anisotropy field of random orientation. The strength and orientation of local magnetic anisotropy of the Tb ion tend to cause the local magnetic moment to align in a direction away from the collinear arrangement. The magnetic properties of R-TM films are found to depend strongly on the film composition and the preparation conditions [16–19]. The perpendicular magnetic anisotropy can be observed from the perpendicular magnetization measurements as well as through the Hall effect measurements.

One of the most important aspects in the research of R–Fe compounds is to achieve large magnetostriction and Hall effect at a low magnetic field. This is particularly true in the case of thin-film materials, since the strength of applied magnetic field is considered to be limited up to hundreds of Oersteds in magneto-optic recording devices, actuators, motors and acoustic wave generators, where thin films are best adopted. To this end, amorphization has most frequently been used. Specifically, this

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* Corresponding author.
E-mail address: kbkaruppanan@utep.edu (K. Kamala Bharathi).

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method is convenient in thin-film-type materials due to the easy formation of amorphous phase under normal sputtering conditions. Therefore, in the present case, an attempt has been made to examine the anomalous Hall effect at low fields and perpendicular magnetic anisotropy through magnetization studies of amorphous Sm–Fe thin films produced by DC magnetron sputtering. We found the interesting anomalous Hall effect at 300 and 80 K for $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ thin films, respectively, and the results are presented and discussed in this paper.

2. Experiment

$Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films were prepared by DC magnetron sputtering on glass substrates. A composite target consisting of Fe disc and Sm chips was used for sputtering. The number of Sm chips was varied to get different compositions of Sm and Fe. The sputtering conditions employed for $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films are listed in Table 1. Structural studies were performed using X-ray diffraction (XRD). XRD patterns were recorded employing CuK_α radiation in a PANalytical (X'pert PRO) X-ray diffractometer. Compositional analysis was performed and confirmed using energy-dispersive X-ray spectrometry (EDS). Measurements were made in a spot mode and selectively choosing various locations on the film surface. Electrical resistivity (ρ) measurements were carried out employing the Van der paw method. Hall resistivity measurements were made at 80 and 300 K in magnetic fields up to 10 KOe, and applied perpendicular to the plane of the film. Magnetization measurements were carried out employing a squid magnetometer up to a magnetic field of 30 kOe at room temperature.

3. Results and discussion

XRD patterns of $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ thin films are shown in Fig. 1. The patterns indicate that both the films are amorphous. The variation in electrical resistivity measured in the temperature range 40–300 K for $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films is shown in Fig. 2. It is evident that ρ increases from 4.75×10^{-6} (300 K) to $5.62 \times 10^{-6}\ \Omega$ m (40 K) for $Sm_{28}Fe_{72}$ films. Similarly, ρ increases from 2.26×10^{-6} (300 K) to $2.84 \times 10^{-6}\ \Omega$ m (40 K) for $Sm_{32}Fe_{68}$ films. The temperature coefficient of resistivity in amorphous materials has been calculated from Ziman's [20] theory proposed in liquid transition metals based on the structure factor. The phonons and thermal variations in the structure factor can give rise to positive and negative temperature coefficients. In the present case, increase in resistivity with decrease in temperature is due to the fact that the increase in anisotropy and the magnetostriction with the decrease in temperature leads to strain induced anisotropy that dominates at low temperatures, contributing to the additional scattering process [21]. This may be due to the larger density of the 4f electrons within the plane, led by strong spin–orbit interactions. As the films are amorphous, within the plane of the film, the anisotropy in the resistivity could have resulted from the additional scattering of electrons by the 4f quadrupole moments.

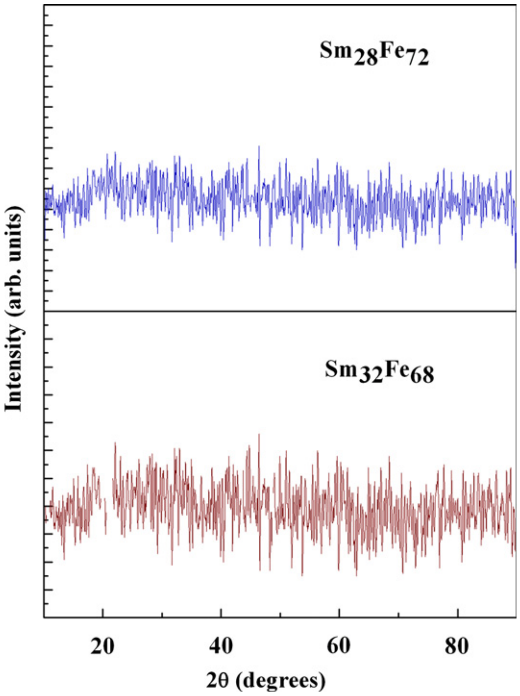

Fig. 1. XRD patterns of $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films.

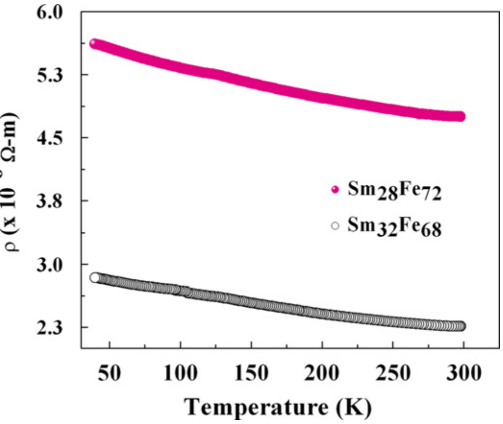

Fig. 2. Temperature variation of electrical resistivity of $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films.

Table 1
Sputtering deposition conditions employed for $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films.

Deposition parameter	Set value
Base pressure	$\sim 10^{-6}$ Torr
Sputtering (Ar) pressure	4×10^{-3} Torr
Substrate temperature (T_s)	RT
Target–substrate distance	5 cm
DC power	300 W
Film thickness	100 nm

Hall resistance curves for $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films are shown in Figs. 3 and 4, respectively. Positive R_S is observed for both films at 300 and 80 K and it could be due to the positive Hall voltage values of Fe and Sm. Large hysteresis is observed at 300 K for both $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films. The saturation is reached at about 9 kOe for both $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films. The existence of hysteresis at 300 K indicates that the $Sm_{28}Fe_{72}$ and $Sm_{32}Fe_{68}$ films possess perpendicular anisotropy. At 80 K, hysteresis is found to be very small. It has been reported that the anisotropy at low temperatures in these films is planar due to the increase in strain induced anisotropy at low temperature because of large magnetostriction [5]. Thus, the in-plane anisotropy could, by forcing the moments into the plane, contribute to the near absence of remanence. In spite of the effect of crystalline electric fields being small in amorphous materials, the presence of perpendicular magnetic anisotropy is mainly due to a significant