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Research articles

Enhancement of magnetostrictive properties of Galfenol thin films

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ABSTRACT

The present study investigates the role of substrate temperatures on the structural, morphological, magnetic and magnetostrictive properties of DC sputtered FeGa thin films grown on Si substrates. These films were deposited at various substrate temperatures between 50 and 350 °C. The structural characterization of the films revealed columnar growth and the transformation of surface morphology from prismatic to spherical at high substrate temperatures. Both $L1_2$ and B2 phases of FeGa existed in the films, with the $L1_2$ phase dominating. The in-plane and out-of-plane vibration sample magnetometry measurements showed the evolution of magnetic anisotropy in these films. It was revealed from the magnetostriction measurements that the films deposited at 250 °C exhibited the maximum value of 59 ppm.

1. Introduction

Functional magnetic materials with magnetostrictive properties have been investigated in recent years owing to their wide range of applications as in sonar systems [1,2], micro-electromechanical systems in the form of transducers and actuators [3,4], sensors [5], vibrational energy harvesting devices and vibration control systems [6,7] etc. Major advantages of these magnetostrictive materials include noncontact operation, high reliability, simple designs and compatibility with semiconductor manufacturing processes thus enabling integration in microelectronic technologies.

Magnetostrictive material research interest resurged in the 1970's with many groups working on single and multilayer thin films [8]. The discovery of Terfenol-D, a rare-earth Fe based alloy attracted much attention in this field of research with its high magnetostriction values of ~2000 ppm in bulk and of nearly 1000 ppm in polycrystalline thin film form [9]. Though it had high magnetostrictive properties, its large magnetocrystalline anisotropy resulting in high saturation fields, limits its use in practical applications. Other constraining factors of this material are the presence of rare-earths and high cost. Alternate materials were considered as a replacement for Terfenol-D which exhibits sufficient magnetostriction. In this pursuance, Fe-based alloys including Fe-Al, Fe-Co, and Fe-Ga showing extraordinary magnetostrictive behaviours were considered [10–12]. Among these, FeGa alloys are promising due to several attractive properties including low cost, corrosion resistance, machinable and with moderate magnetostriction (~400 ppm) [9] at lower saturation fields.

Several groups have been working on FeGa thin films and more focus is being given to improve the magnetostriction. Javed et al., have studied the influence of Ga evaporation rate, power density for Fe sputtering and Ar partial pressure on the film growth and obtained effective magnetostriction constant [13] of 80 ppm at maximum. In-plane anisotropy was induced during sputtering process by an applied magnetic field and the influence of sputter power was studied by Wang et.al. [14]. They found that anisotropy field decreases with the increasing sputter power and obtained a magnetostriction of 66 ppm in the films deposited at 60 W. The effects of Boron addition to the FeGaB films were investigated by Lou et al. [15] and a structural transformation from polycrystalline to amorphous with enhanced soft magnetic and microwave properties along with a high magnetostriction constant of

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70 ppm at a B content of 12 at.% was observed. Basumatary et al. [16] investigated the effect of substrate temperature on FeGa films and observed a maximum magnetostriction of 200 μ-strains for the film deposited at 450 °C. Eliot et al. [17] showed that Galfenol can be deposited by electrodeposition and measured a magnetostriction value of 140 ppm. However, the influence of substrate temperature on the magnetostriction and its concomitant effects on the magnetostriction has to be understood further to ensure the advances in real time applications. Therefore, in this study, we investigate the effect of substrate temperature on the morphological, structural and magnetic properties of FeGa sputtered thin films and how the magnetostriction changes with respect to substrate temperature.

2. Materials and methods

2.1. Material synthesis

A two-inch diameter Galfenol ($Fe_{73}Ga_{27}$) target with a purity of 99.99% (from Able target Inc.) was used to deposit FeGa thin films on Si substrates by DC magnetron sputtering technique. The substrates were cleaned and native oxide layer was removed using HF before the sputter deposition. The sputtering chamber was initially pumped down to a base pressure of 2×10^{-5} mbar. Argon was used as a sputtering gas and the pressure was maintained at 4×10^{-2} mbar. The substrate to target distance was maintained at ~5 cm and the substrate temperature was either 50 °C, 150 °C, 250 °C or 350 °C. The deposition process was carried out at a target power of 80 W and the total time of deposition was 30 min. After the deposition, chamber was purged with Ar for ~30 min. These films were analyzed using different characterization methods as described in the next section.

2.2. Material characterization

The thickness of the thin films was about 500 ± 30 nm and the films were not subjected to any post-deposition treatment. The as prepared films were analyzed by Glancing Incidence X-ray Diffraction (GI-XRD) technique with Cu-Kα radiation to study the crystal and phase structure. A scanning electron microscope (SEM) with a field-emission electron source (Supra 55 by Carl Zeiss) was used to study the microstructure of the films. Both the surface morphology (top view) and fracture cross-section analysis of the films were performed. Energy Dispersive X-ray Spectroscopy (EDS) was employed to analyze the composition of the films. In-plane and out-of-plane room temperature magnetic measurements were carried out using a Vibration Sample Magnetometer (VSM). The topology and roughness of the films were measured by Atomic force microscope (AFM). Magnetostriction of the samples was measured by a custom built magnetostriction measurement system [18].

3. Results and discussions

3.1. Morphological and structural analysis

Fig. 1(a–d) show the cross-sectional image of films grown at 50 °C, 150 °C, 250 °C and 350 °C, respectively. High magnification top view images are shown in the inset. At lower substrate temperatures of 50 °C, thin columns consisting of smaller grains are observed. When the substrate temperature rises to 150 °C, the columnar diameter as well as spherical grain diameter increases. With further increase in substrate temperature to 250 °C, the columnar structure of the films is gradually evolved and separate columns are observed. This columnar morphology dissolves into planar structure towards the surface. At the higher substrate temperature of 350 °C, the columnar structure has collapsed and one gets random orientation in growth leading to planar growth. This loss of structural anisotropy results in the non-uniform growth of thin film with varying particle sizes and shapes in the prepared thin films.

Fig. S1(a–d) shows the top view images of the films grown at substrate temperatures of 50 °C, 150 °C, 250 °C and 350 °C. It is observed that there is a significant change in morphology with increase in substrate temperature. At 50 °C, the morphology of the film was prismatic in nature constituting of smaller particles (~8 nm). These smaller particulates cumulated to form the prismatic structures (~50 nm). This prismatic morphology was homogeneous over the entire film surface. As the substrate temperature increases to 150 °C, the regular prism-like shape of the particles is deteriorated. The films still consist of smaller particulates (~10 nm) and these particulates combines together to form the bigger (~40 nm) partly prismatic particles. A further change in morphology is observed when the substrate temperature was raised to 250 °C. The particles, at this condition, no longer retain the prism-like shape, but have become more or less spherical in shape. The size of the particle is widely distributed (average particle size ~75 nm) though the particles still maintain their innate nature of being constituted of smaller particulates (~25 nm) [19]. At 350 °C, the particles do not retain any certain shape and is flake - like with particle size varying to give an average of ~30 nm.

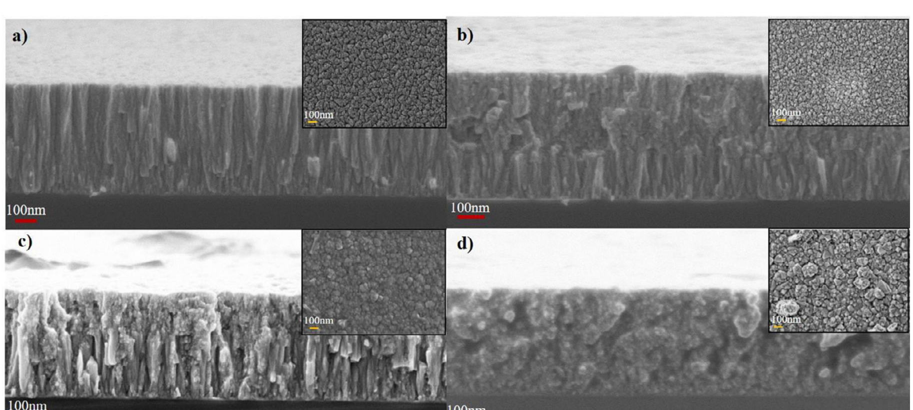

Fig. 1. The fracture cross-sectional SEM images showing the microstructure of the FeGa thin films grown at substrate temperature of (a) 50 °C, (b) 150 °C, (c) 250 °C and (d) 350 °C. The insets show the corresponding magnified plane-view images.