Sensors and Actuators A 235 (2015) 218–226

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Studies of the magnetostriction in thin films: Experimental, analytical and numerical analysis

Harshad Mishra[a], J. Arout Chelvane[b], A. Arockiarajan[a,*]

[a] Department of Applied Mechanics, Indian Institute of Technology Madras, India
[b] Defence Metallurgical Research Lab, Kanchanbagh (PO), Hyderabad, India

ARTICLE INFO

Article history:
Received 20 July 2015
Received in revised form 1 October 2015
Accepted 2 October 2015
Available online 24 October 2015

Keywords:
Magnetostriction
Thin-film
Tip-deflection
COMSOL

ABSTRACT

Magnetostrictive thin films primarily find use for their actuation properties. Micro-electro-mechanical systems (MEMS devices) capitalize on the induced mechanical deformations when these thin films are subjected to a magnetic field. In this study, experiments are conducted on Tb–Dy–Fe thin film samples to determine their characteristic magnetization curves. The thin films are subjected to a periodically varying magnetic field of ±0.6 T and the deflections at the tip are measured. A simple analytical model based on the theories of elasticity and considering transversely isotropic material properties of both the film and the substrate layers has been proposed to predict the deflections. The study has been extended to predict the tip deflections numerically using Comsol Multiphysics. The measured tip deflections are further compared with the simulated analytical and numerical results, which are found to agree with each other.

1. Introduction

Rare earth elements from the lanthanide series usually exhibit the high magnetostriction, due to large spin-orbit interaction, thereby resulting in dimensional change being very strongly affected by their state of magnetization [1]. These materials exhibit a behaviour called magneto-mechanical coupling which enables them to transduce between their magnetic and mechanical energies. An applied magnetic field induces a strain (direct effect) and conversely an applied stress causes a change in the magnetization of the material (indirect effect).

Due to this coupling behavior, magnetostrictive materials find use in many applications, particularly as transducers for SONAR, actuators for flight control surfaces such as flaps, rudders and ailerons and sensors for magnetic field detection, etc [2–5]. Several analytical and numerical models have been developed to study mechanical as well as magnetic characteristics of these materials [6,7]. Huang et al. [8] have developed a non-linear magneto-thermo-mechanical model which takes into account the thermal effects on magnetomechanical coupling while describing the electromagnetic, mechanical and thermal dynamics of the system.

But these materials are highly brittle and therefore in order to improve their ductility several alloying additions with boron, cobalt, carbon etc were attempted. The magnetostriction which is seen as an increase or decrease in the length of the sample in its bulk form is manifested as bending of the film-substrate assembly in thin film form. These materials in thin film form are exploited for a variety of applications in MEMS based devices such as micro-sensors, micro-actuators, structural health monitoring and magnetic storage devices.

Ludwig and Quandt [9] have reviewed the applications of magnetostrictive thin films in MEMS systems considering a cantilever configuration of the bimorph for their experiments as well as discussed the temperature dependence of magnetostriction. Lee and Cho [10] discuss the deposition as well as characterization of multilayered magnetostrictive thin films. Along with magnetic characterization, they have also reported mechanical characterization by considering a cantilever configuration. Both single layer as well as multilayer amorphous films provide good deflections for microactuator and MEMS applications. Honda et al. [11] proposed a new concept for microactuation using magnetostrictive bimorph cantilever thin films. Steiner et al. [12] have presented their design of a planar micromechanical magnetostrictive actuator. They have done a numerical analysis using Comsol along with fabrication and experimental verification of the design. Thin films mainly find use in MEMS devices such as actuators, sensors, micro-pumps as well as magnetic storage devices [13–15].

* Corresponding author.
E-mail addresses: harshad.vr1@gmail.com (H. Mishra), jac@dmrl.drdo.in (J. Arout Chelvane), aarajan@iitm.ac.in (A. Arockiarajan).

http://dx.doi.org/10.1016/j.sna.2015.10.007
0924-4247/

We typically think of thin film based devices in terms of their electronic, magnetic or optical properties. However, it is necessary to understand the mechanical properties of thin films as well. Considering the structure of a thin film alone, it is difficult to study its magnetostriction. On the other hand, the elastic properties of the substrate also play an essential role in determining the strains observed when applying a magnetic field. Hence it is important to consider a bi-morph consisting of the magnetic thin film and its non-magnetic substrate in order to completely study the mechanical properties.

There are various experimental methods for investigating the magneto-elastic properties of thin films [16,17]. Buford et al. [18] have developed a novel method for measuring the effect of strain on the magnetization curves of a magnetic thin film. The indirect ones are based on the stress dependence of any magnetic property – e.g. susceptibility or resonance frequency. However, the most usual direct method is to observe the deflection at the end of the bi-morph when magnetized [19–21]. Raghunathan et al. [22] have compared the direct and indirect methods of measuring magnetostriction in thin films. They have shown that the magnetostriction values obtained through the inverse technique with 1D and 2D models agree well with those obtained through the direct method. Previous analytical studies [23,24] have focused on deriving the tip deflection in thin films based on the theory of elasticity considering isotropic material properties for the active layer as well as the substrate. More recently, studies done by Mudivarthi et al. [25] have developed a finite element based model to predict the magnetic flux density and bending strain for an Al-galfenol unimorph cantilever. Their results agree well with experiments carried out on single-crystal galfenol films.

Experimental studies on the magnetization characteristics have been carried out which not only provide the hysteresis loops but also provide ideas about the magnetic anisotropy in the thin films [26–28]. Although previous studies have mentioned about the ΔE effect in thin films, [29–31] this study does not consider the effect, primarily because transversely isotropic properties have been considered. Numerical simulations of the same have also been carried out using commercially available Comsol Multiphysics software which are then compared with experiments conducted on Tb–Dy–Fe thin film samples.

In view of the above motivating factors, the deflection characteristics of magnetostrictive thin films have been studied in this work. An experimental setup based on the direct method has been developed to measure the deflection induced due to an applied magnetic field. In order to better understand the phenomenon, a simple analytical model which considers transversely isotropic material properties for both the active layer as well as the substrate layers has also been developed to predict the tip deflection using the theory of elasticity. Due to the limitations of the analytical model in emulating the experimental configuration, we have also conducted a numerical simulation to predict the deflection of the Tb–Dy–Fe thin film samples using commercially available Comsol Multiphysics software.

2. Experimental description

A 400 nm thick Tb–Dy–Fe thin film is deposited on a 100 μm thick silicon wafer having ⟨100⟩ orientation at room temperature at a constant rate of 2 Å/s employing an electron beam evaporation system. A base vacuum of ~1 × 10^{-6} Torr is achieved prior to the deposition. Subsequently, these films are annealed at 400 °C for 30 min under vacuum better than 1 × 10^{-6} mbar. A thin layer of chromium (~5 nm thick) is used as a capping layer to avoid oxidation. Structural studies are carried out employing an X-ray diffractometer. Magnetization measurement is carried out using a vibrating sample magnetometer at room temperature up to a maximum magnetic field of 20 kOe. Magnetization measurements are carried out in the plane of the film and perpendicular to the plane of the film. The configuration of the magnetic field with the plane of the film is displayed in Fig. 1.

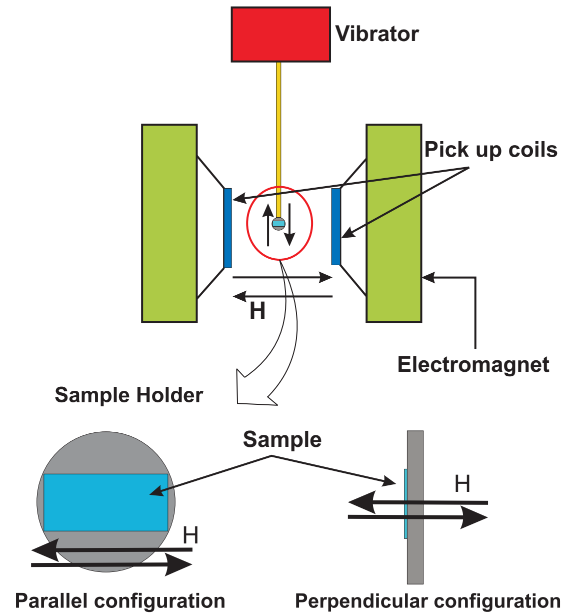

Fig. 1. Schematic representation of the VSM test.

Fig. 2 shows the X-ray diffraction (XRD) patterns of as deposited and annealed Tb–Dy–Fe thin films. Room temperature deposited Tb–Dy–Fe thin films display an amorphous structure. However, after annealing, the film is found to be crystalline in nature and XRD reflections are found to match with the peaks corresponding to the cubic Laves phase structure.

Fig. 3a shows the magnetization curves of Tb–Dy–Fe films deposited at room temperature. The magnetization curves show the presence of strong perpendicular magnetic anisotropy (PMA) along the out-of-plane direction. Amorphous rare-earth iron intermetallic thin films based on Tb–Fe and Tb–Fe–Co is also found to exhibit similar PMA. It has been reported that films deposited at temperatures less than 0.2 times the melting point (T_M) of the alloy usually display near columnar growth with amorphous structure due to limited adjacent atom mobility. Since the film was deposited at 30 °C, which is much less than the 0.2T_M (T_M = 1270 °C), the film exhibits columnar growth with amorphous structure. The presence of such columnar growth can be attributed to the origin of PMA in

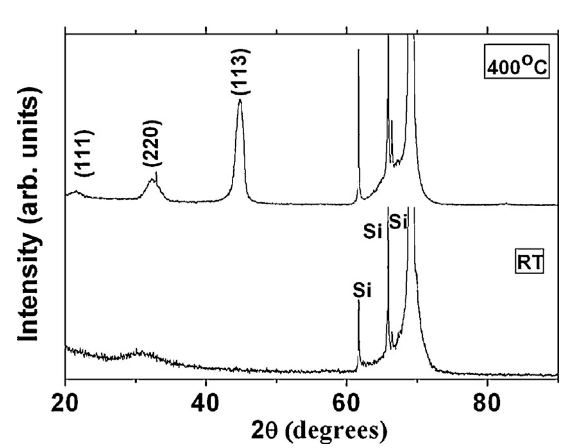

Fig. 2. XRD pattern of as deposited and annealed Tb–Dy–Fe thin film.