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Magnetostriction measurement in thin films using laser Doppler vibrometry

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ABSTRACT

This paper reports the laser Doppler vibrometry based measurement of the magnetostriction in magnetic thin films. Using this method, the strain induced by an AC magnetic field in the polycrystalline cobalt ferrite and nickel ferrite thin films grown on silicon and platinized silicon substrates was measured under a DC magnetic bias. The experimental setup and the derivation of the magnetostriction constant from the experimentally measured deflection values are discussed. The magnetostriction values derived using force and bending moment balances were compared with that derived from an industry standard relationship. In addition, we corroborate our approach by comparing the values derived from bending theory calculations of magnetically induced torque to those from measurements using Vibrating Sample Magnetometer (VSM). At high DC magnetic field bias, the magnitude of magnetization calculated from the measured magnetostriction was found to match the measured magnetization by VSM.

1. Introduction

Magnetic thin films are used in magnetic storage media, generators, and magnetoelectric sensors. The strain induced in such films by an external magnetic field, namely, magnetostriction is a fundamental property. If the magnetostriction is positive, the sample elongates in the direction of the applied field irrespective of the direction of rotation of the magnetic moments and the thickness dimension perpendicular to the applied field shrinks in proportion to Poisson's ratio such that the volume remains constant. If the magnetostriction is negative, the sample length decreases and the deformation in thickness direction increases. Under a varying magnetic field, magnetic thin films deposited on substrates impose a change in curvature of the substrate because of differences in the elastic moduli of the film and the substrate.

Magnetostriction measurement techniques can be broadly classified as either direct or indirect, depending upon the condition whether the strain is being measured directly or the magnetostriction is deduced from a measurement of some other physical property dependent upon the strain. Measurements using strain gauges, capacitance transducers or optical techniques are considered as direct method [1]. In bulk applications, strain gauges (sensitivity 10^{-6}) are commonly used whilst the other commonly used technique is based on the capacitance change (sensitivity 10^{-6}) [2]. However the challenges with both of these methods are the complex sample preparation and the inability to measure saturation magnetostriction respectively. Strain gauges are easy to use but have limited sensitivity typically on the order of ~1 ppm and their performance is highly dependent on transfer of the sample strain across the glue to the gauge. As the saturation magnetostriction (λ_s) has to be determined from measurements conducted in the parallel and perpendicular direction to the applied external field, strain gauge measurements for λ_s have to configured to make both measurements whilst capacitance method cannot measure in the perpendicular mode [2]. However, for unobtrusive (no damage to sample) non-contact strain metrology of thin films, the optimal approach appears to be optically based methodologies.

Prior studies reported in literature have conducted magnetostriction measurement in thin films using optical methods [1,3–11]. The sample was rectangular shaped (with length»width) and clamped as a cantilever. Such a setup requires the clamping of a thin film system inside a DC Helmholtz coil whilst also being under a fixed DC magnetic field of an electromagnet. The alignment of the clamp, sample, coil and electromagnet places limitations on the sample shape and size and mounting configuration. In this study,

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instead of using a cantilevered film–substrate system, we have placed the thin film sample directly on a non-magnetic stage inside a Helmholtz coil that applies an AC magnetic field parallel to the sample. In doing so, we have obviated the need of a clamp, reduced the noise contribution arising due to the vibrations coupling into a cantilever and achieved more freedom with respect to the sample shape and dimensions. Instead of using a rotating DC magnetic field from 3 Helmholtz coils in the x, y and z directions [7–9] or directionally switched DC field in a single Helmholtz coil [10,11], we use a 1 kHz AC field in a single Helmholtz coil surrounding our sample. We then used laser Doppler vibrometry (LDV) to measure the induced displacement at 1 kHz in the unclamped sample. Vibrometry based on Doppler effect is often used in the modal analysis of vibrating structures [12] and has been utilized for magnetostriction measurements of steel sheets (required attaching 2 mirrors on to the mm-scale sheets) [13]. The accuracy and resolution of such systems have improved to the picometer ($1\ \text{pm}=10^{-12}\ \text{m}$; $<0.4\ \text{pm}/\sqrt{\text{Hz}}$) range [14] and therefore opened the possibility of using such equipment for microstrains expected (e.g. the 1–5 ppm strain in <20 nm polycrystalline Fe thin films in [7]) in magnetically induced stresses in thin films. To develop this new metrology approach, we utilized polycrystalline thin film samples of pulsed laser deposited cobalt ferrite ($CoFe_2O_4$; CFO) and RF sputter deposited nickel ferrite ($NiFe_2O_4$; NFO). We introduced variability by (a) varying film thicknesses and (b) using various substrates and finally annealing under different post-deposition conditions.

2. Experimental procedure

The schematic diagram of a typical laser Doppler vibrometry system is shown in Fig. 1 [14]. We utilized a Polytec LDV connected to a Polytec 5000 controller to measure the deflection (Δ) of a magnetostrictive film under two different applied AC magnetic fields of 1 Oe and 1.45 Oe at 1 kHz with varying DC magnetic bias from 0 to 6000 Oe. The AC field was applied parallel to the DC bias (longitudinal or parallel mode). The samples were <10 mm on their sides and were square shaped. The CFO films were deposited at 800 °C on platinized Si (150 nm Pt/10 nm Ti/300 nm SiO_2/0.5 mm Si; Inostek, Korea) substrates whilst NFO films were deposited on both platinized Si and 0.5 mm Si substrates. The room temperature sputtered NFO films were post annealed at 650 °C, 700 °C and 750 °C in an atmospheric vertical furnace. The film thickness was measured by Variable Angle Spectroscopic Ellipsometry. Squid (Superconducting QUantum Interference Device) measurements on a Quantum Design MPMS 3 system were conducted to identify the M–H data on the thin film samples.

The samples were directly placed inside a Helmholtz coil of dimension 34 mm width × 57 mm diameter with 28 Ω coil resistance. The Helmholtz coil was placed between the poles of a GMW Associates 3470 dipole electromagnet driven by a Kepco Model BOP 100-4M power supply. Initially, a Polytec MSA 500 laser head was utilized but the displacement data with applied magnetic field was noisy. The issue was found to be related to the effect of the magnetic fields on the optomechanical mechanism inside the laser head. Polytec OFC 353 laser head which has a depth of field of 450 mm was next utilized but still presented challenges. It was found that a minimum separation distance of 28 in. is required between the magnetic field source (for a DC field of 6000 Oe and 1.45 Oe 1 kHz AC; the minimum separation varies with strength of the applied magnetic fields) and the laser head of the vibrometer. Despite this solution, it was noticed that nonmagnetic samples like Si substrate or a platinized Si substrate showed finite displacement under the 1 kHz AC field. Further investigations led to the finding that the laser vibrometer head, sample holder and magnetic Helmholtz coil plus electromagnet system are coupled structurally and thus any mechanical displacement in one of these components is propagated to the other influencing the overall magnetostriction measurement. Coils under an AC current are known to vibrate, commonly known as coil noise or coil hissing [15,16]. Each of the 3 components of the measurement setup, the coils, sample holder and the vibrometer had to be mechanically isolated from each other in order to avoid the mechanical coupling (Fig. 2 (a)–(c)). The sample was loaded onto a 32 in. wooden spatula that was clamped to a pair of electromagnetic shakers (with shorted coils) capable of providing needed vibration isolation. The Helmholtz coil plus DC electromagnet system was placed on an inflated inner tube and the laser was mounted on a tripod with rubber feet.

3. Results

In response to the applied magnetic field, magnetostrictive thin film extends in the direction of applied magnetic field and shortens in the perpendicular direction developing an anisotropic biaxial stress (thickness being very small compared to other

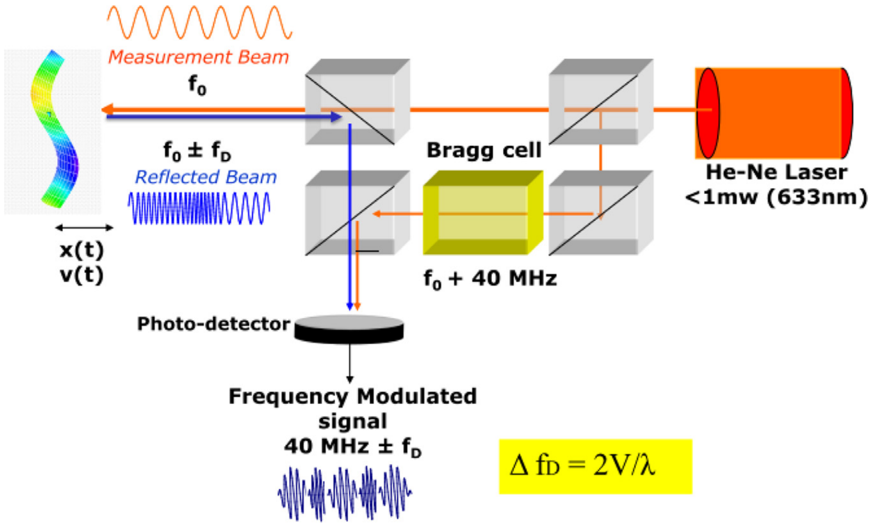

Fig. 1. Laser Doppler vibrometry technique.