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Measuring the inverse magnetostrictive effect in a thin film using a modified vibrating sample magnetometer

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A method for measuring the magnetostriction of thin films using a vibrating sample magnetometer is described. We describe the design of a custom sample holder to apply an adjustable bending stress to the sample during measurement and observe the resulting change in the M-H loop. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4863492]

I. INTRODUCTION

Magnetostrictive materials, which change shape when placed in a magnetic field, are useful in mechanical actuator applications.[1] Characterization of the magnetostrictive effect typically consists of applying a magnetic field and measuring either the change in dimension of a bulk sample or measuring bending of a bimaterial beam. Displacement measurements are typically done via capacitive measurement[2] or using optical interferometry.[3] The percent change of length of the sample as the magnetization increases to the saturation value is referred to as the saturation magnetostriction or λ_s.

The inverse magnetostrictive effect, known as the Villari effect, is the change in magnetic properties of a material when subjected to mechanical stress. It is used in a variety of applications such as magnetic sensors and data storage.[4,5] It has been shown that magnetostriction characterization using the Villari effect and the magnetostrictive effect yields comparable results when the magnetization process and crystallographic texture are known.[6,7] Without this information, the effect of strain on the hysteresis loop cannot be predicted from the saturation magnetostriction alone and it is therefore important to have methods of measuring the inverse effect.

Characterization of the inverse magnetostrictive effect involves applying strain to a sample and examining changes in its magnetic properties. Previous work has demonstrated measurement techniques which stress the sample while measuring the hysteresis loop in a B-H looper[8] and vibrating sample magnetometer (VSM)[9] or measuring the change in anisotropy field by ferromagnetic resonance (FMR).[10]

We present a method of measuring the effect of strain on the magnetic properties of a thin film by straining a sample within a VSM using an adjustable fixture and measuring the resulting M-H loop. This approach is similar to the method presented by Choe and Megdal,[8] but the use of a VSM in lieu of a B-H Looper allows for much larger applied fields and simpler calibration. Our approach differs from that presented by Linville *et al.*[9] in that our fixture allows for adjustment of the applied force instead of a single force created by a curved fixture with constant radius.

II. METHODS

A sample holder was constructed to apply a known bending stress to the sample substrate during measurement. Key features of the design include light weight and axial symmetry to avoid introducing lateral vibrations of the vibrating rod. The sample holder, illustrated in Figure 1 and shown in Figure 2(a), is machined out of acetal plastic (Delrin) and consists of two halves: The top half is mounted rigidly on the end of the vibrating rod and has two downward facing ridges spaced 4.23 mm apart. The bottom half is pulled upwards by four Kevlar strings tensioned by springs. It has two upward facing ridges spaced 7.73 mm apart. A 1 cm square sample is clamped between the two halves. The magnetostrictive film is patterned to fit between the two inner ridges of the sample holder, where the applied strain is uniform.

The stainless steel springs are positioned outside of the magnetic field to avoid magnetic interference and are attached to an adjustable tensioning system mounted on the vibrating rod, as seen in Figure 2(b). The tensioning system consists of a threaded tube that can rotate around the vibrating rod while being held against a stop which is rigidly attached to the vibrating rod. A spring attachment assembly with internal threads rides up and down on the tube to adjust the tension on the springs. The applied force is calibrated by hanging known weights from the sample holder and measuring the spring extension. This same extension is replicated

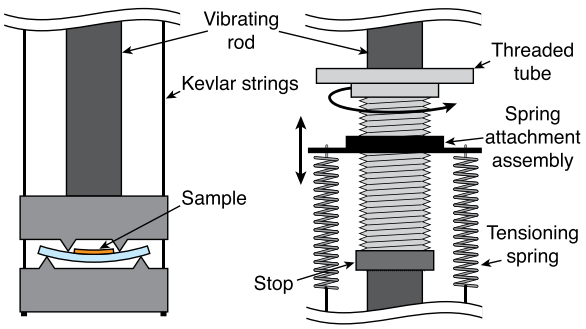

FIG. 1. Schematic of the bending fixture and adjustable tensioning system. The threaded tube can rotate around the vibrating rod but is held at a constant vertical position by a stop. When the knob on top of the threaded tube is rotated, the spring attachment assembly moves vertically to adjust the force on the bending fixture.

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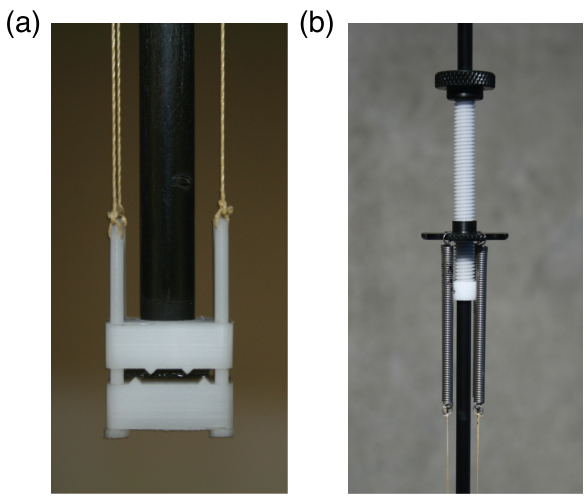

FIG. 2. (a) Image of the bending fixture. (b) Image of the adjustable tensioning system. The white threaded tube is affixed to the rod but can be rotated to raise and lower the black spring attachment assembly.

in situ by rotating the threaded tube to position the spring attachment assembly.

During measurement, the rod vibrates sinusoidally at 40 Hz with a peak-to-peak amplitude of approximately 5 mm. The force required to accelerate the sample and sample holder causes variation in applied force to the sample. The peak acceleration of the rod is calculated to be 160 m/s^2. The mass of the bottom half of the sample holder (which is not rigidly attached) is 0.93 g, while a typical sample weight is 0.1 g. This gives a maximum force due to vibration of 150 mN. Because of this, a minimum force of about 7 N must be applied to the substrate to hold it in place, while the entire fixture vibrates. This firmly holds the sample in place and limits the variation of force to be less than 2.5% of the applied force. The maximum force is greater than 20 N, limited by the fracture strength of the quartz substrate.

This four-ridged method of applying force provides a uniform stress and strain (σ and ϵ) distribution along the substrate surface between the two inner ridges

$$\sigma = \frac{3Fc}{wh^2}, \tag{1}$$

$$\epsilon = \frac{\sigma(1 - v_s^2)}{E_s}, \tag{2}$$

where F is the total force applied by the springs, c is the distance between inner and outer ridges (1.75 mm for our fixture), w is the width of the sample, h is the sample thickness, E_s is the Young's modulus of the substrate, and v_s is the Poisson ratio of the substrate. The dimensions w, h, and c are illustrated in Figure 3. Tensile strain in the film can be obtained by flipping the substrate over.

The sample holder exhibits a small paramagnetic response. For samples with small magnetic moment, the sample holder without a sample, or better yet with a bare substrate, is measured and is subtracted from the measured film response.

While not calculated here, some applications such as force sensors require precise calculation of the saturation magnetostriction. With some knowledge of the magnetization processes, it is possible to determine the magnetostriction constant, λ_s, from the inverse magnetostriction measurement. For samples with a well defined hard axis, it can be determined by measuring the anisotropy field at two different applied forces.[11] Otherwise, a saturating transverse field may be applied during measurement to remove the hysteretic effects and the resulting M-H loops with and without applied strain can be compared.[12]

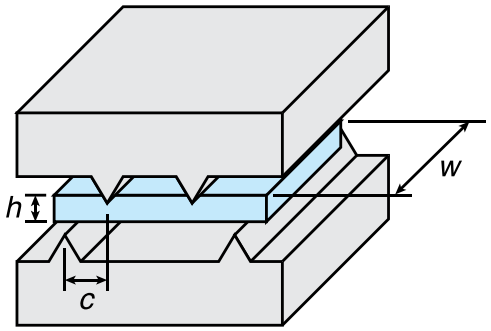

FIG. 3. Dimensions determining the sample strain by Eq. (1).

III. MEASUREMENT

In this work, the effect of strain on a galfenol (FeGa) thin film deposited on a quartz substrate ($E_s = 72$ GPa and $v_s = 0.17$) is characterized. The 57 nm thick galfenol film was sputter deposited from a $Fe_{81.6}Ga_{18.4}$ target. Galfenol was chosen due to its relatively high magnetostriction coefficient and ease of deposition by sputtering.[13] The substrate width, w, is 7.58 mm and thickness, h, is 0.508 mm.

The sample is first mounted in the VSM using a standard sample holder to measure the unstrained M-H loop (due to the minimum force required to hold the sample, it is not possible to measure the sample in an unstrained state within the bending fixture). The sample is then placed in the bending fixture, the spring length adjusted to achieve the desired applied force ranging from 7 to 20 N, and additional M-H loops recorded, as shown in Figure 4. The direction of applied field can be varied by rotating the VSM assembly. The effect of strain on the coercivity of the galfenol film can be seen in Figure 5 for strain applied both parallel and

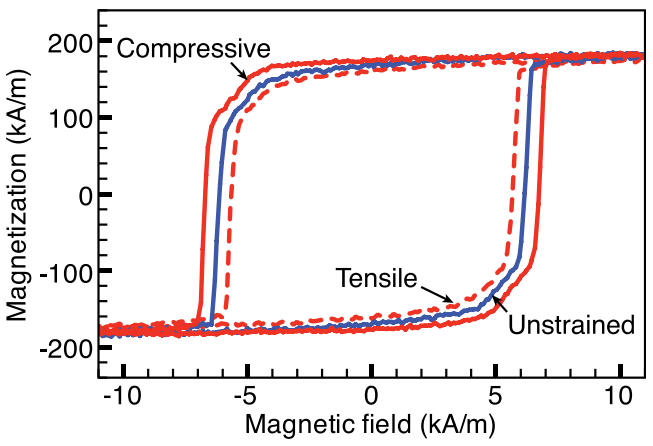

FIG. 4. Measured M-H loop of a galfenol film under unstrained, compressive, and tensile strain conditions.

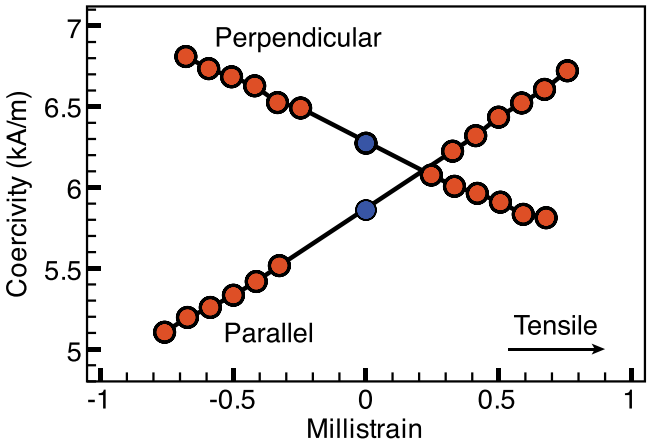

FIG. 5. Measured coercivity as a function of applied strain both parallel and perpendicular to the applied field.

perpendicular to an applied field. The difference seen in zero-strain coercivity is due to the change in measurement direction with respect to the sample. With the application of ± 0.77 millistrain, we see a stress induced change in coercivity of $\pm 15\%$.

IV. CONCLUSION

We have demonstrated a new method of measuring the effect of strain on the M-H loops of magnetic thin films using a vibrating sample magnetometer. Our approach allows for repeatable measurements at high field and variable strain without the need for complex calibration.

ACKNOWLEDGMENTS

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