Magnetostriction Effect of Amorphous CoFeB Thin Films and Application in Spin Dependent Tunnel Junctions

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Abstract

CoFeB thin films and magnetic tunnel junctions using them are studied for magnetostriction effect. The single layer films were sputter deposited with excellent soft magnetic properties including a high saturation magnetization of 1.5 T, a near zero hard axis coercivity, a low easy axis coercivity of 2.0 Oe, and an induced magnetic anisotropy field of 32 Oe. The saturation magnetostriction constant is measured to be 31 ppm. Magnetic tunnel junctions (MTJ) were fabricated and tested for potential strain gauge applications. The gauge factor for the magnetostrictive MTJs, a measure of strain sensitivity, is many times of the best piezoresistive devices.

I. Introduction

CoFeB thin films have attracted much attention especially after very high tunnel magnetoresistance values of >70% was obtained with an easily manufacturable process in spin dependent tunnel (SDT) junctions using this material. [1] It is imperative to study other properties, such as magnetostrictive effect, for practical use of this material. To quantify the magnetostrictive effect for thin magnetic films on thick nonmagnetic substrates, it is convenient to measure the reverse effect of magnetostriction. [2,3] The high TMR value of the most advanced tunnel junctions offers potential for high strain sensitivity for strain gauges, along with other advantages of MTJs. [1] Strain gauges have found wide applications in pressure sensors, [4] accelerometers, force sensor, and others in industrial, automobile, civil engineering, aircraft and aerospace, robotics, and medical arenas. There are mainly two types of strain sensors in use: piezoresistive devices and capacitive devices. Silicon-based piezoresistive strain devices have the highest sensitivity measured by gauge factors ranging from 100 to 200 [5]. However silicon-based strain devices have an extremely high temperature-coefficient-of-resistance (TCR) of 9%/degree and can operate only at relatively low temperatures, and they are widely used in automobiles with rigorous temperature compensation schemes. In contrast, metal piezoresistive devices have a much smaller TCR of ~0.2%/degree and can operate at high temperatures. However they have a much smaller gauge factor of 2-6. Here we present a study of the magnetostriction effect of the CoFeB material and its MTJ device application as strain gauges that offer potential for much better performance.

II. Experiment

CoFeB thin films and SDT wafers were deposited using DC magnetron sputtering in a Shamrock system with a base pressure lower than 1.0×10^{-7} Torr. A ternary alloy CoFeB target was used for the deposition. The Al_2O_3 tunnel barrier was formed by depositing a layer of metallic Al then oxidizing it in a plasma containing Ar/O_2. A magnetic field of 50 Oe was applied during deposition of single layers and SDT stacks to induce the easy axes in the magnetic layers. [6] The film structure was characterized using X-ray diffraction and electron diffraction and found to be amorphous pre and post annealing. [7] The SDT wafers were patterned using typical photolithography techniques to form the junctions. Annealing was done in forming gas at a temperature of 250 °C for one to two hours with a magnetic field applied to the original pinning direction induced during deposition. Magnetic properties of bulk samples were measured using a shb-109A B-H Loop Tracer. Magnetostrictive properties were measured using a homemade fixture by applying controlled strains while enabling both magnetoresistance and BH Looper measurements. All the measurements were done at room temperature unless mentioned otherwise.

III. Results and Discussion

III.1 Single Layer CoFeB Films

Single layer CoFeB films were deposited on different buffer and overcoat layers, which are compatible with the eventual MTJ structure. The crystal structure of these films was measured using X-ray diffraction and electron diffraction and found to be amorphous at both pre and post anneal. Excellent soft magnetic properties were obtained, such as a high saturation magnetization of 1.5 T, a near zero hard axis coercivity, a low easy axis coercivity of 2.0 Oe, and an induced magnetic anisotropy field of 32 Oe. No difference is observed with different buffer (Ta, Ru, TaRu, SiN) and overcoat (Al_2O_3, Ru, none) layers tried. Typical easy and hard axis hysteresis loops are given in Figure 1 with no strain applied.

A homemade strain test fixture was made to allow more versatile magnetostriction tests. It is noted that there are three critical orientations in such testing: the easy magnetic axis due to the field-induced anisotropy (Hk) during deposition/annealing; the direction of the applied strain; and the direction of the applied magnetic field. Figure 2 shows the typical behavior for the hard axis loop with a compressive strain, no strain, and tensile strain applied along the hard axis for a 100Å thick CoFeB film. In another word, the strain direction is parallel to the applied magnetic field and perpendicular to the Hk. As can be seen from Figure 2, the applied tensile strain transforms the hard magnetic axis loop to an easy one, though not completely. The compressive strain doubles the effective anisotropy from 32 Oe to 64 Oe. It is noted that this mode of operation can be readily used for strain gauge applications when CoFeB layer are made into tunnel junctions. The effect can be understood in such a way that a perpendicular tensile strain decreases the effective magnetic anisotropy field, thus making it easier for the magnetization to saturate, whereas a tensile strain does the opposite. The effect of the same strain conditions but with field applied along the easy axis was also studied and the results are consistent with what are shown in Figure 2. The saturation magnetostriction constant λ for such a CoFeB film of 100Å thick is calculated to be +31 ppm, as derived in a later section. In contrast, for none-magnetostrictive materials with a $\lambda < 0.1$ ppm such as Permalloy deposited, there is no discernable difference between the strained and unstrained loop under the same test conditions. Several other materials have also been deposited and tested under similar conditions including $Co_{95}Fe_5$, $Ni_{65}Fe_{15}Co_{20}$ and NiFe with compositions other than Permalloy. It is clear that CoFeB has the highest λ value among the samples tested. Due to the very high TMR value as will be shown later that CoFeB is especially good for strain gauge application when used in MTJ devices.

The anisotropic magnetoresistance (AMR) for single layer-CoFeB films is measured to be on the order of 0.1% when saturated, which is much smaller than the typical value of 2-3% for Permalloy or NiFeCo. This value of 0.1% is also much smaller than the TMR value of >60% for tunnel junctions using this material, as will be described in the next section. Therefore, AMR is not expected to have a significant effect on the measurement or performance of these magnetostrictive-magnetoresistive devices.

III.2 Magnetotransport Properties of MTJs

SDT junctions were formed by patterning and tested for magnetoresistive properties. The highest room-temperature tunnel magnetoresistive value achieved for this type of junctions was 70.4% that was reported in reference. [1] Magnetostriction measurements have been done on similar junctions under a bias voltage of about 100 mV per junction, thus the measured TMR values are slightly lower then 70% due to the bias voltage dependence. The strain effect of TMR plots on tunnel junctions using CoFeB as free layers is shown in Figure 3. When a tensile strain perpendicular to the easy axis is applied to the tunnel junctions, the easy axis TMR loop completely changes to a hard axis TMR loop. Comparing with the results shown in Figure 2 for a single CoFeB layer of 100 Å thick, a thinner CoFeB layer of 50 Å used in a SDT junction has slightly smaller Hk. Therefore the same strain of 233 ppm makes a complete change of the effective anisotropy for the thinner layer. This means that the original induced magnetic anisotropy (when no strain is applied) of the free CoFeB layer is completely overpowered by the strain-induced anisotropy. If one focus on the zero field points on the zero-strain and tensile-perp plots, it is easy to see the effect of the strain which changes the output voltage from either the low or high (depending on the initial state) to a middle point. A minor TMR loop for the tensile-perpendicular situation is shown in Figure 4. There is no discernable hysteresis in the –6 to +6 Oe range, with a field sensitivity of 1.6%/Oe, which is a very respectable value for field sensor device applications.

III.3. Strain Sensitivity Analysis

Magnetostriction effect has long been observed and analyzed, and so has its reverse effect that we actually use [2,3]. Here we present a simple derivation for an equation relating the gauge factor and the magnetoresistive properties of the SDT devices.

For a 2-D free-standing thin film, elastic in the linear region, Hooke's law describes

$$\sigma = \frac{\varepsilon \cdot E}{1-\nu^2} \qquad (1)$$

the strain-stress relationship:

where σ is the stress (force per unit area), E the Young's modulus, $\varepsilon = d\ell/\ell$ the strain, ℓ the length in the strain direction, $d\ell$ the change in length, and ν the Poisson ratio.

Magnetostrictive effect can be described by a magnetic anisotropy field *Hs* induced

$$H_s = \frac{3\sigma\lambda}{Ms} \qquad (2)$$

by stress expressed as: [8]

where λ is the magnetostriction constant and Ms the saturation magnetization.

Substituting σ in (2) by (1) results in:

$$H_s = \frac{3\lambda}{Ms}\frac{\varepsilon \cdot E}{(1-\nu^2)} \qquad (3)$$

The strain ε_f for a thin film (*f*) on a much thicker substrate (*s*) with a bending radius C can be expressed as:

$$\varepsilon_f = \frac{d_s}{2C} = \frac{0.02 inch}{2 * 43 inch} = 233 ppm \qquad (4)$$

combining (3) and (4) results in:

$$\lambda = \frac{2C \cdot MsHs}{3d_s} \cdot \frac{(1-\nu^2)}{E_f} \qquad (5)$$

Equation (5) provides a convenient way to measure the magnetostriction constant λ using C, Hs and other known sample parameters. In our case, λ is calculated to be 31ppm.

When Hs has an equal or greater magnitude but perpendicular to Hk of the magnetostrictive free layer in a MTJ, the magnetization rotates by 90 degrees relative to its original direction of Hk. This free layer Hk direction is parallel to the pinning

$$\frac{dR}{R} = S_e \cdot \varepsilon \qquad (6)$$

direction of the reference layer in a tunnel junction. The relative 90 degree rotation corresponds to relative resistance change of dR/R = 0.5 TMR, where the R is the resistance and TMR is the maximum tunnel magnetoresistance. The gauge factor S_e is normally defined in such a way to represent the strain sensitivity:

Therefore, S_e can be calculated using (4), (6), dR/R = 0.5 TMR and Hs = Hk:

$$S_e = \frac{dR/R}{\varepsilon} = \frac{1.5 \cdot TMR \cdot E \cdot \lambda}{Hk \cdot Ms \cdot (1-\nu^2)} \qquad (7)$$

Some of the parameters have been measured to be: TMR=70%, λ= 31x10^{-6}, Hk = 32 Oe, and Ms=1200 emu/cc (1.5 T). We also assume that E = 1.6x10^{12} dyn/cm^2 which is typical for such alloys as either 80/20 or 90/10 Permalloy, and ν = 0.3 which is typical for all metallic alloys, then (7) yields:

Se = 1.5*70%*1.6x10^{12}*31x10^{-6}/(32*1200*(1-0.3^2))=1490

This is the calculated gauge factor value for such a SDT structure.

Se can also be more directly obtained by measuring dR/R =0.5*66%=33% taken from Figure 3, and the strain ε_f from (4). Therefore,

Se = 33%/233ppm = 1416

This measured Se value is very close to the calculated value given above.

The Gauge factor Se is the best parameter in describing the sensitivity of resistance in response to strain. Typical Se value is 2 for most metallic materials and 100 for Si (maximum value of 200). This measured Se value for SDT using CoFeB is >7 times of the highest value of Si-based devices, and more than 2 orders of magnitude of the metallic devices. Moreover, this Se value for SDT using CoFeB can be further increased by increasing TMR and λ, and decreasing Hk and Ms, which are all possible with improved magnetic layers and the junctions.

In conclusion, magnetostrictive CoFeB single layers and MTJs using CoFeB as free layers were fabricated and tested to have adequate properties to be used for strain gauge applications. The gauge factor is at least 7 times of the best available piezoresistive materials.

IV. Acknowledgment

We appreciate helps in various stages of this project from Mr. Jon Fink, Mr. Dave Brownell, Mr. Loc Tran and Mr. John Taylor at NVE. Funding was provided by MDA, NSF, and DARPA.

References

1. D. Wang, C. Nordman, Z. Qian, J.M. Daughton, and J. Fink, "70% TMR at room temperature for sandwich Tunnel Junctions with CoFeB as free and pinned layers," IEEE TransMag. vol 40, 2269 (2004).
2. M. Lohndorf, T. Duenas, M. Tewes, E. Quandt, M. Ruhrig, and J. Wecker, "Highly sensitive strain sensor based on magnetic tunnel junctions," APL. Vol 81, 313 (2002).
3. L. Baril, B. Gurney, D. Wilhoit, and V. Speriosu, J. Appl. Phys. vol 85, 5139 (1999).
4. Jon Wilson, "Pressure measurement: principles and practice," Sensors Magazine, Vol. 20, 19 (2003).
5. "Handbook of Modern Sensors," 2nd edition, published by Springer-Verlag New York, Inc. edited by Jacob Fraden, 325 (1996).
6. D. Wang, M. Tondra, C. Nordman, Z. Qian, J.M. Daughton, et al. J. Appl. Phys. **91**, 8405 (2002).
7. M. K. Minor, T. M. Crawford, T. J. Lemmer, Y. Peng, and D. E. Laughlin, "Stress dependence of soft, high moment and nanocrystalline FeCoB films," J. Appl. Phys. vol 91, 8453 (2002).
8. B. D. Cullity, "Introduction to Magnetic Materials," Reading, MA: Adison-Wesley, P. 272 (1972).

Figure Captions

Figure 1. Magnetic easy axis and hard loops for a Si(100)-Si_3N_4-Ru-CoFeB-Al_2O_3 sample after 250 °C/1Hr annealing. No strain is applied to the sample.

Figure 2. Magnetic hard axis M-H loops for the same sample shown in Figure 1. The strain applied is about ±230 PPM ("+" means tensile, and "–" means compressive), and perpendicular to the field induced anisotropy.

Figure 3. TMR traces under three strain conditions for a sample of Si(100)-Si_3N_4-Ru-CoFeB-RuTa-CoFeB-Al_2O_3-CoFeB-Ru-FeCo-CrMnPt SDT junction pair after 250 °C/1Hr annealing.

Figure 4. Minor TMR traces under the tensile perpendicular strain for the same sample as shown in Figure 3.

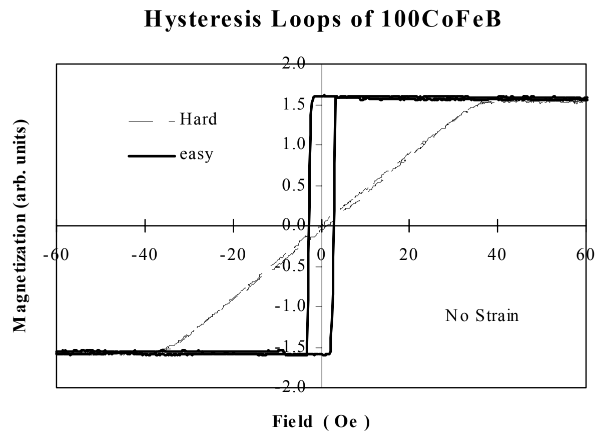
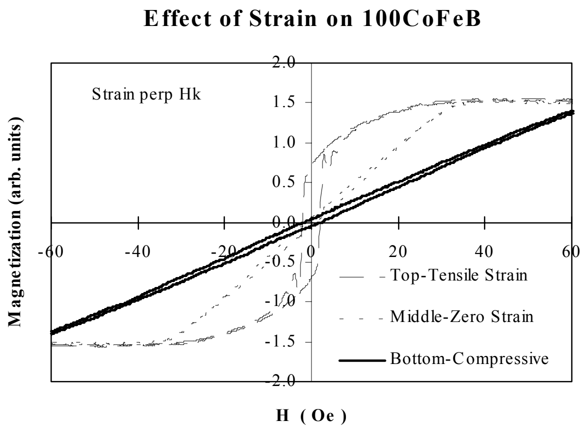


Figure 1. Magnetic easy axis and hard loops for a Si(100)-Si_3N_4-Ru-CoFeB-Al_2O_3 sample after 250 °C/1Hr annealing. No strain is applied to the sample.



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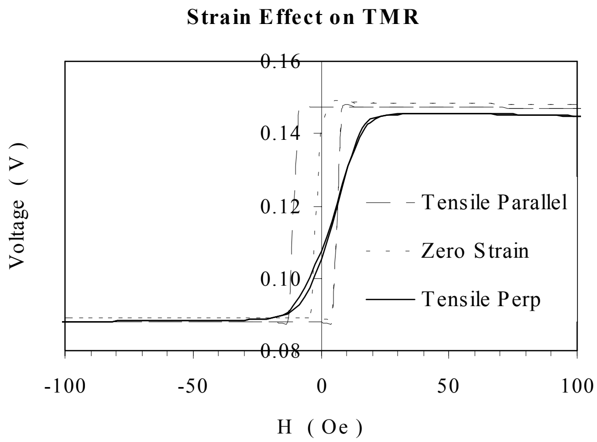

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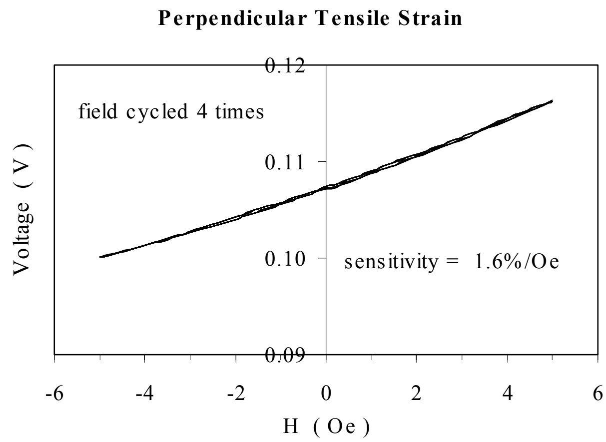

Figure 4. Minor TMR traces under the tensile perpendicular strain for the same sample as shown in Figure 3.