Magnetostriction characteristics of ultrathin permalloy films

Y. K. Kim[a)]
Quantum Peripherals Colorado, Inc., Louisville, Colorado 80028-8188

T. J. Silva
National Institute of Standards and Technology, Boulder, Colorado 80303-3328

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An abrupt and large increase in the absolute magnitude of λ_s in sputtered polycrystalline permalloy ($Ni_{81}Fe_{19}$) films for thicknesses below 7 nm was observed. Permalloy films maintain near-zero magnetostriction with film thicknesses above 7 nm. Film surface studies and microstructural characterizations suggest that the magnetostriction observed in this study is possibly due to an altered surface morphology of microstructural origin. This observation appears to be critical from the viewpoint of permalloy-based giant magnetoresistive or spin-valve sensor fabrication where typical permalloy film thicknesses are 3–10 nm. Because thin films with nonzero magnetostriction can induce an undesirable magnetoelastic anisotropy during sensor operation, the control and adjustment of the film composition seems necessary to minimize magnetostriction. © *1996 American Institute of Physics.* [S0003-6951(96)01920-1]

The fabrication of thin-film magnetic recording heads utilizing materials displaying giant magnetoresistance (GMR) or the spin-valve effect (SV) is emerging as a subject of technological interest. However, there have been limited studies of the magnetostriction characteristics of permalloy thin films with film thicknesses t below 10 nm. Magnetostriction λ_s often induces undesirable anisotropy during head fabrication, and therefore must be tightly controlled.

Previous studies have focused on the effects of composition[1] ($100<t<200$ nm), substrates[2] ($10<t<110$ nm), or deposition conditions[3] ($35<t<45$ nm), on magnetostriction. Recently, the magnetoelastic behavior of evaporated $Ni_{79}Fe_{21}$ thin films ($1<t<10$ nm) on Ag- or Cu-coated Si substrates has been reported.[4] An increase in the magnetoelastic coefficient (which is proportional to λ_s) with decreasing t was interpreted with a phenomenological Néel model[5] where, $\lambda_s = \lambda_s^{\mathrm{bulk}} + 2\lambda_s^{\mathrm{surf}}/t$. Under this model, the surface magnetostriction term dominates the bulk term as film thickness decreases. However, no surface or microstructural information was provided. This model assumes a continuous and flat film morphology. The validity of the model may not hold for polycrystalline thin films where an intrinsically defective microstructure and surface roughness are often associated with film growth.

The purpose of the present study was to characterize λ_s of sputtered permalloy as a function of film thickness from 3 to 40 nm. Our specific goal was to examine the variation in the λ_s with film microstructure and surface topography.

Permalloy films ($Ni_{81}Fe_{19}$) were deposited by rf-diode sputtering in 0.7 Pa of Ar on 76 mm diam (001) Si substrates without intentional substrate heating. The sputtering system was equipped with a load lock and a typical base chamber pressure was less than 1×10^{-5} Pa. The deposition rate was 0.1 nm/s. Control of average film thickness was secured by using time-power deposition with synchronized target shutters.[6] The details of film thickness and composition measurements can be found elsewhere.[6] Substrates were precoated with 200 nm sputtered amorphous alumina to remove substrate orientation effects and to produce smooth substrate surfaces (root-mean-square surface roughness was about 0.04 nm as measured with an atomic force microscope). After deposition, the substrates were diced into 38 mm$\times$6.4 mm strips for λ_s measurement. Samples were prepared from multiple batches at targeted thickness to ensure reproducibility. The λ_s of films was measured at room temperature by a high-precision optical tester where typical background noise was $\sim10^{-9}$. This tester employs an in-plane rotating magnetic field and laser-beam deflection technique.[7] The same technique was used to measure the magnetostriction of discontinuous NiFe/Ag GMR multilayers.[8] Surface profile and microstructure were characterized by atomic force microscopy (AFM) and transmission electron microscopy (TEM), respectively.

The primary result of this letter is illustrated in Fig. 1, which shows the λ_s data as a function of permalloy film thickness. Data points were taken from multiple substrates fabricated at each film thickness. Films exhibit near-zero λ_s above 7 nm. An abrupt transition accompanying a large increase in the magnitude (albeit negative) is observed for

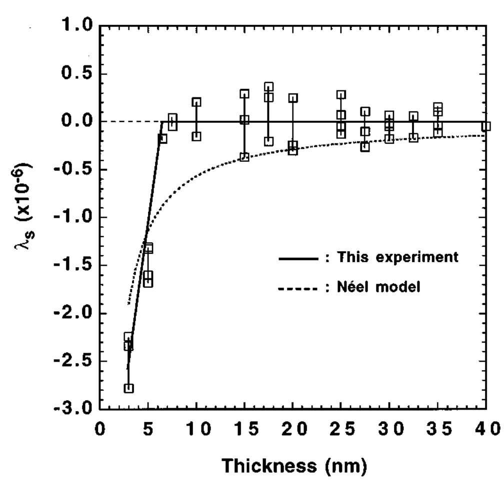

FIG. 1. Magnetostriction λ_s as a function of film thickness. The dashed curve is based on the Néel model.

[a)]Electronic mail: ykim@tdh.qntm.com

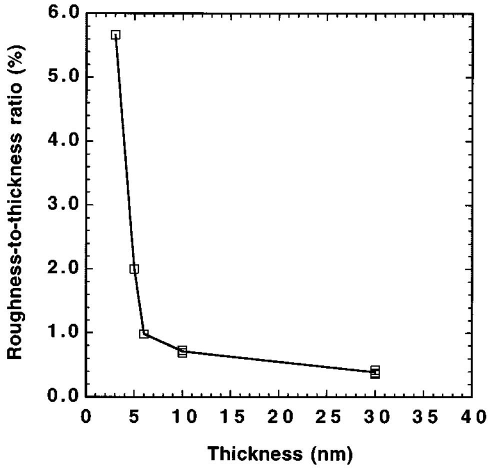

FIG. 2. Roughness-to-thickness ratio as a function of film thickness. Root-mean-square roughness values were used.

films with thicknesses below 7 nm. We think that complicated film morphology resulting from sputter deposition prevents the phenomenological Néel model (dotted line) from accurately representing the experimental data trend observed in this study. Nonetheless, zero magnetostriction is no longer preserved and becomes largely negative when film thicknesses become very small.

The surface roughness may play an important role in magnetic anisotropy by inducing surface anisotropy of a dipolar or magnetocrystalline origin.[9] The surface magnetic anisotropy contribution increases in proportion to the roughness-to-thickness ratio.[9] We have characterized the surface topography by AFM. AFM images were obtained from a 1 μm$\times$1 μm region of the samples. Approximately 0.25 μm$\times$0.25 μm subregions of the image were statistically analyzed for a roughness measurement. Care was taken to select a subregion free from particulate contamination. Figure 2 shows the root-mean-square surface roughness data for selected samples used for λ_s measurements as a function of film thickness. The most outstanding feature of the AFM data is that the roughness-to-thickness ratio changes in a strikingly similar fashion to the λ_s results in Fig. 1. An abrupt increase is observed in the roughness-to-thickness ratio for samples with film thicknesses below 7 nm.

To further understand the details of the evolution of the surface topography, we have characterized the internal microstructures of two selected samples by TEM: one with $t > 7$ nm and the other with $t < 7$ nm. Figure 3 represents dark-field images showing grain size and distribution, and bright field images (insets) of (a) 30 nm, and (b) 3 nm thick film. The 3 nm film possesses fine, uniformly dispersed grains with diameters from 7.5 nm, whereas the 30 nm film possesses a broader distribution of grain diameters from 7.5 to 20 nm. The 3 nm film shows a microstructure characterized by small grain diameter, and defective grain boundaries which often occurs in the early stage of film growth, resulting in rough surface topography in agreement with the AFM data (Fig. 2). In addition, 3 nm film features a considerably deformed lattice of grains with large residual stress measured by selected area diffraction. This indicates that residual stress could also contribute to alter λ_s (under tension λ_s usually becomes more negative).[10]

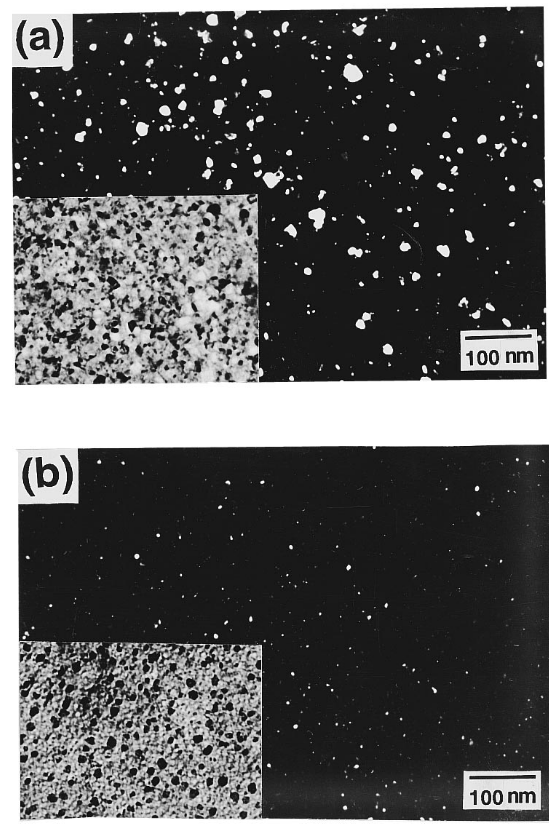

FIG. 3. TEM dark-field images depicting grain size and distribution (inset shows bright-field images) of (a) 30 nm film, and (b) 3 nm film.

From the technological viewpoint, our permalloy films ($t < 70$ nm) exhibit large negative λ_s which may be detrimental in terms of achieving high-performance SV heads. One possible way to compensate for the large negative λ_s for fixed deposition conditions is to modify the permalloy composition:[1] For example, a composition of $Ni_{79}Fe_{21}$ at $t = 3$ nm could be potentially useful to bring λ_s back to zero.

In summary, we have observed an abrupt and large increase in the absolute magnitude of λ_s in sputtered polycrystalline $Ni_{81}Fe_{19}$ films for thicknesses below 7 nm. A Néel model of surface and bulk magnetostriction poorly describes the data. Based upon film morphology characterization, we found that the surface roughness resulting from microstructural changes associated with film thickness reduction correlates strongly with observed increase in the magnitude of λ_s. This thickness-dependent magnetostriction may be critical for spin-valve or giant magnetoresistive sensor fabrication.

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