GIANT MAGNETORESISTANCE AND LOW MAGNETOSTRICTION IN DISCONTINUOUS NiFe/Ag MULTILAYER THIN FILMS

Young Keun Kim

Quantum Peripherals Colorado, Inc., Louisville, CO 80028-8188, U. S. A.

Abstract—Magnetoresistance field sensitivity and magnetostriction were measured as a function of annealing temperature for NiFe/Ag multilayer systems displaying giant magnetoresistance. Key multilayer configurations such as number of NiFe/Ag bilayers and Ag spacer thickness were varied. A high giant magnetoresistance ratio up to 5% with zero magnetostriction and high magnetoresistance field sensitivity was possible to achieve simultaneously with optimal sample geometry and annealing condition.

I. INTRODUCTION

Magnetic recording head technology utilizing giant magnetoresistance (GMR) materials is of emerging technological interest. High areal density (>1 Gb/in^2) information storage can be possible with GMR heads due to an increased signal output resulting from a large change in ΔR/R at low fields. Assuring large MR field sensitivity d(ΔR/R)/dH (%/Oe) is more critical than having large ΔR/R (%) itself from the head operation standpoint.

Annealed NiFe/Ag multilayers (NiFe in permalloy composition), first reported by Hylton et al. [1], appear to be attractive because they exhibit very low saturation fields resulting in large field sensitivity. Post-deposition annealing process induces Ag diffusion into NiFe layer and separates NiFe grain clusters (discontinuous multilayers), resulting in an antiparallel magnetostatic coupling between NiFe grains [2, 3] which induces GMR.

In addition to good MR response, GMR films must have low saturation magnetostriction λ_s to minimize stress-induced anisotropy which could prevent otherwise stable head bias point [4]. We have assessed the effect of NiFe/Ag bilayer number and Ag spacer layer thickness on λ_s and field sensitivity upon post-deposition annealing temperature T_{an}. Understanding microstructural changes resulting from the film fabrication helped to optimize NiFe/Ag multilayer performance.

Y. K. Kim, e-mail: ykim@tdh.qntm.com

II. UNDERSTANDING OF THE MICROSTRUCTURAL EVOLUTION

Before we explain the experimental results, a discussion on the microstructural origin of the GMR in discontinuous NiFe/Ag system is needed for better interpretation of our results.

Sputter-deposited films are, in general, in a state of residual stress. This residual stress is composed of a thermal stress and an intrinsic stress. The former is due to the thermal mismatch between the substrate and the film, whereas the latter is due to the microstructural defects associated with film growth.

The residual stress contributes to the magnetic anisotropy of the films due to the presence of magnetostriction. Both Ni and Fe show a gradual increase in λ_s as compression is increased or tension is decreased [5]. The energy accumulated in the film due to stresses becomes a driving force to relieve the stress [6]. The residual stress can be relieved by changing the microstructure of the film with modest annealing. In general, the microstructural evolution associated with post-deposition annealing includes recovery (defect healing), nucleation (or recrystallization), and grain growth.

A schematic diagram representing NiFe/Ag multilayer system during annealing process is depicted in Fig. 2. In as-deposited state, both polycrystalline NiFe and Ag grains are separated by interfaces as well as grain boundaries after film growth. NiFe (or Ni) and Ag are immiscible from thermodynamics viewpoint. At low T_{an}, Ag grains nucleate through NiFe grain boundary diffusion, while at high T_{an}, grain growth takes place. Previous result by Parker et al. [2] indicated that the NiFe/Ag multilayer possessed a strong (111) columnar texture between NiFe and Ag with the mean grain size of about 200 Å.

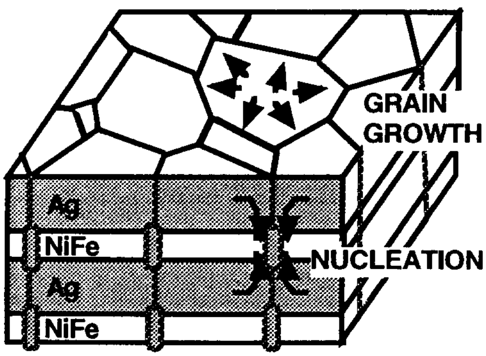

Fig. 1. Schematic diagram representing microstructural evolution of NiFe/Ag multilayers upon annealing [7].

Grain boundary diffusion is probably one of the most effective ways to promote the microstructural evolution in the thin film geometry since thin films comprise of higher surface (or interface) area compared to the bulk material. It is also an effective mass transfer process at low temperature regimes ($T_{an} < 0.3\ T_m$, where T_m is melting temperature of the material).

Gibson and Dobson [8] have grown epitaxial films of 2000 Å Ni on Si substrate with (111) Ag underlayer, and observed a formation of thin Ag layer on top of thick Ni (Ni formed three-dimensional islands) after T_{an} at about 300°C for few minutes. Ag migration was possible due to crystalline defects such as Ni grain boundaries associated with the island formation, and this was attributed to the minimization of surface free energy of the system. Recently, Gall et al. have studied grain boundary diffusion in 250 Å NiFe / 100 Å Ag bilayer thin films in the T_{an} range of 375 to 475°C [9]. Again, Ag migration through NiFe grain boundary diffusion was observed.

Further high temperature annealing could lead to a considerable amount of grain growth. The driving force is to reduce the surface free energy of the grain, therefore, larger grains tend to become much larger at the compensation of smaller grains (Oswald ripening). It should be emphasized that both interface and strain energies also play an important role as part of driving force in grain growth for thin film multilayers [10].

II. FILM FABRICATION AND CHARACTERIZATION

NiFe/Ag multilayers were deposited by magnetron sputtering onto 3 inch Si wafers with 1500 Å of thermal SiO_2. The NiFe was sputtered from a $Ni_{82}Fe_{18}$ alloy target using a dc power supply, whereas the Ag was sputtered using an rf power supply. Deposition pressure was 7 mTorr of Ar, and substrate temperature was ambient. No magnetic field was applied during the deposition. The basic film structure used in this study with varying bilayer number N and Ag thickness t_{Ag} was:

$$Si/SiO_2(1500\ Å)/Ta(45\ Å)/Ag(0.5t_{Ag})/NiFe(20\ Å)$$
$$/[Ag(t_{Ag})/NiFe(20\ Å)]_{N-1}\ /Ag(0.5t_{Ag})/Ta(110\ Å)$$

Table I shows the multilayer configurations. A total of six sample sets were prepared and annealed with a rapid thermal annealing furnace from 320 to 400°C.

Table I. Sample configurations investigated in this study.

Sample Sets	Number of NiFe/Ag Bilayers (N)	Ag Spacer Thickness (t_{Ag})
A1	5	33 Å
A2	5	44 Å
B1	7	33 Å
B2	7	49 Å
B3	7	55 Å
C1	9	33 Å

The details of post-deposition annealing conditions can be found in the previous work by Kim and Sanders [7].

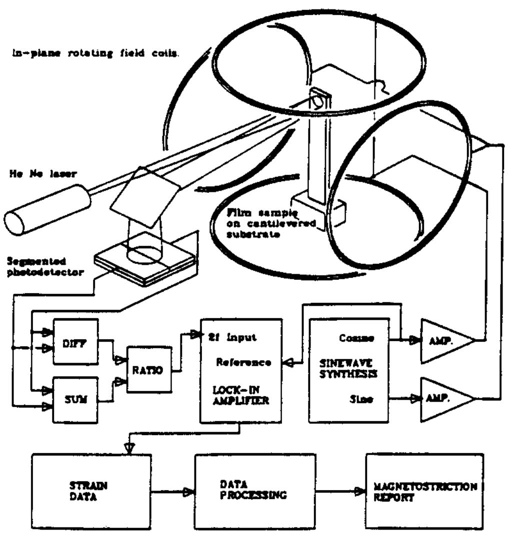

Fig. 2. Schematic diagram representing the magnetostriction tester.

MR transfer curves were characterized with an in-line four point probe (maximum field up to 100 Oe). The MR response was not dependent on the field direction relative to the current for in-plane fields. λ_s was measured at room temperature by a high-precision (background noise level in 10^{-9}) optical tester [11] depicted in Fig. 2. This tester employs an in-plane rotating magnetic field and laser-beam deflection technique [12]. Typical sample size was 1.5 inch x 0.25 inch.

III. RESULTS AND DISCUSSION

A typical GMR transfer curve is represented in Fig. 3 (sample A2). This figure shows the effect of annealing temperature on ΔR/R, ΔR/R being defined as $(R-R_S)/R_S$ where R_S is resistance measured at saturation field. As-deposited samples do not show GMR. With this particular sample set, the maximum ΔR/R was 5.2 % at T_{an} = 340°C. Peak ΔR/R values increase as annealing temperature increases but further increase in annealing reduces the magnitude.

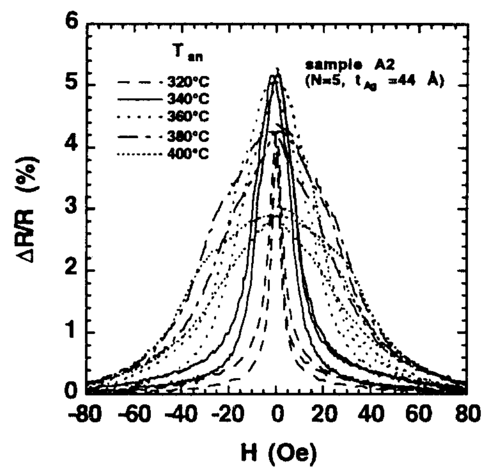

Fig. 3. GMR transfer curve for sample set A2, having N = 5 and t_{Ag} = 44 Å.

This characteristics can be explained by aforementioned microstructural changes with annealing. The initial increase in ΔR/R at low T_{an} is attributed to an increase of net antiparallel spin alignment as Ag grains separates NiFe grains and, therefore, increases the intralayer NiFe grain separation. The decrease in ΔR/R at high T_{an} has been attributed to a possible bridging of the NiFe grains across the Ag layers which would increase the effective ferromagnetic coupling [1, 2]. However, another plausible explanation has been suggested [7] based on the grain growth model: At high T_{an}, the NiFe grains grow and the intralayer separation increases while maintaining interlayer separation, resulting in a net reduction in interfacial area for spin-dependent scattering.

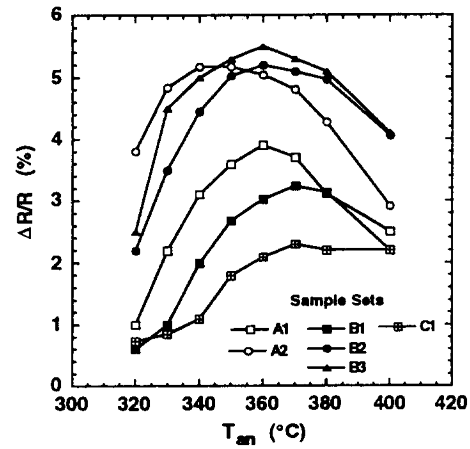

Fig. 4. ΔR/R of NiFe/Ag multilayers as a function of annealing temperature.

Figure 4 shows the GMR response of all six samples as a function of T_{an}. First, it is observed that the peak ΔR/R decreases as Ag spacer layer thickness t_{Ag} decreases. This can be attributed to the fact that the ferromagnetic coupling between NiFe layers increases as t_{Ag} decreases. Comparing sample sets with t_{Ag} = 33 Å (A1, B1, and C1) indicates that the peak value decreases as the number of NiFe/Ag bilayer N increases. This observation is inconsistent with the previous result (t_{Ag} = 40 Å) where ΔR/R was proportional to (N-1)/N [1]. However, when we compare samples with thicker t_{Ag} (44 Å for A2, and 49 Å for B2), no appreciable reduction in the peak ΔR/R is observed, consistent with the previous result. The (N-1)/N dependence appears to be valid for samples with thicker Ag thicknesses where ferromagnetic exchange coupling becomes weak.

Figure 5 shows a summary of λ_s and field sensitivity results for sample sets B (N = 7). λ_s varies systematically with T_{an} and, for all samples, has a zero crossing for annealing temperatures in the range of 330 - 360°C.

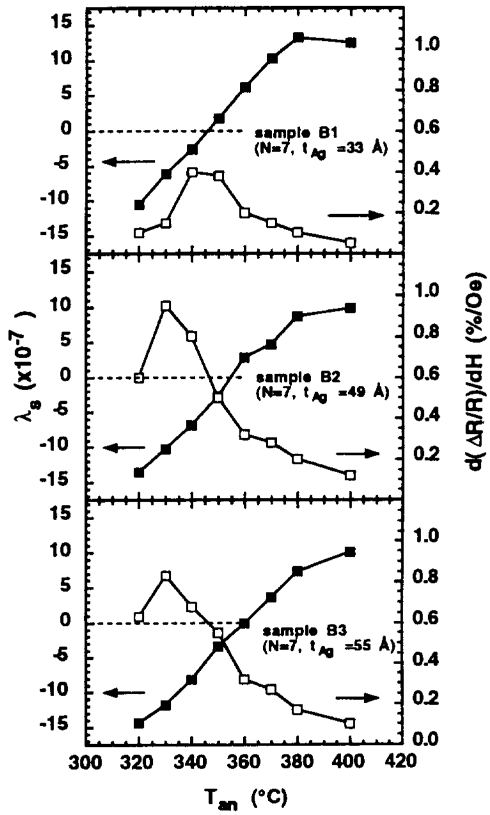

Fig. 5. λ_s and field sensitivity of NiFe/Ag multilayers as a function of annealing temperature for sample sets B. Unannealed samples show λ_s of about -3×10^{-6}.

This temperature range is also a region of relatively high ΔR/R (see Fig. 4) and field sensitivity values. This feature is extremely encouraging from a device manufacturing viewpoint. λ_s changes linearly with strikingly similar slopes up to a certain temperature. At high T_{an}, λ_s is nearly constant or has a slight downturn. The behavior of λ_s with increasing T_{an} is consistent with microstructural changes accompanied by a reduction in the residual stress of the films. It is also observed that the T_{an} for zero-λ_s decreases as t_{Ag} decreases, while T_{an} which offers the maximum field sensitivity increases as t_{Ag} decreases.

The optimal film fabrication condition, for example, to optimize λ_s and field sensitivity for N = 7 samples (set B) is predicted to be t_{Ag} = 28 Å and T_{an} = 343°C.

IV. CONCLUSIONS

Zero magnetostriction concurrent with high magnetoresistance ratio and field sensitivity was observed in discontinuous NiFe/Ag multilayer films. Systematic changes in magnetostriction and giant magnetoresistance characteristics can be explained based on the understanding of the microstructural evolution associated with post-deposition annealing.

ACKNOWLEDMENT

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