Low Magnetostriction in Annealed NiFe/Ag Giant Magnetoresistive Multilayers

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Abstract—Systematic changes were observed in magnetostriction and magnetoresistance ratio for NiFe/Ag multilayers as a function of annealing temperature. Optimal multilayer configurations (number of bilayers and Ag layer thickness) can be engineered to achieve zero magnetostriction concurrent with high magnetoresistance sensitivity. This feature makes the NiFe/Ag multilayers potentially useful for high-performance magnetic recording read-sensors.

I. INTRODUCTION

Among the many giant magneto-resistive (GMR) material systems currently being studied, the NiFe/Ag multilayer system [1, 2] appears to be attractive because, after annealing (previous work [1] showed GMR in as-deposited states only), it exhibits a high MR ratio together with a low saturation field $H_s$, resulting in large field sensitivities. A possible mechanism to explain the onset of GMR after annealing is the diffusion of Ag along the columnar grain boundaries; this diffusion effectively breaks up the NiFe layers into grains that interact magnetostatically [3, 4].

To be useful for read head applications, GMR films must be magnetically soft. The saturation magnetostriction $\lambda_s$ is one of the key soft magnetic properties, which must be low and tightly controlled because it often induces undesirable anisotropy of magnetoelastic origin during head fabrication [5]. The magnetoelastic anisotropy can shift the optimal biasing point of head operation if the sensore structure possesses high $\lambda_s$.

The purpose of this study was to investigate systematic changes in $\lambda_s$ and GMR as a function of annealing temperature $T_{an}$ and multilayer configuration. In addition, we have assessed the effect of NiFe/Ag bilayer number and Ag spacer layer thickness on $\lambda_s$ and GMR. An optimization of NiFe/Ag multilayer performance could be achieved with careful material design based on the understanding of the microstructural evolution in thin films.

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*Formerly known as Rocky Mountain Magnetics, Inc.

II. EXPERIMENTAL

Multilayers were deposited by dc magnetron sputtering with Ni$_2$Fe$_{18}$ and Ag targets onto 76 nm diameter Si wafers coated with 150 nm of thermal SiO$_2$. The basic film structure used in this study with varying bilayer number N and Ag thickness $t_{Ag}$ was:

$$\text{Si/SiO}_2(150 \text{ nm})/\text{Ta}(4.5 \text{ nm})/\text{Ag}(0.5t_{Ag}/\text{NiFe}(2 \text{ nm})/\text{Ag}(t_{Ag}/\text{NiFe}(2 \text{ nm}))_{N-1}/\text{Ag}(0.5t_{Ag})/\text{Ta}(11 \text{ nm})$$

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

<table>
<thead>
<tr>
<th>Sample Set</th>
<th>N</th>
<th>$t_{Ag}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>5</td>
<td>3.3</td>
</tr>
<tr>
<td>A2</td>
<td>5</td>
<td>4.4</td>
</tr>
<tr>
<td>B0</td>
<td>7</td>
<td>2.2</td>
</tr>
<tr>
<td>B1</td>
<td>7</td>
<td>3.3</td>
</tr>
<tr>
<td>B2</td>
<td>7</td>
<td>4.9</td>
</tr>
<tr>
<td>B3</td>
<td>7</td>
<td>5.5</td>
</tr>
<tr>
<td>C1</td>
<td>9</td>
<td>3.3</td>
</tr>
</tbody>
</table>

The details of film deposition, annealing conditions can be found in our previous work [6]. $\lambda_s$ was measured at room temperature by a high-precision optical tester [7] which employs an in-plane rotating magnetic field and laser-beam deflection technique [8].

III. RESULTS AND DISCUSSION

Before we explore $\lambda_s$ behavior, GMR characteristics of annealed NiFe/Ag multilayers are discussed. Fig. 1 shows the effect of annealing temperature $T_{an}$ on the MR ratio ($\Delta R/R_s = (R - R_s)/R_s$, where $R_s$ is the saturation resistance) for sample set A2. The annealing dependence of the MR response is very similar to that reported by Hylton et al. [2] for samples having N = 5 and $t_{Ag} = 4.0$ nm. As $T_{an}$ is increased, $\Delta R/R_s$ increases to a peak value of 5.2% for $T_{an} = 340^\circ$C, and then decreases as $T_{an}$ is increased further. For brevity, $\Delta R/R_s$ refers to the
amplitude of the MR curve. Unannealed samples do not exhibit GMR.

Fig. 1. Room-temperature MR data for sample set A2, having $N = 5$ and $t_{Ag} = 4.4$ nm. The data show a peak in the magnitude of $\Delta R/R_s$ for a 5 minute, 340°C anneal.

Fig. 1 also shows MR hysteresis, which is approximately 0.16 kAm$^{-1}$ (2 Oe) wide at half the saturation field for $T_{an} = 320°C$ and increases with increasing $T_{an}$. The plausible mechanisms to explain the initial increase in $\Delta R/R_s$ with $T_{an}$ at zero field, and the reduction in $\Delta R/R_s$ for high $T_{an}$ have been previously discussed [6].

Fig. 2. Saturation magnetostriiction ($\lambda_s$) and field sensitivity as a function of annealing temperature: (a) $N = 5$ (A1, A2), (b) $N = 7$ (B0, B1, B2, B3), and (c) $N = 9$ (C1). No GMR was observed for B0. Field sensitivity is defined as the maximum $d(\Delta R/R)/dH$. 

*no appreciable GMR observed*
The \( \lambda_s \) and MR sensitivity data are shown in Fig. 2 as a function of \( T_{an} \). \( \lambda_s \) of as-deposited NiFe/Ag (sample sets B) is about -3x10^{-6} (previous magnetostriction study [9] on Ni/Ag multilayers with a comparable Ni thickness also indicated a negative \( \lambda_s = -20x10^{-6} \)). For all sample sets, \( \lambda_s \) exhibits a zero crossover for anneals between 330 and 360°C, which for certain multilayer configurations, is also a region of relatively high \( \Delta R/R_s \) and sensitivity values. This feature is extremely encouraging from a device manufacturing viewpoint.

\( \lambda_s \) changes linearly with strikingly similar slopes up to a certain temperature. At high \( T_{an} \), \( \lambda_s \) is nearly constant or has a slight downturn. The behavior of \( \lambda_s \) with increasing \( T_{an} \) is consistent with microstructural changes accompanied by a reduction in the residual stress of the films. Vacuum-deposited films are, in general, in a state of residual stress. This residual stress can be relieved by changing the microstructure of the film with modest annealing. The microstructural evolution associated with post-deposition annealing includes recovery, nucleation, and grain growth. The residual stress change contributes to the change in magnetostriction. Both Ni and Fe show a gradual increase in \( \lambda_s \) as compression is increased or tension is decreased [10].

As shown in Fig. 3, the linear changes in \( T_{an} \) for zero-\( \lambda_s \) and maximum field sensitivity could be useful for designing multilayers to optimize the material performance. For example, to optimize \( \lambda_s \) and sensitivity, the optimal processing condition for \( N = 7 \) samples (set B) will be \( t_{Ag} = 2.8 \) nm and \( T_{an} = 343°C \). Similarly, the optimal processing condition for \( N = 5 \) samples (set A) will be \( t_{Ag} = 3.3 \) nm and \( T_{an} = 330°C \).

IV. CONCLUSIONS

We have investigated magnetostriction and giant magnetoresistance behaviors of annealed NiFe/Ag multilayered films. Systematic changes observed in magnetostriction and field sensitivity allow one to design multilayers and predict their performance. Zero magnetostriction with high magnetoresistance field sensitivity observed in the NiFe/Ag multilayers makes them potentially useful for high-performance read-sensor application.

REFERENCES

[7] Lafouda Solutions, San Diego, California.

Fig. 3. \( T_{an} \) for zero-\( \lambda_s \) and maximum field sensitivity as a function of \( t_{Ag} \) for \( N = 5 \) (set A), \( N = 7 \) (set B), and \( N = 9 \) (set C).

To better understand the \( \lambda_s \) and sensitivity behavior, \( T_{an} \) for zero-\( \lambda_s \) and maximum sensitivity was replotted, as shown in Fig. 3, from the previous figure as a function of \( t_{Ag} \). When we compare zero crossover temperatures for all film sets investigated, we observe systematic data trends: i) the zero-\( \lambda_s \) temperature decreases as \( t_{Ag} \) decreases, and ii) the zero-\( \lambda_s \) temperature decreases as the number of bilayers (N) decreases. Meanwhile, the temperature which offers the maximum field sensitivity behaves differently: i) it increases as \( t_{Ag} \) decreases, but ii) decreases as N decreases.