Large enhancement of anisotropic magnetoresistance and thermal stability in Ta/NiFe/Ta trilayers with interfacial Pt addition

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Ta/NiFe/Ta trilayers, extensively used for anisotropic magnetoresistance (AMR) sensors, exhibit severely reduced MR ratio at small NiFe thickness and appreciable moment loss, especially after annealing. By inserting ultrathin Pt layers at the interfaces of the trilayers, AMR can be significantly enhanced for thin NiFe films due to the strong electron spin-orbit scattering at Pt/NiFe interfaces along with suppression of interfacial magnetic dead layers. Furthermore, the Pt layers also reduce Ta and NiFe interdiffusion and result in negligible moment loss and AMR degradation after annealing at 350 °C. © 2010 American Institute of Physics. [doi:10.1063/1.3334720]

Anisotropic magnetoresistance (AMR) effect, originating from the anisotropic scattering of conduction electrons due to the spin-orbit interaction,1 has been extensively utilized in compassing, position sensing, dead reckoning and other applications including the magnetic tape recording systems for huge capacity data storage. Because of its relatively large AMR amplitude and excellent magnetic softness, permalloy (~Ni81Fe19) is the most adopted material for AMR devices, and the sensing component typically contains a Ta/NiFe/Ta trilayer for desired microstructure and performance. Technologically, it is desirable for the NiFe films to have smaller thickness, e.g., 100 Å or less, to diminish the demagnetization effect as device size scales down. However, the AMR ratio of the thin NiFe films decreases rapidly with film thickness decrease (tniFe < 200 Å).1 Furthermore, the Ta/NiFe/Ta films exhibit appreciable moment loss,2–4 and after high temperature annealing the AMR ratio degrades along with further moment loss due to Ta and NiFe interdiffusion.5,6 Deposition of a NiFeCr seed layer has been explored and yields improved AMR ratios and thermal stability.6,7 However, the NiFeCr seed layer significantly increases NiFe film grain size and causes substantial enhancement in coercivity,7 thus lower the AMR sensor field sensitivity. Other studies indicated that the addition of Pt to NiFe can appreciably enhance the film resistivity difference between the current parallel and perpendicular to the magnetization geometries (Δρ=ρ∥−ρ⊥). Unfortunately, the impurity scattering also rapidly increases the absolute value of the resistivity (ρ0=(1/3)ρ∥+(2/3)ρ⊥), and consequently reduces corresponding AMR ratio.5 Considering the strong electron spin-orbit interactions in Pt, in this letter, the study of effect of interfacial Pt insertion layers in Ta/NiFe/Ta is reported. The increased spin-orbit scattering at the outer surfaces of the NiFe layer, avoiding the NiFe layer resistivity increase, induces a significant AMR enhancement. Meanwhile, the Pt layers effectively eliminate the interfacial magnetic dead layer formation and suppress thermally driven interdiffusion between Ta and NiFe thus result in almost no AMR degradation after annealing.

Films with a structure of Ta(40 Å)/Pt(0–25 Å)/Ni81Fe19(50–400 Å)/Pt(0–25 Å)/Ta(30 Å) were deposited on thermally oxidized Si wafers at room temperature by dc magnetron sputtering. The vacuum was better than 4×10−5 Pa, and the working Ar pressure was 0.5 Pa. Ta, Pt, and Ni81Fe19 alloy targets with 99.99% purity were used. A deposition field of about 350 Oe was applied to induce an in-plane easy axis in NiFe. Samples were post-annealed at 350 °C for 2 h in a vacuum with a pressure of 3×10−5 Pa and a field of 1 kOe along the easy axis. All samples were magnetically characterized using a vibrating sample magnetometer at room temperature. The MR-H curves were measured by a conventional four-probe method. X-ray specular diffraction (SD) and in-plane grazing incident diffraction (IP-GID) were performed on a Bruker D8 advanced x-ray diffractometer using Cu Kα radiation.

AMR of Ta/Pt/NiFe(150 Å)/Pt/Ta films with different Pt layer thickness was first studied with the results summarized in Fig. 1(a). For the Ta/NiFe/Ta trilayer, the AMR ratio is measured to be 2.92%. After Pt layer insertion, the AMR

FIG. 1. (a) Pt thickness dependence of the AMR ratio for the Ta/Pt/NiFe(150 Å)/Pt/Ta samples; (b) MR-H curves for the Ta/NiFe(150 Å)/Ta and Ta/Pt(15 Å)/NiFe(150 Å)/Pt(15 Å)/Ta multilayers before and after annealing.

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ratio quickly increases and reaches a maximum value of about 3.21% at a Pt layer thickness of 15 Å, then it decreases and approaches the trilayer AMR ratio at a Pt thickness of 25 Å. Series of samples prepared under the same conditions in different deposition runs always give the same tendency of AMR variation. Apparently, thin Pt insertion layers are beneficial to the AMR increase in Ta/NiFe/Ta films, but the increasing Pt layer thickness will also result in a current shunting effect and thus reduce AMR ratio.

Figure 1(b) compares the MR-H curves of the Ta/NiFe(150 Å)/Ta trilayer and the multilayer sample with 15 Å Pt layers in the as-deposited state and after annealing. The smaller AMR magnitude for the Ta/NiFe/Ta trilayer is further reduced to 1.85% upon annealing. In contrast, the AMR degradation for the annealed Ta/Pt/NiFe/Pt/Ta film is negligible with the AMR magnitude remained at 3.14% after annealing. This demonstrates that the addition of Pt layers significantly improves the thermal stability of the Ta/NiFe/Ta film.

Figure 2 shows the x-ray SD and IP-GID spectra taken from above two samples before and after annealing. In the as-deposited state, the trilayer exhibits a strong NiFe (111) reflection in the SD pattern and an appreciable NiFe (220) peak in the IP-GID spectrum. With the insertion of Pt layers, the out-of-plane NiFe (111) peak locates at the same position ($2\theta=44.22^\circ$) and its full width at half maximum (FWHM) remains unchanged ($\Delta 2\theta=0.66^\circ$), but with a moderate intensity decrease. Meanwhile, the in-plane NiFe (220) peak with unvaried peak position becomes slightly broader with the corresponding FWHM increasing from 1.58° to 1.94°. These results suggest that the lateral NiFe grain size is reduced after the thin Pt layers inserted at the interfaces, most probably due to the large lattice mismatch between Pt and NiFe. It should also be pointed out that multiple interference fringes were observed around the Pt (111) and NiFe (111) peaks in the SD patterns, reflecting high quality of the films with very small interface and surface roughness. In view of the fact that the smaller NiFe grains would lead to a reduction in AMR, the observed AMR enhancement in the as-sputtered Ta/Pt/NiFe/Pt/Ta film should not come from the microstructure of the film but rather from the electronic effect, which will be discussed in details later. After annealing, the structures of the Ta/NiFe/Ta trilayer and the film with Pt insertion layers evolve quite differently. For the former, the out-of-plane NiFe (111) peak shifts from 44.22° to 44.37°, whereas the in-plane NiFe (220) peak moves from 76.02° to 74.90°. This change can be attributed to the tensile stress development in the NiFe layer during the annealing, most probably resulted from the Ta atoms diffusion into the interface region of the NiFe layer. Since the Ta intermixing with NiFe can seriously deteriorates the AMR ratio, the annealed Ta/NiFe/Ta shows a much reduced AMR. On the other hand, the NiFe (111) peak for the annealed Ta/Pt/NiFe/Pt/Ta film stays closely to its initial position for the as-deposited sample and the corresponding NiFe (220) peak moves leftwards in amount less than half of that observed in the trilayer. In addition, the broad Pt diffraction peaks change very little before and after annealing. Undoubtedly, the Pt insertion layers appreciably suppressed the thermally driven interdiffusion between the NiFe and Ta layers.

Figure 3 shows the NiFe thickness dependence of areal magnetic moment for films with the structures of (a) Ta/NiFe/Ta and (b) Ta/Pt(15 Å)/NiFe/Pt(15 Å)/Ta before (solid) and after annealing (open). The straight lines are the linear fitting results. The inset of Fig. 3(b) shows the easy-axis and hard-axis loops of the as-deposited film Ta/Pt(15 Å)/NiFe(150 Å)/Pt(15 Å)/Ta.
effects of Ta on the magnetic properties of NiFe films. It should also be pointed out that all samples with or without the Pt insertion layers possess ideal magnetic softness with an easy axis coercivity $H_c$ less than 2.0 Oe and a anisotropy field $H_A$ below 7 Oe. The inset of Fig. 3(b) shows the representative easy and hard axis M-H curves for a Ta/Pt(15 Å)/NiFe(150 Å)/Pt(15 Å)/Ta film with $H_c = 1.1$ Oe and $H_A = 5$ Oe.

Figure 4 shows the NiFe thickness dependence of the AMR ratio for Ta/NiFe/Ta multilayers with and without the 15 Å Pt insertion layers before and after annealing. Pt layers help to enhance the as-deposited trilayers AMR ratio for the whole NiFe thickness range studied here, and the thinner the NiFe thickness, the larger the enhancement. In fact, the AMR ratio of the trilayer containing a 50 Å NiFe is only 1.17%, whereas the corresponding film with Pt layers exhibits a much higher AMR ratio of about 1.95%. With an AMR ratio of about 2%, the 50 Å thick NiFe layer can find practical device applications. For the 100 Å NiFe samples, the Pt insertion layers increase the AMR ratio from 2.36% to 2.78%. More significant advantage of adding Pt layers can be observed for the annealed samples. As shown in Fig. 4, the trilayer samples show severely reduced AMR ratio while the multilayers containing the Pt insertions exhibit almost no reduction in AMR ratio. For films with thin NiFe layer, which are more important for technological applications, this effect is really noteworthy. The AMR ratio of the annealed trilayers drops to 0.3% at $t_{\text{NiFe}}=50$ Å and 1.1% at $t_{\text{NiFe}}=100$ Å. In contrast, the corresponding AMR ratio of the annealed films with Pt layers maintains at 1.47% and 2.55% for above two NiFe thicknesses. The significantly improved thermal endurance of AMR in Ta/Pt/NiFe/Pt/Ta films is consistent with the suppression of the Ta interdiffusion with NiFe. Parenthetically, the Ta buffer layer is indispensable to the optimized microstructure of the NiFe films for high AMR ratios. We actually found that the films of Pt(15 Å)/NiFe/Pt(15 Å)/Ta(30 Å) possess smaller NiFe grains, weaker (111) texture, and much lower MR ratios.

Removal of magnetic dead layers by adding Pt insertion layers can contribute to the AMR ratio enhancement. However, the additional Pt layers will also cause a current shunting effect that can lead to AMR ratio reduction. To separate the two factors and to better understand the AMR behaviors, samples with Cu insertion layers were studied. Magnetic measurements show that for Ta/Cu(15 Å)/NiFe/Cu(15 Å)/Ta samples, the Cu layers also eliminated magnetic dead layers. Structural characterizations show that the Cu layers do not alter the NiFe crystalline structures including the NiFe grain size. The measured AMR ratios are almost identical to those of the Ta/NiFe/Ta trilayers, e.g., MR = 2.89% and 2.92% for the 150 Å NiFe films with and without the Cu layers, respectively. Table I compares the film sheet resistance ($R$), the change of the sheet resistance ($\Delta R$) and MR for the Ta/NiFe/Ta, Ta/Pt(15 Å)/NiFe/Pt(15 Å)/Ta, and Ta/Cu(15 Å)/NiFe/Cu(15 Å)/Ta films with a NiFe layer thickness of 50 Å. The Cu and Pt insertion layers both appreciably reduce the sheet resistance due to current shunting, however, $\Delta R$ is significantly smaller for the Cu added sample in comparison to the Pt added sample. Thus we conclude that the Pt layers introduce strong electron spin-orbit scattering and result in the AMR ratio increase. It should also be pointed out that even though the Cu insertion layers can effectively suppress the magnetic dead layer, the thermally driven Ta interdiffusion is not hampered by the Cu and there remains considerable AMR deterioration after annealing. Our results suggest that, insertion of interfacial non-reactive diffusion barriers that have strong spin-orbit interaction is an avenue to improve the AMR of Ta/NiFe/Ta trilayer and its thermal stability for very thin film devices.

In summary, the addition of ultrathin Pt layers at the Ta/NiFe/Ta interfaces is found to significantly enhance the AMR ratio of thin NiFe layers by introducing strong electron spin-orbit scattering. The Pt layers help to suppress the interfacial magnetic dead layer formation. Moreover, the serious thermally driven interdiffusion between Ta and NiFe has also been effectively reduced by the Pt layers, and the Pt encapsulated thin NiFe films exhibit negligible moment loss and AMR degradation after high temperature annealing.

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<table>
<thead>
<tr>
<th>Sample</th>
<th>$R$ (Ω)</th>
<th>$\Delta R$ (Ω)</th>
<th>MR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta/NiFe(50 Å)/Ta</td>
<td>10.3</td>
<td>0.121</td>
<td>1.17</td>
</tr>
<tr>
<td>Ta/Pt(15 Å)/NiFe/Pt(15 Å)/Ta</td>
<td>6.4</td>
<td>0.125</td>
<td>1.95</td>
</tr>
<tr>
<td>Ta/Cu(15 Å)/NiFe/Cu(15 Å)/Ta</td>
<td>5.9</td>
<td>0.070</td>
<td>1.17</td>
</tr>
</tbody>
</table>