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Enhanced spin-valve giant magneto-resistance in non-exchange biased sand-wich films

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Abstract-**A large giant magnetoresistance (GMR) value of 7.5% has been measured in simple NiFeCo(1)/Cu/NiFeCo(2) sandwich films grown on a 30 Å Cr seed layer. This spin-valve GMR effect is consistent with the differential switching of the two NiFeCo layers due to an enhanced coercivity of the NiFeCo(1) layer grown on the Cr seed layer. A change in growth texture of the NiFeCo(1) layer from *fcc* (111) to *bcc* (110) crystallographic orientation leads to an increase in magnetic anisotropy and and an enhancement in coercivity.**

The GMR value increases to 8.7% when a thin CoFe interfacial enhancing layer is incorporated. Further enhancement in GMR values up to 14% is seen in the sandwich films by nano-oxide layer formation. The specular reflection at oxide/magnetic layer interface further extends the mean free path of spin-polarized electrons.

Index terms-spin-valve, GMR, coercivity, specular reflection, seed layer, nano-oxide layer, sandwich.

I. INTRODUCTION

Spin-valve giant magnetoresistive (GMR) effect shows a great potential for application in magnetic random access memory (MRAM). Spin-valve effect is a result of differential switching of two weekly exchange coupled ferromagnetic (F) layers across a non-magnetic spacer. In distinction to the conventional exchange biased spin-valve structure where one of the two F layers is pinned by an antiferromagnetic layer, differential switching mechanism can also be created by designing the two F layers with different materials or different thicknesses [1,2]. The MRAM operation utilizing the second type spin-valve structure is conceptually simple [1,2]. A large read-out signal combined with a simple bit structure is always a desirable MRAM design point. We report in this paper the development of non-exchange biased F/Cu/F sandwich films with an enhanced GMR effect.

II. EXPERIMENTAL METHODS

$F^1/Cu/F^2$ sandwich films, where F^1=NiFeCo, NiFeCo/CoFe, CoFe, and F^2=NiFeCo, CoFe/NiFe, CoFe/NiFe/CoFe, were

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deposited on 4 in. Si substrates using a 6-target planetary DC magnetron sputtering system. A magnetic field of 50 Oe was present during film deposition to induce uniaxial anisotropy in the magnetic layers. A seed layer or a seed layer/nano-oxide composite layer was formed prior to the sandwich deposition, with varying thicknesses. A SHB-109 BH-loop tracer and a quasi-static tester were used for electric and magnetic characterization of the sheet films. The crystallographic properties and layered structure of the sandwich films were evaluated using x-ray diffraction and x-ray reflectivity measurements.

III. Results and discussion

Symmetric NiFeCo(1)40Å/Cu23Å/NiFeCo(2)40Å sandwich films only show anisotropic magnetoresistance. Large GMR values above 7% have been measured in the sandwich films once a proper seed layer is used. As shown in Fig. 1,

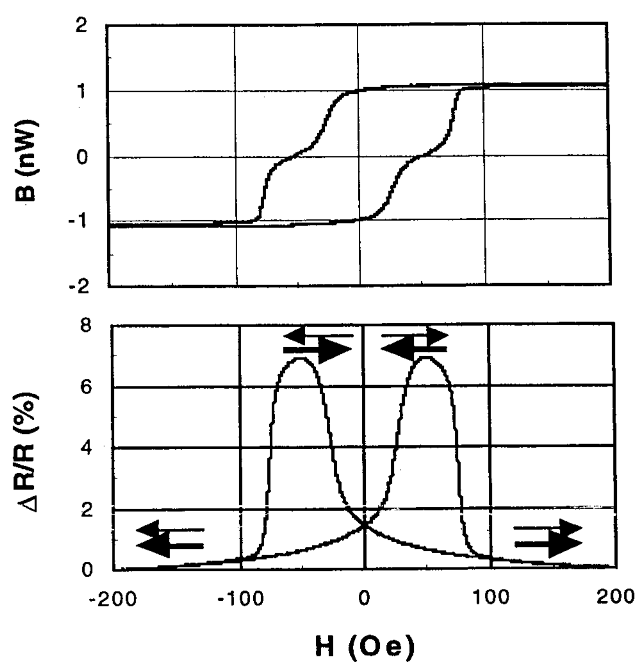

Fig. 1 Typical BH loop and GMR as a function of applied magnetic field for a Cr30Å/NiFeCo40Å/Cu23Å/NiFeCo40Å sandwich film.

introducing a Cr seed layer leads to a difference in the switching fields between the two NiFeCo layers. NiFeCo(1) layer grown directly on the Cr seed layer exhibits a larger coercivity value, which prevents its magnetization from switching along with that of NiFeCo(2) layer. The occurrence of an antiparallel configuration of the magnetization between the two NiFeCo layers gives rise to the spin-valve GMR effect.

Fig. 2 shows the dependence of coercivity for the two NiFeCo layers and GMR value on Cr seed layer thickness for NiFeCo(1)/Cu/NiFeCo(2) sandwich films. While the coercivity of NiFeCo(2) layer, H_{C2}, remains almost unchanged

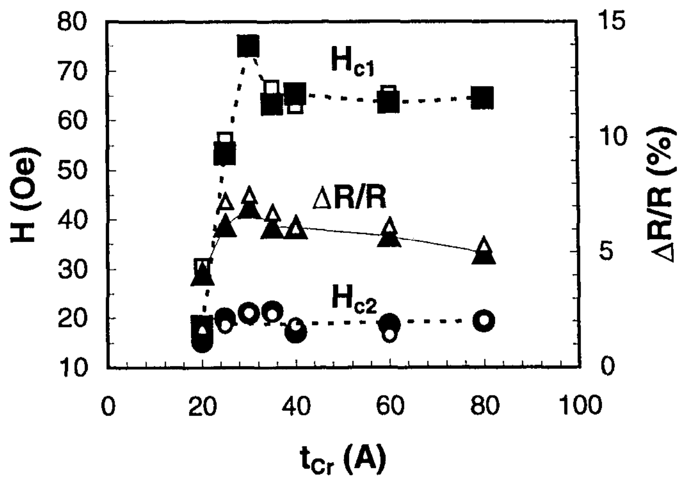

Fig. 2 Dependence of coercivity and ΔR/R on Cr seed layer thickness for $Cr(t_{Cr})$/NiFeCo(1)40Å/Cu23Å/NiFeCo(2)40Å sandwich films. Close and open symbols represent data from as-deposited and annealed samples, respectively.

with increasing Cr layer thickness, the coercivity of NiFeCo(1) layer, H_{C1}, increases quickly and reaches a plateau of ~70 Oe at $t_{Cr} \geq 30$ Å. This enhancement in H_{C1} is accompanied by a corresponding increase in GMR value. A large ΔR/R of 7% is observed at $t_{Cr}=30$ Å. The decrease in ΔR/R with further increasing t_{Cr} is due to the increasing current shunting through the seed layer. Annealing at 225 C under an aligning magnetic field further improves GMR values to 7.5%, as shown in Fig. 1.

The enhancement in H_{C1} and ΔR/R in NiFeCo(1)/Cu/NiFeCo(2) sandwich films grown on Cr seed layer is associated with a change in growth texture of the NiFeCo(1) layer. X-ray diffraction measurements of these sandwich films confirm a significant change in the crystallographic orientation of the films with increasing t_{Cr}. Two partly overlapping diffraction peaks at $2\theta=43.9^{\circ}$ and 44.9° have been identified to result from *fcc* NiFeCo/Cu/NiFeCo(111) and *bcc* Cr(110) diffractions, respectively. The peaks are very well described by Lorentzian line shape. The deconvoluted peak intensities are shown in Fig. 3(a) as a function of t_{Cr}.

It is clear that while the Cr(110) diffraction peak is gradually enhanced with increasing t_{Cr}, the diffraction intensity of NiFeCo/Cu/NiFeCo(111) peak exhibits a significant initial decrease and it remains constant with further increasing $t_{Cr} \geq 40$ Å. Although the diffraction intensity of NiFeCo/Cu/NiFeCo(111) peak is contributed from three

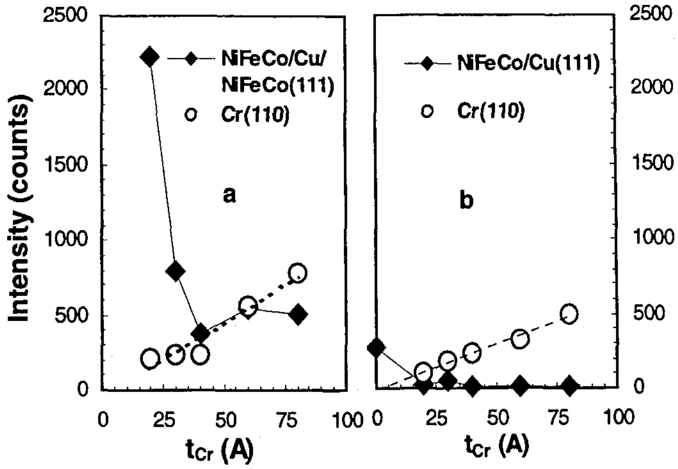

Fig. 3 X-ray diffraction peak intensity of (a) NiFeCo(1)40Å/ Cu23Å/NiFeCo(2)40Å sandwich with a 20 Å Cr capping layer and (b) NiFeCo(1)40Å/Cu23Å bilayer films grown on a Cr seed layer with varying thickness.

consecutive component layers, the intensity decrease is a direct result of the change in the *fcc* (111) texture of NiFeCo(1) layer grown on the *bcc* Cr seed layer. The nature of intra-grain epitaxial growth of multilayer thin films suggests that NiFeCo(1) layer grow into *bcc* crystalline structure, resulting in an increase in the magnetocrystalline

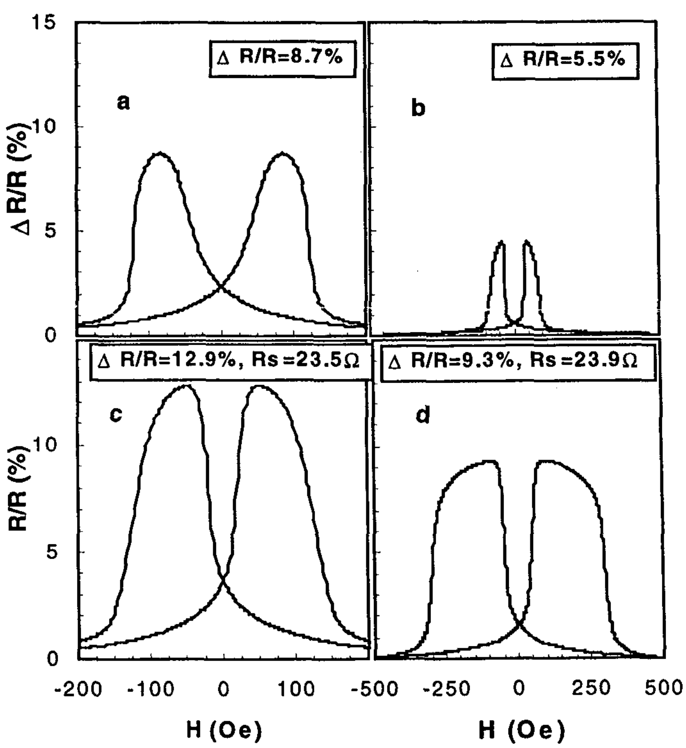

Fig. 4 Magnetoresistance as a function of applied magnetic field for four different sandwich films: (a) Cr30Å/NiFeCo30Å/CoFe10Å/ Cu23Å/CoFe10Å/NiFeCo30Å, (b) Ta20Å/CoFe40Å/Cu23Å/ CoFe10Å/NiFeCo30Å/CoFe10Å/Ta4Å, (c) Cr30Å/CoFeO/CoFe30Å/ Cu23Å/CoFe10Å/NiFeCo30Å/CoFe10Å/Ta4Å, (d) Cr30Å/ CoFe40Å/ Cu23Å/CoFe10Å/ NiFeCo30Å/CoFe10Å/Ta4Å.

anisotropy and therefore the coercivity. The suppression of *fcc* (111) texture in NiFeCo(1) layer with increasing Cr seed layer thickness is clearly demonstrated by the results of x-ray diffraction measurements on NiFeCo(1)/Cu bilayer films, as shown in Fig. 3(b). On the other hand, it also confirms that (111) crystallographic orientation is not a necessary condition to observe large GMR effect.

Our previous studies [3] on $[NiFeCo/Cu]_{20}$ and $[CoFe/Cu]_{20}$ multilayers have shown that these two multilayer systems show equivalent GMR values ~20% at 20Å Cu spacer layer thickness. The insertion of thin CoFe layers at NiFeCo and Cu interfaces, however, in the present NiFeCo(1)/Cu/NiFeCo(2) sandwich films enhances interfacial spin dependent scattering and further increases GMR values to 8.7%, as shown in Fig. 4(a). A large GMR value of 9.3% has been measured [Fig. 4(d)] in the asymmetric sandwich films of structure Cr30Å/CoFe40Å/Cu23Å/CoFe10Å/NiFe30Å/CoFe10Å/Ta4Å. This is in contrast to the sandwich film using a 20 Å Ta seed layer [Fig. 4(b)] that exhibits a GMR value of only 5.5%. A direct comparison of the Fig. 4(b) and (d) indicates that a larger difference in the switching fields between the two composite ferromagnetic layers for Cr-seeded films ensures a well defined anti-parallel magnetization alignment and a large dynamical range to observe a large spin-valve GMR effect.

The large GMR value of the Cr-seeded asymmetric sandwich film may also result from specular enhancement of spin polarized electrons at the top surface due to the formation of a Ta oxide layer [4]. X-ray reflectivity measurements, as

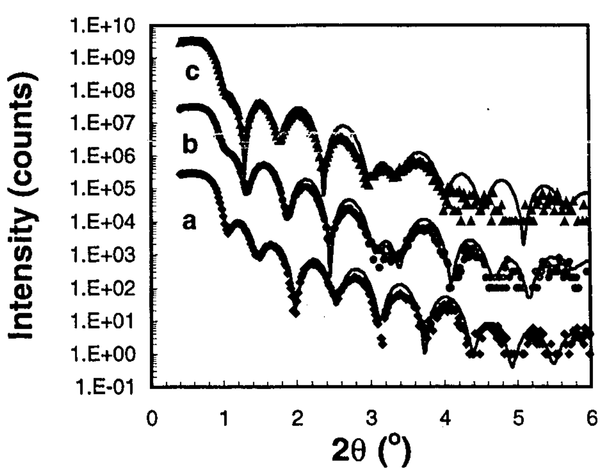

Fig. 5 X-ray reflectivity for three different sandwich films Cr30Å/CoFe(x_1)Å/CoFeO(y_1)Å/CoFe30Å/Cu23Å/CoFe10Å/NiFe30Å/CoFe(x_2)Å/CoFeO(y_2)Å/Ta4Å; (a) $x_1=x_2=0$, $y_1 \approx y_2 \approx 18$ Å; (b) $x_1=y_2=0$, $y_1 \approx 18$ Å, $x_2=10$ Å; (c) $x_1=x_2=10$ Å, $y_1=y_2=0$. The solid lines are the results from simple multilayer model analyses.

shown in Fig. 5, confirm that the 4 Å Ta capping layer has been naturally oxidized into a 8 Å TaO_x. Electron specular reflection at top $CoFe/TaO_x$ interface could further extend the mean free path of spin polarized electrons.

The insertion of ~18 Å of CoFeO layer, estimated by the x-ray reflectivity measurements, at Cr/CoFe interface by oxidizing a 10 Å CoFe layer in pure O_2 atmosphere further increases GMR value to 13 %, as shown in Fig. 4(c). This corroborates the specular enhancement of GMR effect through specular reflection of electron at oxide/ferromagnetic layer interfaces [4,5]. The insertion of the CoFe nano-oxide layer at both sides of the sandwich films increases the GMR value only to 14 %, implying the role of naturally formed TaO_x at the top surface of the sandwich films. A 1.5% reduction in film sheet resistance is seen with the insertion of nano-oxide layers, as indicated by Table 1. An optimization of the individual component layer thicknesses and the oxidation condition is currently underway and is expected to further improve the GMR values.

Table 1 Summary of the GMR and sheet resistance values for three different sandwich films with or without nano-oxide layer insertion. a, b, c refer film structures specified in Fig. 5.

	a	b	c
insertion	none	one side	two sides
$\Delta R/R$(%)	9.3	12.9	13.9
Rs(Ω/sq)	23.91	23.54	23.63

IV. CONCLUSIONS

Large GMR values up to 14 % have been measured in non-exchange biased $F^1/Cu/F^2$ sandwich films. The enhancement in spin-valve GMR effect in $F^1/Cu/F^2$ sandwich films grown on Cr seed layer is associated with an increase in magnetic anisotropy of the F^1 layer resulting from a change in growth texture of the F^1 layer. Specular enhancement of electron reflection at F/nano-oxide interfaces can be used to further exploit the GMR effect in simple sandwich and exchange biased spin-valve films.

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