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C. I. Pettiford  
*Northeastern University*

A. Zeltser  
*Hitachi Global Storage Technologies*

S. D. Yoon  
*Northeastern University*

V. G. Harris  
*Northeastern University*

C. Vittoria  
*Northeastern University*

*See next page for additional authors*

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**Author(s)**

C. I. Pettiford, A. Zeltser, S. D. Yoon, V. G. Harris, C. Vittoria, and N. X. Sun



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# Magnetic and microwave properties of CoFe/PtMn/CoFe multilayer films

C. I. Pettiford<sup>a)</sup>

Center of Microwave Magnetic Materials and Integrated Circuits, Northeastern University, Boston, Massachusetts 02115

A. Zeltser

Hitachi Global Storage Technologies, San Jose, California 95193

S. D. Yoon, V. G. Harri, C. Vittoria, and N. X. Sun

Center of Microwave Magnetic Materials and Integrated Circuits, Northeastern University, Boston, Massachusetts 02115

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CoFe/PtMn/CoFe films were deposited on seed layers of Ru or NiFeCr with CoFe film compositions being either Co-10 at. %Fe or Co-16 at. %Fe. Eight periods of the CoFe/PtMn/CoFe trilayers were also prepared. The magnetic properties and ferromagnetic resonance (FMR) of these films were characterized with vibrating-sample magnetometer, and field-sweep FMR system at  $X$  band ( $\sim 9.5$  GHz). The Ru-seeded CoFe/PtMn/CoFe sandwich films show excellent magnetic softness with a low hard axis coercivity of 2–4 Oe, an easy axis  $M_r/M_s$  of  $>98\%$ , and a significantly enhanced in-plane anisotropy of 57–123 Oe when CoFe layer thickness is above 200 Å. Contrary to what was observed in the ferromagnetic/antiferromagnetic bilayer systems that have reduced FMR linewidth with the increase of film thickness, the CoFe/PtMn/CoFe trilayers with Ru seed layer show a minimum FMR linewidth of 45 Oe at an intermediate CoFe layer thickness of 300 Å at  $\sim 9.5$  GHz. © 2006 American Institute of Physics. [DOI: 10.1063/1.2163843]

## I. INTRODUCTION

Polycrystalline metal magnetic thin films are being actively explored for applications in rf/microwave devices, such as magnetic band stop filters<sup>1,2</sup> and magnetic integrated inductors,<sup>3–5</sup> primarily due to their high saturation magnetization and low-temperature processing technologies which are compatible to the silicon integrated circuits and monolithic microwave integrated circuits (MMIC) process technologies. Magnetic thin films that are suitable for microwave applications typically need to have excellent magnetic softness with a uniaxial anisotropy field and a low coercivity. The magnetic softness desired for rf/microwave applications is often associated with a relatively low anisotropy field, less than 10–20 Oe for most polycrystalline metal magnetic films.<sup>1–6</sup> The low anisotropy fields of these metal magnetic thin films correspond to a low ferromagnetic resonance (FMR) frequency  $f_{\text{FMR}}$ , as described by the well-known Kittel equation:  $f_{\text{FMR}} = \gamma \sqrt{H_k(4\pi M_s + H_k)}$  (cgs units), with  $\gamma$  being the gyromagnetic constant of 2.8 MHz/Oe,  $4\pi M_s$  the saturation magnetization, and  $H_k$  being the effective anisotropy field of the magnetic thin films. The typical FMR frequency of the soft magnetic thin films is less than 1–2 GHz,<sup>1–6</sup> which severely limits their applications.

Ferromagnetic/antiferromagnetic (FM/AFM) bilayer thin-film structures show enhanced effective anisotropy fields  $H_{A,\text{eff}}$  due to exchange coupling, which can be expressed as  $H_{k,\text{eff}} = H_{ki} + H_{\text{ex}} + \Delta H_c$  for ideal films,<sup>7</sup> with  $H_{ki}$  the intrinsic anisotropy field,  $\Delta H_c$  the increased coercivity due to exchange coupling, and  $H_{\text{ex}}$  being the exchange bias field which can be expressed as  $H_{\text{ex}} = J_{\text{ex}}/(M_s t_F)$  with  $J_{\text{ex}}$  being the

interfacial exchange energy. The enhanced effective anisotropy field and the improved FMR frequencies of the bilayer FM/AFM thin films are desired for many rf/microwave applications. Exchange coupling in the FM/AFM bilayer thin-film structure can also lead to a shifted hysteresis with increased coercivity of the FM layer, and with a single domain state with an  $\sim 100\%$  squareness ratio ( $M_r/M_s$ ) which is desired for many microwave device applications. Recent works show that the FMR frequency can be significantly boosted to over 5 GHz for exchange-coupled IrMn/CoFe multilayers.<sup>8,9</sup>

Compared to the AFM/FM/AFM trilayers<sup>9</sup> and FM/AFM bilayers,<sup>10–12</sup> trilayers of FM/AFM/FM have their advantages for many microwave applications. First, trilayers of FM/AFM/FM have a higher effective magnetization  $M_{s,\text{eff}}$ , which can be expressed as  $M_{s,\text{eff}} = \sum t_{\text{FM}} M_s / (\sum t_{\text{FM}} + \sum t_{\text{NM}})$ , with  $M_s$  and  $t_{\text{FM}}$  being the saturation magnetization and thickness of the magnetic layers and  $t_{\text{NM}}$  being the nonmagnetic layer thickness, such as AFM layer, etc., and therefore, a higher flux conduction capability. Second, FM/AFM/FM trilayer leads to lower coercivity compared to the bilayers of AFM/FM,<sup>10</sup> which was possibly due to a magnetic charge compensation at the magnetic film edges.<sup>13</sup>

FMR linewidth ( $\Delta H_{\text{FMR}}$ ) of magnetic materials is a parameter of paramount importance for rf/microwave applications such as microwave band stop filters.<sup>1,2</sup> Large FMR linewidth leads to a reduced quality factor and increased insertion loss, which are among the major problems associated with the microwave band stop filters. Significant progress has been made on the understanding of the FMR behavior of exchange-coupled FM/AFM bilayers and the physical contribution to the FMR linewidth.<sup>11,12</sup> However, relatively less amount of work is done on the exchange-

<sup>a)</sup>Electronic mail: pettiford.c@neu.edu

coupled FM/AFM/FM trilayers, and their microwave performances are not well understood. In this work, we examine the magnetic and microwave properties of FM/AFM/FM trilayers as well as multilayers of [FM/AFM/FM/seed/dielectric] $\times n$  consisting of trilayers with ferromagnetic layers of  $\text{Co}_{90}\text{Fe}_{10}$  or  $\text{Co}_{84}\text{Fe}_{16}$ , and an antiferromagnetic layer of  $\text{Pt}_{50}\text{Mn}_{50}$  on different seed layers. Results show that the FMR performances of the FM/AFM/FM trilayers are significantly different from those of the FM/AFM bilayers.

## II. EXPERIMENT

FM/AFM/FM trilayers of  $\text{Co}_{90}\text{Fe}_{10}/\text{Pt}_{50}\text{Mn}_{50}/\text{Co}_{90}\text{Fe}_{10}$  with a 30 Å Ru seed layer and 30 Å Ru cap layer (referred to as  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  in the context) and  $\text{Co}_{84}\text{Fe}_{16}/\text{Pt}_{50}\text{Mn}_{50}/\text{Co}_{84}\text{Fe}_{16}$  with a 30 Å Ru seed layer and 30 Å Ru cap layer (referred to as  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$ ) were deposited. To compare the seed layer effects, multilayers of  $\text{Co}_{84}\text{Fe}_{16}/\text{Pt}_{50}\text{Mn}_{50}/\text{Co}_{84}\text{Fe}_{16}$  with a 30 Å NiFeCr seed and cap layer (referred to as  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$ ) were also deposited. All magnetic thin films were deposited on oxidized silicon coupons by dc magnetron sputtering with base pressures in the order of  $10^{-9}$  Torr. All the ferromagnetic CoFe layers ( $t_F$ ) was varied from 10 to 500 Å, while the AFM layer  $\text{Pt}_{50}\text{Mn}_{50}$  remained fixed at 120 Å. Multilayers with eight periods of the  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  and  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  trilayer structures alternated with  $\text{Al}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3/\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$ , and  $\text{Al}_2\text{O}_3/\text{Co}_{84}\text{Fe}_{16}$  were deposited with a fixed CoFe layer thickness of 200 Å, and with 100 Å  $\text{Al}_2\text{O}_3$  dielectric layers to suppress eddy current loss. Magnetic-field annealing was carried out for these films to induce the *unidirectional* anisotropy field by exchange coupling before characterizing these films. In-plane hysteresis along the hard axis (HA) and easy axis (EA) directions to the pinned direction was measured with vibrating-sample magnetometer (VSM). The hysteresis loops along the easy axis show clear hysteresis loop shift due to exchange coupling from the AFM layer, while the hard axis hysteresis loops are typically slim with no hysteresis shift. Effective anisotropy fields of these magnetic films were measured by extrapolating the hard axis minor hysteresis loops (50% saturated), a standard method for extracting anisotropy fields for magnetic materials.<sup>14</sup> Magnetic field such as coercive fields, exchange coupling fields, etc., were all measured with a VSM with an error of <1 Oe. FMR line-width of these films was measured at  $\sim 9.5$  GHz (*X* band) by using a field sweep FMR/electron paramagnetic resonance (FMR/EPR) facility with both dc magnetic field and microwave excitation field in the plane of the thin-film samples. Due to weak FMR absorption signal in the FMR spectra, only samples with  $t_F$  at or above 50 Å were measured. Microstructures of selected films were characterized using x-ray diffraction (XRD) using a Cu  $K\alpha$  source.

## III. RESULTS AND DISCUSSION

The EA coercivity  $H_{c\_EA}$ , HA coercivity field  $H_{c\_HA}$ , effective anisotropy field  $H_{k\_HA}$ , exchange bias field along the easy axis  $H_{ex}$ , and  $H_{ex} + H_{c\_EA}$  were plotted versus the magnetic layer thickness  $t_F$  for each of the sandwich thin-film

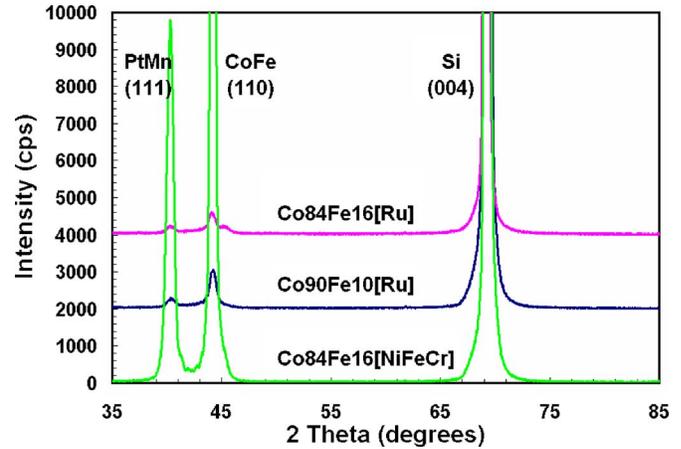


FIG. 1. XRD results for the samples in the sample sets of  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$ ,  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$ , and  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  with a CoFe layer thickness of 200 Å.

sample sets of  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$ ,  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$ , and  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$ . The effective anisotropy field  $H_{k\_HA}$  decreases with the increase of  $t_F$ , and matches well with the  $H_{ex} + H_{c\_EA}$  curve in all three sample sets, indicating that the  $H_{k\_HA} \approx H_{ex} + H_{c\_EA}$ , as observed in different thin-film systems.<sup>7</sup>

The two sets of sandwich films  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  and  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  both show a low hard axis coercivity of 2–4 Oe, a squareness ratio of >98%, and a relatively large exchange bias field of over 40 Oe at a CoFe layer thickness of 100 Å. The sandwich film set  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$ , however, shows higher hard axis coercivities in the range of 7–25 Oe, and a very low exchange bias field less than 7 Oe when the CoFe layer thickness is in the range of 100–500 Å. The interfacial exchange energies can be calculated to be about 0.058, 0.049, and 0.023 erg/cm<sup>2</sup> for the three sets of samples  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$ ,  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$ , and  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$ , respectively. The effective anisotropy fields of the CoFe films was enhanced to be  $\sim 160$  Oe for both  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  and  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$ , corresponding to a boosted FMR frequency of above 5 GHz at zero bias field.

The low hard axis coercivity and relatively large exchange bias field of the two sets of sandwich films  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  and  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  are associated with a fine grain size for the PtMn and CoFe layers, as indicated by the broad and low-intensity PtMn {111} and CoFe {110} x-ray-diffraction peaks in the out-of-plane “theta-2 theta” XRD patterns in Fig. 1. The  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  film set shows significantly higher intensity and narrower PtMn {111} and CoFe {110} diffraction peaks. Grain-size evaluation by using the Scherrer equation<sup>15</sup> was done with the PtMn {111} and FeCo {110} peaks of the XRD pattern, as indicated in Table

TABLE I. Grain size obtained from the Scherrer equation with the PtMn {111} and CoFe {110} peaks. Uncertainty of the grain-size evaluation is  $\sim 10\%$ .

Sample ID	PtMn grain size (nm)	CoFe grain size (nm)
$\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$	12	16
$\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$	12	16
$\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$	17	31

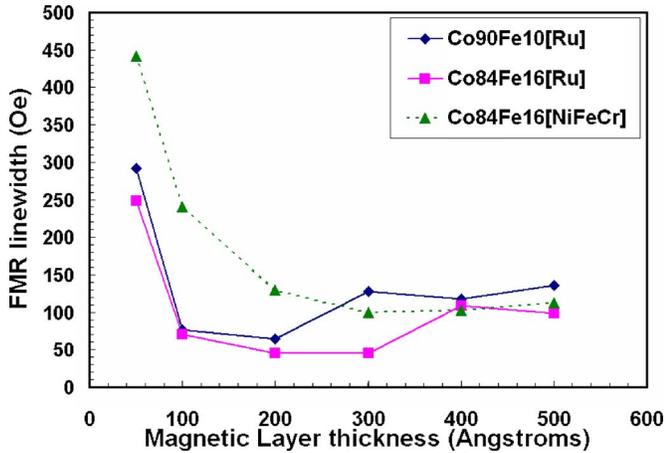


FIG. 2. In-plane X band ( $\sim 9.5$  GHz) FMR linewidth of the samples of  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$ ,  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$ , and  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  with a CoFe layer thickness of  $200 \text{ \AA}$ .

I. The  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  film shows a relatively large grain size of  $17 \text{ nm}$  for the PtMn and  $31 \text{ nm}$  for the CoFe phase than those of the  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  and  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$ , which show similar grain size of  $12 \text{ nm}$  for the PtMn and  $16 \text{ nm}$  for the CoFe phase. The large grain sizes in the PtMn and CoFe layers in the  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  film sets may account for their high hard axis coercivity and low exchange bias fields.

The FMR linewidth of these samples was measured and shown in Fig. 2. The  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  sample set shows a monotonically decreasing FMR linewidth with the increase of the FeCo layer thickness, with the minimum FMR linewidth of  $100 \text{ Oe}$ . This behavior is similar to what is observed in the exchange-biased NiFe/NiO bilayer films.<sup>16,17</sup> The  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  and  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  sample sets, however, show different behavior, wherein the minimum FMR linewidth is obtained at an intermediate CoFe layer thickness of  $200 \text{ \AA}$ , rather than at the maximum CoFe layer thickness. The minimum FMR linewidth among all three sample sets was achieved for the  $200\text{-\AA}$ -thick  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  film, which is  $45 \text{ Oe}$ . The relatively large FMR linewidth of the  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  sample set at  $400$  and  $500 \text{ \AA}$  CoFe layer thicknesses is related to the appearance of an anomalous absorption peak that interferes with the uniform mode FMR peak, as shown in Fig. 3, which is in the  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  sample set at  $100\text{--}500 \text{ \AA}$ . The anomalous absorption peak, however, is

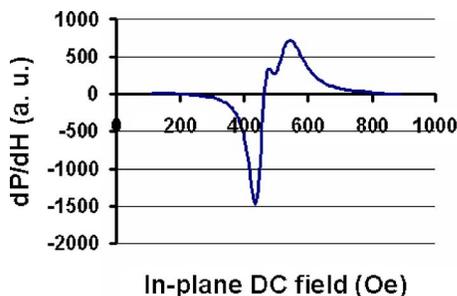


FIG. 3. Field sweep FMR spectrum showing the differential absorption power with respect to field vs the applied in-plane dc magnetic field for the  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  with a CoFe layer thickness of  $200 \text{ \AA}$ .

TABLE II. Magnetic and microwave properties of the eight-period multilayers.

Eight-period film structures	Anisotropy field (Oe)	Hard axis coercivity (Oe)	Easy axis coercivity (Oe)	FMR linewidth at $9.5 \text{ GHz}$ (Oe)
$\text{Al}_2\text{O}_3/\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$	121	4.5	72	148
$\text{Al}_2\text{O}_3/\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$	121	3.5	66	132

not observed in either  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  or  $\text{Co}_{84}\text{Fe}_{16}[\text{NiFeCr}]$  sample set. The FMR linewidth in  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  increases with the increase of the FeCo layer thickness when the FeCo layer thickness is over  $200 \text{ \AA}$ , which cannot be explained by the enhanced eddy current damping with the increased film thickness, as the total film thickness in all film sets is less than or equal to  $1120 \text{ \AA}$ , which is significantly lower than the skin depth at X band, which is calculated to be about  $4000 \text{ \AA}$ . Further investigation is needed to understand why the FMR linewidth in  $\text{Co}_{90}\text{Fe}_{10}[\text{Ru}]$  increases with the increase of the FeCo layer thickness.

The eight-period structures multilayers were deposited with a fixed CoFe layer thickness of  $200 \text{ \AA}$ . Their effective anisotropy fields, coercivities, and FMR linewidth are shown in Table II. Clearly the eight-period multilayer based on  $\text{Co}_{84}\text{Fe}_{16}[\text{Ru}]$  trilayer has the best combination of magnetic and microwave properties, a high anisotropy field of  $121 \text{ Oe}$ , a low hard axis coercivity of  $3.5 \text{ Oe}$ , an easy axis coercivity of  $66 \text{ Oe}$ , and a FMR linewidth of  $132 \text{ Oe}$ .

In summary, the Ru-seeded CoFe/PtMn/CoFe sandwich films show excellent magnetic softness with a low hard axis coercivity of  $2\text{--}4 \text{ Oe}$ , an easy axis  $M_r/M_s$  of  $>98\%$ , a significantly enhanced in-plane anisotropy of  $123 \text{ Oe}$ , and a low FMR linewidth of  $45 \text{ Oe}$  at  $\sim 9.5 \text{ GHz}$  when the CoFe layer thickness is above  $200 \text{ \AA}$ . With the combination of these magnetic and microwave properties, the CoFe/PtMn/CoFe films could play an important role in microwave applications.

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