Effective Anisotropy Fields and Ferromagnetic Resonance Behaviors of CoFe/PtMn/CoFe Trilayers

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Ferromagnetic (FM)/antiferromagnetic (AFM)/ferromagnetic trilayers of Ru seeded $Co_{90}Fe_{10}/Pt_{50}Mn_{50}/Co_{90}Fe_{10}$ and $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ were deposited, and their magnetic properties characterized at dc and at microwave frequencies. A ferromagnetic resonance (FMR) linewidth of 45 Oe at X-band (~9.5 GHz) was achieved in the $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ trilayer. The minimum FMR linewidth occurs at an intermediate CoFe thickness, which is in contrast to the typical monotonic drop of FMR linewidth with the increment of FM layer thickness in the exchange-coupled FM/AFM bilayers. The CoFe/PtMn/CoFe trilayers show significantly enhanced anisotropy field up to 340 Oe at X band, which is more than double of that at dc frequency, indicating an obvious discrepancy between the anisotropy field at dc and at X band.

***Index Terms*—Antiferromagnetic/ferromagnetic (AFM/FM), exchange coupling, ferromagnetic resonance, magnetic multilayer.**

I. Introduction

HIGH saturation magnetization soft magnetic thin films typically have quite limited anisotropy fields, which severely restrict their applications at RF/microwave frequencies. A unidirectional anisotropy field can be achieved in exchange biased ferromagnetic (FM)/antiferrromagnetic (AFM) composite materials as a result of an interfacial interaction or exchange coupling, which can be used to boost the effective anisotropy field of high saturation magnetization materials [1], [2]. Exchange-coupled AFM/FM bilayers [3]–[6], [18] and FM/AFM/FM trilayers [7] exhibit enhanced anisotropy fields due to exchange coupling, and are promising candidates for RF and microwave applications [6]–[10]. However, strong exchange coupling typically leads to enhanced ferromagnetic linewidth [8]–[13] in exchange coupled multilayer films. A monotonic drop of ferromagnetic resonance (FMR) linewidth as well as a drop in the effective anisotropy field was typically observed in exchange coupled FM/AFM bilayers with the increase in thickness of the FM layer, which is undesired for real applications. Furthermore, it has been observed that the measured exchange bias field at dc can differ from that measured at microwave frequencies in exchange coupled AFM/FM bilayers [14], [15].

In this paper, we examined the magnetic properties of the CoFe/PtMn/CoFe trilayer thin films at dc and at microwave frequencies. It was shown that a significantly enhanced anisotropy field and a low FMR linewidth can be achieved in the CoFe/PtMn/CoFe trilayer simultaneously, which corresponds to zero or a very low exchange bias field at the FMR frequency.

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II. Experiment

FM/AFM/FM trilayers of $Co_{90}Fe_{10}/Pt_{50}Mn_{50}/Co_{90}Fe_{10}$ and $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ seeded with 30 Å of Ru were deposited on oxidized silicon coupons by dc magnetron sputtering with base pressures in the order of 10^{-9} Torr. The ferromagnetic CoFe layer (t_F) thicknesses were varied from 10–500 Å, while the AFM layer $Pt_{50}Mn_{50}$ remained fixed at 120 Å. Magnetic field annealing was carried out for these films to induce the *unidirectional* anisotropy field by exchange coupling before characterizing these films. Magnetic fields like coercive fields, exchange coupling fields, etc., were all measured with a vibrating sample magnetometer (VSM) with an error of <1 Oe. The FMR linewidth of these films were measured at ~9.5 GHz (X-band) by using a field sweep FMR/EPR (electron paramagnetic resonance) facility with both dc magnetic field and microwave excitation field in the plane of the thin film samples.

III. Results and Discussion

VSM results of the trilayer structures were measured and plotted versus FM Layer thickness in Fig. 1(a) and (b). The results for the exchange coupled $Co_{90}Fe_{10}/Pt_{50}Mn_{50}/Co_{90}Fe_{10}$ trilayer structures with Ru seed and cap layer show a monotonic drop in the easy axis coercivity, effective anisotropy field, and exchange bias field with the increase in FM layer thickness, as shown in Fig. 1(a). It has a low hard-axis coercivity of ~2 to 4 Oe, and significantly enhanced effective anisotropy field in the range of 60–160 Oe, much higher than those expected for the single layer CoFe films which are typically in the range of ~10 Oe. Both the low hard-axis coercivity and enhanced anisotropy field are desired for RF/microwave applications. The $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ trilayer structures with Ru seed and cap layer [Fig. 1(b)] have similar characteristics to the $Co_{90}Fe_{10}$ results of Fig. 1(a).

The FMR linewidth (ΔH) of both sets of CoFe/PtMn/CoFe samples were extracted from the FMR absorption curves

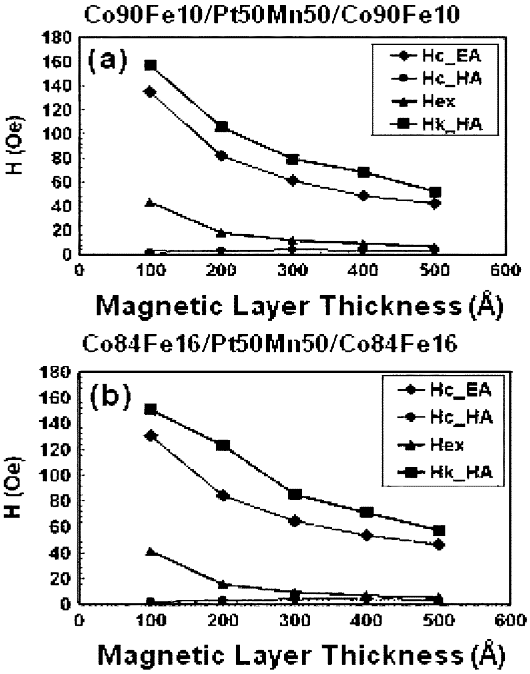

Fig. 1. Easy axis coercivity (Hc_EA), hard-axis coercivity field (Hc_HA), effective anisotropy field (Hk_HA), and exchange bias field along easy-axis H_{ex}, versus the magnetic layer thickness t_{FM} of (a) $Co_{90}Fe_{10}/Pt_{50}Mn_{50}/Co_{90}Fe_{10}$ with Ru and (b) $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ with Ru, sandwich thin-film sample sets.

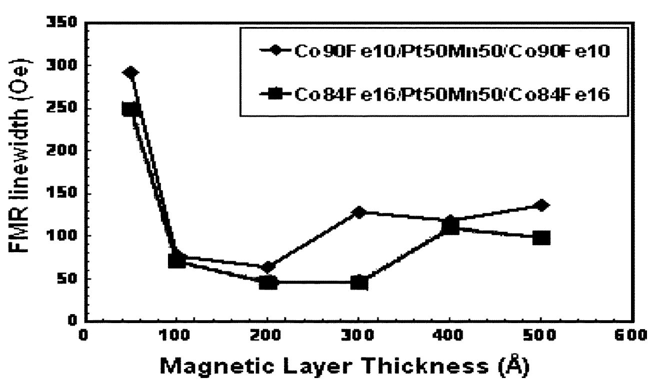

Fig. 2. Linewidth (ΔH) versus magnetic CoFe layer thickness t_{FM} for the two sets of trilayers as labeled in graph.

and shown in Fig. 2 as a function of the FM layer thickness. The error bar for the FMR linewidth of the trilayer samples with a CoFe layer thickness of 50 Å and 100 Å is in the range of 10–20 Oe, which drops to about 3–5 Oe for the trilayer samples with thicker CoFe layer thicknesses due to the relatively sharper FMR absorption peaks. Both trilayers of $Co_{90}Fe_{10}/Pt_{50}Mn_{50}/Co_{90}Fe_{10}$ and $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ exhibit an intermediate drop in linewidth with thickness. The lowest achieved linewidth being $\sim$45 Oe for the $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ trilayer. The total film thickness in all film sets is less than or equal to 1120 Å. This is significantly lower than the skin depth at X-band, which is calculated to be about 4000 Å. Therefore, this behavior is not likely due to eddy current loss.

The minimum FMR linewidth at an intermediate FM layer thickness as observed in these trilayer samples are obviously different from what was reported for the FM/AFM bilayers, which typically show a monotonic drop with the increment of the FM layer thickness [8]–[15]. To understand why there is such a different FMR behavior in these trilayers, we investigated the in-plane FMR fields $(H_{\rm FMR})$, the field at which $dP/dH = 0$, or maximum absorption power of the uniform mode absorption occurs.

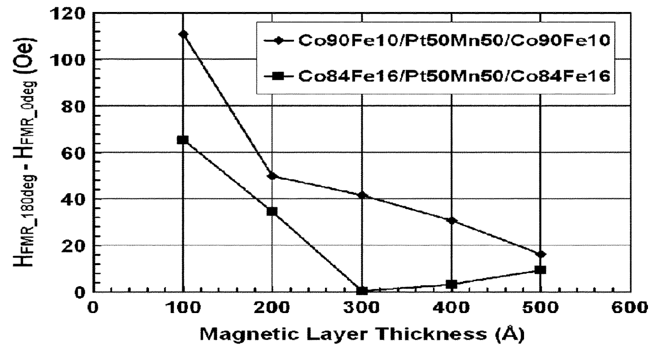

Fig. 3. Difference in FMR field with the applied field at 0° and 180° with respect to the CoFe layer thickness.

Fig. 3 is a plot of the difference in FMR field $H_{\rm FMR}$ along 0° and 180° away from the dc exchange bias field directions as a function of the magnetic layer thickness $t_{\rm FM}$. The error bar for these $H_{\rm FMR}$ measurements (not shown in the figure) is 2–3 Oe. The FMR field difference along the parallel (0°) and antiparallel (180°) direction relative to the exchange bias field direction is expected to be twice the exchange bias field $H_{\rm ex}$ at FMR frequency. The extracted FMR $H_{\rm ex}$ field versus the thickness of the FM layer $t_{\rm FM}$ of the $Co_{90}Fe_{10}/Pt_{50}Mn_{50}/Co_{90}Fe_{10}$ trilayer roughly correlates with the dc H_{ex} [(Fig. 1(a)], but higher in value by as much as 75%. On the contrary, the $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ trilayer FMR $H_{\rm ex}$ does not correlate with the dc $H_{\rm ex}$ results and trend lower by as much as 98%. In examining the profile for the $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ sample set, the 200 Å structure shows a clear presence of exchange bias field at FMR frequency as indicated by the difference between the 0° and 180° results, while no exchange bias field is observed for the 300 Å structure. To confirm this odd behavior, a full rotational (0°–360° away from the dc exchange bias field direction) FMR field $H_{\rm FMR}$ measurement was taken for these two structures. The plotted $H_{\rm FMR}$ versus rotation (not shown) produce butterfly-shaped patterns that give an indication of exchange bias. The symmetrical pattern in the 300 Å trilayer indicated that the $H_{\rm ex}$ at FMR frequency is roughly zero, consistent with Fig. 3. This observed behavior appears to be linked to an anomalous absorption peak (or mode), shown in Fig. 4, which is close to the uniform mode when the CoFe layer thickness is 300 Å or above. The anomalous mode is at the left side of the uniform mode for the trilayer with 300 Å, which shifts to the right side of the uniform mode when the CoFe layer thickness increases. The origin of this anomalous mode is not clear at this time. However, this behavior, once fully understood, could conceivably be utilized during thin-film growth to optimize the linewidth.

The FMR fields for both sample sets are shown in Fig. 5. The FMR field increases monotonically, with the increase of the CoFe layer thickness, from 220 Oe to as high as 550 Oe. According to the Kittel equation $f_{\rm FMR} = \gamma \cdot \sqrt{(H_{K,{\rm eff}} + H_{\rm FMR}) \cdot 4\pi M_s}$ with $\gamma \cong$

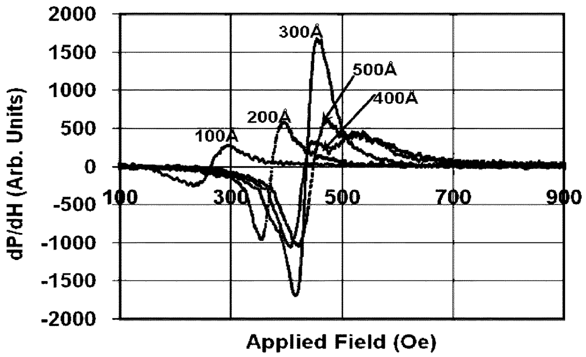

Fig. 4. FMR versus in-plane bias field along the 0° axis for $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ with Ru seed and cap layer with different CoFe layer thicknesses as indicated in the chart.

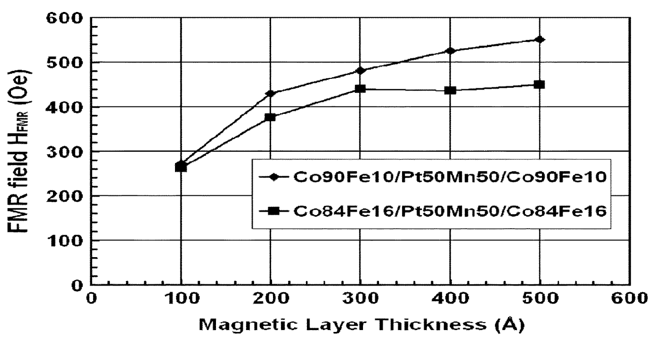

Fig. 5. FMR field versus magnetic CoFe layer thickness t_F for the two sets of trilayers as indicated in the figure.

2.8 MHz/Oe, $f_{\mathrm{FMR}} = 9.6$ GHz and $4\pi M_s = 20$ kG for the CoFe alloys, we get $H_{K,\mathrm{eff}} + H_{\mathrm{FMR}} = 560$ Oe. This indicates an effective anisotropy field $H_{K,\mathrm{eff}}$ in the range of 10–340 Oe for the CoFe/PtMn/CoFe trilayers, corresponding to a self-biased FMR frequency in the range of 1.8–7.2 GHz. The combination of low FMR linewidth, high saturation magnetization, the low coercivity, and significantly enhanced effective magnetic field in the Ru seeded CoFe/PtMn/CoFe trilayer films make them great candidates for RF/microwave frequency applications.

It is notable that the effective anisotropy fields of these CoFe/PtMn/CoFe trilayer films at microwave frequency are completely different from those at dc frequency. At a CoFe layer thickness of 100 Å, the anisotropy fields of the trilayers at X-band are more than twice those at dc frequency. Rodriguez–Suarez *et al.* [17] attribute this discrepancy to the magnetic behavior of stable and unstable AFM grains at the AFM–FM interface. The conditions of the FMR measurements are different because the static applied field values are much larger than the applied fields in the dc VSM measurements. However, they observe H_{ex} and H_K values at FMR frequency to be consistently lower than at dc, contrary to our observations. Further work is needed to understand the origin of this difference between the effective anisotropy fields at dc and microwave frequencies, in order to fully exploit this behavior for microwave applications.

IV. Conclusion

In summary, the Ru seeded CoFe/PtMn/CoFe trilayer films show excellent magnetic softness with an enhanced in-plane anisotropy field. FMR behaviors at the X-band of these samples show that the FMR linewidth does not drop monotonically with CoFe layer thickness for the Ru seeded trilayer films, which is in contrast to the typical behavior of the FM/AFM bilayers. FMR linewidth as low as 45 Oe was achieved together with strong FMR absorption for the Ru seeded $Co_{84}Fe_{16}/Pt_{50}Mn_{50}/Co_{84}Fe_{16}$ trilayers, which corresponds to zero exchange bias field at the X-band.

The exchange-coupled CoFe/PtMn/CoFe trilayers show different effective anisotropy fields at dc and microwave frequencies. Significantly enhanced effective anisotropy fields up to 340 Oe was observed at microwave frequency, corresponding to a self-biased FMR frequency of 7.2 GHz. These exchange coupled CoFe/PtMn/CoFe trilayers with excellent magnetic softness, low FMR linewidth and significantly enhanced anisotropy fields could be a future direction for the engineering of microwave magnetic materials for RF and microwave devices.

Acknowledgment

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