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

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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 (≈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 $M_s/M_F$ 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 ≈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 and magnetic integrated inductors, 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. The low anisotropy fields of these metal magnetic thin films correspond to a low ferromagnetic resonance (FMR) frequency $f_{FMR}$, as described by the well-known Kittel equation: $f_{FMR} = \frac{\gamma}{4\pi M_s H_k}$ (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, which severely limits their applications.

Ferromagnetic/antiferromagnetic (FM/AFM) bilayer thin-film structures show enhanced effective anisotropy fields $H_{K,eff}$ due to exchange coupling, which can be expressed as $H_{K,eff} = H_{K,eff}^{FM} + H_{K,eff}^{AFM} + \Delta H_e$, for ideal films, with $H_{K,eff}^{FM}$ the intrinsic anisotropy field, $\Delta H_e$ the increased coercivity due to exchange coupling, and $H_{K,eff}^{AFM}$ being the exchange bias field which can be expressed as $H_{K,eff}^{AFM} = J_{ex}/(M_F t_F)$ with $J_{ex}$ 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 ~100% squareness ratio ($M_s/M_F$) 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.

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

FMR linewidth ($\Delta H_{FMR}$) of magnetic materials is a parameter of paramount importance for rf/microwave applications such as microwave band stop filters. 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. However, relatively less amount of work is done on the exchange-
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] × n consisting of trilayers with ferromagnetic layers of Co90Fe10 or Co84Fe16, and an antiferromagnetic layer of Pt50Mn50 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 Co90Fe10/Pt50Mn50/Co90Fe10 with a 30 Å Ru seed layer and 30 Å Ru cap layer (referred to as Co90Fe10[Ru] in the context) and Co84Fe16/Pt50Mn50/Co84Fe16 with a 30 Å Ru seed layer and 30 Å Ru cap layer (referred to as Co84Fe16[Ru]) were deposited. To compare the seed layer effects, multilayers of Co90Fe10/Pt50Mn50/Co90Fe16 with a 30 Å Ru seed layer and 30 Å Ru cap layer (referred to as Co90Fe16[Ru]) were 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 were deposited with a fixed CoFe layer thickness of 200 Å, and with 100 Å Al2O3 dielectric layers with a 30 Å Ru seed layer and 30 Å Ru cap layer. AFM/FM trilayers are significantly different from those of Co90Fe10/Pt50Mn50/Co90Fe16 with a 30 Å NiFeCr seed and 30 Å Ru cap layer (referred to as Co84Fe16[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 were deposited with a fixed CoFe layer thickness of 200 Å, and with 100 Å Al2O3 dielectric layers to suppress eddy current loss. Magnetic-field annealing was performed 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. The two sets of sandwich films Co90Fe10[Ru] and Co84Fe16[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 Co90Fe10[NiFeCr], however, shows a much lower hard axis coercivity 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/cm2 for the three sets of samples Co90Fe10[Ru], Co84Fe16[Ru], and Co84Fe16[NiFeCr], respectively. The effective anisotropy fields of the CoFe films was enhanced to be ~160 Oe for both Co90Fe10[Ru] and Co84Fe16[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 Co90Fe10[Ru] and Co84Fe16[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 Co84Fe16[NiFeCr] film set shows significantly higher intensity and narrower PtMn (111) and CoFe (110) diffraction peaks. Grain-size evaluation by using the Scherrer equation was done with the PtMn (111) and CoFe (110) peaks of the XRD pattern, as indicated in Table I.

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 samples sets.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>PtMn grain size (nm)</th>
<th>CoFe grain size (nm)</th>
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<tbody>
<tr>
<td>Co90Fe10[Ru]</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Co84Fe16[Ru]</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Co84Fe16[NiFeCr]</td>
<td>17</td>
<td>31</td>
</tr>
</tbody>
</table>
The relatively large FMR linewidth of the minimum FMR linewidth among all three sample sets was not obtained in either Co$_{90}$Fe$_{10}$[Ru] or Co$_{84}$Fe$_{16}$[NiFeCr] sample set. The FMR linewidth in Co$_{84}$Fe$_{16}$[Ru] increases with the increase of the FeCo layer thickness when the FeCo layer thickness is over 200 Å, 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 Å, which is significantly lower than the skin depth at X band, which is calculated to be about 4000 Å. Further investigation is needed to understand why the FMR linewidth in Co$_{84}$Fe$_{16}$[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 Å. Their effective anisotropy fields, coercivities, and FMR linewidth are shown in Table II. Clearly the eight-period multilayer based on Co$_{84}$Fe$_{16}$[Ru] trilayer has the best combination of magnetic and microwave properties, a high anisotropy field of 121 Oe, a low hard axis coercivity of 3.5 Oe, an easy axis coercivity of 66 Oe, and a FMR linewidth of 132 Oe.

In summary, 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 $M_s/M_L$ of >98%, a significantly enhanced in-plane anisotropy of 123 Oe, and a low FMR linewidth of 45 Oe at ~9.5 GHz when the CoFe layer thickness is above 200 Å. With the combination of these magnetic and microwave properties, the CoFe/PtMn/CoFe films could play an important role in microwave applications.

![Fig. 2. In-plane X band (~9.5 GHz) FMR linewidth of the samples of Co$_{90}$Fe$_{10}$[Ru], Co$_{84}$Fe$_{16}$[Ru], and Co$_{84}$Fe$_{16}$[NiFeCr] with a CoFe layer thickness of 200 Å.](image)

![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 Co$_{84}$Fe$_{16}$[NiFeCr] with a CoFe layer thickness of 200 Å.](image)

<table>
<thead>
<tr>
<th>Eight-period film structures</th>
<th>Anisotropy field (Oe)</th>
<th>Hard axis coercivity (Oe)</th>
<th>Easy axis coercivity (Oe)</th>
<th>FMR linewidth at 9.5 GHz (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$<em>2$O$<em>3$/Co$</em>{90}$Fe$</em>{10}$[Ru]</td>
<td>121</td>
<td>4.5</td>
<td>72</td>
<td>148</td>
</tr>
<tr>
<td>Al$<em>2$O$<em>3$/Co$</em>{84}$Fe$</em>{16}$[Ru]</td>
<td>121</td>
<td>3.5</td>
<td>66</td>
<td>132</td>
</tr>
</tbody>
</table>

15A. Gainier, X-ray Diffraction (Freeman, San Francisco, 1963), p. 121.