Perpendicular standing spin wave and magnetic anisotropy study on amorphous FeTaC films

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Magnetic anisotropy, spin wave (SW) excitation and exchange stiffness constant of amorphous FeTaC ($d = 20-200$ nm) films were studied as a function of thickness using micro-strip ferromagnetic resonance (MS-FMR) technique. The MS-FMR spectra for in-plane applied magnetic field show the presence of uniform precessional mode ($n = 0$) along with first perpendicular standing spin wave (PSSW) mode ($n = 1$) especially for $d = 50, 100$ and 200 nm films. The angular ($\varphi_H$) dependence of resonance field ($H_r$) and magnetic field dependence of resonance frequencies ($f_r$) in planar configuration for the uniform and PSSW modes were modeled successfully by using dispersion relation which arises from a combination of exchange and dipolar interactions. The relevant parameters such as saturation magnetization ($k\varphi_M$), uniaxial anisotropic constant ($K_u$), $g$-factor, and exchange stiffness constants ($A_{ex}$) are estimated for different FeTaC film thickness. $A_{ex}$ is found to increase from $1.52(4) \times 10^{-7}$ to $5.0(5) \times 10^{-6}$ erg/cm as the thickness of film increases from 50 to 200 nm, possibly due to surface pinning effect or significant inhomogeneity especially at higher thickness films.

Index Terms—Ferromagnetic resonance, Soft ferromagnetic alloy, Perpendicular standing spin wave, Exchange stiffness constant.

I. INTRODUCTION

Soft ferromagnetic (FM) alloys have been promising candidates towards potential technological applications in various magneto-electronic devices like magnetoresistive random access memories (MRAM), magnetic tunnel junctions (MTJs) and soft underlayer in perpendicular magnetic recording media. The amorphous nature of those alloys reduces the number of pinning centers which may lead to the spin transfer torque (STT)-driven domain wall motion along with the number of pinning centers which may lead to the spin wave resonances and magnetic anisotropy. The experimental results. The free energy density of a single magnetic thin film can be written as,

$$E = -M_S H [\sin \theta_H \sin \theta_M \cos (\varphi_H - \varphi_M) + \cos \theta_H \cos \theta_M]$$

$$-2\pi M_S^2 \sin^2 \theta_M - K_u \left( \frac{\sin^2 \theta_M \cos^2 \varphi_M \cos^2 \varphi_u}{\sin^2 \theta_M \sin^2 \varphi_M \sin^2 \varphi_u} + \sin^2 \theta_M \sin^2 \varphi_M \sin^2 \varphi_u \right)$$

$$+ K_\perp \sin^2 \theta_M$$

(1)

In the above expression, $\varphi_H$ and $\varphi_M$ are azimuthal angles corresponding to $H$ and $M$ directions, respectively. $\theta_H$ and

Manuscript received November 7, 2015; revised September 00, 0000.
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$\theta_M$ are polar angles. The first term in the above expression corresponds to the Zeeman energy, and the second term is dipolar demagnetization energy, where as the third and fourth terms correspond to the uniaxial planar and perpendicular magnetic anisotropy energies, respectively. $M_S$ is the saturation magnetization, $K_u$ and $K_\perp$ are in-plane and out-of-plane uniaxial magnetic anisotropy constants, respectively. The resonance frequency $f_r$ of the uniform precession mode is deduced from the energy density by using the following expression [12],

$$f_r = \left( \frac{\gamma}{2\pi} \right)^2 \frac{1}{M_S^2 \sin^2 \theta_M} \left[ \frac{\partial^2 E}{\partial \theta_M^2} \frac{\partial^2 E}{\partial \varphi_M^2} - \left( \frac{\partial^2 E}{\partial \theta_M \partial \varphi_M} \right)^2 \right].$$

(2)

The resonance equations for planar configuration are solved at equilibrium position of $M$ under the applied magnetic field ($H$) by using the condition, $\frac{\partial E}{\partial H} = 0$ and the solution of $H$ from the energy minimization condition is derived as,

$$H = \frac{2K_u \cos \varphi_M \sin \varphi_M}{M_S \sin (\varphi_H - \varphi_M)}$$

(3)

The in-plane ($\theta_H = \theta_M = \pi/2$) dispersion relation of the uniform and PSSW modes can be modeled in combined way from the total magnetic energy density which arises from the exchange and dipolar interactions and is given by [13], [14],

$$f_r = \frac{\gamma}{2\pi} \left( \frac{H \cos (\varphi_M - \varphi_H)}{4\pi M_S} + \frac{A_{ex}}{M_S} \cos 2(\varphi_M - \varphi_H) + \frac{2A_{ex}}{M_S} \left( \frac{\pi}{d} \right)^2 \right)^{1/2}$$

$$+ \frac{H \cos (\varphi_M - \varphi_H)}{4\pi M_S} + \frac{A_{ex}}{M_S} \cos^2 (\varphi_M - \varphi_H) + \frac{2A_{ex}}{M_S} \left( \frac{\pi}{d} \right)^2 \right)^{1/2}$$

(4)

where $\gamma$ is the gyromagnetic ratio, $A_{ex}$ is the exchange stiffness constant and $n$ is the quantized number for the PSSW along the thickness direction. $n=0$ represents the uniform precession mode and the higher order modes ($n=1, 2, 3, ...$) represent PSSW mode.

**IV. RESULTS AND DISCUSSION**

The room temperature magnetic hysteresis loops ($M - H$) for planar configuration are shown in Fig. 1 for different thickness of FeTaC films. The 20 nm sample shows rectangular shaped loop with remanence ratio of around 90%. The loop shape is changed to flat loop along with low remanence for 50 nm sample. The coercivity fields ($H_C$) for 20 and 50 nm samples are found to be 1.5 and 2 Oe, respectively which is a characteristic feature of soft ferromagnetism. By increasing the film thickness (≥100 nm), the $M - H$ clearly shows the transcritical loop manifesting the presence of stress induced perpendicular anisotropy during the film deposition [5]. $M_S$ is found to increase from 6125 ± 30 Oe to 7740 ± 40 Oe as the film thickness increases from 20 to 200 nm. The room temperature soft magnetic properties degrade drastically as thickness increases due to the transition from in-plane orientation of magnetization to the strip domain patterns [6].

The typical FMR spectra for planar orientation are shown in Fig. 2 for different thickness of films at 10 GHz precessional frequency along the direction $\varphi_H=0^\circ$. It is observed that the 20 nm thick film shows a clear uniform precession mode without any other spin wave resonance (SWR) mode, in which the dynamic magnetization is uniform across the film thickness. However, by increasing the film thickness from 50 nm onwards, the first PSSW mode is excited at lower absorption fields. The signal intensity of this mode in 50 nm thick film is 7 times smaller than the uniform mode. The absence of higher order ($n > 1$) exchange-dominated PSSW modes could be due to very weak excitation and the intensity of those modes may be lower than our detection sensitivity. The separation between the uniform mode and first PSSW mode increases with decreasing the film thickness, which could be understood on the basis that the perpendicularly quantized spin wave vector is inversely proportional to the film thickness, i.e. $q = n\pi/d$. For thicker film, especially for $d = 200$ nm, the separation between the PSSW and uniform mode is even smaller (not shown) and the broadening in uniform mode is
observed along with a small kink at lower absorption field. As the thickness of the film increases, $H_r$ shifts towards higher absorption fields due to higher saturation magnetization. Fig. 3(a) shows the $\varphi_H$ dependence of $H_r$ for uniform mode at 6, 8, and 10 GHz precessional frequencies for 20 nm thick film, which depicts that the angular dependence of resonance fields is governed by uniaxial magnetic anisotropy. The typical field dependence of resonance frequencies is shown in Fig. 3(b). The experimental data points are successfully modeled using Eq.(4) by incorporating the condition $n = 0$. By increasing the thickness of the film from 50 nm onwards, $\varphi_H$ dependence of $H_r$ for uniform mode and the first PSSW mode at three different frequencies were modeled by incorporating the condition $n = 0$ and $n = 1$, respectively and are shown as solid lines in Fig. 4(a). The respective $H$ dependence of $f_r$ along easy and hard axis of the magnetization is also shown in Fig. 4(b). The numerically data points yielded a good fit and the relevant parameters such as $M_S$, $K_u$, $g$-factor, and $A_{ex}$ for different film thickness are listed in Table-1. The origin of in-plane uniaxial magnetic anisotropy in FeTaC thin films ($d = 20$ and 50 nm) could be understood on the basis that the strong exchange coupling between the FM atoms plays an important role during deposition process, which allows to form aligned FM atom pairs parallel to the film plane. The small $K_u$ values of $4.5(5)\times10^3$ and $1.3(2)\times10^3$ erg/cm$^3$ are estimated for 20 and 50 nm thick films, respectively and the consequent planar anisotropic fields ($H_u$) are 18.3 and 5 Oe. On further increase in thickness of the film from 100 to 200 nm, the in-plane uniaxial magnetic anisotropy disappears. $H$ dependence of $f_r$ for both the modes for 100 [Fig. 5] and 200 nm [not shown] thick films are also modeled. Interestingly, $M_S$ values obtained from MS-FMR analysis are close to that observed in $M - H$ loop measurements and are found to increase with film thickness. $g$-factor shows $1/d$ dependence behavior. $A_{ex}$ also increases with increase in thickness, which may be due to the surface pinning effect [13]. The values of $A_{ex}$ for 50 and 100 nm thick films are found to be one order of magnitude smaller than the known value $1\times10^{-6}$ erg/cm for bulk Fe [15], whereas it is comparable to
FePt film of thickness 105 nm [16]. On the other hand, $A_{ex}$ for 200 nm film is 5 times larger than that of Fe. The reason may be due to the significant inhomogeneity which adequately excites the spin waves or segregation of Fe clusters in such thick films.

V. Conclusions

MS-FMR technique has been employed to explore the magnetic anisotropy and spin wave excitations in FeTaC based soft FM films. The azimuthal angular dependence of resonance fields depicts the presence of small uniaxial magnetic anisotropy in $d = 20$ and 50 nm thick films. The existence of first PSSW mode along with uniform mode gives rise to the evidence of exchange and dipolar interactions. The exchange stiffness constant for these amorphous films are deduced from evidence of exchange and dipolar interactions. The exchange first PSSW mode along with uniform mode gives rise to the resonance fields depicts the presence of small uniaxial magnetic anisotropy in FeTa-C soft underlayer for Fe-Ta-N magnetic film system for 250 Mb/in$^2$ recording.

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