Spin dynamics and frequency dependence of magnetic damping study in soft ferromagnetic FeTaC film with a stripe domain structure

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Perpendicular magnetic anisotropy (PMA) and low magnetic damping are key emerging factors for the free layer magnetization switching by spin transfer torque technology in magnetic tunnel junction devices. The magnetization precessional dynamics of FeTaC based soft ferromagnetic thin film with PMA and stripe domain structure were explored in broad band frequency range by employing micro-strip ferromagnetic resonance technique. Polar angle variation of resonance field ($H_r$) and linewidth ($\Delta H_{PP}$) at different frequencies have been analyzed numerically using Landau-Lifshitz-Gilbert equation by taking into account of total energy density function ($E$) for magnetic thin film. The numerically estimated parameters are found to be Landau $g$-factor 2.1, PMA constant, $K_1 = 2 \times 10^5$ erg/cm$^3$ and effective magnetization, $4\pi M_{eff} = 7145$ Oe. Gilbert damping parameter ($\alpha$) at different frequencies are evaluated by taking intrinsic Gilbert damping contribution and dispersion of $4\pi M_{eff}$ as an extrinsic contribution into total linewidth ($\Delta H_{PP}$) analysis. The values of $\alpha$ are estimated to be on the order of $10^{-3}$, but increase monotonically by decreasing the precessional frequency ($f$).

I. INTRODUCTION

Spin transfer torque (STT) has greater credibility towards ultrafast spin dynamics in ferromagnets by switching the magnetization of spin valves and magnetic tunnel junctions (MTJ). The current researchers are more keen to be focused on STT technology for its high density magnetic random access memories (MRAM), STT-driven domain wall devices and perpendicular magnetic recording media applications. The key emerging factor in STT effect is spin polarized current ($J_C$) with low density which brings out magnetization reversal in the free layer and requires the material specifications with low saturation magnetization ($M_S$), high spin polarization, high uniaxial perpendicular anisotropy (PMA) constants and low magnetic damping ($\alpha$). The magnetic damping parameter, $\alpha$ can be well described by phenomenological Landau-Lifshitz-Gilbert equation and is known as Gilbert damping. Many attempts have been tried on single layer and multilayered magnetic alloys to understand the origin of Gilbert damping term in spin dynamics relaxation, which is contributed by intrinsic and extrinsic part of the materials. Intrinsic Gilbert damping parameter have been studied by tuning the strength of spin-orbit coupling recently. Ikeda etal. have reported that CoFeB-MgO based MTJ with PMA would be reliable for high-density non-volatile memory application due to its high thermal stability and more efficient towards STT technology. The investigation on magnetic dynamics, PMA and the apparent magnetic damping have been studied extensively in CoFeB based soft ferromagnetic thin film by ferromagnetic resonance (FMR) and time-resolved magneto-optical Kerr effect (TRMOKE) techniques. Malinowski et al have reported large increase in Gilbert damping with applied magnetic field in perpendicularly magnetized CoFeB thin film.

In this current letter, we have been focused on amorphous FeTaC ferromagnetic (FM) layer due to its interesting soft ferromagnetic properties. The amorphous soft FM layer reduces the amount of pinning centers which may lead to the STT-driven domain wall motion applications along with high TMR ratio. The transcrirical loop along with stripe domain structure which is the manifestation of PMA component was reported on FeTaC thin film with thickness of 200 nm. To shed more light into its dynamic magnetic properties, this film was further studied by using ferromagnetic resonance (FMR) technique. Moreover, angular dependence of magnetic anisotropy, magnetization dynamics and Gilbert damping have been studied by FMR technique in several magnetic thin films like Heusler alloys, Permalloy, soft magnetic materials and multilayered (FM/AFM or non magnetic/FM) magnetic films for magnetic recording, MTJ and TMR reader applications. However, most of the reports are limited to single frequency due to X-band electron-spin-resonance spectrometer and resonance cavity measurement. In this report, spin dynamics and magnetic relaxation were studied in broad band frequency range by using vector network analyzer (VNA) based micro-strip ferromagnetic resonance (MS-FMR) spectrometer.

II. EXPERIMENTAL DETAILS

Soft ferromagnetic amorphous Fe$_{80}$Ta$_{8}$C$_{12}$ single layer film with thickness 200 nm was deposited in DC mag-
neutron sputtering technique and the detail growing environment was reported in earlier report. The static and dynamic magnetic properties were explored by VNA-based homemade MS-FMR spectrometer. The microstrip line which was coupled with VNA and Schottky Diode Detector (Agilent 8473D) through high frequency co-axial cables was mounted in between the pole gap of the electromagnet. The magnetic thin film with film side downward was mounted on the strip line. The different constant frequencies were varied by using Agilent Technologies made VNA (Model no. PNA-X, N-5242A) with a constant microwave power of 5 dBm. The first derivative of the absorption spectra w.r.t magnetic field \( H \) were collected by field modulation and lock-in detection technique. The FM thin film was treated in-plane and out-of-plane orientation and FMR spectra were carried out by varying two parameters: frequency and angle. The frequency \( f \) and polar angle \( \theta_H \) dependence of resonance fields \( H_r \) and line widths \( \Delta f \) were extracted from each FMR spectra and the numerical calculations were carried out by mathematica program for different relaxation processes.

### III. RESULTS AND DISCUSSION

The precession of magnetization \( M \) in sample plane under the influence of microwave and external magnetic field \( H \) in polar co-ordinate system is illustrated in Fig. 1. \( \varphi_M \) and \( \varphi_H \) are in-plane angles between \( H(M) \) and x-axis and \( \theta_H(\theta_M) \) are polar angles between \( H(M) \) and z-axis respectively. The uniform precession extended by damping is described by Landau-Lifshitz-Gilbert (LLG) equation of motion and can be written as:

\[
\frac{\partial \vec{M}}{\partial t} = -\gamma (\vec{M} \times \vec{H}_{eff}) + \frac{G}{\gamma M_s^2} \left[ \vec{M} \times \frac{\partial \vec{M}}{\partial t} \right] \tag{1}
\]

The first term corresponds to the precessional torque in the effective magnetic field and the second term is Gilbert damping torque. \( \gamma = g \mu_B / \hbar \) is denoted as gyromagnetic ratio and is written in terms of Landé \( g \) factor, Bohr magneton \( \mu_B \), and Planck constant \( \hbar \). \( G = \gamma \alpha M_s \) is related to the intrinsic relaxation rate of the material in \( s^{-1} \). \( \alpha \) is dimension less Gilbert damping parameter. The free energy density of a single magnetic thin film can be written as,

\[
E = -M_S H \left[ \sin \theta_H \sin \theta_M \cos (\varphi_H - \varphi_M) + \cos \theta_H \cos \theta_M \right] -2\pi M_s^2 \sin^2 \theta_M + K_1 \sin^2 \theta_M \tag{2}
\]

where the first term is analogous to Zeeman energy, the second term is dipolar demagnetization energy and finally the third term signifies to the anisotropy energy, \( M_S \) is the saturation magnetization, \( K_1 \) is the PMA constant with corresponding anisotropic field \( H_{f1} = 2K_1/M_S \). The resonance frequency \( f_r \) of the uniform precession mode is deduced from the energy density by using the following expression and the derivatives are evaluated at equilibrium positions of \( M \) and \( H \):

\[
f_r^2 = \left( \frac{\gamma}{2\pi} \right)^2 \frac{1}{M_s^2 \sin^2 \theta_M} \left[ \frac{\partial^2 E}{\partial \theta_M^2} \frac{\partial^2 E}{\partial \varphi_M^2} - \left( \frac{\partial^2 E}{\partial \theta_M \partial \varphi_M} \right)^2 \right] \tag{3}
\]

#### A. In-plane measurements and analysis

The typical FMR spectra for in-plane orientation at different frequencies have been shown in Fig. 2(a). The measurements were carried out by varying frequency from 1-18 GHz with the interval of 0.5 GHz. At lower frequencies, 1-6 GHz range the FMR spectra show two resonance peaks. The low field resonance peaks named as secondary mode and are marked by 2 and 2* for 2.5 and 6 GHz respectively in Fig. 2(a). This mode arises due to the linear unsaturated zone of the transcritical loop in \( M \sim H \) curve and is usually observed in stripe domain structures. Where as, the primary mode usually called uniform mode are marked as 1 and 1*. The \( H_r \) of this secondary resonance peak increases with the increase in \( f \) up to 4.5 GHz and then follows the reverse trend as depicted in Fig. 2(b). This could be explained on the basis that above 4.5 GHz the \( H_r \) value of uniform
mode overcomes the parallel saturation field, i.e., 280 Oe as observed in $M \sim H$ curve\cite{19}. Above 6 GHz, the $H_r$ value exceeds the parallel saturation field in large extent and this could be the reason for the strong attenuation of secondary phase. In planar configuration, the magnetization lies in the plane of the film, $\theta_{M}=\theta_{H}=\pi/2$. The solution for the in-plane resonance frequency ($f_r$) can be calculated by incorporating the total energy ($E$) in eq\textsuperscript{n}-3 and is given by,

$$f_r = \frac{\gamma}{2\pi} [(4\pi M + H \cos (\varphi_H - \varphi_M)) (H \cos (\varphi_H - \varphi_M))]^{1/2}$$ \tag{4}

The $\varphi_M$ value can be calculated by using the solution of $H$ at equilibrium condition, i.e., $\frac{\partial E}{\partial \varphi_M} = 0$. However in the present thin film case, we could not find any planar anisotropy from the $\varphi_H$ dependence of $H_r$ and hence be concluded as $\varphi_H = \varphi_M$. The $f$ dependence of $H_r$ is numerically calculated by using eq\textsuperscript{n}-4 and is shown as a solid line in Fig. 2(b). The numerically calculated values yielded good fit and the reliable parameters are concluded as

The equilibrium angle of magnetization ($\theta_M$) are numerically calculated for each values of $\theta_H$ by minimizing the energy, i.e., $\frac{\partial E}{\partial \theta_M} = 0$ and is depicted in Fig. 3 for different frequencies. The Fig. 3 demonstrates that magnetization $\mathbf{M}$ suddenly attempt to align in planar direction as the magnetic field goes away from the $\theta_H = 0^\circ$ and $180^\circ$. Fig. 4 shows one complete round of $\theta_H$ dependence of $H_r$ at different frequencies. Uniaxial PMA is found to be observed along with singularities at $\theta_H = 0^\circ$ and $\theta_H = 180^\circ$, which signifies that in perpendicular configuration the infinite magnetic field is required to turn out the $\mathbf{M}$ vector parallel to the $\mathbf{H}$. The $H_r$ Vs. $\theta_H$ values are modeled at different frequencies starting from 4 to 10 GHz with 2 GHz intervals by using eq\textsuperscript{n}-5 and the interpolated values of $\theta_M$ form Fig. 3. The modeled $H_r$ values are plotted as a solid lines in Fig. 4 and a very good agreement with experimental data is observed. The parameters deduced from this calculations are found to be, $K_\perp = 2 \times 10^5$ erg/cm\textsuperscript{3}, $4\pi M_{sat} = 7145$ Oe. This $K_\perp$ value is found to be comparable to the DC magnetization result\cite{19}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Equilibrium angle of the magnetization $\theta_M$ as a function of the applied field $\theta_H$ direction in out-of-plane configuration at different frequencies.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Angular dependence of resonance field $H_r$ in out-of-plane configuration at different frequencies. (o) shows the experimental points and the line(-) shows the modeled data.}
\end{figure}

Finally, the damping of magnetization precession has been analyzed from FMR linewidth ($\Delta H_{PP}$) measurements. The $\theta_H$ dependence of $\Delta H_{PP}$ was extracted from polar angle variation of FMR spectrum at different frequencies starting 4-10 GHz with interval of 2 GHz and shown in Fig. 5 as open circles. In order to get better clarity of Fig. 5, the data of 4 GHz frequency are hidden. The total line width broadening contributed by intrinsic and extrinsic part of the material has been expressed in the following expression:\cite{9}
The dispersion in magnitude and direction of effective magnetization are found to decrease monotonically with the precessional frequency has been attributed to the intrinsic Gilbert damping term were analyzed at different frequencies. The extrinsic contribution is found to be negligible away from 0° and some considerable magnitude near the perpendicular configuration. The Gilbert damping parameter at different frequencies for the FeTaC thin film of thickness 200 nm is plotted in inset of Fig. 5. The curves are shown for a single frequency for better clarity. The linewidth broadening due to the spatial dispersion of magnitude and the direction of 4πMreff respectively. The Gilbert damping constant for present FeTaC magnetic thin film is found to be comparable to those reported in Fe-based magnetic thin films, such as FePd ternary alloy, permalloy, NiFe/CoFeB/CoFe multilayered structure and (FeCo)1–xGdx. However, the Mn and Co-based magnetic thin films have been reported larger damping parameter as compared to the current study which could be understood due to the strong spin-orbit coupling.

IV. CONCLUSIONS

In conclusion, PMA and Gilbert damping which are more important and crucial parameters for STT, STT-MRAM and TMR applications, were analyzed in FeTaC soft ferromagnetic thin film with a striped domain structure by using MS-FMR technique in broad band frequency range. The precise estimation of Landé g-factor, PMA constant and 4πMreff were carried out by using total energy density function for magnetic thin film. Spin dynamics relaxation which is quantified by Gilbert damping term were analyzed at different frequencies and were found to be in the order of 10⁻³ which falls in the most reliable order from application point of view. The values of α were found to be comparable to those reported Fe-based single layer and multilayered magnetic thin films.

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FIG. 5. Out-of-plane angular dependence of linewidth ∆Hpp at different frequencies. (o) shows the experimental points and the line (−) shows the modeled data.

\[ \Delta H_{PP} = \Delta H(\alpha) + \Delta H(4\pi M_{eff}) + \Delta H(\Delta \theta_H) \]

\[ \Delta H(\alpha) = \frac{2}{\sqrt{3}} \frac{1}{\pi M_S} \alpha g \left( \frac{\partial^2 E}{\partial \theta M^2} + \frac{1}{\sin^2 \theta M} \frac{\partial^2 E}{\partial \phi M^2} \right) + \frac{1}{\sqrt{3}} \left( \frac{\partial H}{\partial \theta M} \right) \Delta 4\pi M_{eff} + \frac{1}{\sqrt{3}} \left( \frac{\partial H}{\partial \phi M} \right) \Delta \theta_H \] (6)

where \( 4\pi M_{eff} = 4\pi M_S - 2K_{||}/M_S \), is the effective magnetization. ∆H(α) arises from an intrinsic Gilbert type damping and have large contribution towards linewidth broadening. The parameter α signifies how fast the precessional energy is dissipated into the lattice. The ∆H(4πM_{eff}) and ∆H(Δθ_H) represent line width broadening due to the spatial dispersion of magnitude and the direction of 4πM_{eff} respectively. The ∆θ_H dependence of total ∆H_{PP} was modeled by using eqn -6 and the interpolated values of θM from Fig. 3 at different frequencies. The numerically calculated ∆H_{PP} values are shown as solid lines in Fig. 5. The independent line width contributions towards the total line width ∆H_{pp} is shown in Fig. 6. The curves are shown for a single frequency for better clarity. The linewidth broadening is observed mainly due to the intrinsic Gilbert damping. The extrinsic contribution is found to be negligible when θH away from 0° and some considerable magnitude near the perpendicular configuration. The Gilbert damping parameter at different frequencies for the FeTaC thin film of thickness 200 nm is plotted in inset of Fig. 6. It shows that the α decrease monotonically with the increase in frequency. The low value of damping parameter in the order of 10⁻³ is observed in the present thin film and can be more relevant towards the STT technology or MTJ applications. Such minute increase of α by decreasing precessional frequency has been attributed to the inhomogeneous line width broadening due to the dispersion of anisotropic field. The dispersion in magnitude and direction of effective magnetization are found to be ∆4πM_{eff}=0.06 kOe, ∆θ_H ≈ 3 × 10⁻³ degree. The value of Gilbert damping constant for present FeTaC magnetic thin film is found to be comparable to those reported in Fe-based magnetic thin films, such as FePd ternary alloy, permalloy, NiFe/CoFeB/CoFe multilayered structure and (FeCo)1−xGdx. However, the Mn and Co-based magnetic thin films have been reported larger damping parameter as compared to the current study which could be understood due to the strong spin-orbit coupling.
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