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Near-\(T_c\) Ferromagnetic Resonance and Damping in FePt-Based Heat Assisted Magnetic Recording Media

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High-temperature ferromagnetic resonance (FMR) in FePt-based media materials was studied for the first time. The FMR linewidth (\(\Delta H\)) as a function of temperature (\(T\)), field angle (\(\theta_H\)), and the volume fraction (\(x\)) of carbon in the material were determined, and the effective Gilbert damping constant and the Bloch-Bloembergen relaxation time were estimated. The data suggest that at temperatures 10-45 K below the Curie temperature, two-magnon scattering and spin-flip magnon-electron scattering make comparable contributions to \(\Delta H\). With a decrease in \(T\), \(\Delta H\) increases due to enhancement of the two-magnon scattering. \(\Delta H\) can be tuned via varying \(x\) and shows a maximum at \(\theta_H=45^\circ\) when varying \(\theta_c\).

I. Introduction

Heat assisted magnetic recording (HAMR), the most promising technology for next-generation hard disk drives, makes use of a laser to heat the recording media to an elevated temperature, near the Curie temperature (\(T_c\)), to significantly reduce the coercivity of the media material and thereby ease the switching of the magnetization.\(^{1,2,3,4}\) HAMR drives have been promised to be released to the market in the near future, but understanding of the damping at high temperatures near \(T_c\) in HAMR media has not been realized yet, though it is of great fundamental and practical interest.

Fundamentally, the physical mechanisms underlying the near-\(T_c\) damping in HAMR media are unclear, although there have been interesting experimental studies on damping properties at room temperature (RT) in perpendicular recording media materials including HAMR media.\(^{5,6,7,8,9}\) Further, it is also unknown which macroscopic model is more suitable to describe the near-\(T_c\) damping in HAMR media, although several different models have been previously used to analyze damping at high temperature (\(T\)), including the Gilbert equation,\(^{10,11}\) the Bloch-Bloembergen (BB) equation,\(^{12}\) the Landau-Lifshitz-Bloch equation,\(^{13,14,15,16}\) the Xu-Zhang equation,\(^{17,18}\) and the Tzoufras-Grobis equation.\(^{19}\) Practically, the nature and strength of the damping in the HAMR media is directly related to the switching time and the signal-to-noise ratio of the reading which significantly impact hard drive performance.

The previous experimental efforts on investigating damping in perpendicular recording media include three studies on damping in \(L1_0\)-ordered FePt thin films,\(^{7,8,9}\) which have been widely accepted as the media material for next-generation HAMR drives. Those studies used the same approach, the optical pump-probe technique, to measure the effective Gilbert damping constant (\(\alpha_{\text{eff}}\)), but the \(\alpha_{\text{eff}}\) values obtained are inconsistent, possibly due to the differences in the sample properties, such as the degree of \(L1_0\) order and the strength of the perpendicular anisotropy, or the experiment details. Specifically, Mizukami \textit{et al.} found \(\alpha_{\text{eff}}=0.055\) and also emphasized that the intrinsic damping should be much larger value than this value,\(^{1}\) while Becker \textit{et al.} found a much larger value \(\alpha_{\text{eff}}=0.1\) and claimed that this value was mostly intrinsic and contained little extrinsic contribution if any.\(^{8}\) Lee \textit{et al.} obtained an even larger value which was 0.21.\(^{9}\) Though these studies represent the first attempts on exploring damping in FePt-based HAMR media, the measurements were all carried out at RT, rather than at elevated temperatures at which the writing operation occurs. Possible relaxation routes in FePt media include spin-flip magnon-electron scattering (SF-MES, inter-band scattering),\(^{20,21,22,23}\) magnon-electron scattering associated with Fermi surface breathing (intra-band scattering),\(^{20,21,22,23}\) two-magnon scattering (TMS),\(^{5,6,24,25,26}\) and magnon-phonon scattering.\(^{27}\) As these relaxation processes all exhibit strong \(T\) dependence, the damping value near \(T_c\) in FePt HAMR media may differ significantly from the RT values cited above.

This paper reports on the first experimental study of near-\(T_c\) damping in FePt-C granular films that have structure and properties very similar to practical \(L1_0\)-FePt-based HAMR media. Specifically, ferromagnetic resonance (FMR) experiments were performed along three distinct dimensions of important relevance to HAMR applications, (1) the volume fraction of carbon (\(x\)) in the media, (2) the media temperature (\(T\)), and (3) the angle of the external magnetic field (\(\theta_H\)) relative to the film normal direction, at temperatures right below \(T_c\). The FMR linewidth (\(\Delta H\)) data as a function of \(T\), \(x\), and \(\theta_H\) were determined, and the effective damping constant \(\alpha_{\text{eff}}\) in the Gilbert model\(^{10,11}\) and the transversal relaxation time \(T_2\) in the BB model\(^{12,22}\) were estimated. The data indicate that at temperatures about 10-45 K...
below $T_c$, relevant to $T$ in HAMR writing operation, the TMS and SF-MES processes co-exist and make comparable contributions to $\Delta H$. With a decrease in $T$, however, $\Delta H$ increases, mostly due to the enhancement of the TMS process. Via varying $x$, $\Delta H$, $\alpha_{\text{eff}}$, and $T_2$ can be tuned as a factor of four near $T_c$. When varying $\theta_H$, $\Delta H$ and $\alpha_{\text{eff}}$ show a maximum at about $45^\circ$, which is an angle relevant to the actual HAMR writing operation. The $\alpha_{\text{eff}}$ values obtained are smaller than those measured at RT in previous works.\textsuperscript{7,8,9}

II. Structure and Static Magnetic Properties of Samples

The samples were grown on single-crystal (001) MgO substrates by DC magnetron sputtering and consist of a 10-nm-thick FePt-C granular layer with the carbon volume fraction $x=0\%$, 10\%, 20\%, or 30\% and a 3-nm-thick carbon capping layer. The base pressure of the sputtering chamber was $5.0 \times 10^{-7}$ Pa or lower. Prior to the sputtering growth, the MgO substrate surface was thermally cleaned at 600 °C for 1 hour. After that, the MgO substrate was maintained at the same temperature, and a FePt-C granular film was deposited by co-sputtering a FePt alloy target and a carbon target under an Ar pressure of 0.48 Pa at a deposition rate about 0.2 Å/s. The Fe:Pt atomic ratio in the FePt films is nearly 1:1. The alternating layer deposition technique was used to suppress the growth of the secondary mis-oriented FePt grains and obtain single-columnar, highly-(001)-textured FePt-C nano-granular films.\textsuperscript{28}

Following the FePt growth, a 3-nm-thick carbon over-coating layer was deposited at RT, which works as the protection layer of the FePt film. The microstructure properties of the samples were measured by transmission electron microscopy (TEM) using an “FEI Tecnai T20” TEM system at an electron accelerating voltage of 200 kV. The magnetization curves and hysteresis loops were measured by a superconducting quantum interference device vibrating sample magnetometer using magnetic fields of up to ±70 kOe. More details about the sample growth and characterization are provided in Refs. [28], [29], [30], and [31].

Figure 1 presents the main data about the microstructure and static magnetic properties of the samples. Figure 1(a) shows the TEM images of the four samples, with the carbon volume fraction $x$ indicated at the left-top corners. Figures 1(b), 1(c), and 1(d) give the average grain size ($d$), coercivity ($H_c$) measured with perpendicular fields, and the ratio of the in-plane remnant magnetization ($M_{r,\text{IP}}$) to the out-of-plane remnant magnetization ($M_{r,\text{OP}}$), respectively, as a function of $x$. The data were all measured at RT.
The data in Figs. 1(a) and 1(b) show that the addition of carbon to FePt can effectively break big FePt grains with \( d=75 \text{ nm} \) into much smaller grains with \( d=10 \text{ nm} \); the higher the carbon volume fraction is, the smaller the grains are. The data in Fig. 1(c) indicate that the introduction of 10% carbon can result in a significant increase in \( H_c \), which is mostly due to the formation of physically separated, vertically oriented, small-size columnar FePt grains and a corresponding transition from domain wall motion-type magnetization reversal to rotation reversal. However, an increase in \( x \) to 20% and then 30% results in a notable decrease in \( H_c \), which is mainly due to the size effect of the grains, namely, that the smaller the grains are, the stronger role the thermal energy plays in magnetization reversal. In contrast, the \( M_{r-IP}/M_{r-OP} \) ratio exhibits a completely different trend – it increases very little when \( x \) increases from 0% to 10% and then 20% but increases substantially when \( x \) is raised to 30%, as shown in Fig. 1(d). This result suggests that, an increase in \( x \) from 0% to 10% and then 20% results in big changes in both \( d \) and \( H_c \) but not in the (001) orientation of the FePt grains, while an increase to \( x=30\% \) leads to the presence of some mis-oriented grains in the FePt layer. This degrading of the (001) orientation also explains in part the relatively low \( H_c \) value measured for \( x=30\% \). These results together clearly indicate that one can use the carbon volume fraction as a very effective tool to widely tune the microstructural and magnetic properties of the FePt media, as well as the FMR and damping properties as described below.

### III. High-Temperature FMR Experiments

Figure 2 shows the high-\( T \) FMR approach which was used to study the near-\( T_c \) damping in the above-described samples. Figure 2(a) shows a schematic diagram of the experimental system. The main components include a rectangular microwave cavity (purple), a diamond rod (yellow) with a diameter of 2 mm that loads the sample (red) into the cavity, and a ceramic heater (gray) that heats the sample through the diamond rod. These components are housed in a high-vacuum chamber, and the measurements are performed at a pressure of about \( 6.7 \times 10^{-3} \text{ Pa} \) (or about \( 5 \times 10^{-5} \text{ Torr} \)) to prevent changes in sample properties due to oxygen during high-\( T \) measurements. For the FMR data presented in this paper, the microwave frequency (\( f \)) was kept constant at 13.7 GHz, which was also the
IV. Temperature Dependence of FMR Properties

The resonant frequency of the microwave cavity, while the external magnetic field was swept. Field modulation and lock-in detection were used, so all the FMR profiles presented in this paper are the derivatives of the FMR power absorption. The sample temperature \( T \) was calibrated through separate measurements using a thermocouple. Prior to placing the sample in the FMR system, the sample was saturated by an out-of-plane field of 80 kOe at room temperature. After placing the sample in the FMR system and heating it, prior to each FMR measurement the sample was saturated by a field of 15 kOe.

Figure 2(b) presents the FMR data (blue dots) measured at \( T=648 \) K on the “\( \chi=20\% \)” sample and a numerical fit (red curve) to the derivative of a Lorentzian trial function. The Lorentzian fitting-yielded peak-to-peak FMR linewidth \( \Delta H \) and field \( H_{\text{FMR}} \) are indicated in the figure. A fit (green curve) to the derivative of a Gaussian trial function is also included in the figure. One can see that the Lorentzian fit is better than the Gaussian fit, indicating that the inhomogeneity line broadening contribution, if any, to \( \Delta H \) is small. In the case that a film sample has strong spatial inhomogeneity and the associated line broadening is large, the Gaussian function would fit the data better than the Lorentzian function.\(^{32}\) It should be noted that the inhomogeneity line broadening contribution may be significant at room temperature due to the presence of very strong anisotropy. Note also that one can carry out frequency-dependent FMR measurements to determine the inhomogeneity line broadening contribution, as reported in Refs. [33] and [34].

IV. Temperature Dependence of FMR Properties

Turn now to the high-\( T \) FMR data measured using the approach described above. Figure 3 presents the data measured on the “\( \chi=20\% \)” sample at six different \( T \). Figure 3(a) gives the FMR data (blue dots) measured at four different \( T \), as indicated, and the corresponding Lorentzian fits (red curves). Figures 3(b) and 3(c) plot the Lorentzian fitting-yielded \( H_{\text{FMR}} \) and \( \Delta H \), respectively, as a function of \( T \). Figure 3(d) shows the saturated magnetic moment \( (m_s) \) and coercivity \( (H_c) \), as a function of \( T \). The big blue arrows in Figs. 3(b) and 3(c) indicate the overall trends, while the blue rectangle in Figs. 3(d) indicates the \( T \) range of the FMR measurements. All the measurements were taken with a perpendicular magnetic field, namely, \( \theta=0^\circ \).

Prior to discussing the data in Fig. 3, it should be noted that the FMR measurements were carried out over a \( T \) range of 634-673 K, as indicated by the blue rectangle in Fig. 3(d). No FMR measurements were taken at \( T<634 \) K. This is because, with a decrease in \( T \), the FMR profile shifts to negative fields, which can be inferred from the trend shown in Fig. 3(b); and the signal-to-noise ratio of the FMR data also become smaller at low \( T \), due to linewidth enhancement which is shown in Fig. 3(c). At \( T=673 \) K, the FMR signal becomes non-detectable, mainly due to a significant drop in \( m_s \) which is evident from the red curve in Fig. 3(d). It should be highlighted that although the highest measurement temperature \( 673 \) K is about 22 K below \( T_c \), which is about 695 K as shown in Fig. 3(d), it is already near or close enough in terms of HAMR applications, in which the writing operation occurs at temperatures about 10-25 K below \( T_c \).

The data in Fig. 3(b) show an overall increase of \( H_{\text{FMR}} \) with \( T \), and this result suggests that with an increase in \( T \) over 634-673 K, the effective perpendicular anisotropy field \( H_0 \) drops by a larger amount than the saturation magnetization \( 4\pi M_s \) does. The Kittel equation for the FMR concerned here can be written as

\[
2\pi f = |\gamma| (H_{\text{FMR}} + H_0 - 4\pi M_s) \tag{1}
\]

where \( |\gamma| \) is the absolute gyromagnetic ratio. One can see that for a given \( f \), an increase in \( H_{\text{FMR}} \) would mean a decrease in \( H_0 - 4\pi M_s \). Since the \( T \) dependences of \( H_0 \) and \( 4\pi M_s \) differ in different samples due to differences in the microstructures, one would expect different \( H_{\text{FMR}} \) vs. \( T \) trends in the four samples. This expectation is discussed below.

The data in Fig. 3(c) suggest an overall decrease of \( \Delta H \) with increasing \( T \). This result may indicate that two-magnon scattering is a dominant relaxation mechanism in the \( T \) range considered here. Generally speaking, the damping mechanisms in FePt medium samples should include spin-flip magnon-electron scattering (SF-MES),\(^{20,23}\) magnon-electron scattering associated with Fermi surface breathing,\(^{20,23}\) two-magnon scattering (TMS),\(^{24,26}\) and magnon-phonon scattering,\(^{27}\) as listed in the introduction section. Practically, the contributions to \( \Delta H \) from both the Fermi surface breathing-associated magnon-electron scattering and the magnon-phonon scattering should be notably smaller than those from the SF-MES and TMS processes. The damping due to the Fermi surface breathing-associated scattering usually decreases with an increase in \( T \), so it is large at low \( T \) but can be ignored near \( T_c \).\(^{20,21,22}\) The magnon-phonon scattering generally plays important roles in relaxation in magnetic insulators, such as \( \text{Y}_3\text{Fe}_5\text{O}_{12} \) and \( \text{BaFe}_2\text{O}_{19} \),\(^{35,36}\) but in metallic systems it usually makes much less contributions to the damping than the
magnon-electron scattering processes. Thus, for the FMR data in this work one can approximately write

$$\Delta H = \Delta H_{\text{SF-MES}} + \Delta H_{\text{TMS}}$$

(2)

where $\Delta H_{\text{SF-MES}}$ and $\Delta H_{\text{TMS}}$ denote the contributions of the SF-MES and TMS processes, respectively.

It is known that both $\Delta H_{\text{SF-MES}}$ and $\Delta H_{\text{TMS}}$ exhibit strong $T$ dependences. $\Delta H_{\text{SF-MES}}$ generally increases with $T$. This is because the SF-MES process requires both the momentum and energy conservations which can be satisfied more easily at high $T$. In contrast, $\Delta H_{\text{TMS}}$ usually decreases with an increase in $T$ in magnetic thin films with perpendicular anisotropy. This is because the damping due to the TMS generally scales with the square of $H_M$ while the latter drops as $T$ approaches $T_c$. For this reason, the data in Fig. 3(c) seem to indicate that $\Delta H_{\text{TMS}}$ may be dominant over $\Delta H_{\text{SF-MES}}$ over the $T$ range of 634-673 K. This result is further discussed below.

V. Effects of Carbon Volume Fraction on FMR Properties

To confirm the above conclusions and also evaluate the effects of the carbon volume fraction $x$, the same FMR measurements and analyses were performed on the other three samples. Figure 4 summarizes the main results of all the four samples. Note that the measurement temperature range is different for different samples, due to the temperature limitations mentioned above.

The data in Fig. 4(a) show that the four samples share the same trend, namely, that $H_{\text{FMR}}$ increases with $T$. This result indicates that in all the samples $H_u$ drops by a larger amount than $4\pi M_s$ when $T$ increases, as discussed above. The data also show that the “$x=10\%$” and “$x=30\%$” samples exhibit much stronger $T$ dependences than the other two samples. This suggests that with an increase in $T$, $H_u-4\pi M_s$ drops faster in the “$x=10\%$” and “$x=30\%$” samples. In other words, $H_u$ decreases by a larger amount than $4\pi M_s$ does in the “$x=10\%$” and “$x=30\%$” samples, but not as large in the other two samples. This result supports the above-drawn conclusion that one can effectively manipulate the magnetic properties of the HAMR media via tuning the carbon volume fraction in the media.

The data in Fig. 4(b) show that $\Delta H$ decreases with an increase in $T$ for all the four samples, indicating that the TMS process is a dominant relaxation mechanism in all the samples. The data also indicate that the “$x=10\%$”

![Image of FMR data and figures](image-url)
and “x=30%” samples show much stronger $T$ dependences than the other two samples. This result is consistent with the above-described result on the $T$ dependences of $H_{\text{FMR}}$. This consistency supports the above conclusion that the TMS is a dominant damping mechanism. In general, $H_{\text{FMR}}$ increases with a decrease in $H_u$ as shown in Eq. (1) while $\Delta H_{\text{TMS}}$ scales with $H_u^2$ as discussed in Ref. [25]. For this reason, a larger drop in $H_u$ would give rise to a larger increase in $H_{\text{FMR}}$ and a larger decrease in $\Delta H$.

VI. Field Angle Dependence of FMR Properties

The FMR data presented in Figs. 2-4 were all measured with a perpendicular magnetic field ($\theta_o=0$), but in actual HAMR applications the writing operation occurs at $\theta_o=35^\circ-45^\circ$. For this reason, high-$T$ FMR measurements were also performed at different field angles, with the major results presented in Fig. 5. Note that the largest angle used in the experiments was $65^\circ$, and the physical constraints of the FMR system did not allow for measurements at larger angles ($\theta_o>65^\circ$).

The data in Fig. 5(a) indicate that the $H_{\text{FMR}}$ vs. $T$ responses show different trends for different $\theta_o$. This is because the roles of $H_u$ and $4\pi M_s$ in the FMR strongly depend on the equilibrium direction of the magnetization vector in the materials, as described by

$$
\left(\frac{2\pi f}{|\gamma|}\right)^2 = \frac{[H_{\text{FMR}} \cos(\theta_H - \theta_M) + (H_u - 4\pi M_s) \cos(2\theta_H)] \cdot [H_{\text{FMR}} \cos(\theta_H - \theta_M) + (H_u - 4\pi M_s) \cos^2(\theta_M)]}{[H_{\text{FMR}} \cos(\theta_H - \theta_M) + (H_u - 4\pi M_s) \cos^2(\theta_M)]}
$$

where $\theta_H$ is the angle of the equilibrium magnetization relative to the film normal direction. It is expected that as $T$ is increased towards $T_c$, one has $\theta_H, \theta_M, H_u$, and $4\pi M_s$ approach zero and $H_{\text{FMR}}$ becomes closer to $(2\pi f)/|\gamma| = 4.89$ kOe. This trend for $H_{\text{FMR}}$ is somewhat shown in Fig. 5(a).

The data in Figs. 5(b) and 5(c) together indicate that the $\Delta H$ data show a clear $\theta_o$ dependence, and this dependence is very strong at lower $T$ but less pronounced at higher $T$. These results agree with the expectations of the TMS process. Specifically, the strength of the TMS strongly relies on the spin-wave manifold, while the latter varies with the magnetic field direction. This gives rise to a strong $\theta_o$ dependence of $\Delta H_{\text{TMS}}$. With an increase in $T$, however, $\Delta H_{\text{TMS}}$ decreases due to its proportionality to $H_u^2$, and the weight of $\Delta H_{\text{TMS}}$ in $\Delta H$ decreases accordingly, leading to a weaker $\theta_o$ dependence. It should be noted that the $\Delta H$ vs. $\theta_o$ data in Fig. 5(c) seem to show more than one peak. This multi-peak behavior differs from the TMS-associated single-peak responses discussed in Refs. [5] and [6]. Future studies are of great interest that confirm the existence of the second peak at $\theta_o>65^\circ$ and explore its physical origin.

Further, the data in Figs. 5(b) and 5(c) also suggest that near $T_c$, the SF-MES process makes notable contributions to $\Delta H$ and $\Delta H_{\text{SF-MES}}$ is comparable to $\Delta H_{\text{TMS}}$. This result is supported by two observations. First, the extrapolation of the data shown in Fig. 5(b) to $T_c$ seems to give a nonzero $\Delta H$ value, as indicated by the dashed gray lines in the figure. This non-zero contribution is mostly from the SF-MES process, because $\Delta H_{\text{TMS}}$ decreases to zero when $T$ approaches $T_c$, while $\Delta H_{\text{SF-MES}}$ usually increases with $T$ and makes a notable contribution near $T_c$. Second, the data in Fig. 5(c) indicate a non-trivial component of $\Delta H$ that does not vary with $\theta_o$. This component is most likely $\Delta H_{\text{SF-MES}}$, as it is known to exhibit a very weak $\theta_o$ dependence. Thus, one can see that the SF-MES and TMS processes co-exist and make comparable contributions to $\Delta H$ at $T=675$ K.

One can draw the four main conclusions from the above-discussed results on the $T$, $x$, and $\theta_o$ dependences of the FMR data. (1) At temperatures about 10-45 K below $T_c$, which are the temperatures relevant to the HAMR writing operation, the TMS and SF-MES processes co-exist in the FePt-based HAMR media and make comparable contributions to $\Delta H$. (2) With a decrease in $T$, $\Delta H$ increases due to the enhancement of
Table 2. Comparison of near-$T_c$ FMR linewidth ($\Delta H$), effective Gilbert damping constant ($\alpha_{\text{eff}}$), and the BB transversal relaxation time ($T_2$) for six different field angles ($\theta_h$). The data were measured on the "$x=20\%$" sample.

<table>
<thead>
<tr>
<th>$\theta_h$ ($^\circ$)</th>
<th>$T$ (K)</th>
<th>$\Delta H$ (Oe)</th>
<th>$\alpha_{\text{eff}}$</th>
<th>$T_2$ (ns/\text{rad})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>673</td>
<td>88</td>
<td>0.0155</td>
<td>0.373</td>
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<td>30</td>
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<td>102</td>
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<td>675</td>
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<td>0.0277</td>
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<td>675</td>
<td>182</td>
<td>0.0321</td>
<td>0.180</td>
</tr>
</tbody>
</table>

The TMS process. (3) When $\theta_h$ is varied, $\Delta H$ shows a maximum at about 45°, which is an angle relevant to the HAMR writing operation. (4) The strength of the $T$ dependence of $\Delta H$ correlates with that of the $T$ dependence of $H_{\text{c}}$-4$\pi M_s$, while the latter can be effectively tuned by the carbon volume fraction.

**VII. Estimation of Damping Constants**

One can use the $\Delta H$ data to estimate the effective damping constant $\alpha_{\text{eff}}$ in the Gilbert model\textsuperscript{10,11} as

$$\alpha_{\text{eff}} = \frac{\sqrt{3}|\gamma|\Delta H}{2(2\pi f)}$$  

(4) as well as the transversal relaxation time $T_2$ in the BB model\textsuperscript{12} as

$$T_2 = \frac{1}{\sqrt{3}|\gamma|\Delta H}$$  

(5) where $|\gamma|/(2\pi)=2.8$ MHz/Oe. The estimated values together with the $\Delta H$ data are listed in Tables 1 and 2.

It should be mentioned that the reason why the $\alpha_{\text{eff}}$ values are estimated and listed here is that the Gilbert model has been widely considered in previous studies on damping in perpendicular media,\textsuperscript{5,6,7,8,9,11} not that the Gilbert model is the most appropriate model to describe near-$T_c$ magnetization dynamics. It is known that the Gilbert model assumes a conserved magnetization vector length during the relaxation, but most likely this is not the case at high $T$. In comparison, the BB model appears as a better model because it involves two separate relaxation processes – the longitudinal relaxation or the $T_1$ process, and the transversal relaxation or the $T_2$ process, and thereby does not assume a conserved magnetization vector length; it could be described by the $T_2$ process, but not the Gilbert model.\textsuperscript{27}

There are five important points that should be made about the data listed in Tables 1 and 2. (1) The data in Table 1 indicate that by varying the carbon volume fraction $x$ one can tune the $\Delta H$, $\alpha_{\text{eff}}$, and $T_2$ parameters of the FePt-based HAMR media by as large as a factor of four. (2) The data in Table 2 show that the damping at field angles relevant to the HAMR writing operation is relatively larger. For example, the damping at $\theta_h=45^\circ$ is about 1.8 times of that at $\theta_h=0^\circ$. (3) The $\alpha_{\text{eff}}$ values in Tables 1 and 2 represent the upper limit of the Gilbert damping constant, as $\Delta H$ may include a small contribution due to inhomogeneity line broadening.\textsuperscript{32} This contribution was ignored during the estimation for the reason mentioned in the discussion about the numerical fits in Fig. 2(b). (4) The $\alpha_{\text{eff}}$ values listed are all smaller than the values (0.055-0.21) measured on FePt materials at RT in previous studies.\textsuperscript{7,8,9} Possible reasons for this inconsistency include that the TMS process\textsuperscript{25} and the Fermi surface breathing-associated damping\textsuperscript{20,21,22} make stronger contributions to the overall damping when $T$ is decreased. (5) Strictly speaking, one cannot use Eq. (4) to obtain the $\alpha_{\text{eff}}$ values listed in Table 2. In addition to the fact that $\Delta H$ includes a contribution from the TMS which cannot be described by the Gilbert model as explained above, the calculations also assumed $\theta_h=\theta_{\text{eff}}$. The difference between these two angles can be small near $T_c$, but it is definitely non-zero.

**VIII. Conclusions and Outlook**

In summary, the near-$T_c$ ferromagnetic resonance (FMR) of FePt-C heat assisted magnetic recording (HAMR) media was studied in this work. The FMR linewidth ($\Delta H$) data as a function of the sample temperature ($T$), the carbon volume fraction ($x$) in the media, and the magnetic field angle ($\theta_h$) were determined, and the effective damping constant in the Gilbert model and the transversal relaxation time in the Bloch-Bloembergen (BB) model were estimated. The data indicate that at temperatures above 10-45 K below $T_c$, the two-magnon scattering (TMS) and spin-flip magnon-electron scattering (SF-MES) processes co-exist and make comparable contributions to $\Delta H$. With a
decrease in $T$, $\Delta H$ increases due to the enhancement of the TMS process. The strength of the $T$ dependence of $\Delta H$ correlates with that of the $T$ dependence of $H_{u-}$ and the latter can be effectively tuned by $x$. As a result, via varying $x$ one can tune the relaxation parameters by a factor of four. The FMR linewidth and damping parameters exhibit a strong $\theta_1$ dependence, showing a maximum at $\theta_1=45^\circ$.

It should be noted that although the contributions of the TMS and SF-MES processes to the damping were found to be comparable near $T_c$, they were not quantified in this work. Future work is of great interest that takes FMR measurements over a wider angle range ($0^\circ$-$90^\circ$) as well as frequency-dependent FMR measurements and then numerically fit the angle- and frequency-dependent linewidth data to separate and quantify those two contributions, as in previous studies. Possible approaches for enabling frequency-dependent FMR measurements at high temperatures include (1) the use of multiple microwave cavities that have different dimensions and therefore have different resonant frequencies and (2) the replacement of the microwave cavity with a hot-resistant, co-planar waveguide structure that, with the help of a vector network analyzer, can allow for broadband FMR measurements. The development of such broadband high-temperature FMR spectrometers is of practical interest to the magnetics community in general and the HAMR community in particular. Finally, it should be mentioned that it is currently still unclear whether the Gilbert and BB equations represent appropriate models for near-$T_c$ magnetization dynamics or not, although the corresponding damping parameters have been estimated in this work. Future studies that compare the suitability of various models in terms of describing near-$T_c$ damping is of great interest.

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