Impedance of nanometer thickness ferromagnetic Co$_{40}$Fe$_{40}$B$_{20}$ films

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Abstract
Nanocrystalline Co$_{40}$Fe$_{40}$B$_{20}$ films, with film thickness $t_f = 100$ nm, were deposited on glass substrates by the magnetron sputtering method at room temperature. During the film deposition period, a dc magnetic field, $h = 40$ Oe, was applied to introduce an easy axis for each film sample: one with $h||l$ and the other with $h||w$, where $L$ and $w$ are the length and width of the film. Ferromagnetic resonance (FMR), ultrahigh frequency impedance (IM), dc electrical resistivity ($\rho$), and magnetic hysteresis loops (MHL) of these films were studied. From the MHL and $\rho$ measurements, we obtain saturation magnetization $4\pi M_s = 15.5$ kG, anisotropy field $H_k = 0.031$ kG, and $\rho = 168 \text{ mW.cm}$. From FMR, we can determine the Kittel mode ferromagnetic resonance (FMR-K) frequency $f_{\text{FMR-K}} = 1.963$ MHz. In the $h||l$ case, IM spectra show the quasi-Kittel-mode ferromagnetic resonance (QFMR-K) at $f_0$ and the Walker-mode ferromagnetic resonance (FMR-W) at $f_n$, where $n = 1, 2, 3, \text{ and 4}$. In the $h||w$ case, IM spectra show QFMR-K at $f_0$ and FMR-W at $f_n$. We find that $f_0$ and $F_0$ are shifted from $f_{\text{FMR-K}}$, respectively, and $f_n = F_n$. The in-plane spin-wave resonances are responsible for those relative shifts.

Keywords: spin-wave resonance, impedance, magnetic films

Introduction
It is known that impedance (IM) of a ferromagnetic (FM) material is closely related to its complex permeability ($\mu \equiv \mu_R + i \mu_I$), where $\mu_R$ and $\mu_I$ are the real and imaginary parts, in the high-frequency ($f$) range [1,2]. Past experience has also shown that there should exist a cutoff frequency ($f_c$), where $\mu_R$ crosses zero and $\mu_I$ reaches maximum [3], for each FM material. According to Ref. [3], $f_c$ increases as the thickness of the FM sample decreases and finally reaches an upper limit. The thickness dependence is due to the eddy current effect, while the upper limit is due to the spin relaxation (or resonance) effect. Hence, in a sense, we would expect the $f$ dependence of impedance $Z = R + iX$, where $R$ is resistance and $X$ reactance, behaves similarly. In Ref. [1], we had the situation that the thickness ($t_f$) of the FM ribbon was thick to meet the criterion: $t_f \geq \delta \equiv 10 \mu m$, where $\delta$ is skin depth (at $f = 1$ MHz), but in this article, we have a different situation wherein the thickness ($t_f$) of the FM film is thin to meet the criterion: $t_f = 100$ nm $<< \delta \equiv 654$ nm (at $f = 1$ GHz). That means the time varying field $H_{ac}$ generated by the ac current ($i_{ac}$), in the IM experiment should penetrate through the film sample even under an ultrahigh frequency condition this time. Moreover, there are various kinds of mechanisms to explain the resonance phenomena: the film size (FZ), the magnetic domain wall (MDW), the RLC-circuit, the ferromagnetic resonance of the Kittel mode (FMR-K), the ferromagnetic resonance of the Walker mode (FMR-W), the relaxation time, and the standing spin-wave resonance mechanisms. We shall examine all these mechanisms one by one, based on the experimental data collected in this study.

Experimental
The composition of the film sample in this test was Co$_{40}$Fe$_{40}$B$_{20}$. We used magnetron sputtering technique to deposit the film on a glass substrate at room temperature. The film thickness $t_F$ as mentioned before, was 100 nm. During the deposition period, an external dc field, $h = 40$ Oe, was applied to define the easy axis, as shown in Figure 1, for each nanometer thick sample. In
Figure 1, we have length, $L = 10.0 \text{ mm}$, and width, $w = 500 \mu\text{m}$, in case (a) $h \parallel L$, and in case (b) $h \parallel w$. $\vec{M}_s$ is the saturation magnetization and $\vec{h}$ is the deposition field. $\vec{q}_{/L}$ and $\vec{q}_{/T}$ are the in-plane spin-wave wave vectors. (a) The $\vec{q}_{/L}$ case and (b) the $\vec{q}_{/T}$ case.

In a typical IM experiment, there were three features: (1) the rectangular film sample, either as shown in Figure 1a or Figure 1b, was placed at the center of a pair of Helmholtz coils, which could produce a field $H_E \perp L$, (2) $Z$ was measured by an Agilent E4991A RF impedance/material analyzer (Agilent Technologies, Santa Clara, CA, USA) with a two-point (ECP18-SG-1500-DP) pico probe, and (3) the peak-to-peak amplitude of the ac current, $i_{ac}$, was fixed at 10 mA, and the frequency $f$ of the current was scanned from 1 MHz to 3 GHz.

A circular film sample was taken for the FMR experiment. The cavity used was a Bruker ER4102ST X-band resonator (Bruker Optics Taiwan Ltd., San Chung, Taiwan, Republic of China) which was tuned at $f = 9.6 \text{ GHz}$, and the film sample was oriented such that $\vec{E} \parallel ||$ and $\vec{h} \perp \vec{E}$, where $\vec{E}$ was an in-plane field which varied from 0 to 5 kG, and $\vec{h}$ was the microwave field. The result is shown in Figure 2, where we can spot an FMR (or FMR-K) event at $H = H_R = 0.68 \text{ kOe}$, and define the half-peak width $\Delta H = 53 \text{ Oe}$.

Other magnetic and electrical properties of the Co$_{40}$Fe$_{40}$B$_{20}$ film were obtained from vibration sample magnetometer measurements: $4\pi M_s = 15.5 \text{ kG}$ and the anisotropy field, $H_k = 0.031 \text{ kG}$, and from electrical resistivity ($\rho$) measurement: $\rho = 168 \mu\Omega\text{ cm}$. Note that because of the nanocrystalline and the nanometer thickness characteristics, the $\rho$ of our Co$_{40}$Fe$_{40}$B$_{20}$ films is very high. Here, since $\delta \propto (\rho)^{1/2}$, a larger $\rho$ will lead to a longer $\delta >> \kappa$.

**Results and discussion**

In order to interpret the IM data (or spectrum) of this work, as shown in Figure 3 (the $h \parallel L$ case) and in Figure 4 (the $h \parallel w$ case), we have the following definitions. First, whenever there is a resonance event, we should find a peak located at $f = f_0$ and $f = f_n$, where $n = 1, 2, 3, 4$ in the R-spectrum, and a wiggle (or oscillation) centered around the same $f_0$ and $f_n$ in the X-spectrum. To summarize the data in Figures 3 and 4, we have in the $h \parallel L$ case, $f_0 = 2,081, f_1 = 1,551, f_2 = 1,291, f_3 = 991$, and $f_4 = 781 \text{ MHz}$; and in the $h \parallel w$ case, $F_0 = 2,431, F_1 = 1,551, F_2 = 1,281, F_3 = 991$, and $F_4 = 721 \text{ MHz}$. From these experimental facts, we reach two conclusions: (1) $f_0 \neq F_0$ and (2) within errors, $f_n = F_n$. Since at either $f_0$ or $F_0$, each corresponding wiggle crosses zero, we believe there is a quasi-FMR-K event. Notice for the moment that because $f_0 \neq F_0$, we use the prefix “quasi” to describe the event. More explanation will be given later.

Here, we discuss the possibilities of the FZ resonance first. From Ref. [4], we know an electromagnetic (EM) wave may be built up inside the film during IM experiments. In Figure 1a, supposing $L = \lambda_{||}$, where $\lambda_{||}$ is the longitudinal EM wavelength, $\varpi = \lambda_{\perp}$, where $\lambda_{\perp}$ is the transverse EM wavelength, and $\mu = 10^3$, we find the FZ resonance frequencies: $f_{EM(||)} = \eta_{||} \times 7 \text{ MHz}$ and $f_{EM(\perp)} = \eta_{\perp} \times 27 \text{ MHz}$, where $\eta_{||}$ and $\eta_{\perp}$ are positive integers. Since based on the experimental findings, $f_n = f_{EM(||)}$ should be
equal to \( F_n = f_{EM}(L) \), \( f_n \) or \( F_n \) must be a positive integer number of times of the frequency 189 MHz. Simple calculations show that the above statement cannot be satisfied. Besides, if the statement were true, there would exist at least as many as eight different FZ resonance peaks, instead of only the four resonance peaks observed so far.

Next, the MDW mechanism is discussed. As the size of the sample is large, there are magnetic stripe domains, parallel to \( \vec{M}_s \) in Figures 1a, b. According to Ref. [5], the MDW resonance for the CoFeB film should occur at \( f = 78 \) MHz. However, we have reasons to believe that this kind of resonance does not exist in our IM spectra. First, in Figures 3 and 4, there is neither a peak nor a wiggle at \( f = 78 \) MHz. Second, when \( H_E = 150 \) G, much larger than the saturation field, was applied to eliminate magnetic domains, those peaks (at \( f_0 \) to \( f_4 \) or \( F_0 \) to \( F_4 \), respectively) still persisted.

Further, the RLC-circuit resonance mechanism is discussed. If the Co\(_{40}\)Fe\(_{40}\)B\(_{20}\) film is replaced by a Cu film with the same dimensions, there is also one single resonance peak at \( f_d(Cu) = (1/2\pi)(L_sC)^{(1/2)} = 2.641 \) GHz, where \( L_s \) is the self-inductance and \( C \) is the capacitance of the film [6]. However, we believe that \( f_0 \) and/or \( F_0 \) are less likely due to the RLC-circuit resonance mechanism for the reason below. Since \( L_s = \mu \times GF \sim (10^7 \text{ to } 10^8) \times \mu_0 \times GF \) for Co\(_{40}\)Fe\(_{40}\)B\(_{20}\), where GF depends only on the geometrical size and shape of the sample, \( L_s = 1 \times \mu_0 \times GF \) for Cu, and \( C_{CoFeB} \geq C_{Cu} \), in principle, we find \( f_d(Co_{40}Fe_{40}B_{20}) \equiv [(1/10) \text{ to } (1/30)] \times f_d(Cu) = 0.26 \text{ to } 0.08 \) GHz, which is too small to meet the facts, i.e., \( f_0 = 2.081 \) GHz and \( F_0 = 2.431 \) GHz.

With regard to the FMR-W mechanism, we have the following discussion. At \( f = f_n \) and/or \( F_n \), we believe each resonance should correspond to a specific FMR-W mode. The reasons are summarized below. First, in the
typical FMR result, as shown in Figure 2 because the sample was placed in the homogeneous \( h_{ef} \) region, no FMR-W modes could be observed. However, as indicated in Ref. [4], if \( h_{ef} \) is sufficiently inhomogeneous to vary over the sample, one will observe various FMR-W modes at \( H = H_n \) and \( H_n < H_R \). From a simple relationship [4], such as \( f = \nu H_{\text{eff}} \), where \( H_{\text{eff}} \) is the effective field and \( \nu = \gamma/2\pi t \) is the gyromagnetic ratio, it is easy to recognize that since \( H_n < H_R \), we have \( f_n < f_0 \) and/or \( f_n < f_0 \), which is what has been observed. Second, from Refs. [7] and [8], it is known that \( h_{ef} \equiv H_{ef} = (i_{zc} z)/(w t z) \), where \( z \) is a variable parameter along \( t \). Therefore, in a typical IM measurement, \( h_{ef} \) or \( H_{ef} \) cannot be homogeneous all over the sample. That is why in Figure 2, there is no FMR-W mode, but in Figures 3 or 4, there are various FMR-W modes.

With regard to the FMR-K mechanism, we propose the following model: When FMR-K occurs in Figure 2, we have [9].

\[
(f_0/\nu)^2 = H_{R}^2 + (2H_k + 4\pi M_s)H_K + H_K (H_{R} + 4\pi M_s). \tag{1}
\]

By substituting the values of \( f_R = 9.6 \) GHz, \( H_R, H_K, \) and \( 4\pi M_s \), it is found \( \nu = 2.833 \) for Co40Fe40B20. Thus, the main (or FMR-K) resonance (at \( H = 0 \)) would occur at \( f = f_{\text{FMRK}} = \nu (H_K (H_{R} + 4\pi M_s))^{1/2} = 1.963 \) MHz. According to our previous arguments, this frequency, \( f_{\text{FMRK}} \), should be equal to \( f_0 \) and/or \( f_0 \) in ML. Obviously, what we have is \( f_{\text{FMRK}} \neq f_0 \). The reasons for the frequency shifts of the quasi-FMR-K resonances in IM are given below. According to Refs. [9-11], the quasi-FMR-K-resonance relationship for \( f_0 \) or \( f_0 \) at \( H = 0 \) and under the exchange-dominated condition is expressed as

\[
[(f_0/\nu)^2 - \nu^2 (H_K (H_{R} + 4\pi M_s))^{1/2} (2H_k + 4\pi M_s)\xi (w t z)) \nu^2 (H_k (H_{R} + 4\pi M_s))^{1/2} (2H_k + 4\pi M_s)\xi (w t z)]^{1/2} (\nu/\tau)^2. \tag{2}
\]

where \( A = 1.0 \times 10^{11} \) J/m is the exchange stiffness, \( i = L \) or \( T \), \( q_{i//i} \) is the in-plane (IP) standing spin-wave vector, \( (p\pi/t) \) is the out-of-plane (OPF) standing spin-wave vector, \( p = 0, 1, 2, \ldots \), \( \theta_\parallel \) is the angle between \( \vec{n} \) or the \( z \)-axis, hence for \( \vec{q}_{i//L} \) and \( \vec{q}_{i//T} \), as shown in Figure 1, \( \theta_\parallel = \pi/2 \) always, and \( \tau \) is the relaxation time [9], where \( 1/\tau = (\gamma H_0) = 94.3 \) MHz and \( \gamma = \nu (\Delta H)/(2f_0) = 0.00777 \). Therefore, if the relaxation time \( (1/\tau) \) mechanism dominated in Equation 2, \( f_0 \) would be equal to 267 MHz, which is much lower than the \( f_0 \) or \( f_0 \) in Figures 3 and 4.

Next, we consider the OPF standing spin-wave case only, i.e., temporarily assuming \( q_{i//i} = 0 \) or negligible in Equation 2, simple calculations show that \( f_0(p = 0) = 1.963 \) GHz, \( f_0(p = 1) = 4.874 \) GHz, and \( f_0(p = 2) = 9.136 \) GHz. Because our Agilent E4991A works only up to 3.0 GHz, \( f_0(p = 1) \) and \( f_0(p = 2) \), although existing, were not observed in this work.

In the following, we shall refer to the \( p = 0 \) case only. From Equation 2, if \( p = 0 \) and the \((1/\tau)\) term is negligible, we consider the following two cases: in Figure 1a, \( \vec{q}_{i//L} || L \), where the azimuth angle \( \phi \) of \( \vec{q}_{i//L} \) is \( (\pi/2) \) and in Figure 1b, \( \vec{q}_{i//T} || w \), where \( \phi = 0 \). Then, Equation 2 can be simplified as

\[
f_0 = \nu (4\pi M_s H_k + [(2A/M_s)(\vec{q}_{i//L})^2]^{1/2}) \tag{3a}
\]

\[
F_0 = \nu (4\pi M_s H_k + [(2A/M_s)(\vec{q}_{i//T})^2]^{1/2}). \tag{3b}
\]

By substituting the values of \( f_0, A, \) and \( H_k \) in Equations 3a, b, respectively, we find \( \vec{q}_{i//L} = 1.326 \times 10^6 \) (1/m) and \( \vec{q}_{i//T} = 3.216 \times 10^6 \) (1/m). Two features can be summarized. First, since \( [1/(2\pi)](\vec{q}_{i//L} \times t_i) = (0.5 \times 1.2) \times 10^{-1} \), it confirms that we do have a long wavelength in-plane spin wave (IPSW), \( \vec{q}_{i//L} \) or \( \vec{q}_{i//T} \) traveling in each film sample. Second, due to the boundary conditions of the film sample, we should have \( \vec{q}_{i//L} \propto (1/L) \) and \( \vec{q}_{i//T} \propto
(1/\nu). Thus, because \( L > \nu \), our previous results are reasonable that \( \tilde{q}_{||} < \tilde{q}_{//} \).

Finally, as to why the IP spin-waves can be easily excited in the IM experiment, but cannot be found in the FMR experiment, we have a simple, yet still incomplete, explanation as follows. The film sample used in the latter experiment is circular, which means by symmetry \( L = \nu \), while the one used in the former experiment is rectangular, which means that the symmetry is broken, with \( L \neq \nu \). Thus, even if \( \tilde{q}_{||} \) exists in the FMR case, there should be only one \( \tilde{f} \), where \((\tilde{f})^2 = (f_{\text{FMR}})^2 + 8\pi A^2(\tilde{q}_{||})^2\), by symmetry argument. Nevertheless, for some reasons, such as (1) that a high-current density \( j_{\text{ac}} \) may be required to initiate IPSW, and (2) that \( j_{\text{ac}} \) flowing in the FMR experiment may be too low to initiate any IPSW, we think the \( q_{||}\) term in \( \tilde{f} \) is likely to be negligible. As a result, in Figure 2, we find only one \( \tilde{f} \) in the FMR case and \( \tilde{f} = f_{\text{FMR}} \). However, due to reason (1) above, and the symmetry breaking issue in the IM case, as discussed before, \( \tilde{f} \) should be shifted from \( f_{\text{FMR}} \) to \( f_0 \) and \( F_0 \), respectively.

Moreover, if we take the formula \( Z = (B/A_0)(1 + i)\coth[(t/2A_0)(1 + i)], \) where \( B = (\rho L)/(2\nu), A_0 = [\mu/(\pi\nu\mu_0)](\cos(\delta/2) + i\sin(\delta/2)), \mu \equiv \xi\mu_0, \) and \( \mu_0 = 4\pi \times 10^{-7} \) H/m. By using the Newton-Raphson method [12], we may calculate the \( f \) dependence of \( \mu_R \equiv \xi\cos\delta \) or \( \mu_I \equiv \xi\sin\delta \) from the \( K \) and \( X \) data. From the \( \mu_R \) vs. \( f \) or the \( \mu_I \) vs. \( f \) plot, as shown in Figure 5, we can define the cutoff frequency \( f_c = 2,051 \text{ MHz in the } h||L \text{ case}. \) Clearly, \( f_c \) in Figure 5 is almost equal to \( f_0 \) found in Figure 3.

**Conclusion**

We have performed IM and FMR experiments on nanometer thickness Co_{80}Fe_{40}B_{20} film samples. Film thickness \( t_f \) was deliberately chosen much smaller than eddy current depth \( \delta \) in the frequency range 100 MHz to 3 GHz. From the FMR data, we find that the Kittel mode resonance occurs at \( f_{\text{FMR}} = 1,963 \text{ MHz}, \) while from the IM data, we find that (1) the quasi-Kittel-mode resonance occurs at \( f_0 = 2,081 \text{ MHz in the } h||L \text{ case and } F_0 = 2,431 \text{ MHz in the } h||\nu \text{ case}, \) respectively, and (2) the Walker-mode resonances at \( f_{w} = F_{w} \) for both cases. It is believed that the shift of \( \tilde{f} \) from \( f_{\text{FMR}} \) to \( f_0 \) or from \( f_{\text{FMR}} \) to \( F_0 \) is due to the existence of IPSWs. Moreover, we have estimated the values of wave vectors of IPSW, \( \tilde{q}_{||}/L \) in the \( h||L \) case and \( \tilde{q}_{//}/T \) in the \( h||\nu \) case, and found that \( \tilde{q}_{||}/L \) is smaller than \( \tilde{q}_{//}/T \) as expected.