High Frequency Measurements of CoFeHfO Thin Films

Stephen E. Russek, Pavel Kabos, Tom Silva, Frederick B. Mancoff, Dexin Wang, Zhenghong Qian, and James M. Daughton

***Abstract*—High-frequency measurements of the transverse susceptibility and damping constant of CoFeHfO thin films have been made over a frequency range of 0.1 GHz to 6 GHz as a function of film resistivity, thickness, and temperature. The film resistivity varied from 250 $\mu\Omega$cm to 2100 $\mu\Omega$cm. The films show relatively low damping at high frequencies with the damping constant α ranging from 0.01 to 0.06. The damping constant increases with film resistivity and, for the highest resistivity films, the damping constant decreases as the thickness increases. The damping constant, induced anisotropy, and film resistivity show weak temperature dependence over a temperature range from 4 K to 300 K. The low damping constant, in conjunction with the high anisotropy, large resistivity, and large spin-dependent-tunneling magnetoresistance, makes this material attractive for several high-frequency magnetic device applications.**

***Index Terms*—CoFeHfO, FMR, magnetic device dynamics, magneto-electronics.**

I. Introduction

FERROMAGNETIC CoFeHfO thin films (and related oxide systems) exhibit several properties, including high resistivity, large high-frequency susceptibility, and large spin-dependent tunneling [1], [2], which indicate that this material may be useful in high-frequency magneto-electronic applications. The resistivities of CoFeHfO films range between 250 and 2500 $\mu\Omega$cm which places these materials in a regime between that of good metals and insulators. The device and high-frequency properties of this type of intermediate-impedance magnetic materials have not yet been fully explored.

Here, we present a study of the high-frequency properties of CoFeHfO thin films as a function of film resistivity, thickness, and temperature. The high-frequency damping constant α increases with film resistivity. For high resistivity films, the damping decreases as the thickness is increased, indicating that eddy-current damping does not dominate the high-frequency losses.

Manuscript received October 13, 2000.

This work was supported by the NSF under Contract DMI-9961165 and the National Institute of Standards and Technology, under the Advanced Technology Program (ATP) Cooperative Agreement 70NANB8H 4025 and Contract 50-DKNB-0-90087.

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Publisher Item Identifier S 0018-9464(01)06567-0.

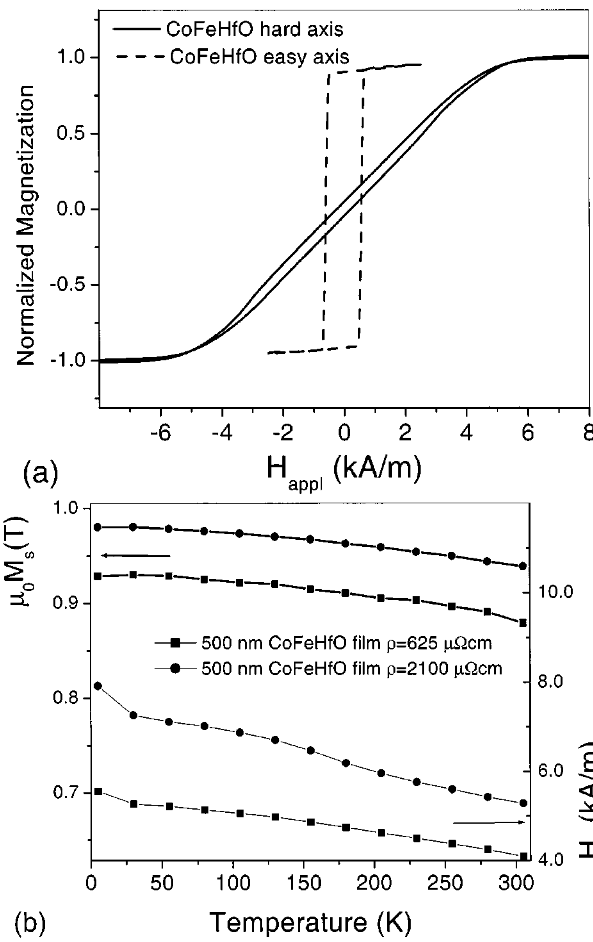

Fig. 1. (a) Easy and hard axis hysteresis loops of a 1 μm thick CoFeHfO film. The coercive field is $H_c = 0.40$ kA/m and the induced anisotropy is $H_k = 4.9$ kA/m. (b) Temperature dependence of the saturation magnetization (M_s) and the induced anisotropy field (H_k) for 500 nm thick CoFeHfO films with low and high resistivity.

II. Experiment

CoFeHfO films were RF-diode sputter-deposited from a metal–alloy target with a composition of $Co_{57}Fe_{24}Hf_{19}$ in the presence of oxygen. The processing details are contained in [1]. The resistivity was varied by changing the sputtering power, with larger powers giving lower resistivities. The films were deposited in a magnetic field to provide an induced uniaxial anisotropy. Typical easy and hard axis hysteresis loops are shown in Fig. 1. The room temperature saturated magnetization for all samples ranges from $\mu_0 M_s \approx 0.9$ T to 1.2 T and the room temperature anisotropy field $H_k$varied

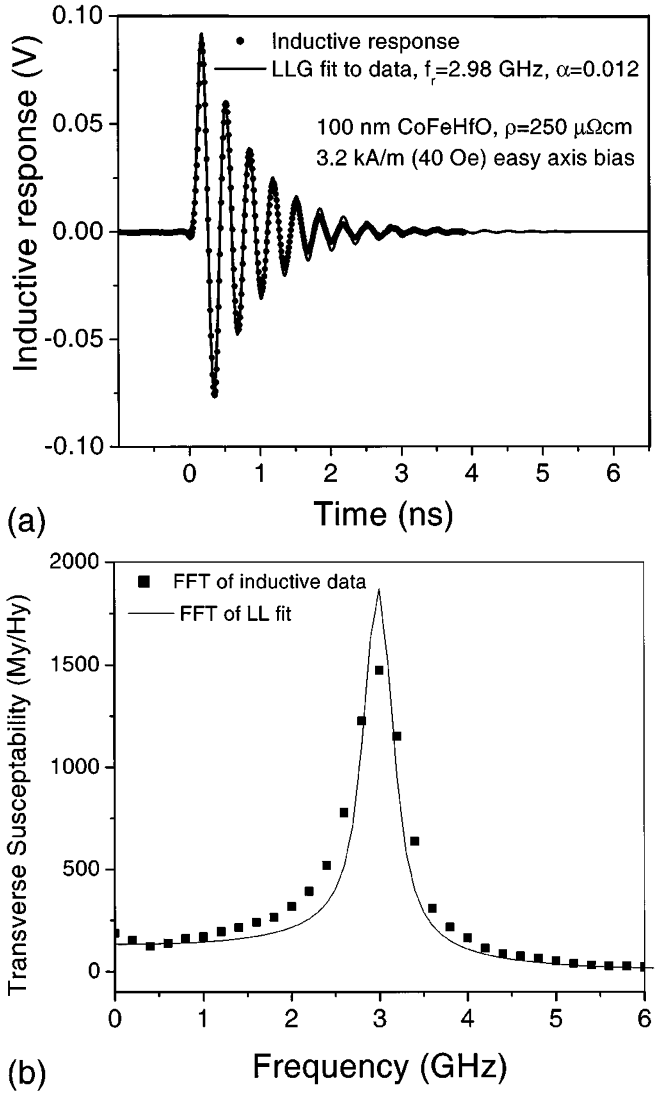

Fig. 2. (a) Inductive response of a 100 nm thick CoFeHfO thin film with a resistivity of 250 $\mu\Omega$cm and a LL fit giving a resonance frequency of 2.98 GHz and a damping constant of $\alpha = 0.012$. (b) Magnitude of Fourier transform of the inductive response and LL fit giving the transverse susceptibility as a function of frequency.

from 4.5 kA/m to 7 kA/m, as seen in Fig. 3. The temperature dependences of M_s and H_k were measured on a SQUID magnetometer. M_s showed a gradual increase as the temperature was decreased, as shown in Fig. 1(b), consistent with standard ferromagnetic behavior. H_k shows a gradual increase as the temperature decreases as shown in Fig. 1(b) with typically $H_k(4\mathrm{K})/H_k(300\mathrm{K}) \approx 1.2 - 1.6$.

X-Ray diffraction measurements show that the material is nanocrystalline or an amorphous/nanocrystalline composite. There are two broad peaks, with peak widths $>5^\circ$, corresponding to CoFe (111) and HfO_2 oxide (111) lattice spacings. There is an increase in the ratio of the HfO_2 to CoFe peak height as the film resistivity increases.

The high-frequency properties were measured using a pulsed inductive technique [3] in which the films were placed on a coplanar waveguide and excited with a 10 V step pulse. The pulse had a rise time of 50 ps and duration of 10 ns. The easy axes of the films were placed along the axis of the waveguide

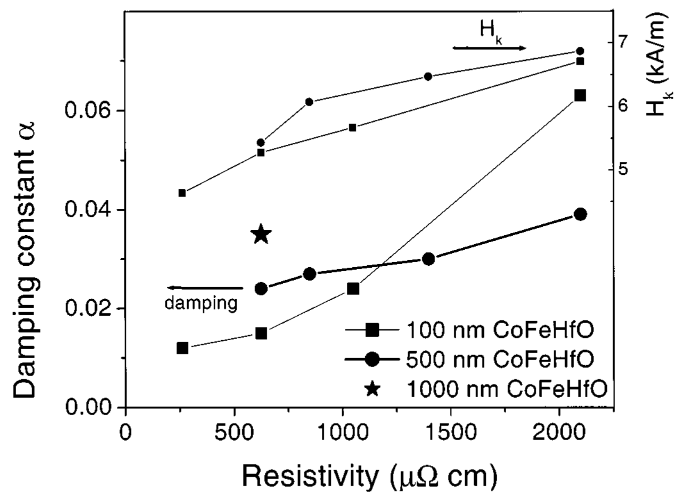

Fig. 3. Dependence of the room-temperature damping constant α and induced anisotropy field H_k on film resistivity for 100 nm and 500 nm thick CoFeHfO samples. Also shown is the damping for a single 1000 nm thick CoFeHfO film. All of the data were taken in a 3.2 kA/m longitudinal bias field.

so that the pulsed fields were directed along the film hard axis. A DC bias field, H_b, with amplitude varying between 0 kA/m and 4 kA/m, was applied along the easy axis. Measurements were made on two different waveguides, a copper waveguide on a composite microwave substrate with a 500 μm center conductor width and a gold waveguide on a GaAs substrate with a 100 μm center conductor width. Variable temperature measurements were made with the Au waveguide on GaAs using a cryogenic microwave probe station. The magnetization dynamics were determined by measuring the inductive voltage generated by the time-varying magnetization of the film. The magnetization signal, which is proportional to the time derivative of the magnetization along the hard axis, is superimposed on top of the large applied voltage pulse. The magnetization signal is separated by subtracting the voltage signals with and without a large DC saturating field along the hard axis. For the Cu and Au waveguides, the transverse field pulse amplitudes were approximately 0.2 kA/m and 0.5 kA/m, respectively, which corresponds to hard-axis rotations of 2.4 and 5.7 degrees for the case of zero longitudinal bias field.

III. Results

Fig. 2(a) shows the inductive response from a 100 nm thick low-resistivity CoFeHfO film. The magnetization oscillates at its resonant frequency, f_r, of 2.98 GHz and the oscillations damp in a characteristic time $\tau_E = 2/\gamma\mu_0 M_s \alpha \approx 1$ ns, where α is the damping constant and γ is the gyromagnetic ratio. The data can be fit using the Landau–Lifshitz (LL) equation [3] to extract values for α and f_r. The response can be Fourier transformed to obtain the frequency-dependent transverse susceptibility, as shown in Fig. 2(b). The Fourier transform is normalized to the DC transverse susceptibility $\chi_{\mathrm{DC}} = M_s/H_k + H_b$ at low frequencies.

The damping coefficient can be obtained either by determining the width of the resonant peak, or by directly fitting the dynamical data using the LL equation. The damping constants for two series of films of varying resistivity, one series with

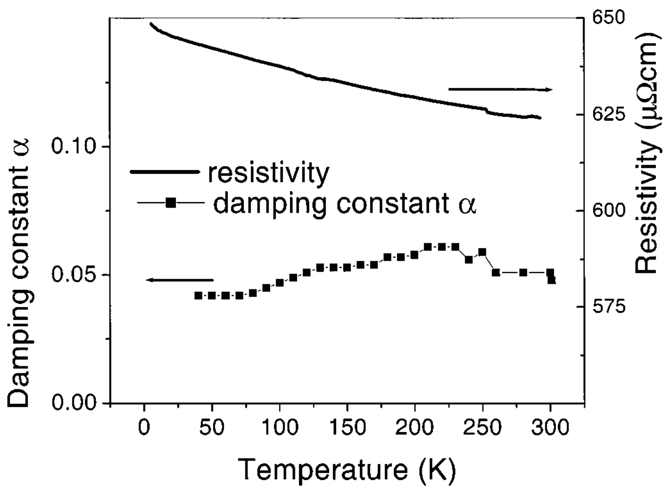

Fig. 4. Damping constant α and resistivity versus temperature for a 500 nm thick CoFeHfO thin film. Both quantities show relatively weak dependence on temperature.

film thickness of 100 nm and the other with a film thickness of 500 nm, are shown in Fig. 3. Both series show an increase in the high-frequency damping as the resistivity increases. Note that the resistivity and damping vary by factors of 9 and 6, respectively, while the variation of the magnetic properties, such as M_s and H_k, is much less.

The thicker films show higher damping relative to the 100 nm films at low resistivities and then cross over to a region of lower damping at high resistivities. A partial explanation comes from the fact that eddy currents are contributing to the damping in the thicker films. As the resistivity increases, the contribution of the eddy currents to the damping decreases. The damping at low resistivities would then represent the sum of intrinsic damping and eddy-current damping, while at high resistivities it is due only to intrinsic damping. However, calculations based on the model presented in [1] indicate that eddy currents represent only 10% of the damping in the 650 $\mu\Omega$ cm, 1000 nm film and 4% of the damping in the 650 $\mu\Omega$cm, 500 nm film. Hence, eddy currents alone are not sufficient to explain the thickness dependence of the damping.

The CoFeHfO films show a weak dependence of the film resistivity, high-frequency damping, and magnetic properties on temperature in the range between 4 K and 300 K. The temperature dependence of the resistivity and damping coefficient for a low-resistivity 500 nm thick sample is shown in Fig. 4. The low-resistivity samples show a small ($\sim$4%) increase in the resistivity as the temperature is reduced to 4 K. The high resistivity samples show a similar, slightly larger increase ($\sim$6%), in resistivity as the temperature is reduced to 4 K. The damping coefficient also shows a weak temperature dependence, as shown in Fig. 4, with a weak maximum around 220 K.

IV. Discussion

The damping of the magnetization is due to the coupling of the uniform magnetization precession to magnons, phonons, and conduction electrons whereas the resistivity represents the scattering of conduction electrons with defects, magnons, and phonons. It is likely that the mechanisms responsible for the increase in resistivity and the increase in damping are correlated. The weak temperature dependence of the resistivity indicates that this material is behaving as a "dirty" metal, with the scattering of electrons being dominated by fixed defects rather than phonons or magnons. These defects may be related to the defects that couple the uniform magnetization to magnons. In particular, highly resistive grain boundaries that are efficient scatterers of conduction electrons may also be efficient generators of magnons as the magnetization rotates.

The observed damping coefficient in CoFeHfO is relatively temperature independent similar to that observed in Permalloy [4]. This is in contrast to systems that have paramagnetic oxides or have rare-earth dopants [5] that show large temperature dependent damping due to a changing thermally activated magnetic structure. The lack of temperature dependence in the resistivity further indicates the absence of any paramagnetic components.

In summary, measurements of the high-frequency properties of CoFeHfO show that this material has low damping, or equivalently, a large transverse susceptibility at frequencies of several gigahertz, even for films with relatively large thicknesses between 0.5 μm and 1.0 μm. The resistivity can be tuned over a relatively large range with a trade-off of increasing the intrinsic damping while lowering the eddy current damping. Both the film resistivity and damping coefficient are weakly temperature dependent, indicating that the system is fairly uniform with no paramagnetic components.

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