Microwave Resonances in Nanogranular $(Fe_{0.7}Co_{0.3})_{71}B_{22}Ni_7$ Films

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We have analyzed the microwave behavior of soft nanogranular $(Fe_{0.7}Co_{0.3})_{71}B_{22}Ni_7$ films which present a dc permeability from 60 to 280, a resistivity of 8 to 9 10^{-7} Ω m and a zero-field double ferromagnetic resonance peak at frequencies ranging from 3.8 to 8.35 GHz. The high frequency and large line-width of the observed resonances allows for possible applications in microwave absorbers in a frequency range extending from 6 to 10 GHz.

***Index Terms*—Anisotropy, FeCo films, ferromagnetic resonance, magnetic thin films, microwave properties, nanogranular films.**

I. INTRODUCTION

MAGNETIC films with a nanogranular structure can be used in the development of novel applications, which include microwave filters, inductors and absorbers at frequencies up to several GHz. Nanogranular materials are specifically designed and developed in order to overcome the limitations of nonconductive magnetic materials such as ferrites with a low saturation magnetization and a low Curie point, which influence their range of applicability.

Fe-Co-based thin-films with a nanogranular structure possess a high saturation magnetization as well as an increased electrical resistivity of 8 to 9 10^{-7} Ωm due to the presence of the B-based amorphous matrix. If the dimension of the grains and their mean separation are optimized, several benefits can be achieved, since a large suppression of the magnetocrystalline anisotropy may be coupled to a resistivity increase.

In this paper, we present a characterization and detailed analysis of the microwave properties of a set of nanogranular $(Fe_{0.7}Co_{0.3})_{71}B_{22}Ni_7$ films under an applied magnetic dc field up to 200 kA/m. The films present a zero-field ferromagnetic resonance (FMR) from 3.8 to 8.3 GHz and a relative dc permeability between 60 and 280.

In most cases, a zero-field double FMR peak was observed, and this feature is here presented since it may become useful for the development of microwave circuits such as wide-band filters and noise suppressors.

II. EXPERIMENT

$(Fe_{0.7}Co_{0.3})_{71}B_{22}Ni_7$ nanogranular films with thickness t ranging from 136 to 236 nm were prepared by magnetron sputtering, in Ar atmosphere, on 200-μm-thick Si substrates. A Fe-Co target with additional Ni and B chips was used for deposition. The films have a well-defined uniaxial in-plane anisotropy, achieved by the application in the film plane of an 80 kA/m magnetic field during the sputtering process. Static magnetization curves were measured using an alternating gradient force magnetometer (AGFM). Details about the structural and magnetic characteristics of these films can also be found in [1]. This work focuses on the microwave behavior of films, which were characterized using a Vector Network Analyzer (VNA) and two different setups: a) a matched microstrip line loaded with the films and connected to the VNA using a universal test fixture; and b) a matched coplanar waveguide connected to the VNA using end-launch connectors. In both cases the film samples (4 × 4 mm × 200 μm) were positioned face down in the center of the microstrip/coplanar waveguide (with a 30-μm polyimide foil interposed), and with the easy magnetization axis parallel to the propagation direction. The microstrip line was positioned in the gap of Helmholtz coils producing a dc magnetic field from 0 to 45 kA/m, while the coplanar waveguide was inserted in the gap of a small electromagnet with fields up to 380 kA/m. The film characterization consisted of repeated measurements of the scattering matrix S parameters, as a function of the applied bias field. The data were then analyzed offline.

III. RESULTS AND DISCUSSION

The results and the FMR frequencies for the different samples are summarized in Table I. The frequency of the main FMR peak and the associated line-width were determined by the real and imaginary parts of the normalized permeability [2] obtained from a set of two-port differential measurements of the S parameters for different values of the applied dc field. These measurements were repeated using the different microwave fixtures with similar values. The zero field FMR frequency is very large for this type of films, reaching values up to 8.3 GHz. The field evolution of the main FMR peak follows the Kittel formula [3] for thin films. In the case where the external field H_a is applied in-plane, parallel to the easy axis of the film, the resonance frequency can be expressed as

$$f = \frac{\gamma M_s}{2\pi}\sqrt{(h_a + h_k + 1)(h_a + h_k)}$$
$$h_a = H_a/M_s; h_k = H_k/M_s \qquad (1)$$

where H_k represents the anisotropy field and M_s the saturation magnetization of the materials. In our case $\mu_0 M_s = 2.1\ T$.

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TABLE I

CHARACTERISTICS OF $(Fe_{0.7}Co_{0.3})_{71}B_{22}Ni_7$ THIN FILMS SATURATION MAGNETIZATION $M_S = 2.1$ T. LINE-WIDTH OF PEAKS ≈ 0.5 GHz. ZERO FIELD FMR DATA AND CORRESPONDING KITTEL FORMULA CURVE FITTING PARAMETERS $\mathbf{H}_{K1}$ (MAIN PEAK) AND $\mathbf{H}_{K2}$ (SECONDARY PEAK)

	Main peak		Second peak	
t (nm)	FMR (GHz)	H_{k1} (A/m)	FMR (GHz)	H_{k2} (A/m)
136	8.3	30000	6.63	19000
195	5.5	13500	2.83	3500
236	5.26	12000	3.8	5000

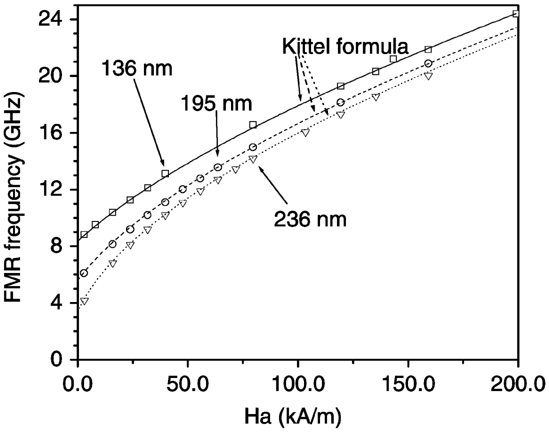

Fig. 1. Evolution of the FMR frequency with the applied field Ha. Open squares, dots, and triangles—measurements; solid, dashed, and dotted lines—data fit using (1) and the following parameters: $\mu_0 M_s = 2.1$ T, $\gamma = 185$ GHz $T^{-1}(g = 2.1)$, $H_{k1} = 30$, 13.5 and 5 kA/mm respectivelym for 136-, 195-, and 236-nm films. Data points are derived from the FMR peaks of Figs. 3 and 4.

Equation (1) yields to an excellent fit (see Fig. 2) of the experimental FMR data in different samples with the parameters shown in Table I using a value of $\gamma = 185$ GHz T^{-1} which corresponds to a Landè factor $g = 2.1$ [4]. The microwave behavior appears to be dominated by the anisotropy field H_k, whose values are in reasonable agreement with those estimated from the magnetization curves measured in plane along the hard magnetization axis (see Fig. 1). From the static magnetization data shown in Fig. 1 it appears evident that the field assisted deposition leads to an average uniaxial anisotropy behavior.

The observed differences between the samples are quite important: the anisotropy field value for the thinner film is on the order of the magnetocrystalline anisotropy field of cubic Fe-Co, while in the thicker films it decreases by almost an order of magnitude. These differences are due to the interplay between the field applied during deposition and the different film geometries, which produce the final nanostructure, consisting of elongated and 45 ° canted columnar grains of a few nanometers diameter which cause the appearance, in zero field, of magnetic domains with an area of 100-150 $\times$ 50 nm, as observed by MFM [1]. The interplay between shape and induced anisotropy leads to the observed uniaxial anisotropy and causes a very large increase in the FMR frequency that can be exploited in several applications, which require high permeability and high frequency resonances.

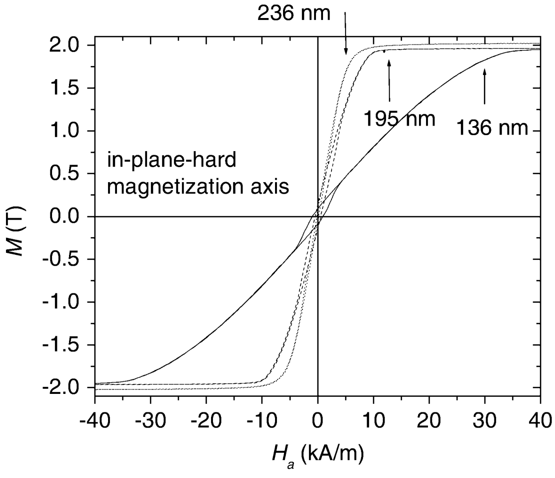

Fig. 2. In-plane hard-axis magnetization curves measured by AGFM for three nanogranular Fe-Co-B-Ni films. The arrows depict the anisotropy field values used in the fitting of the FMR evolution with the applied field shown in Fig. 1.

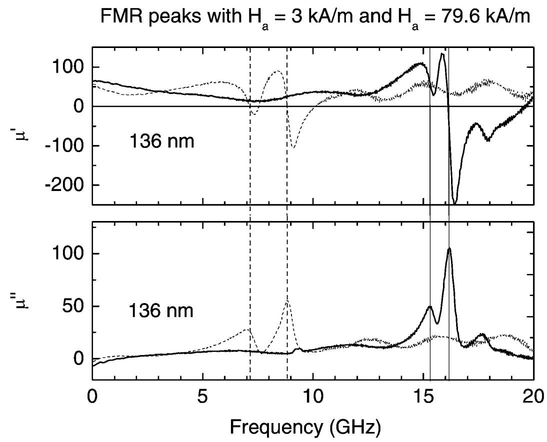

Fig. 3. Real and imaginary part of the permeability obtained from differential S_{21} measurements performed on the 136-nm-thick film. The curve (thin line) with FMR at 6.2 and 8.9 GHz was measured with applied field $\mathbf{H}_a = 3$ kA/m; the second curve (thick line) with FMR at 15.2 and 16.1 GHz was measured with $\mathbf{H}_a = 79.6$ kA/m.

A peculiar feature observed in these samples is related to the presence of multiple FMR peaks. Double peaks were observed in all the available samples, even though their relative intensity changes greatly, as shown in Figs. 3 and 4. The main peak was chosen for its larger intensity and its association with the H_k estimated from dc magnetization curves. Under this assumption all the secondary peaks are found at a frequency lower than that of the main FMR peak (see Figs. 3 and 4). The line width of both peaks remains roughly constant with a value of 0.5 GHz. This result is possibly associated to the similarity in grain and domain size distribution of all the samples, regardless of the sample thickness. It was verified that the field dependence of the second FMR peak frequency could itself be described by the Kittel formula using the anisotropy field as an adjustable parameter. Fits as good as the ones shown in Fig. 2 for the main peak where obtained for the secondary peaks, by choosing for H_k values listed in Table I. These values describe in a simple and compact form the microstructure-related mechanisms responsible for the appearance of the secondary FMR peaks. Similar results were found in other nanogranular films [5] and associated with different sources of anisotropy due to different concentrations of Fe-Co. The presence of a double FMR peak, depicted in Figs. 3 and 4, seems to be related to the intrinsic inhomogeneity of the films. The H_k values found for the thinner films identify the

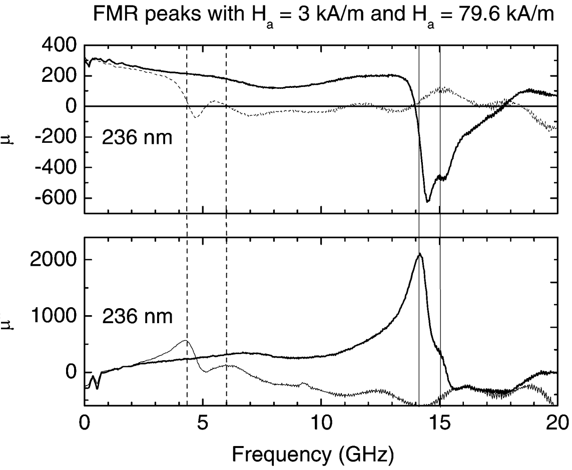

Fig. 4. Real and imaginary part of the permeability obtained from differential S_{21} measurements performed on the 236-nm-thick film. The curve (thin line) with FMR at 4.3 and 6 GHz was measured with applied field $H_a = 3$ kA/m; the second curve (thick line) with FMR at 14.1 and 15.1 GHz was measured with $\mathbf{H}_a = 79.6$ kA/m.

Fe-Co nanograins and the related domain structure as the available source of anisotropy. Lower values of the FMR frequency may also be associated with the emergence of additional bulk or optical modes [6]–[8], which progressively increases under increasing film thickness. Atomic/magnetic force microscopy imaging, together with the AGFM and resistivity measurements have identified a superposition between the nanostructure and the domain structure [1] establishing a connection between the topology and the magnetic and electrical properties of the thin films. In particular, the average separation between the Fe-Co nanograins, associated with the presence of an amorphous interlayer plays a very important role in the definition of the properties of nanogranular films. As shown in [9] for a similar system, the anisotropy, resistivity and magnetostriction of the nanogranular films are strictly connected; a slight increase of resistivity is accompanied by an increase of in the induced anisotropy and a decrease of the hard-axis magnetostriction.

It is expected that further enhancements of the microwave properties and even an increase of the FMR frequency might be achieved by a structural fine tuning of the canting angle [9], [10], the composition and thickness of the films or by increasing the resistivity and induced anisotropy values. Additionally, photolithographic or deposition patterning methods can be employed in order to increase the anisotropy utilizing the demagnetizing fields. All these improvements are instrumental to the application of these films in wide-band noise suppressors and filters [11], [12] where a high permeability and a tunable cut off band are desired.

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