



Ferromagnetic resonance study of structure and relaxation of magnetization in NiFe/Ru superlattices

W. Alayo^{a,*}, S. Landi^b, E. Baggio-Saitovitch^c, F. Pelegrini^d

^a Depto. de Física, Univ. Federal de Pelotas, Campus Universitário, 96010-900, Pelotas, RS, Brazil

^b Instituto Federal Goiano, Rio Verde 75901-970, Brazil

^c Instituto de Física, Universidade Federal de Goiás, Goiânia 74001-970, Brazil

^d Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro 22290-180, Brazil

ARTICLE INFO

Article history:

Received 20 March 2013

Received in revised form

16 August 2013

ABSTRACT

The structural properties and relaxation processes of magnetization in $[\text{Ni}_{81}\text{Fe}_{19}(t_1)/\text{Ru}(t_2)]_N$ superlattices (N =number of bilayers) were analyzed by ferromagnetic resonance (FMR) with a fixed microwave frequency. One series of samples was deposited with constant NiFe layer thickness (t_1) and variable Ru layer thickness (t_2); the other series, with constant t_2 and variable t_1 . A single FMR mode was observed for $t_2 < 15 \text{ \AA}$ and $t_1 > 75 \text{ \AA}$ and it has been attributed to the resonance of the exchange-coupled NiFe layers across the Ru interlayers. For the other values of t_1 and t_2 , several FMR modes appeared and they were associated to non-coupled magnetic phases with different effective magnetization formed during the multilayer growth. The FMR linewidths were analyzed as a function of the magnetic layer thickness and a strong dependence on t_1^{-2} was observed. It was attributed to the contribution of the two-magnon scattering mechanism for the linewidth.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

The properties of metallic multilayer films have been widely investigated in last three decades because they present an ample variety of physical phenomena originated by interactions between materials in the form of thin layers. In particular, magnetic layers separated by non-magnetic spacers, which allowed so many technological applications for spintronic devices [1,2]. Nowadays, the development of sophisticated equipments for both preparation and analysis of structure and magnetic properties in ultra high vacuum increased the interest in the experimental and theoretical research of physics and technology of thin films. In this context, there are still many questions about the behavior of magnetic multilayers, whose understanding will allow a control of its properties and further technological applications. Among these questions we have the role of the relaxation processes of magnetization of the film in the presence of an external magnetic field [3,4] and of the magnetic microstructure on the macroscopic response of multilayers [5]. Thin films based in permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) layers, here denoted as NiFe, are very good systems for analyzing crystalline quality, interfacial and surface structural disorder induced during the deposition processes, which strongly

influence on the magnetic behavior. These films, combined with other magnetic, non-magnetic and/or antiferromagnetic layers, has been intensively studied for analyzing exchange coupling [6–8], magnetic relaxation [9,10], exchange bias [11–13] and spin valve effects [14–16], among many other phenomena.

For the analysis of the above phenomena, the ferromagnetic resonance is one of the main and most used techniques; it is very sensitive to variations of magnetic anisotropies and to the energy of exchange interactions [17,18]. In the FMR spectra of $[\text{FM}/\text{NM}]_N$ like structures, where FM and NM are magnetic and a non-magnetic layers, respectively and N is the number of FM/NM bilayers, several resonance modes are usually observed and they were attributed to distinct magnetic phases in the samples [19–22]. However, the major attention has been provided to the behavior of these modes in Co-based multilayers. In this paper, we analyzed the $[\text{NiFe}/\text{Ru}]_N$ multilayer system, which samples having different NiFe and Ru thicknesses, by the FMR technique. The behavior of the several modes observed in the spectra was interpreted in terms of the structure of the samples and the interlayer exchange coupling between NiFe layers. On the other hand, the magnetization relaxation of thin films has been also widely studied in diverse systems, mainly in single ultrathin layers. The mechanisms of relaxation of thin films are principally due to the Gilbert or intrinsic damping, inhomogeneous damping and the two-magnon scattering mechanism. Here, the linewidth of the main mode of the FMR spectra as a function of the out of the film plane angle and of the ferromagnetic layer thickness is used for characterizing the

* Corresponding author. Tel.: +55 53 3275 7431.

E-mail addresses: arwillian@gmail.com,
willian.rodriguez@ufpel.edu.br (W. Alayo).

contributions to the relaxation processes of magnetization. The presented analysis about the structural and magnetic properties in [NiFe/Ru] superlattices by FMR has not been reported before.

2. Experiment

The $\text{Ni}_{81}\text{Fe}_{19}/\text{Ru}$ superlattices were deposited onto a $\text{Ru}(50 \text{ \AA})$ buffer layer on $\text{Si}(100)$ substrates at room temperature in a magnetron sputtering system. The multilayer structure is denoted by $[\text{NiFe}(t_1)/\text{Ru}(t_2)]_N$, where t_1 and t_2 denote the thickness of the NiFe and Ru layers, respectively and N , the number of bilayers. In one series of samples, the thickness of the NiFe layer was varied between 10 and 200 $\text{\AA}$ and the Ru layer thickness was kept constant at 25 $\text{\AA}$, whereas in the other series, the NiFe layer thickness is 50 $\text{\AA}$ and the Ru layer was varied between 7 and 40 $\text{\AA}$. The multilayer samples were capped with a 50 $\text{\AA}$ thick Ta or Cr layer.

The base pressure inside the deposition chamber was of the order of 5×10^{-8} Torr and the films were grown in an Ar ambient, with a working pressure of 2×10^{-3} Torr. The deposition rates were 1.1 $\text{\AA}/\text{s}$ for NiFe and 0.8 $\text{\AA}/\text{s}$ for Ru, and they have been estimated by determining the thickness of pure calibration films for each material by X-ray reflectivity.

The structure of the samples was studied by X-ray reflectivity and X-ray diffraction at room temperature in a conventional $\theta-2\theta$ diffractometer using the K_α radiation of Cu. The FMR experiments were performed at room temperature, using a high sensitive Bruker ESP-3000 spectrometer, operating at the X-band microwave frequency (9.79 GHz) and swept static magnetic field. The FMR spectra were taken using standard modulation and phase sensitive detection techniques, with the film at the center of a high-Q cylindrical resonant cavity.

3. Results and discussion

3.1. Structural characterization

X-Ray reflectivity and high angle x-ray diffraction measurements were performed in all samples. In Fig. 1 are shown the representative reflectivity and diffraction patterns corresponding to the $[\text{NiFe}(30 \text{ \AA})/\text{Ru}(25 \text{ \AA})]_{20}$ multilayer. Here, the layer thicknesses in parenthesis are nominal values estimated with the deposition rates obtained with calibration films for each material. In the reflectivity pattern

(inset of Fig. 1), the Bragg peaks and the Kiessing fringes are observed. The Bragg peaks are originated from interferences of beams reflected at the NiFe/Ru interfaces and up to four peaks can be distinguished. The presence of Bragg peaks indicates a multilayered structure with defined interfaces; the separation between these peaks provides the thickness of a NiFe/Ru bilayer, that is, the multilayer period. The presence of Kiessing fringes is also a signature of well defined interfaces and the separation between the peaks of these fringes provides the total thickness of the multilayer. The layer thicknesses have been calculated by fitting, to the experimental data, a theoretical curve calculated with a refinement program based on Parrat formalism [23]. The fitting curve is also shown in the inset of Fig. 1, superposed to the experimental data, and the layer thicknesses obtained for this sample are 36.8 $\text{\AA}$ for NiFe and 27.7 $\text{\AA}$ for Ru, which are close to the values estimated with the deposition rates.

The mean square interface roughness (σ) was also obtained from this fit; it is estimated by the root mean-square deviation of the position of an interface atom in a perfectly smooth interface. The σ values obtained from the fit are around 4.0 $\text{\AA}$ and 2.1 $\text{\AA}$ for the NiFe/Ru and Ru/NiFe interfaces, respectively. For the protective layer, the calculated thickness is 46.9 $\text{\AA}$ and the surface roughness is about 4.3 $\text{\AA}$. An oxide layer in the sample surface has not been considered for calculations. The specular reflectivity measurements provide good information about the stacking of the layers in a superlattice structure, mainly the multilayer period and interfacial roughness. However, it is not sensitive to the crystalline properties (lattice spacing, strain, etc.) of the layers and atomic diffusion between them, which results in a fluctuation of the layer thicknesses and plays a very important role in the magnetic properties of the whole structure. This additional information about short length scale disorder can be obtained from high-angle X-ray diffraction measurements. The high-angle XRD measurements for all samples have been performed around the vicinity of the bulk hcp Ru(0002) and fcc NiFe (111) diffraction peaks. In Fig. 1, the spheres represent the experimental data and the solid line is a fit obtained by calculations using SUPREX [24]. For this fitting, several parameters were taken into account: lattice spacing, thicknesses and strain of the layers, interfacial roughness and diffusion. The layer thickness (37.6 $\text{\AA}$ for NiFe and 26.7 $\text{\AA}$ for Ru) and interfacial roughness, obtained from the fit, are very close to that obtained from the fit of the reflectivity profile.

In Fig. 2 are shown some of the high angle X-ray diffraction profiles of the $[\text{NiFe}(t_1)/\text{Ru}(25 \text{ \AA})]_N$ and $[\text{NiFe}(50 \text{ \AA})/\text{Ru}(t_2)]_{20}$ superlattices with different NiFe(t_1) and Ru(t_2) layer thicknesses. In all diffractograms, the main Bragg peak is indicated by (0) and, around it, we can observe several satellite peaks, which are indicated by an index ($n = \pm 1, \pm 2, \dots$). The quality of the films is confirmed by the presence of these satellite peaks, which appears when the structural coherence length (ξ) perpendicular to film is bigger than the multilayer period. So, the presence of these peaks is a signature of well-defined multilayered structures, indicating a good stacking of the layers. In both series of samples, we can see that the number of satellites increases for increasing NiFe or Ru layer thicknesses. This reflects a well defined repeat distance of the [NiFe/Ru] bilayers for increasing layer thicknesses, assuming coherence between successive layers. We can also observe that the sharpness of the satellites changes with the layer thickness. This indicates also a short amount of step disorder for samples with thicker layer thicknesses. The structural coherence length or grain size, in the film growth direction, has been calculated with the Scherrer formula, given by $\xi = 0.89 \lambda / (B \cos \theta)$, where λ is the wavelength (1.5418 $\text{\AA}$), B is the full width at half maximum of the peak and θ is the angle at the maximum of the peak. In samples with different NiFe layer thicknesses from 10 $\text{\AA}$ to 100 $\text{\AA}$, with the Ru layer thickness constant (25 $\text{\AA}$) we observed an increase of ξ between 150 $\text{\AA}$ and 260 $\text{\AA}$ with increasing t , whereas for samples with different Ru layer thickness

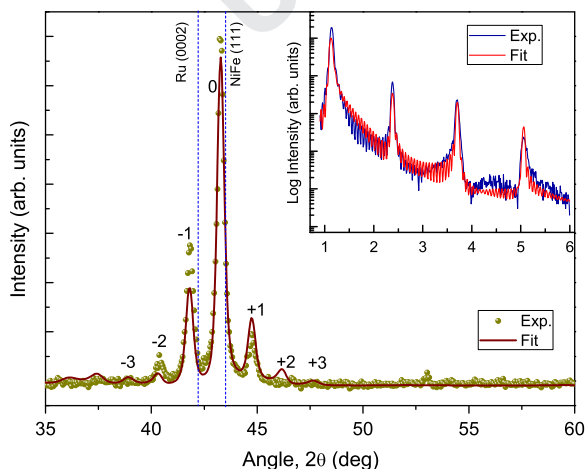


Fig. 1. High angle X-ray diffraction pattern of the $[\text{NiFe}(30 \text{ \AA})/\text{Ru}(25 \text{ \AA})]_{20}$ superlattice. The solid line is a fit calculated with SUPREX. The satellite peaks are indicated by an index $\pm n$ and the dashed lines points the position of the diffraction peaks for the bulk Ru and NiFe. The inset shows the X-ray reflectivity of the same sample.

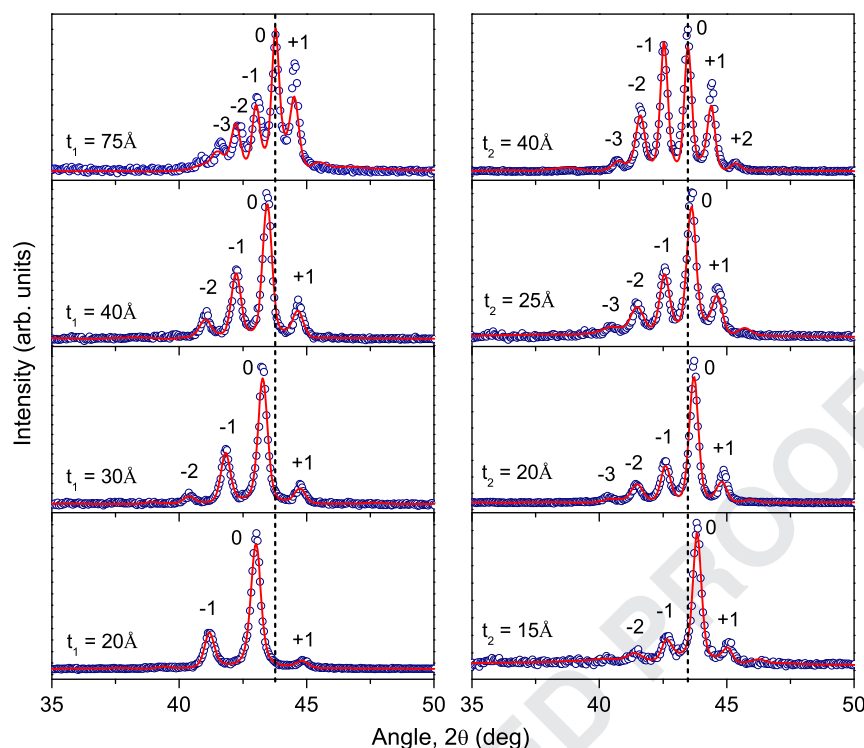


Fig. 2. High angle X-ray diffraction patterns for some of the $[\text{NiFe}(t_1)/\text{Ru}(25 \text{ Å})]_N$ (left hand) and $[\text{NiFe}(50 \text{ Å})/\text{Ru}(t_2)]_{20}$ (right hand) superlattices. The solid lines are fits calculated with SUPREX. The dashed lines help to observe the shift of the zero order satellite peaks.

Table 1

Structural parameters obtained from fits of the X-ray diffraction data of the NiFe/Ru superlattices. The values in parentheses of the sample column are the nominal layer thickness values. The meaning of each parameter is detailed in the text.

Sample	$t_1(\text{Å})$	$t_2(\text{Å})$	$d_{in}(\text{Å})$	$N_1(\text{ML})$	$N_2(\text{ML})$	$d_1(\text{Å})$	$d_2(\text{Å})$	$\delta d_1(\%)$	$\delta d_2(\%)$
$[\text{NiFe}(50 \text{ Å})/\text{Ru}(40 \text{ Å})]_{20}$	63.33	37.80	0.15	31.42	9.58	2.0588	4.3233	0.73	0.97
$[\text{NiFe}(50 \text{ Å})/\text{Ru}(35 \text{ Å})]_{20}$	63.28	36.00	0.20	31.33	9.26	2.0632	4.3154	0.94	0.78
$[\text{NiFe}(50 \text{ Å})/\text{Ru}(25 \text{ Å})]_{20}$	62.14	26.00	0.18	30.79	6.84	2.0605	4.3253	0.81	1.02
$[\text{NiFe}(50 \text{ Å})/\text{Ru}(20 \text{ Å})]_{20}$	62.29	20.14	0.16	30.89	5.46	2.0607	4.3583	0.82	1.79
$[\text{NiFe}(50 \text{ Å})/\text{Ru}(15 \text{ Å})]_{20}$	59.00	16.50	0.15	29.30	4.61	2.0572	4.3714	0.65	2.09
$[\text{NiFe}(75 \text{ Å})/\text{Ru}(25 \text{ Å})]_{14}$	99.60	25.62	0.19	48.45	7.08	2.0934	4.1683	2.42	2.64
$[\text{NiFe}(40 \text{ Å})/\text{Ru}(25 \text{ Å})]_{20}$	52.05	26.56	0.15	26.03	6.90	2.0886	4.2369	2.19	1.04
$[\text{NiFe}(30 \text{ Å})/\text{Ru}(25 \text{ Å})]_{20}$	37.62	26.71	0.17	18.52	7.13	2.0859	4.1790	2.05	2.39
$[\text{NiFe}(20 \text{ Å})/\text{Ru}(25 \text{ Å})]_{22}$	25.34	26.15	0.17	12.43	7.03	2.1070	4.1246	3.09	3.66
$[\text{NiFe}(15 \text{ Å})/\text{Ru}(25 \text{ Å})]_{22}$	20.45	25.66	0.16	10.10	6.87	2.1134	4.1643	3.40	2.73

from 7 Å to 40 Å and the NiFe layer thickness kept constant (50 Å), the ξ values varied between 215 Å and 225 Å. According to the grain size values, the samples are polycrystalline, and at least two bilayers are coherent in the growth direction.

All diffractograms were refined with SUPREX. In Fig. 2, the solid lines represent the fitting curves superposed to the respective experimental data and the parameters used are summarized in Table 1. Here, d_{in} is the interfacial disorder, σ_1 and σ_2 are the roughness for NiFe and Ru layers, respectively, N_1 (for NiFe) and N_2 (for Ru) are the layer thicknesses in monolayers (ML). The zero order peak is slightly shifted for the different NiFe and Ru thicknesses, as indicated by the dashed line, following a change of the average lattice spacing (d_{av}) of multilayers, given by [24]:

$$\frac{2 \sin \theta}{\lambda} = \frac{1}{d_{av}} \pm \frac{n}{\Lambda}$$

where $d_{av} = \Lambda / (N_1 + N_2)$, with the period $\Lambda = t_1 + t_2 + t_i$, in which, t_i is the interfacial distance. In Table 1, it is also shown the average lattice spacing for the NiFe (d_1) and Ru (d_2) layers. It is also shown the difference between the average lattice spacing (δd_1 and δd_2) with respect to the bulk values for NiFe and Ru. These bulk values

are $c = 4.2816 \text{ Å}$ for *hcp* Ru and $d_{111} = 2.0438 \text{ Å}$ for *fcc* NiFe, where the last one has been calculated from the standard lattice constant $a = 3.5400 \text{ Å}$ for *fcc* NiFe. This difference between the average lattice spacing provides a measure of the lattice strain in multilayers, which results in an interfacial disorder and layer thickness fluctuations. According to the model of Fullerton et al. [24], the lattice spacing (d) normal to the layers of three monolayers near the interface, in a superlattice, can be expanded or contracted a quantity of $(\Delta d)e^{-m\alpha}$, where m indicates the position of the monolayer away from the interface ($m = 1, 2, 3$) and α is a constant decay exponent of the strain. Furthermore, in all experimental data, an interdiffusion term of about 0.3 Å was necessary for refinement. Thus, this structural analysis clearly shows that in all samples there is lattice strain, interfacial disorder and interdiffusion and fluctuation of the layer thickness, which become very important for understanding the magnetic properties.

3.2. Ferromagnetic resonance study

The FMR measurements were performed in all samples with a fixed microwave frequency and sweep magnetic field. The applied

magnetic field direction (θ_H) was varied from 90 to 0° with respect to the film normal.

3.2.1. Resonance modes and absorption fields

The FMR spectra of the NiFe/Ru superlattices analyzed here presented one resonance mode in the parallel configuration ($\theta_H=90^\circ$), when the magnetic field is applied parallel to the film plane. However, the asymmetric shape of the spectra suggests the superposition of two or more resonance modes. This can be confirmed in the perpendicular configuration ($\theta_H=0^\circ$), in which the magnetic field is applied perpendicular to the film plane. In this orientation, the FMR spectra exhibited several resonance modes for some of the $[\text{NiFe}(50\text{ Å})/\text{Ru}(t_2)]_{20}$ and $[\text{NiFe}(t_1)/\text{Ru}(25\text{ Å})]_N$ superlattices. In the first system, for $\theta_H=0^\circ$, we observed multimodes FMR spectra for the Ru thicknesses of $t_2=40, 35, 30, 25$ and 20 Å , while for $t_2=15, 13, 11, 9\text{ Å}$ and 5 Å , a single FMR mode has been observed. In Fig. 3, the FMR spectra for some samples of the $[\text{NiFe}(50\text{ Å})/\text{Ru}(t_2)]_{20}$ system are presented. The main mode has the highest resonance field and the other modes (secondary modes) have a resonance field lower than the main one.

In the other system, we also observed a single mode FMR spectra (for $\theta_H=0^\circ$), but only for samples with NiFe thicknesses of $t_1=200, 150$ and 100 Å , whereas for samples with $t_1=75, 40, 30, 20, 15$ and 10 Å , multimodes FMR spectra were observed. In Fig. 4, the FMR spectra of some samples of the $[\text{NiFe}(t_1)/\text{Ru}(25\text{ Å})]_N$ system are shown. As in the first case, the main mode has the highest resonance field and the other modes (secondary modes) have a resonance field lower than the main one.

The FMR spectra for the samples of the $[\text{NiFe}(50\text{ Å})/\text{Ru}(t_2)]_{20}$ system with t_2 below 15 Å and for the samples of the $[\text{NiFe}(t_1)/\text{Ru}(25\text{ Å})]_N$ system with t_1 above 75 Å presented a single resonance mode for all orientations of the applied field with respect to the film plane. From the point of view of the magnetic microstructure, a magnetic layer in a film with in-plane magnetic anisotropy has several magnetic domains separated by the so-called Neel domains walls. Each domain has a magnetization orientation that changes in order to align with the applied field direction.

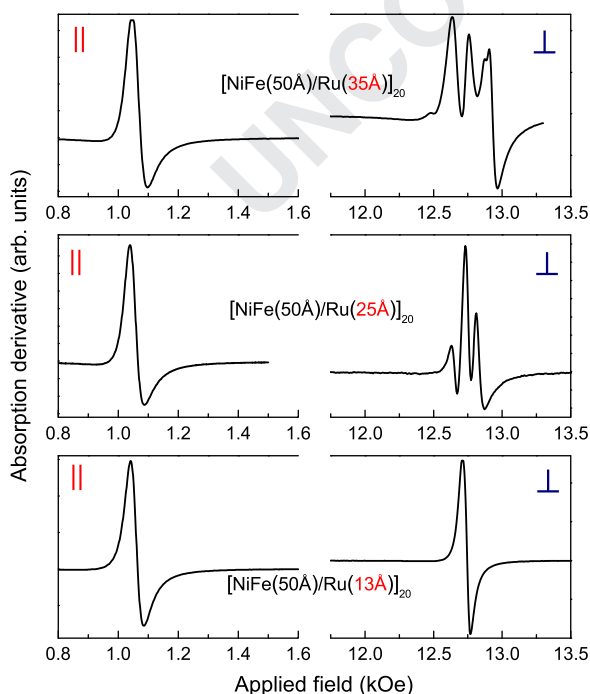


Fig. 3. FMR spectra for some of the $[\text{NiFe}(50\text{ Å})/\text{Ru}(t_2)]_{20}$ superlattices measured with the parallel ($\parallel$) and perpendicular ($\perp$) orientation of the applied magnetic field with respect to the film plane.

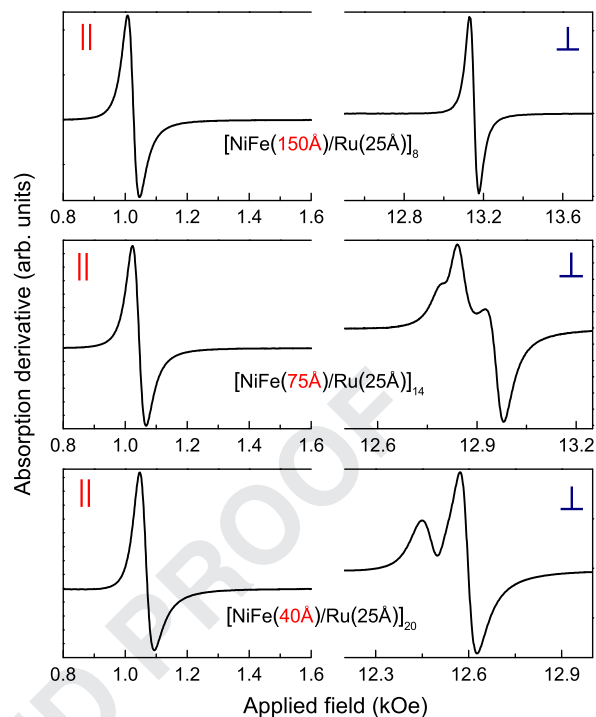


Fig. 4. FMR spectra for some of the $[\text{NiFe}(t_1)/\text{Ru}(25\text{ Å})]_N$ superlattices measured with the parallel ($\parallel$) and perpendicular ($\perp$) orientation of the applied magnetic field with respect to the film plane.

Furthermore, the structural disorder, like roughness and diffusion, at the NiFe/Ru and Ru/NiFe interfaces lead to the formation of magnetic regions with an effective magnetization less than the value for bulk NiFe. The single FMR mode, observed for the samples above, indicates that the magnetic domains and regions of the NiFe layers are coupled through an exchange interaction across the non-magnetic Ru layer and rotates as a single domain with magnetization M . For confirming the magnetic coupling between NiFe layers, magnetization measurements at room temperature were performed with a SQUID magnetometer in samples with different Ru thickness. The data are shown in Fig. 5, in which we can observe that the saturation field oscillates and decreases as a function of the Ru thickness, which is an indication of oscillatory interlayer coupling. For Ru thicknesses larger than 15 Å , the hysteresis loops (not shown here) has the typical shape of a single NiFe ferromagnetic layer. This suggests that the exchange coupling energy reduces and lies to zero for these range of interlayer Ru thicknesses. This is in agreement with studies of M. Belmuguenai et al. [6], where it was shown that for Ru thicknesses larger than 15 Å , in NiFe/Ru/NiFe trilayers deposited by dc magnetron sputtering at room temperature, the exchange coupling constant reduces and lies to zero.

Thus, the single mode observed in the FMR spectra of the $[\text{NiFe}(50\text{ Å})/\text{Ru}(t_2)]_{20}$ system for $t_2 < 15\text{ Å}$ can be understood as the resonance of the exchange-coupled domains and interfacial regions of NiFe layers across the Ru interlayers. For $t_2 > 15\text{ Å}$, the coupling strength becomes weak and for larger t_2 lies to zero. This result in the resonance of the non-coupled NiFe layers in FMR measurements, which gives origin to the multi-modes spectra observed in the perpendicular configuration. These phases can be associated to the non uniform NiFe layers thicknesses and interfacial regions, which can be explained by the structural disorder: The thickness of the layers grown on the same deposition conditions can vary due to the lattice strain and/or an increase of the bilayer number, resulting in non uniform layer thicknesses throughout the same sample. The X-ray diffraction analysis point out for fluctuations of the layer

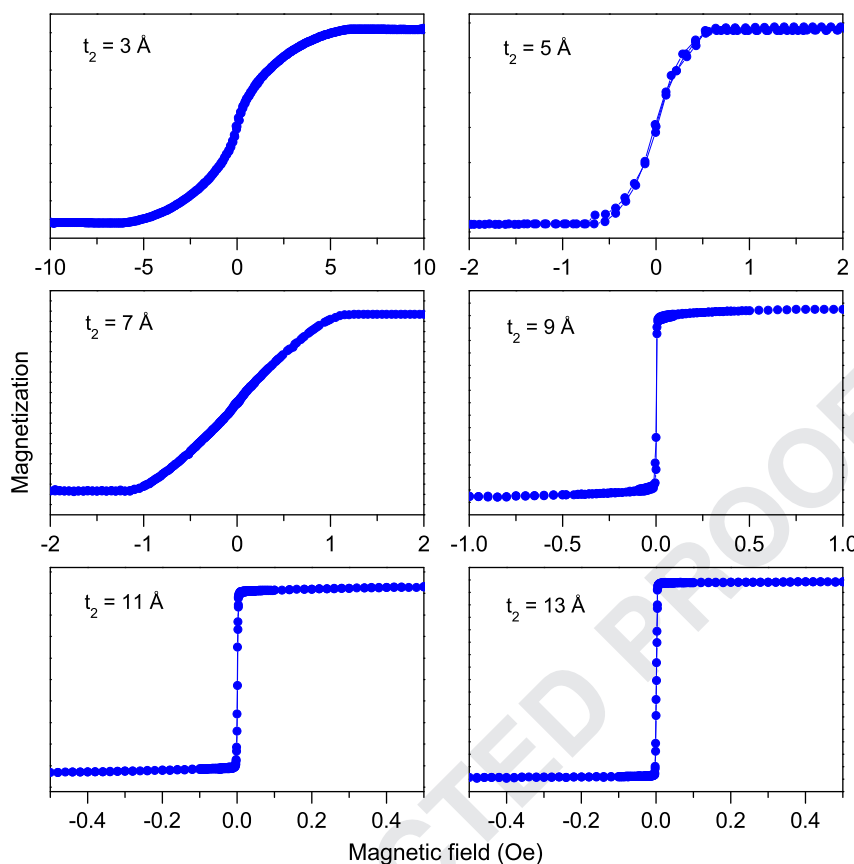


Fig. 5. Magnetic hysteresis loops measured at room temperature with the applied magnetic field in the sample plane for some of the $[\text{NiFe}(50 \text{ Å})/\text{Ru}(t_2)]_{20}$ superlattices.

thicknesses. This results in magnetic phases with different effective magnetizations giving rise to the additional peaks. The high sensitivity of the FMR technique to small variations of magnetic anisotropies and the low FMR linewidth of NiFe allow for the observation of well resolved FMR lines at the perpendicular orientation. All these modes have a resonance field lower than the main mode in the perpendicular configuration, indicating an effective magnetization lower than that for the pure NiFe. Additional and strong FMR peaks has been also attributed to non homogeneous layers in $[\text{Co}/\text{Cu}]$ multilayers grown on Si/SiO_2 substrates by magnetron sputtering [25]

On the other hand, for the FMR spectra of $[\text{NiFe}(t_1)/\text{Ru}(25 \text{ Å})]_N$ multilayers with variable t_1 , the single mode observed for $t_1 = 100 \text{ Å}$, 150 Å and 200 Å indicates that the samples behaves as exchange-coupled systems, also mediated by an exchange interaction across Ru layers. According to the model of Bruno [26], the strength of the exchange coupling between ferromagnetic layers, decays with t_1^{-2} , for a fixed non-magnetic spacer layer. This can explain observation of a single mode for thick NiFe ($t_1 > 75 \text{ Å}$) and several modes observed for $t_1 \leq 75 \text{ Å}$, which must be associated to the non-coupled NiFe layers. Thus, the origin of these secondary modes can be also understood in terms of fluctuations of the thicknesses, which lead to non-uniform layers. In both systems, $[\text{NiFe}(50 \text{ Å})/\text{Ru}(t_2)]_{20}$ and $[\text{NiFe}(t_1)/\text{Ru}(25 \text{ Å})]_N$, the single resonance mode observed in the parallel orientation of the applied magnetic field, for all samples, is due to the proximity of the resonance fields of the main and secondary modes at these orientation, and then a superposition of the modes is observed.

In order to analyze the angular dependence of the resonance fields of the main resonance mode, we used the dispersion relation and the equilibrium condition, given the well known equations [17]

$$H_r \cos(\theta_M - \theta_H) = 4\pi M_{\text{eff}} \sin \theta_M \cos \theta_M \quad (1)$$

and

$$\begin{aligned} (\omega/\gamma)^2 = & [H_r \cos(\theta_M - \theta_H) - 4\pi M_{\text{eff}} \cos^2 \theta_M] \\ & \times [H_r \cos(\theta_M - \theta_H) - 4\pi M_{\text{eff}} \cos 2\theta_M] \end{aligned} \quad (2)$$

where, $4\pi M_{\text{eff}}$ is the effective magnetization; it is defined as $4\pi M_{\text{eff}} = 4\pi M_s - H_k$, where H_k is the perpendicular anisotropy field and M_s is the saturation magnetization. ω is the angular microwave frequency, $\gamma(-g\mu_B/\hbar)$ is the electronic gyromagnetic ratio, where g is the Landé-factor. The angles θ_M and θ_H are the equilibrium orientations of magnetization and applied magnetic field, respectively, with respect to the film normal.

By fitting the out-of-plane angular dependence of the resonance field for the main mode, using Eqs. (1) and (2), the effective magnetization could be calculated for all samples. In Fig. 6 is presented the H_r vs. θ_H curve for the $[\text{NiFe}(50 \text{ Å})/\text{Ru}(25 \text{ Å})]_{20}$ superlattice, where open triangles represent the experimental data and the dotted line is a fit obtained with Eqs. (1) and (2) using $4\pi M_{\text{eff}} = 9.49 \text{ kOe}$ and $g = 2.12$. For samples with different NiFe thicknesses, the $4\pi M_{\text{eff}}$ values present a systematic decrease for decreasing NiFe thickness. This behavior is attributed to the interface and surface effects and it can be described with the following equation [27]:

$$4\pi M_{\text{eff}} = 4\pi M_{\text{eff}}(\infty) \left(1 - \frac{2\Delta d}{t_1} \right) \quad (3)$$

where $4\pi M_{\text{eff}}(\infty)$ correspond to the effective magnetization of bulk NiFe and the offset from the origin, Δd , is attributed to nonmagnetic layers at the NiFe/Ru interfaces. This parameter gives the thickness of magnetically inactive layers at interfaces. Eq. (3) describes the effect of the reduced magnetization between the NiFe/Ru and Ru/NiFe interfaces. In the inset of Fig. 6 are shown the $4\pi M_{\text{eff}}$ values as a function of the NiFe thickness of the $[\text{NiFe}(t_1)/\text{Ru}(25 \text{ Å})]_N$ samples, where the spheres represent the values obtained

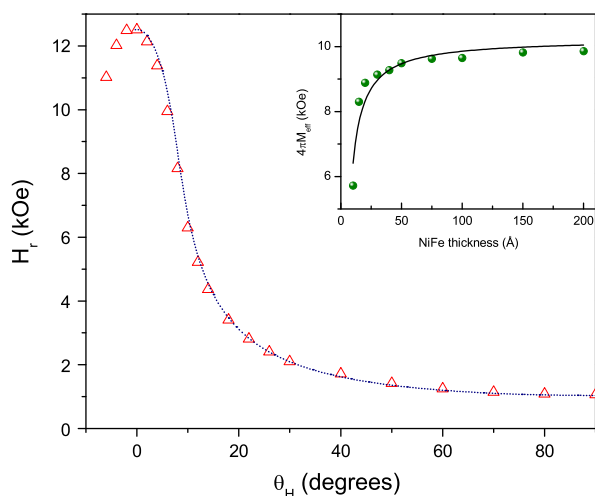


Fig. 6. Out-of-plane angular dependence of the resonance fields extracted from the spectra of the [NiFe(50 Å)/Ru(25 Å)]₂₀ superlattice. The dashed line is a fit obtained with Eqs. (1) and (2) using $4\pi M_{\text{eff}} = 9.49$ kOe and $g = 2.12$. The inset shows the NiFe layer thickness dependence of the effective magnetization obtained from the fit of the H_r vs θ_H curves of the [NiFe(t_1)/Ru(25 Å)]_N samples. The solid line is a fit obtained with Eq. (3).

from the FMR spectra and the solid line is a fit of Eq. (3) to the data. This fit gives $4\pi M_{\text{eff}}(\infty) = 10.23$ kOe and $2\Delta d = 3.74$ Å, which are close to the values obtained for [NiFe/Cu]₁₀₀ multilayers deposited on Si(100) by magnetron sputtering [27].

3.2.2. Analysis of the linewidth: magnetic relaxation

The FMR linewidth is one of the most sensitive parameters of ferromagnetic resonance in thin films. It can provide information about relaxation processes of magnetization, which can be influenced by structural and magnetic inhomogeneities. The basic contributions to the peak to peak FMR linewidth can be written as

$$\Delta H = \Delta H_{\text{hom}} + \Delta H_{\text{inhom}} + \Delta H_{\text{ext}} \quad (4)$$

where ΔH_{hom} is the homogeneous or intrinsic linewidth, which describes an intrinsic mechanism of relaxation in terms of the Gilbert-damping parameter (G) and the saturation magnetization (M_s) of the ferromagnetic material. For out-of-plane angles, it is written as [31]:

$$\Delta H_{\text{hom}} = \frac{2}{\sqrt{3}} \frac{G}{\gamma^2 M_s} \frac{\omega}{D(\theta_H, \theta_M)} \quad (5)$$

where $D(\theta_H, \theta_M)$ is a function which describes the magnetization dragging. However, for the purposes of this work, no explicit expression of this function is needed; the explicit formula can be found in reference [31].

The ΔH_{inhom} term in Eq. (4) is the inhomogeneous linewidth and it represents a broadening of ΔH due to sample defects. The mechanism for the inhomogeneous part is described in terms of spreads of crystallographic axes and variations of the internal magnetic fields. For angular spread of crystallographic axes, we have [4,31].

$$\Delta H_{\text{inhom}} = \left| \frac{\partial H_r}{\partial \theta_H} \right| \Delta \theta_H \quad (6)$$

where $\Delta \theta_H$ represent the spreads in the orientation of the crystallographic axes.

Furthermore, there is another mechanism which contributes to ΔH . This is the two-magnon scattering of defects on film surfaces. The scattering of the precession of the uniform mode into non uniform ones is mediated by sample defects and results in this extrinsic

contribution to ΔH . The two magnon scattering mechanism is, in general, dependent of the out-of-plane angle of the film's magnetization direction (θ_M), and consequently, of the out-of-plane angle of the applied magnetic field direction (θ_H). However, this mechanism remains active only up to a given angle θ_H , which decreases with the microwave frequency. For 9.8 GHz, this value of θ_H is approximately 82° and the magnetization angle θ_M is around 45° , both with respect to the film plane [31]. An explicit expression for the out-of-plane angular dependence of the linewidth due to the two-magnon scattering is found in [31]. In this work, we only report the contribution the two-magnon scattering mechanism to the FMR linewidth in NiFe/Ru superlattices by analyzing the magnetic layer thickness dependence of the peak to peak linewidth measured with the magnetic field applied parallel to the film plane. The extrinsic linewidth, for in-plane angles, can be written in a simplified form as [9,28]:

$$\Delta H_{\text{ext}} = \frac{1}{\sqrt{3}} \frac{16sH_k^2}{\pi D} \frac{\sqrt{H_r}}{\sqrt{H_r + 4\pi M_{\text{eff}}}} \quad (7)$$

where H_k is the perpendicular anisotropy field, D is the exchange stiffness constant and s is a geometrical factor of the surface roughness. Since the perpendicular anisotropy field is proportional to t_1^{-1} , then the extrinsic contribution to the linewidth varies proportionally to t_1^{-2} , which has been observed experimentally.

In order to see the contributions to the linewidth, measurements of ΔH as a function of the out-of-plane angle, θ_H , were performed. In Fig. 7(a) is shown the representative ΔH vs. θ_H curve and it corresponds to the [NiFe(40 Å)/Ru(25 Å)]₂₀ superlattice. In parallel configuration ($\theta_H = 90^\circ$), $\Delta H = 41$ Oe, for perpendicular configuration ($\theta_H = 0^\circ$), $\Delta H = 57$ Oe and at an intermediate angle of $\theta_H \approx 9.0^\circ$, the linewidth has a maximum value of $\Delta H = 241$ Oe. The sharp peak of the ΔH vs. θ_H curve indicates that the linewidth is composed by a homogeneous and inhomogeneous part. The major contribution to the maximum value of ΔH , giving this peak, comes from the orientation distribution of independent grains with respect to the applied magnetic field direction, described by the Eq. (6). In the inset of Fig. 7(a) is shown the calculated curve for the angular dependence of the inhomogeneous linewidth for the same sample, using Eq. (6) and considering an angular spread of $\Delta \theta_H = 0.32^\circ$. As it is observed, the inhomogeneous broadening has its major contribution for $\theta_H \approx 9.0^\circ$ and it becomes inactive for the parallel and perpendicular configuration of the applied field. Thus, when the applied magnetic field is parallel to the film plane, the contribution of the inhomogeneous damping can be neglected and the linewidth is well described by the Gilbert damping and the extrinsic two-magnon contribution [28].

In Fig. 7(b) is shown the NiFe thickness dependence of the peak to peak linewidth measured for the parallel configuration of the applied field. Very small variations of the resonance field and linewidth values for in-plane angles were observed, due to the in-plane magnetic anisotropy of NiFe. So, average values have been considered for the ΔH vs. t_1 curve. Furthermore, the t_1 values obtained from fits of the X-ray diffraction data has been considered. From the fit of these data we can obtain the intrinsic and extrinsic contributions to ΔH . Due to the dependence of the extrinsic linewidth on the surface anisotropy field as H_s^2 (therefore on t_1^{-2}), the equation $\Delta H = \Delta H_{\text{hom}} + \Delta H_{\text{ext}} t_1^{-2}$ can be used for fitting the data, in which ΔH_{hom} is the Gilbert damping contribution and $\Delta H_{\text{ext}} = \Delta h_{\text{ext}} t_1^{-2}$ is the extrinsic contribution. We obtained $\Delta H_{\text{hom}} = (40.1 \pm 2.0)$ Oe and $\Delta h_{\text{ext}} = (18.2 \pm 1.0)$ kOe Å². This dependence of the linewidth on t_1^{-2} indicates, as proposed by Arias and Mills [29], that the extrinsic damping processes of magnetization are influenced by the two-magnon scattering mechanism. These values are close to the obtained ones for pure NiFe layers deposited on Si(100) by magnetron sputtering [30].

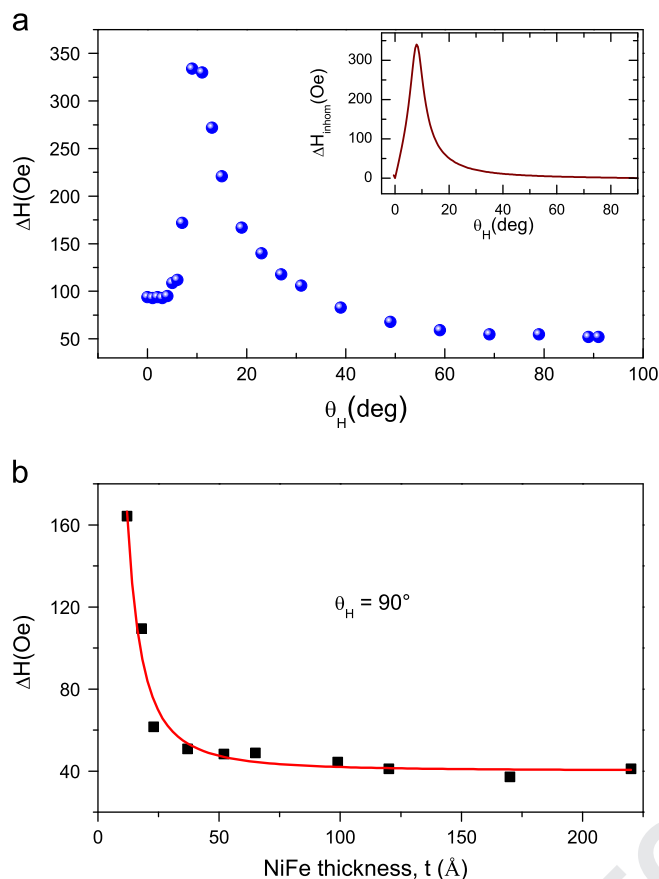


Fig. 7. (a) Representative out-of-plane angular dependence of the peak to peak linewidth, corresponding to the $[\text{NiFe}(40 \text{ Å})/\text{Ru}(25 \text{ Å})]_{20}$ sample, in which the solid line is a guide to eyes. In the inset is shown the inhomogeneous linewidth for the same sample, calculated with Eq. (6), using $\Delta\theta_H = 0.32^\circ$. (b) NiFe layer thickness dependence of ΔH for the $[\text{NiFe}(t_1)/\text{Ru}(25 \text{ Å})]_N$ superlattices, where the open squares are the experimental data and the solid line is a fit calculated with $\Delta H = \Delta H_{\text{hom}} + \Delta h_{\text{ext}} t_1^{-2}$.

4. Summary and conclusions

The structural and magnetic properties of the $\text{Ni}_{81}\text{Fe}_{19}/\text{Ru}$ superlattices were investigated using samples with different NiFe or Ru thicknesses. The analysis by X-ray reflectivity provided the layer thickness and interfacial main-square-roughness. The high angle X-ray diffraction patterns revealed layer thicknesses close to that obtained by reflectivity, interfacial diffusion and lattice strain. This structural disorder leads to the formation of non uniform layer thicknesses, giving rise to magnetic regions with different effective magnetizations. In the FMR spectra of some samples, several resonance modes were identified and attributed distinct magnetic phases of samples. These modes were evident in samples with very low or zero interlayer exchange coupling between NiFe layers across Ru. For samples with strong exchange coupling, only a single FMR mode has

been observed and attributed to the resonance of the exchange coupled NiFe layers. In the analysis of the linewidth, the dependence of ΔH on t_1^{-2} , where t_1 is the NiFe layer thickness, indicates clearly a contribution of the two-magnon scattering mechanism.

Acknowledgments

The authors acknowledge to the Brazilian Institutions: CNPq, FAPERJ, CAPES and CLAF for financial support.

References

- [1] James Lenz, Alan S. Edelstein, IEEE Sensors Journal 6 (2006) 3.
- [2] P.P. Freitas, R. Ferreira, S. Cardoso, F. Cardoso, Journal of Physics: Condensed Matter 19 (2007) 165221.
- [3] B. Heinrich, R. Urban, G. Woltersdorf, Journal of Applied Physics 91 (2002) 7523.
- [4] W. Platow, A.N. Anisimov, G.L. Dunifer, M. Farle, K. Baberschke, Physical Review B 58 (1998) 5611.
- [5] E.Y. Vedmedenko, H.P. Oepen, J. Kirschner, Physical Review B 66 (2002) 214401.
- [6] M. Belmeguenai, T. Martin, G. Woltersdorf, M. Maier, G. Bayreuther, Physical Review B 76 (2007) 104414.
- [7] S.M. Rezende, C. Chesman, M.A. Lucena, A. Azevedo, F.M. de Aguiar, S.S.P. Parkin, Journal of Applied Physics 84 (1998) 958.
- [8] I.F. Lee, J.C. Jan, J.W. Chiou, H.M. Tsai, et al., Journal of Physics: Condensed Matter 16 (2004) 7163.
- [9] Antonio Azevedo, A.B. Oliveira, F.M. de Aguiar, S.M. Rezende, Physical Review B 62 (2000) 5331.
- [10] S.J. Yuan, K. Xu, L.M. Yu, S.X. Cao, C. Jing, J.C. Zhang, Journal of Applied Physics 101 (2007) 113915.
- [11] V.P. Nascimento, E.C. Passamani, A. Biondo, V.B. Nunes, E. Baggio Saitovitch, Applied Surface Science 253 (2007) 6248.
- [12] N.J. Gökemeijer, T. Ambrose, C.L. Chien, Physical Review B 79 (1997) 4270.
- [13] V. Baltz, J. Sort, S. Landis, B. Rodmacq, B. Dieny, Physical Review Letters 94 (2005) 117201.
- [14] W. Alayo, M.A. Sousa, F. Pelegrini, E. Baggio-Saitovitch, Journal of Applied Physics 109 (2011) 083917.
- [15] W. Alayo, E. Baggio-Saitovitch, Journal of Applied Physics 107 (2010) 073909.
- [16] W. Alayo, Y.T. Xing, E. Baggio-Saitovitch, Journal of Applied Physics 106 (2009) 113903.
- [17] Michael Farle, Reports on Progress in Physics 61 (1998) 755.
- [18] J. Lindner, K. Baberschke, Journal of Physics: Condensed Matter 15 (2003) R193.
- [19] Antony Ajana, Shiva Prasad, R. Krishnan, N. Venkataramani, M. Tessier, Journal of Applied Physics 91 (2002) 1444.
- [20] J.A. Romano, E.C. da Silva, L.F. Schelp, J.E. Schmidt, R. Meckenstock, J. Pelzl, Journal of Magnetism and Magnetic Materials 205 (1999) 161.
- [21] W. Alayo, E. Baggio-Saitovitch, F. Pelegrini, V.P. Nascimento, Physical Review B 78 (2008) 134417.
- [22] W. Alayo, Miguel Tafur, E. Baggio-Saitovitch, F. Pelegrini, V.P. Nascimento, Journal of Applied Physics 105 (2009) 093905.
- [23] L.G. Parrat, Physical Review 95 (1954) 359.
- [24] E.E. Fullerton, I.K. Schuller, H. Vanderstraeten, Y. Bruynseraede, Physical Review B 45 (1992) 9292.
- [25] V.F. Meshcheryakov, A.G. Vasil'ev, K.V. Timonin, I.A. Khorin, Crystallography Reports 47 (6) (2002) 1063–1071.
- [26] P. Bruno, Physical Review B 52 (1995) 411.
- [27] J. Dubowik, F. Stobiecki, T. Lucinski, Physical Review B 57 (1998) 5955.
- [28] J. Dubowik, K. Zaleski, H. Glowinski, Physical Review B 84 (2011) 184438.
- [29] Rodrigo Arias, D.L. Mills, Physical Review B 60 (1999) 7395.
- [30] R.C. Oliveira, R.L. Rodríguez-Suárez, et al., Journal of Magnetism and Magnetic Materials 272–276 (2004) e795–e796.
- [31] J. Lidner, I. Barsukov, C. Raeder, C. Hassel, O. Posth, R. Meckenstock, P. Landeros, D.L. Mills, Physical Review B 80 (2009) 224421.