AIP Journal of Applied Physics

Static and dynamic properties of Fibonacci multilayers

L. D. Machado, C. G. Bezerra, M. A. Correa, C. Chesman, J. E. Pearson, and A. Hoffmann

Citation: Journal of Applied Physics **113**, 17C102 (2013); doi: 10.1063/1.4794190
View online: http://dx.doi.org/10.1063/1.4794190
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/113/17?ver=pdfcov
Published by the AIP Publishing

Static and dynamic properties of Fibonacci multilayers

L. D. Machado,[1,2] C. G. Bezerra,[1,3,a)] M. A. Correa,[1] C. Chesman,[1,4] J. E. Pearson,[4] and A. Hoffmann[4]

[1]*Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, Natal-RN 59072-970, Brazil*
[2]*Departamento de Física Aplicada, Unicamp, Campinas-SP 13083-459, Brazil*
[3]*School of Physics, Trinity College Dublin, Dublin 2, Ireland*
[4]*Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

(Presented 18 January 2013; received 31 October 2012; accepted 28 November 2012; published online 6 March 2013)

We theoretically investigate static and dynamic properties of quasiperiodic magnetic multilayers. We considered identical ferromagnetic layers separated by non-magnetic spacers with two different thicknesses chosen based on the Fibonacci sequence. Using parameters for Fe/Cr, the minimum energy was determined and the equilibrium magnetization directions found were used to calculate magnetoresistance curves. Regarding dynamic behavior, ferromagnetic resonance (FMR) curves were calculated using an approximation known from the literature. Our numerical results illustrate the effects of quasiperiodicity on the static and dynamic properties of these structures. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4794190]

The discoveries of the antiferromagnetic bilinear coupling[1] and the so-called giant magnetoresistance effect (GMR)[2] in magnetic metallic multilayers have aroused a great interest from both the theoretical and experimental perspectives. One of the most important reasons is because the control of the electrical resistance, by the external magnetic field, in these systems, led to a large range of applications in information storage and magnetic sensors technology. For example, currently GMR effect has been applied in storage devices,[3] spin torque transfer (STT) based devices,[4] and biosensors.[5] It has been shown that magnetoresistance (M_R) varies linearly with the angular difference between adjacent magnetizations when electrons form a free-electron gas, i.e., there are no barriers between adjacent ferromagnetic films. In metallic systems, such as Fe/Cr, this angular dependence is valid and once the set $\{\theta_i\}$ of equilibrium angles is determined, we obtain normalized values for magnetoresistance,[6] i.e.,

$$M_R(H) = \frac{R(H)}{R(0)} = \frac{\sum_{i=1}^{N-1}[1-\cos(\theta_i - \theta_{i+1})]}{2(N-1)}, \qquad (1)$$

where $R(0)$ is the electric resistance at zero field and N is the number of ferromagnetic layers.

The effects of the quasiperiodic order in many different physical systems have been extensively studied. It has been shown that quasiperiodic stacking patterns have strong influence on the physical properties of layered systems (including the non-critical properties).[7] Furthermore, the recent developments in the experimental growth techniques allow the building of layered systems whose properties are subject to control and design. Considering this aspect, the physical properties of a new class of magnetic system, namely, quasiperiodic magnetic multilayers, became an attractive field of research.[8–12] For instance, a quasiperiodic stacking pattern in Fe/Cr magnetic multilayers induces new magnetic phases which would not be observed in a periodic arrangement. The consequences of these new phases are observed in the static[9] and dynamic properties[13] of these magnetic structures.

It is known from the literature that M_R usually monotonically decreases with the magnetic field. However, in a recent work on the magnetoresistance properties of Fe/Cr magnetic multilayers,[15] in which the Cr layers follow a Fibonacci sequence, it was observed a region where one can see a positive change of the magnetoresistance, i.e., a region where an increase in the magnetic field leads to a rise in magnetoresistance, that is, $\Delta M_R/\Delta H > 0$. The aim of this work is to push a little more the understanding of the effects of a quasiperiodic stacking pattern, of the non-magnetic spacers, on the dynamic properties by calculating ferromagnetic resonance (FMR) curves.

A quasiperiodic multilayer can be built by juxtaposing two building blocks (A, B) following a quasiperiodic sequence. The Fibonacci sequence is widely used, with building blocks transforming according to the following rule: $A \to AB$, $B \to A$. Therefore, the first Fibonacci sequence is $S_1 = A$, the second is $S_2 = AB$, the third is $S_3 = ABA$, and so on. In the present study, non-magnetic Cr layers, between ferromagnetic Fe layers, were chosen with thicknesses following the Fibonacci sequence. A is a Cr layer with thickness t_1 and B is a Cr layer with thickness t_2. For instance, the multilayer $Fe/Cr(t_1)/Fe/Cr(t_2)/Fe/Cr(t_1)/Fe$ corresponds to $Fe/A/Fe/B/Fe/A/Fe$.

We considered four energy terms in the magnetic energy: Zeeman energy (owing to interaction between the magnetization of the ferromagnetic films and the applied external magnetic field), [100] cubic anisotropy energy (due to interaction between the crystalline structure and electronic

[a)]Author to whom correspondence should be addressed. Electronic mail: cbezerra@dfte.ufrn.br.

spins), and two terms which couple the magnetization of Fe layers separated by Cr layers, namely, bilinear and biquadratic energies.[15] For the description of the dynamic properties, we must include two additional energy terms: dipolar and surface anisotropy energies. Considering all these energy terms, the total magnetic energy can be written as[13]

$$E_T = E_Z + E_{ca} + E_{bl} + E_{bq} + E_{sa} + E_{dip}. \quad (2)$$

Here, the subscripts denote Zeeman, cubic anisotropy, bilinear and biquadratic exchanges, surface anisotropy, and dipolar terms, respectively.

From now on, we follow the lines of Refs. 13 and 14. Our initial goal is to find the set $\{\theta_i\}$ of equilibrium angles, which is determined by the minima of the total magnetic energy. In the cases studied in this paper, these minima were found numerically using the gradient method, which takes into account the gradient of E_T in relation to the set $\{\theta_i\}$.

This approach has proven successful in interpreting magnetoresistance and magnetization data in magnetic multilayers,[9–11,15] and provides a self-consistent correlation between the static configuration and the dynamic response of the system, characterized by FMR dispersion relations, considered below.

The equation of motion for the magnetization of film i is written as

$$\frac{d\vec{M}_i}{dt} = \gamma \vec{M}_i \times \vec{H}^{(i)}_{eff}, \quad (3)$$

where $\gamma = g_i \mu_B/\hbar$ is the gyromagnetic ratio (2.8 GHz/kOe for $g = 2$) and $\vec{H}_{eff}$ is the effective field acting on $\vec{M}_i$. The relation between the effective field and the total energy is well known, being defined by

$$\vec{H}^{(i)}_{eff} = -\vec{\nabla}_{\vec{M}_i} E_T. \quad (4)$$

All fields and magnetizations are decomposed into a static part and a small-signal dynamic component. Since the spin-wave frequencies are determined by the linearized equations, we introduce convenient coordinate axes for each film in which the z-axis is along the magnetization equilibrium direction. The x and y components are then small-signal variables. Assuming the $\exp(i\omega t)$ time variation and retaining only terms to first order in small quantities, we obtain a set of $2N$ coupled equations, the solutions of which are found by requiring that the secular determinant vanishes. This leads to magnetic excitation frequencies which are given by the zeroes of the equation

$$\left(\frac{\omega}{\gamma}\right)^{2N} + \left[\sum_{k=0}^{N-1} \alpha_k \left(\frac{\omega}{\gamma}\right)^{2(N-1-k)}\right] = 0. \quad (5)$$

The coefficients α_k are given by lengthy expressions involving the magnetic multilayer parameters, the equilibrium angles, and the external field.[13] For any given applied field, Eq. (5) presents N real solutions, corresponding to the spin-wave modes.

In the following numerical applications, we performed calculations for two different values of spacer thickness corresponding to two sets of exchange fields, namely,

1. $t = 1.5$ nm for which $H_{bq} = 0.3|H_{bl}|$ with $H_{bl} = -0.15$ kOe;
2. $t = 3.0$ nm for which $H_{bq} = |H_{bl}|$ with $H_{bl} = -0.035$ kOe.

We selected the first set of parameters for Cr films associated with A letters of the quasiperiodic sequence and the second set of parameters for Cr films associated with B letters of the quasiperiodic sequence. For both sets, we considered the [100] cubic anisotropy field $H_{ca} = 0.5$ kOe, the surface anisotropy field $H_{sa} = 2.0$ kOe, $4\pi M = 20.0$ kG and the thicknesses of Fe layers are fixed and equal to 4.5 nm. Additional information about the structural parameters of Fe/Cr multilayers can be found elsewhere.[14] In Fig. 1, we show the magnetoresistance for magnetic multilayers whose Cr layers follow the third ($S_3 = ABA$) and fourth ($S_4 = ABAAB$) Fibonacci generations, which means 4 ($Fe/A/Fe/B/Fe/A/Fe$) and 6 ($Fe/A/Fe/B/Fe/A/Fe/A/Fe/B/Fe$) Fe films, respectively. Because of the strong biquadratic field (compared to the bilinear one) and cubic anisotropy, all transitions are of first order type, characterized by discontinuous jumps in the magnetoresistance. We can also note a clear self-similar pattern of the magnetoresistance, by comparing Figs. 1(a) and 1(b),

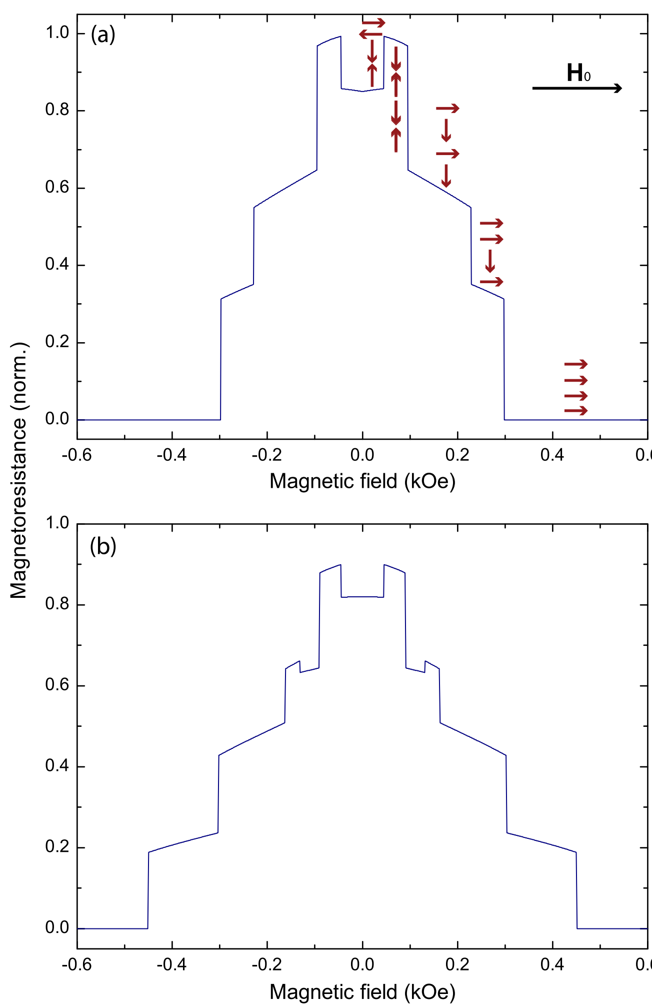

FIG. 1. Normalized magnetoresistance curves for the (a) third ($Fe/A/Fe/B/Fe/A/Fe$) and (b) fourth ($Fe/A/Fe/B/Fe/A/Fe/A/Fe/B/Fe$) Fibonacci generations.

which is the basic signature of a quasiperiodic system. However, in the low-magnetic-field region, one can see a much more interesting feature of these multilayers: Fig. 1 shows, for both third and fourth Fibonacci generations, regions in which is observed a positive change of the magnetoresistance. In those regions, an increase in the magnetic field leads to a rise in magnetoresistance, that is, $\Delta M_R/\Delta H > 0$. As discussed in a previous work,[15] this unusual behavior is a direct consequence of the quasiperiodic distribution of the Cr layers in the magnetic multilayer structure.

Let us now present numerical results for the FMR dispersion relation. Fig. 2 shows the spin wave spectra for the third and fourth Fibonacci generations. We plotted the frequency shift (in GHz) against the external magnetic field (in kOe). The number of spin wave modes is associated with the number of ferromagnetic layers. Therefore, we have four modes for the third Fibonacci generation. Once the dynamic response is correlated to the static response, the dispersions shown in Fig. 2 reflect the magnetic phases presented by the magnetic multilayer. For example, the bottom curve in Fig. 2(a) represents the acoustic mode and it clearly shows five distinct regions of dispersion, corresponding to the five magnetic phases observed in Fig. 1(a), with the same transition fields. The saturation is reached at $H \sim 300$ Oe. Fig. 2(b) presents the FMR dispersion relation for the fourth Fibonacci generation. One can see 6 spin waves modes and, as for the third Fibonacci generation, various phase transitions are observed. Although the numerical results for the fourth generation are similar to the previous numerical results for the third generation, the number of spin wave modes for this case makes difficult a direct physical interpretation. The saturation is reached at $H \sim 450$ Oe.

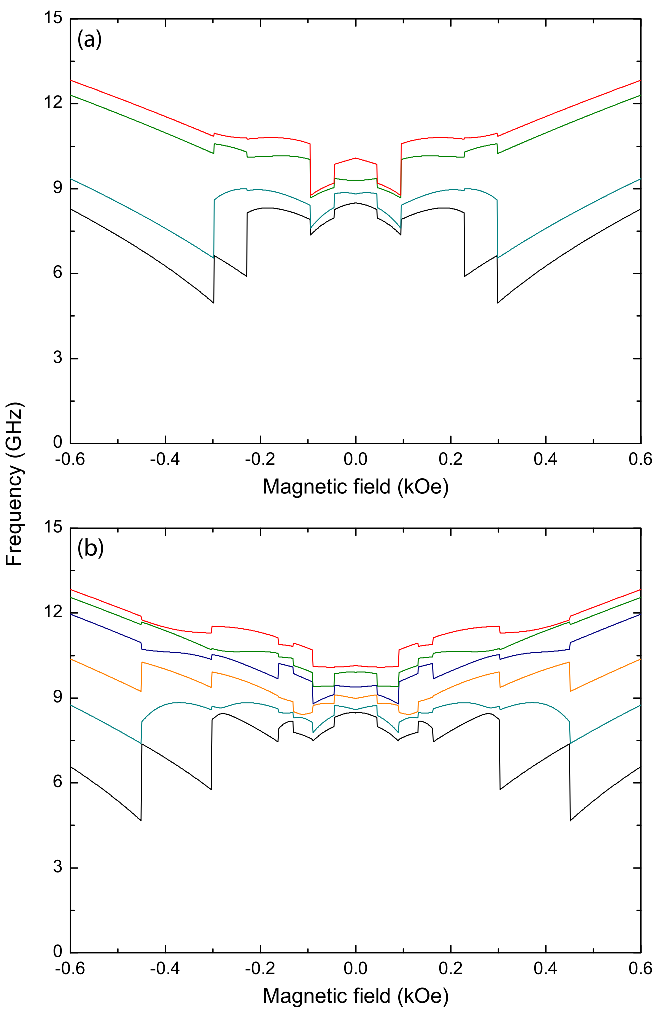

FIG. 2. FMR dispersion relation curves for the (a) third (*Fe*/*A*/*Fe*/*B*/*Fe*/*A*/*Fe*) and (b) fourth (*Fe*/*A*/*Fe*/*B*/*Fe*/*A*/*Fe*/*A*/*Fe*/*B*/*Fe*) Fibonacci generations.

In conclusion, we have presented in this work a theory to deal with static and dynamic properties of quasiperiodic magnetic multilayers composed by identical ferromagnetic layers separated by non-magnetic layers with two different thicknesses chosen based on the Fibonacci sequence. Using parameters for Fe/Cr multilayers, our theory takes full account of Zeeman, cubic anisotropy, bilinear and biquadratic couplings, dipolar and surface anisotropy. We present analytical expressions for magnetoresistance and FMR dispersion relation generalizing any Fibonacci generation number. Finally, we believe that the new features related here may open new possibilities of future applications in M_R sensors and devices, since the positive jumps, in sharp magnetic field values, can be used in logic devices with more than two logic states.

We would like to thank the Brazilian Research Agencies CNPq, FINEP, FAPERN, and FAPESP for the financial support. Work at Argonne was supported by the US Department of Energy, Basic Energy Sciences under Contract No. DE-AC02-06CH1135. CGB acknowledges financial support from CAPES (Grant No 10144-12-9).

[1]P. Grünberg, R. Schreiber, Y. Pang, M. B. Brodsky, and H. Sowers, Phys. Rev. Lett. **57**, 2442 (1986).
[2]M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988); G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989).
[3]G. A. Prinz, Science **282**, 1660 (1998); J. C. S. Kools, IEEE Trans. Magn. **32**, 3165 (1996).
[4]M. D. Stiles and A. Zangwill, Phys. Rev. B **66**, 014407 (2002); Y. Lakys, W. S. Zhao, T. Devolder, Y. Zhang, J. O. Klein, D. Ravelosona, and C. Chappert, IEEE Trans. Magn. **48**, 2403 (2012).
[5]R. C. Chaves, S. Cardoso, R. Ferreira, and P. P. Freitas, J. Appl. Phys **109**, 07E506 (2011).
[6]A. Vedyayev, B. Dieny, N. Ryzhanova, J. B. Genin, and C. Cowache, Europhys. Lett. **25**, 465 (1994).
[7]E. L. Albuquerque and M. G. Cottam, *Polaritons in Periodic and Quasiperiodic Structures* (Elsevier, Amsterdam, 2004).
[8]C. G. Bezerra and E. L. Albuquerque, Physica A **245**, 379 (1997).
[9]C. G. Bezerra, J. M. de Araujo, C. Chesman, and E. L. Albuquerque, Phys. Rev. B **60**, 9264 (1999).
[10]C. G. Bezerra, J. M. de Araujo, C. Chesman, and E. L. Albuquerque, J. Appl. Phys. **89**, 2286 (2001).
[11]C. G. Bezerra and M. G. Cottam, J. Magn. Magn. Mater. **240**, 529 (2002).
[12]C. G. Bezerra and M. G. Cottam, Phys. Rev. B **65**, 054412 (2002).
[13]P. W. Mauriz, E. L. Albuquerque, and C. G. Bezerra, J. Phys.: Condens. Matter **14**, 1785 (2002).
[14]E. E. Fullerton, M. J. Conover, J. E. Mattson, C. H. Sowers, and S. D. Bader, Phys. Rev. B **48**, 15755 (1993).
[15]L. D. Machado, C. G. Bezerra, M. A. Correa, C. Chesman, J. E. Pearson, and A. Hoffmann, Phys. Rev. B **85**, 224416 (2012).