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Magnetoresistance profiles of quasiperiodic Fe/Cr structures

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Abstract

We study theoretically the magnetoresistance properties of magnetic films (Fe/Cr) grown following the Fibonacci sequence. We use a theoretical Hamiltonian which includes Zeeman, cubic and uniaxial anisotropy, bilinear and biquadratic exchange energies. In particular, the presence of the uniaxial anisotropy in the Hamiltonian gives new symmetries to the system which were not discussed in previous works. Our physical parameters are based on experimental data recently reported, which contain biquadratic exchange coupling with magnitude comparable to the bilinear exchange coupling. We show the influence of the biquadratic exchange and anisotropies on the self-similar properties of the magnetoresistance profiles.

Keywords: Semi-empirical models and model calculations; Iron; Chromium; Magnetic films; Metal–metal magnetic thin film structures

The discovery of quasicrystals in 1984 [1] aroused a great interest, both theoretically and experimentally, in quasiperiodic systems. One of the most important reasons for that is because they can be defined as an intermediate state between an *ordered* crystal (their definition and construction follow purely deterministic rules) and a *disordered* solid (many of their physical properties exhibit an erratic-like appearance) [2]. On the theoretical side, a wide variety of particles, namely electrons [3], phonons [4], polaritons [5], spin waves [6], etc. have been and are currently being studied. A quite complex *fractal energy spectrum*, which can be considered as their basic signature, is a common feature of these systems. On the experimental side, the procedure to grow quasiperiodic superlattices became standard after Merlin et al. [7], who reported the realization of the first quasiperiodic superlattice following the Fibonacci sequence by means of molecular beam epitaxy (MBE).

Parallel to these developments in the field of quasicrystals, the properties of magnetic exchange interactions between ferromagnetic films separated by non-magnetic spacers have been also widely investigated [8]. In these magnetic structures, the interfilm couplings are very weak when compared to the strong exchange coupling between spins in a given ferromagnetic film. Thus, this system can be modeled by representing each ferromagnetic film as a spin with a classical magnetization $\vec{M}$, formed by the spins within the film. These classical spins interact through the interfilm exchange couplings and can also experience some anisotropy. The discovery of physical properties like antiferromagnetic coupling [9], giant magnetoresistance (GMR) [10], oscillatory behavior of the exchange

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coupling [11], and biquadratic exchange coupling [12], made these films attractive objects of research.

Recent theoretical studies [13], applied to Fe/Cr Fibonacci multilayers, showed that a self-similar behavior of the magnetic properties occur when the biquadratic and bilinear exchanges are comparable and there are first order phase transitions induced by the external magnetic field. In those articles the authors included effects of a cubic anisotropy. However, some magnetic multilayers may instead exhibit uniaxial anisotropy [14], and this gives a new symmetry to the system that may lead to new configurations and phase transitions. In fact, Bezerra and Cottam [15] very recently found a self-similar magnetization curve in Fe/Cr Fibonacci multilayers presenting uniaxial anisotropy even when the biquadratic coupling is small compared to the bilinear one. They surmized that the lower symmetry of the uniaxial anisotropy changes the nature of the phase transitions and consequently the conditions for a self-similar pattern to occur in the magnetization curves. Therefore, an analogous behavior may also apply for the transport properties of the system.

The study of GMR properties in magnetic multilayers has attracted a lot of attention due to their potential for technological applications. For example, the GMR in magnetic multilayers has been widely considered for applications in information storage technology [16]. On the other hand, a self-similar magnetoresistance, due to the presence of a quasiperiodic arrangement of the system, can open new possibilities in reading/writting magnetic sensors [13]. The aim of this work is to investigate the influence of the anisotropy (cubic or uniaxial) on the self-similar pattern of the magnetoresistance curves of Fe/Cr Fibonacci multilayers.

Let us now briefly describe a Fibonacci structure. In order to construct a Fibonacci magnetic multilayer we juxtapose two building blocks (or layers) A and B following a Fibonacci sequence. In our specific case we choose Fe as the building block A, with thickness t, and Cr as the building block B (thickness d). A Fibonacci sequence S_N is generated by appending the $N-2$ sequence to the $N-1$ one, i.e., $S_N = S_{N-1}S_{N-2}$ ($N \geqslant 2$). This construction algorithm requires initial conditions which are chosen to be $S_0 = B$ and $S_1 = A$. Thus, for example, the well known trilayer Fe/Cr/Fe is the magnetic counterpart of the third Fibonacci generation sequence $S_3 = A/B/A$ and the magnetic counterpart for the fifth Fibonacci generation sequence $S_5 = A/B/A/A/B/A/B/A$ is Fe/Cr/Fe/Fe/Cr/Fe/Cr/Fe, respectively. We remark that only odd Fibonacci generations have a magnetic counterpart because they start and finish with an A (Fe) building block.

We consider the ferromagnetic films with magnetization in the xy-plane and take the z-axis as the growth direction. The very strong demagnetization field generates by tipping the magnetization out of plane will suppress any tendency for the magnetization to tilt out of plane. The global behavior of the system is well described by a simple theory in terms of the magnetic energy per unit area [17], i.e.:

$$E_{\mathrm{T}} = E_{\mathrm{Z}} + E_{\mathrm{bl}} + E_{\mathrm{bq}} + E_{\mathrm{a}}, \tag{1}$$

where E_{Z} is the Zeeman energy, E_{bl} is the bilinear energy, E_{bq} is the biquadratic energy and E_{a} is the anisotropy energy, which can be cubic or uniaxial. More explicitly, for n magnetic films we have,

$$\begin{aligned} \frac{E_{\mathrm{T}}}{tM} = {} & \sum_{i=1}^{n} (t_i/t)\{-H_0 \cos(\theta_i - \theta_H) + E_{\mathrm{a}}\} \\ & + \sum_{i=1}^{n-1} \{-H_{\mathrm{bl}} \cos(\theta_i - \theta_{i+1}) \\ & + H_{\mathrm{bq}} \cos^2(\theta_i - \theta_{i+1})\}, \end{aligned} \tag{2}$$

where t and M are the thickness and the saturation magnetization of a single Fe layer (the basic tile). Also, H_{bl} is the conventional bilinear exchange coupling field which favors antiferromagnetic alignment (ferromagnetic alignment) if negative (positive). We are concerned here to the case $H_{\mathrm{bl}} < 0$ because magnetoresistive effects occur only for this case. The biquadratic exchange coupling H_{bq} is responsible for a 90° alignment between two adjacent magnetizations and is experimentally found to be positive [12]. We consider H_0 as an external in-plane magnetic field and θ_H is its angular orientation. From now on we take $\theta_H = 0$ which means that the magnetic field is applied along the easy axis. The thickness and the angular orientation of the ith Fe layer are given by t_i and θ_i, respectively. The explicit form for the anisotropy energy E_a be uniaxial is,

$$E_a = -\sum_{i=1}^{n} (t_i/t)\frac{H_{ua}}{2}\cos^2(\theta_i - \theta_{ua}). \quad (3)$$

For cubic anisotropy energy E_a, we have:

$$E_a = \sum_{i=1}^{n} (t_i/t) H_{ca} \sin^2(2\theta_i). \quad (4)$$

From a theoretical point of view, the spin-dependent scattering is accepted as responsible for the GMR effect [18]. It has been shown that GMR varies linearly with $\cos(\Delta\theta)$, when electrons form a free-electrons gas (there is no barriers between adjacent films) [19]. Here $\Delta\theta$ is the angular difference between adjacent magnetizations. In metallic systems like Fe/Cr, this angular dependence is valid and thus we ought to determine the set $\{\theta_i\}$ of equilibrium angles in order to obtain normalized values for magnetoresistance from [13],

$$\frac{R(H_0)}{R(0)} = \sum_{i=1}^{n-1} \frac{1-\cos(\theta_i - \theta_{i+1})}{2(n-1)}, \quad (5)$$

where $R(0)$ is the resistance at zero field.

The set $\{\theta\}_i$ of equilibrium angles is calculated numerically by minimizing the magnetic energy given by Eq. (2). For that purpose we use two methods, namely, the simulated annealing and the gradient methods (see [13] for descriptions). The simulated annealing method is based on the fact that heating and then cooling a material slowly brings it into a more uniform state, which is the minimum energy state. In this process, the role played by a pseudo temperature T is to allow the configurations to reach higher energy states with probability p given by the Boltzmann law $p = \exp(-\Delta E/kT)$, where ΔE is the energy difference. Energy barriers, that would otherwise force the configurations into local minima, can then be overcome. On the other hand, the gradient method is based on finding the directional derivative of the magnetic energy in the search for its global minimum in the n-dimensional space composed of the variables $\{\theta\}_i$. It is the gradient of the magnetic energy with relation to the angles that provides the direction, and eventually the location, of the required global minimum. Both cited methods are used for each value of the applied magnetic field and for each set of magnetic parameters. We choose the configuration with the lowest energy provided by both methods as giving the equilibrium configuration $\{\theta\}_i$.

Now we present numerical calculations for the magnetoresistance curves for Fibonacci multilayers. We assume two specific situations: (i) the system presents a *cubic anisotropy* energy [20] and (ii) the system presents a *uniaxial anisotropy* energy (that for simplicity we consider $\theta_{ua} = 0$) [14]. We chose the biquadratic and bilinear fields, H_{bq} and H_{bl}, in such a way that the absolute value of their ratio $r = H_{bq}/|H_{bl}|$ is between zero and the unit.

Magnetoresistance curves found for the (a) third, (b) fifth and (c) seventh Fibonacci generations are shown in Fig. 1. We assumed $r \sim 0.33$ and a cubic anisotropy field $H_{ca} = 0.5$ kOe (see [13,17]). For $N = 3$ one can see two first order phase transitions at $H_1 \sim 100$ Oe and $H_2 \sim 220$ Oe. There are three magnetic phases: (i) antiferromagnetic ($H_0 < 100$ Oe); (ii) 90° phase ($100 < H_0 < 220$ Oe); and (iii) saturated phase ($H_0 > 220$ Oe). $N = 5$ presents four first order phase transitions at $H_1 \sim 100$ Oe, $H_2 \sim 150$ Oe, $H_3 \sim 220$ Oe, and $H_4 \sim 440$ Oe. Five magnetic phases are present: (i) antiferromagnetic phase ($H_0 < 100$ Oe); (ii) almost antiferromagnetic phase ($100 < H_0 < 150$ Oe); (iii) 90° phase ($150 < H_0 < 220$ Oe); (iv) almost saturated phase ($220 < H_0 < 440$ Oe); and (v) saturated phase ($H_0 > 440$ Oe). For $N = 7$ there are nine first order phase transitions between $H_1 \sim 40$ Oe and $H_8 \sim 440$ Oe. Eight magnetic phases are present from the antiferromagnetic phase ($H_0 < 40$ Oe) to the saturated one ($H_0 > 440$ Oe). Our numerical results recover the results of Ref. [13] and they show a beautiful *self-similar pattern* of the magnetoresistance curves which is associated with the strong value of the biquadratic coupling [13].

In Fig. 2 we show the magnetoresistance curves for the (a) third, (b) fifth and (c) seventh Fibonacci generations with $r \sim 0.1$ and a uniaxial anisotropy field $H_{ua} = 0.5$ kOe (see [14,15]). For $N = 3$, as before, the magnetizations in adjacent layers are

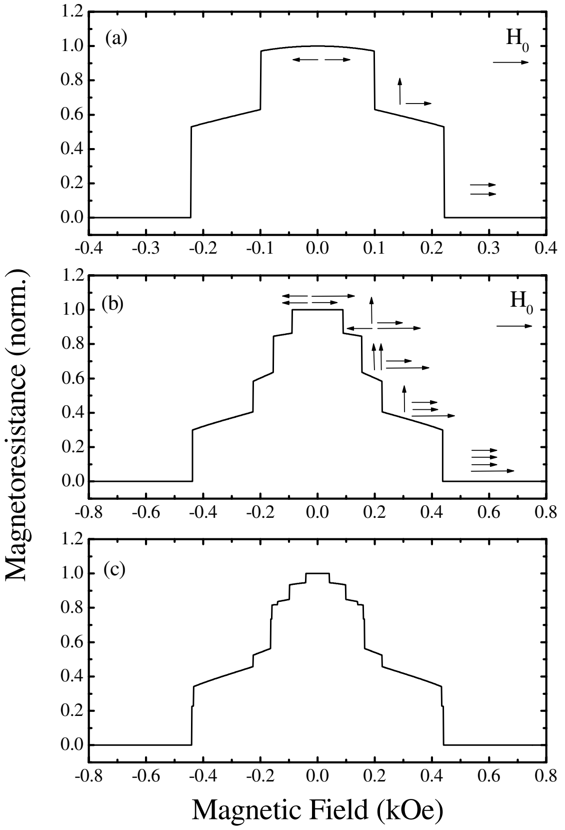

Fig. 1. Magnetoresistance versus applied field H_0 for the (a) $N = 3$, (b) $N = 5$ and (c) $N = 7$ Fibonacci generations. The parameters are $r \sim 0.33$ and a cubic anisotropy field $H_{ca} = 0.5$ kOe.

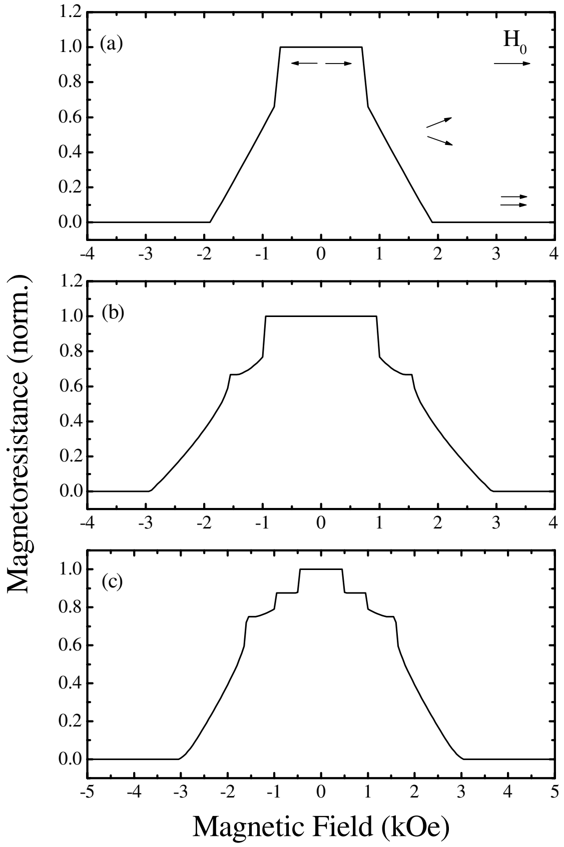

Fig. 2. As in Fig. 1 with physical parameters $r \sim 0.1$ and a uniaxial anisotropy field $H_{ua} = 0.5$ kOe.

antiparallel at low fields (antiferromagnetic phase). As the external magnetic field increases, a first order phase transition occurs (at ~0.8 kOe) and a spin-flop phase emerges [15]. The saturated phase is reached at $H_0 \sim 1.9$ kOe. For $N = 5$, there are four magnetic phases from antiferromagnetic phase ($H_0 < 1.0$ kOe) to the saturated one ($H_0 > 2.9$ kOe). There are first order phase transitions at $H_0 \sim 1.0$ kOe and $H_0 \sim 1.6$ kOe. When $N = 7$ there are three first order phase transitions at $H_0 \sim 0.5$, 1.0 and 1.6 kOe. Five magnetic phases are present from antiferromagnetic phase ($H_0 < 0.5$ kOe) to the saturated one ($H_0 > 3.0$ kOe). Although the biquadratic field is weak when compared to the bilinear one ($r \sim 0.1$) a *self-similar pattern* is again present in the curves.

Another set of magnetoresistance curves is shown in Fig. 3, taking a larger biquadratic exchange ($r \sim 0.7$) and other parameters as in Fig. 2. For $N = 3$, due to the strong H_{bq} the adjacent layer magnetizations are only approximately antiparallel at low field (corresponding to an asymmetric phase [15]). A first order phase transition occurs at $H_0 \sim 0.4$ kOe to a spin-flop phase and saturation is reached at $H_0 \sim 4.3$ kOe. For $N = 5$ all transitions appear continuous (second order phase transitions) and saturation is reached at $H_0 \sim 6.4$ kOe. For $N = 7$ there appears to be a first order phase transition at $H_0 \sim 0.15$ kOe and saturation is reached at $H_0 \sim 6.6$ kOe. For this set of parameters, although there is a strong biquadratic field, there is no *self-similar pattern* at all! One can

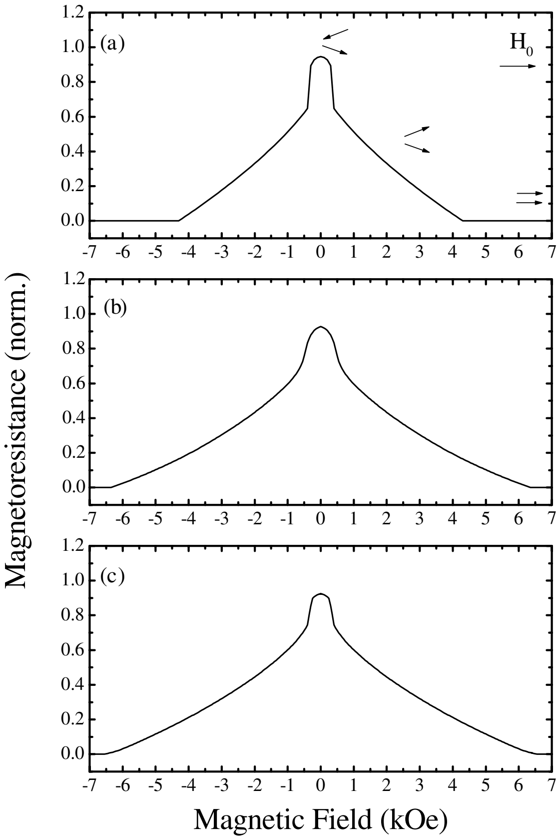

Fig. 3. As in Fig. 2 but for $r \sim 0.7$.

conclude that the presence of the uniaxial anisotropy changes the nature of the phase transitions. Moreover, it means that the presence of first order phase transitions is a necessary condition for a self-similar pattern in the observable of these quasiperiodic multilayers.

In conclusion, we have modeled the magnetoresistance versus applied field curves of Fe/Cr Fibonacci multilayers including both bilinear and biquadratic exchange couplings. The role of cubic and uniaxial anisotropies is studied. One can see a self-similar pattern in the system when most transitions are of the first order type. Specifically, the magnetoresistance curves of higher generation N reproduce some aspects of the magnetoresistance curves of lower generation $N-2$. By contrast, when most of the transitions are second order type, there is no apparent self-similarity. We can conclude that the lower symmetry of uniaxial anisotropy changes the nature of the phase transitions and consequently the conditions for a self-similar pattern to occur in the magnetoresistance curves.

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