Magnetic microwires as macrospins in a long-range dipole-dipole interaction

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The long-range dipole-dipole interaction in an array of ferromagnetic microwires is studied through magnetic hysteresis measurements and Monte Carlo simulation. The experimental study has been performed on glass-coated amorphous $Fe_{77.5}Si_{7.5}B_{15}$ microwire with diameter of 5 μm and lengths from 5 to 60 mm. Hysteresis loops performed at room temperature for an array of N microwires ($N=2$, 3, 4, and 5) exhibit jumps and plateaux on the demagnetization, each step correspondent to the magnetization reversal of an individual wire. A model has been constructed taking into account the fact that the magnetization reversal is nucleated at the ends of each wire, under the influence of a dipolar field due to all other wires. Measurements for two wires allowed us to conclude that the dipolar field (or constant coupling) is independent of distance, at least for an array of a few wires. With the exception of three wires, where frustration seems to be present, the predicted reversal fields of our model are in good agreement with measurements. In order to study the role played by the number of wires on the demagnetization process, we calculate hysteresis loops for a large number of wires through the Monte Carlo method.

I. INTRODUCTION

Long-range interactions are very common in nature in a wide range of sizes, varying from astrophysical to atomic scales. In condensed matter physics, one of the more remarkable manifestations of long-range interactions is in magnetism. Interactions among magnetic entities are the core of basic and applied studies of modern magnetic materials. For instance, in magnetic materials the long-range dipolar interactions can play a fundamental role in the magnetic properties, being responsible for the formation of certain domain structures and the dynamics of magnetization reversal processes. In addition, advances in fabrication techniques (including lithography) have given rise to the possibility of producing nanostructured solids with especially interesting physical properties. In particular, it is possible to obtain controlled arrays of magnetic wires with diameters of a few nanometers, which are of practical interest in the design and optimization of magnetoresistive heads for ultrahigh-density data storage applications. In such systems the contribution of the dipole-dipole interaction on the magnetic properties becomes yet more relevant, because long-range interactions can strongly modify the magnetic response of the system to an external excitation.

Although an array composed of a few ferromagnetic wires could in principle seem a quite simple problem to study and model, it is striking to notice how complex this problem can turn out to be. Some recent investigations have dealt with the dynamics of magnetization processes, which can include localized excitations and/or collective modes, independent of the parity of the system,[1] weak chaotic behavior,[2] and even the possibility to tailor the value of the coercivity, in the case of nanoscopic flat wires.[3] The complication in the study of dipolar interactions is that the magnetic fields resulting from the interaction depend on the magnetization state of each entity, which, in turn, depend on the effective field of neighboring elements. In spin systems the long-range character of a dipole-dipole interaction is an inherent difficulty to solve the Hamiltonians due to the large number of neighbors that one has to take into account in calculations. Several works have been made using Monte Carlo simulations calculating the magnetic domain structure and magnetic hysteresis including the dipolar interaction term in the Ising or Heisenberg Hamiltonian.[4,5]

An intrinsic difficulty in the study of magnetic interactions is the fact that it is extremely difficult to characterize a single magnetic element using most conventional magnetometry techniques. Also, the predictions of numerical simulations are intricate to compare with real systems, owing to the necessity to introduce several approximations in the modeled problem. However, in this work we make use of a convenient macroscopic configuration, placing together several ferromagnetic microwires covered with glass. Such microwires exhibit a strong magnetic anisotropy with an easy magnetization direction along the axis of the wire with a main single domain practically extending along the whole wire. This fact will allow us to consider each one of such microwires as a elemental magnetic moment. The stray fields created by the microwires couple the magnetization of the neighboring wires, affecting the magnetic state of each single

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wire. This system is relatively easy to study both experimentally and theoretically, and, in the case of few wires it is possible to obtain analytical solutions. Some interesting aspects of the long-range character of dipole-dipole interaction and their influences on the magnetic properties appear clearly in the obtained results. The exact solutions and experimental data can be compared with Monte Carlo simulations, which are necessary to employ when the array is formed by a large number of wires. As mentioned before, although this arrangement seems to be rather simple, it displays a variety of interesting aspects which certainly would apply in other physical systems.

II. EXPERIMENTAL DETAILS AND MEASUREMENTS

Concerning the experimental measurements, they have been performed in glass-coated amorphous microwires with nominal composition $Fe_{77.5}Si_{7.5}B_{15}$, diameter of 5 μm, and the thickness of the glass coating of 7.5 μm. Glass-coated amorphous microwires are presently attracting an increasing interest from both basic and applied points of view (for reviews see Ref. 6). Their metallic core, being structurally amorphous and with typical diameter from 1 to 30 μm, is covered by an insulating Pyrex-like coating with thickness between 1 and 20 μm. They are fabricated by means of Taylor-Ulitovsky technique by which the molten metallic alloy and its glassy coating are rapidly quenched and drawn to a kind of composite microwire typically a few kilometers long. This family of microwires displays quite remarkable magnetic properties, that together with their tiny dimensions and the protective coating make them potential candidates for many sensor applications.[7]

Owing to the amorphous nature of such microwires, their unique magnetic behavior depends on the strength and the distribution of magnetoelastic anisotropy. That is first determined by the magnetostriction constant, which is mainly a function of composition.[8] For the present alloy composition the saturation magnetostriction takes a value of 2×10^{-5}. In turn, the internal stresses (as strong as 10^3 MPa) depend on the ratio cover thickness to core diameter, which is controlled by the fabrication parameters, and also on particular processing as thermal treatments and chemical etching of the coating.[8] When axially magnetized these wires exhibit low-field square hysteresis loops with a single and large Barkhausen jump.

We have measured magnetic hysteresis loops in arrays of N microwires ($1\leq N\leq5$) placed side by side, all parallel, each one touching its nearest neighbors. Their lengths vary from 5 to 60 mm, cut from a single long microwire. We performed the measurements by using either a superconducting quantum interference device (SQUID) magnetometer (Quantum Design, MPMS XL model) or a very sensitive magnetic-flux integrator. Essentially, the difference in these two systems is the sensitivity and the time of measurement. Although the hysteresis loops measured in the SQUID do not exhibit either noise or drift, which appear in the flux-integrator, a single hysteresis measurement can take a few hours in the SQUID, while the same loop in the flux-integrator takes about 1 min. The flux-integrator was used for rapid measurements, for instance, to measure the distribution of reversal field values. We will focus our attention on

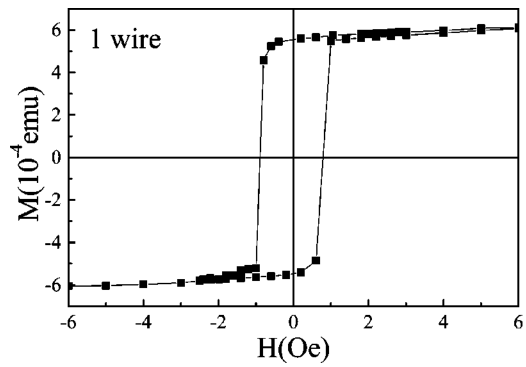

FIG. 1. Hysteresis loop for one microwire at room temperature. The reversal field is -0.89 Oe for negative reversal field and 0.79 Oe for positive reversal field. The coercive field is defined as the mean value, $|H_C|=0.85$ Oe.

measurements performed at room temperature, but also several loops were performed at low temperatures $[4\leq T(\mathrm{K})\leq300]$, in several attempts to strengthen the interactions among the wires. However, at low temperatures there is a change in the domain structure of the microwires, probably owing to the increasing internal stresses induced by the different thermal expansion coefficients of the ferromagnetic alloy and the covering glass. Therefore, the loops which are rather square at room temperature turn out to lose this property at low temperatures. This characteristic has been also reported for Co-based microwires.[9]

In the case of one 5 mm long wire ($N=1$, see Fig. 1) the hysteresis curve exhibits a typical square loop, with characteristic large Barkhausen jumps. The observation of such square loops, labeled as magnetic bistability, has been interpreted as in the case of in-water-quenched wires, considering the remagnetization processes of the inner core between two stable remanence states.[10] That internal core mainly consists of a single axial domain, but at the ends of the wire a closure domain structure appears at finite applied fields to reduce the otherwise quite high magnetostatic energy. Of course, for very short microwires closure structures coming from both ends overlap at the middle of the sample, destroying the magnetic bistability.[11] The critical length to observe bistability in the microwires of the present study is less than 5 mm. Nevertheless, in spite of the existence of these closure structures some stray field is generated in the surroundings of the microwire. Upon application of reversed field a domain wall depins from one end of the wire and propagates along the wire resulting in the observed magnetization jump.

Small differences in the measured coercive fields (H_C) were detected when the magnetic field was applied along positive or negative directions (in Fig. 1 the H_C values correspond to -0.89 and 0.79 Oe, respectively). There can be several origins for the fluctuation of H_C values. When different samples are investigated, the fluctuation in H_C is probably due to different magnetoelastic anisotropies induced in the wire ends during the cutting process, which can generate different levels of mechanical stresses. Since the nucleation of a domain wall starts in defects located at the extremities of the wires, and the number and strength of these defects depend on the cutting, the switching field of one wire can be slightly different for magnetic fields applied in opposite directions, and it can also vary in different samples. We have

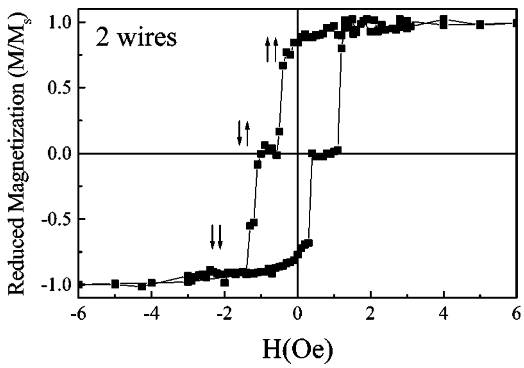

FIG. 2. Hysteresis loop for two microwires at room temperature. The mean reversal fields on the demagnetization are $H_2^i = -0.43$ Oe and $H_2^{ii} = -1.11$ Oe. The magnetization is normalized to the saturation value. The arrows represent the magnetic configuration of the wires.

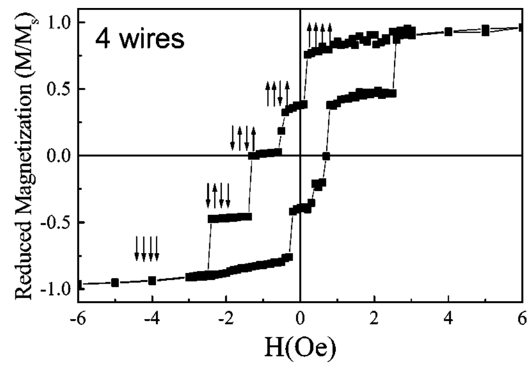

FIG. 4. Hysteresis loop for four microwires at room temperature. The magnetization is normalized to the saturation value. The arrows represent the magnetic configuration of the wires.

investigated this fluctuation in several samples, and we have found a maximum variation in H_C of about 0.10 Oe. Another distribution in the H_C values arises from thermal fluctuations, and it occurs even when the same sample is measured several times. To determine this distribution, we measured H_C several times in the same sample and with the field applied in the same direction, and it was found that the width of this distribution is around 0.03 Oe. However, we cannot exclude that this intrinsic fluctuation of the reversal field can arise simply from the fact that after each reversal the closure domain structures cannot be exactly the same, thus introducing a fluctuation in the next magnetization reversal. From the above discussions we consider the absolute value of H_C of this microwire as the mean value obtained from many different measurements, $H_C = 0.85$ Oe.

Let us now consider two wires (5 mm long) placed side by side with their axes parallel. In this case the distance between their axes is twice the thickness of the coating plus twice the radius of the ferromagnetic core, i.e., around 20 μm. The corresponding hysteresis loops exhibit two clear Barkhausen jumps steps and a plateau nearly at zero magnetization (see Fig. 2). This plateau corresponds to the configuration of two wires with opposite magnetization directions. It is worth noting that the first jump occurs at magnetic fields lower than H_C, while the second one occurs for fields larger than H_C. These reversal fields will be named H_2^i and H_2^{ii}, and their values are 0.38 and 1.10 Oe, respectively, for positive demagnetizing field. For negative demagnetizing field the values of H_2^i and H_2^{ii} were found to be -0.49 and -1.12 Oe, respectively. As will be shown below, the splitting of the H_C in two reversal fields has its origin in the dipole-dipole interaction between the wires. Varying the number of wires, the hysteresis loops exhibit several steps on the demagnetization (see Figs. 2–5), each one corresponding to the reversal of the magnetization of a single wire. As observed, the number of jumps equals the number of wires with the exception of the particular case of 3 wires.

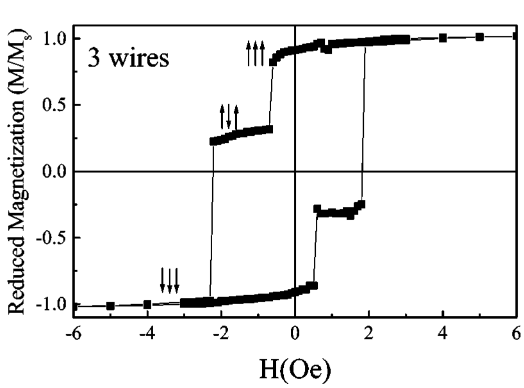

FIG. 3. Hysteresis loop for three microwires at room temperature. Note that the second step does not appear. The magnetization is normalized to the saturation value. The arrows represent the magnetic configuration of the wires.

III. MODEL AND DISCUSSIONS

In order to understand the existence of jumps and plateaux in the demagnetization curves, let us initially consider the simplest arrangement: two parallel magnetic wires in the presence of a positive and saturating magnetic field applied parallel to the axis of wires. Such a situation yields the magnetization of both wires and the applied field to stay parallel, pointing in the same direction. Notice that beyond the applied magnetic field (H) each wire feels the influence of a dipolar field ($H_{i,j}$) due to the presence of the other wire, where $H_{i,j}$ is the field of the wire i over the wire j. This dipolar field $H_{i,j}$ is given by[2]

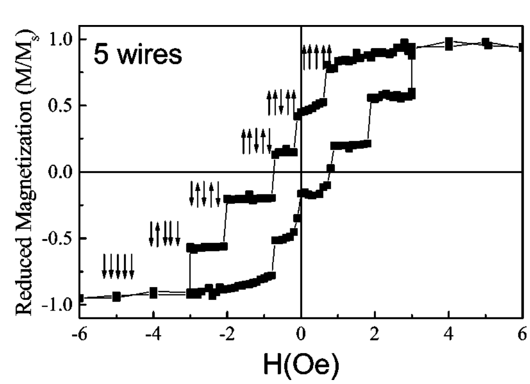

FIG. 5. Hysteresis loop for five microwires at room temperature. The magnetization is normalized to the saturation value. The arrows represent the magnetic configuration of the wires.

$$\mathbf{H}_{i,j} = -K_n \mathbf{M}_i , \tag{1}$$

where K_n is a geometric factor and $\mathbf{M}_i$ is the magnetization of the ith wire. As the coefficient K_n depends in principle on the distance between interacting wires, the subscipt n denotes the distance between the wires, K_1 corresponds to nearest neighbors, K_2 to second neighbors, and so on. Thus, for two wires one can easily write down the mutual dependence produced by the dipole-dipole interaction through the functions $M_1 = M_1(H + H_{2,1})$ and $M_2 = M_2(H + H_{1,2})$ with $\mathbf{H}_{i,j} = -K_n \mathbf{M}_i$.

Applying now a reversal magnetic field, one notices that both applied field and dipolar fields act in the same direction, antiparallel to the magnetization of both wires. Let us simplify the analysis by considering two quasi-identical wires, i.e., both wires have the same magnetization M and coercive field H_C. It is important to emphasize that on the ideal demagnetization process the field necessary to reverse the magnetization of an individual wire has always the same value (the coercive field, H_C) and this value, but for the above-mentioned fluctuations, is characteristic of the internal magnetic properties (anisotropies) of that particular wire. Hence, at the first jump (H_2^i), in spite of the fact that the applied field is H_2^i, the effective field is equal to H_C. Therefore, the condition to the first wire to reverse its magnetization is given by $-H_2^i - K_1 M = -H_C$, and thus:

$$H_2^i = H_C - K_1 M. \tag{2}$$

Once the first wire reverses its magnetization, the configuration of the system is given by two wires with compensated magnetization ($\uparrow\downarrow$), which is more stable than the previous configuration since the dipolar fields now act parallel to the magnetization of both wires. Now, to reverse the magnetization of the second wire a stronger external field is required because this field has to compensate the dipolar contribution. Therefore, at the second jump (H_2^{ii}), the effective field is $-H_2^{ii} + K_1 M = -H_C$, and therefore:

$$H_2^{ii} = H_C + K_1 M. \tag{3}$$

Actually, the dipolar interaction acts on the wires as a bias field with opposite direction, decreasing and increasing the reversal field of the first step and the second jumps, respectively. Note that the plateau or difference between the reversal fields H_2^i and H_2^{ii} corresponds to dipole-dipole interaction between the wires, and it is given by $2K_1 M$.

Before proceeding with the discussion and extending the reasoning to the case of several wires, let us discuss several important points regarding the dipole-dipole interactions of two wires. First, it is worth noticing that although we have considered, for the sake of simplicity, two wires with the same magnetization and coercive field, the fluctuations in these values are essential to observe the effects of dipolar interaction.[2] If both wires would have exactly the same magnetic properties they would feel exactly the same effective field, and would reverse at exactly the same field value, H_2^i. However, in real situations the wires are not identical, and they can display fluctuations in both magnetization and coercive fields (see above), and therefore one of the wires reverses the magnetization before the other one, leading to an intermediate, more stable structure, and to the splitting of the reversal field.

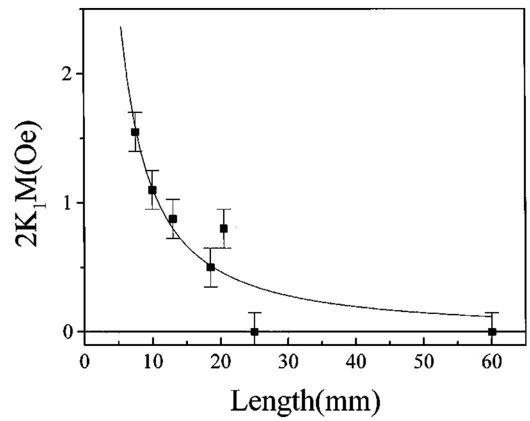

FIG. 6. Width of the plateau in compensated magnetic configuration (zero magnetization) measured from the demagnetization curve of two wires. It represents the strength of dipole-dipole interaction (see text). The line is a fitting following the power law $L^{-1.2}$.

Second, it is important to further discuss some details about the coupling constant K_n. We consider that the magnetization reversal is nucleated at the ends of the wires when the effective magnetic field acting on the wire is equal to H_C. Calculating the dipolar field nearby one of the wires it is easy to show that the component of its dipolar field along the axis of the second wire at its ends is given by

$$H_d = pL/(r_{ij}^2 + L^2)^{3/2}, \tag{4}$$

where p is the strength of the point poles, located at the extremeties of the wire of length L and r_{ij} is the distance between the wires i and j.[12] Note that in our configuration the magnetizations of the wires are either parallel or antiparallel, and the distances among wires are well known. Since the magnetization is pL, one identifies K_n as given by

$$K_n = 1/(r_{ij}^2 + L^2)^{3/2}. \tag{5}$$

We write $K_n = K_1$ when $i - j = 1$ (first neighbors), $K_n = K_2$ when $i - j = 2$ (second neighbors), and so on. Since our systems are composed of a few wires with distances never exceeding a few tenths of millimeters, with length of the wires of about 5 mm we have always the condition $r_{ij} \ll L$ fulfilled. Therefore, the constants of coupling K_n become independent of distance, at least in the range of a few wires.

In order to better understand the role of the constant of coupling and its dependence on r_{ij} and L we have evaluated the dipole-dipole interaction $2K_1 M$ for various lengths of the wires. The distance between the wires is fixed since the wires are placed side by side adjacent to each other as mentioned above. The experimental value of $2K_1 M$ was obtained from the width of the plateau of the hysteresis loops measured for two wires using the flux-integrator setup. The results are shown in Fig. 6. Note that the coupling rapidly increases for the shortest wires and seems to become negligible for wires longer than around 40 mm, at least within our experimental sensitivity. For the range of lengths larger than 5 mm the hysteresis loop for one wire exhibits bistability (square loop) and the hysteresis loop for two wires are all identical differing only on the width of the plateau. However, for wires with length of about 1 mm the hysteresis loop for one wire does not exhibit bistability anymore, preventing equivalent analysis.

According to our model the quantity $2K_1M$ is proportional to $L/(r_{ij}^2+L^2)^{3/2}$ [Eq. (4)]. The limit $r_{ij} \ll L$ produces a power-law decay to $2K_1M$ with L following L^{-2}, and on the other hand, in the limit $r_{ij} \gg L$, the factor $2K_1M$ varies linearly on L following L/r_{ij}^3. The conjunction of the two limits should exhibit a maximum in the plot $2K_1M$ vs L, which was clearly not experimentally observed. Thus, from Fig. 6 we conclude that in our samples we are always working in the limit $r_{ij} \ll L$. In this range of length, the data were fitted by the power law, $L^{-1.2}$, which, however, is not in good agreement with the expected dependence (L^{-2}).

However, one should always keep in mind that considering each microwire as a single magnetic dipole with two magnetic charges at both ends is an idealized approach (that is nevertheless supported by the observation of single jumps for multiwire loops). Indeed, a fully realistic approach should have to consider that magnetic charges could be distributed along the whole length of the wire, making much more complex the calculations of the fields created by these charges around each microwire.[13] Therefore, the lack of full agreement between experiments and model can be regarded as the result of an oversimplification of the model.

It is important to clarify that the dependence on length measured for $2K_1M$ is not related to the demagnetizing field. The wires as long cylinders have a very low demagnetizing factor. For instance, in our samples the wires are 5 μm in diameter and for a typical length of 5 mm the demagnetizing factor is around 10^{-6},[14] which, considering a saturation magnetization of 1240 emu/cm^3, results in a calculated demagnetizing field, H_{dm}, of about 10^{-2} Oe. This value is well below the reversal field of one wire (H_C) and it does not play an important role in the demagnetization process. Even though the demagnetizing effects are very small compared to the reversal fields, it is easy to calculate how the width $2K_1M$ would be modified by taking them into account. As discussed in Eqs. (2) and (3), and since the demagnetizing field is opposite to the magnetization, the first wire to reverse the magnetization feels the resulting field, $-H_2^i+K_1M-H_{dm}$, and the corresponding reversal field is given by $-H_2^i-K_1M+H_{dm}$. For the second wire, because the magnetization is also positive, the demagnetization field has the same sense as before; the resulting field is $-H_2^{ii}+K_1M-H_{dm}$. Therefore, the reversal field is given by $H_2^i=H_C+K_1M+H_{dm}$. Hence, note that the width of the step, $H_2^{ii}-H_2^i$, the demagnetizing field cancels out and the plateau in the hysteresis loop remains equal to $2K_1M$.

It is worth noting that the above discussion provides support to the idea that we are dealing with a magnetic system, which displays a dipolar coupling that is independent of distance, in other words, the dipole-dipole interaction is constant, at least for a few wires. Furthermore, it reinforces the applicability of the model to explain the presence of regular steps in the demagnetization curves, as will be shown below for the cases of more than two wires.

Now, it is straightforward to extend the above developed reasoning to an array of a few wires. For example, for three wires, the first step (H_3^i) arrives from the magnetization reversal of the wire that is in the middle position due to the greatest dipolar field from the two others—it corresponds to ↑↓↑ magnetic configuration. Thus, at H_3^i, identifying the effective field that this wire feels to its coercive field (H_C), one has $-H_3^i-2K_1M=-H_C$, and therefore

TABLE I. Magnetic configuration, expressions and measured values (in Oe) of reversal fields on the demagnetization for an array of 2, 3, 4, and 5 wires. The symbol (*) in the configuration of three wires means that respective transitions were not observed (see text).

2 wires			
↑↑	↓↑	$H_2^i=H_C-K_1M$	−0.43
↓↑	↓↓	$H_2^i=H_C+K_1M$	−1.11
3 wires			
↑↑↑	↑↓↑	$H_3^i=H_C-2K_1M$	−0.63
↑↓↑	↓↓↑	$H_3^{ii}=H_C-(K_1-K_2)M$	*
↓↓↑	↓↓↓	$H_3^{iii}=H_C+(K_1+K_2)M$	*
4 wires			
↑↑↑↑	↑↑↓↑	$H_4^i=H_C-(2K_1+K_2)M$	0.16
↑↑↓↑	↓↑↓↑	$H_4^{ii}=H_C-(K_1-K_2+K_3)M$	−0.45
↓↑↓↑	↓↑↓↓	$H_4^{iii}=H_C+(K_1-K_2+K_3)M$	−1.35
↓↑↓↓	↓↓↓↓	$H_4^{iv}=H_C+(2K_1+K_2)M$	−2.45
5 wires			
↑↑↑↑↑	↑↑↓↑↑	$H_5^i=H_C-(2K_1+2K_2)M$	0.69
↑↑↓↑↑	↓↑↓↑↑	$H_5^{ii}=H_C-(K_1-K_2+K_3+K_4)M$	−0.13
↓↑↓↑↑	↓↑↓↑↓	$H_5^{iii}=H_C-(K_1-K_2+K_3-K_4)M$	−0.73
↓↑↓↑↓	↓↑↓↓↓	$H_5^{iv}=H_C+(2K_1-K_2+K_3)M$	−1.90
↓↑↓↓↓	↓↓↓↓↓	$H_5^{v}=H_C+(2K_1+K_2+K_3)M$	−3.0

$$H_3^i=H_C-2K_1M. \tag{6}$$

At the second jump (H_3^{ii}) the magnetic configuration of the wires goes from ↑↓↑ to ↑↓↓, or ↓↓↑, and hence at H_3^{ii} the resulting field on the wire is $-H_3^{ii}-(K_1-K_2)M$ and again setting it to H_C, one finds

$$H_3^{ii}=H_C-(K_1-K_2)M. \tag{7}$$

Finally, the third step from ↑↓↓, or ↓↓↑, to ↓↓↓; the magnetization reversal of the wire at the other extremity occurs at

$$H_3^{iii}=H_C+(K_1+K_2)M. \tag{8}$$

Performing similar calculations we found the reversal fields with their respective magnetic configuration for four and five wires, and the corresponding reversal fields are summarized in Table I, from two to five wires. *Note that our model reveals that the dipole-dipole interaction among the wires, associated with fluctuations of M and/or H_C values, is the origin of the splitting of the reversal field in different values.*

In order to evaluate the applicability of our model, we initially compare for the case of two wires the calculated and measured values of the reversal fields H_2^i and H_2^{ii}. In a demagnetization process, an initially saturating magnetic field (defined here as positive) is monotonously decreased, reaches zero, and then is reversed and increased until it reaches a saturating, negative value. In this way, calculating the average of H_2^i and H_2^{ii} we find -0.77 Oe, which should correspond to H_C [see Eqs. (2) and (3)]. Calculating the difference between H_2^i and H_2^{ii}, we find -0.68 Oe which should be equal to $2K_1M$ [see Eqs. (2) and (3) and Table I). Since the mean value of H_C measured for a single wire is -0.85 Oe, we may consider that H_C obtained from the average and the one measured are in good agreement. This is really acceptable if we take into account several sources of fluctuations or peculiarities of each wire, as different defect structures originated from the cutting, imperfect alignment of the wires, etc. Note that the term that represents the dipole-dipole interaction (K_1M) corresponds in modulus to 0.34 Oe.

The discussion can be extended for an even number of wires, i.e., for four parallel microwires. One can immediately remark that the first and fourth (H_4^i and H_4^{iv}) and the second and third reversal fields (H_4^{ii} and H_4^{iii}) are approximately equidistant from H_C. In other words, the average of these values should be equal to H_C as should be expected from calculations (see Table I). From Fig. 4, we obtain these average values to be -0.9 Oe and -1.3 Oe, respectively. As previously discussed, we have measured fluctuations around H_C to be approximately 0.1 Oe, in the case of single wires. However, increasing the number of wires, the error in the measured values of reversal fields should accordingly increase. With that consideration in mind, the latest values (-0.9 and -1.3 Oe) are in reasonable agreement with H_C.

From previous discussions we can consider the dipolar interactions in our case as almost constant, i.e., independent of distance. In this case, K_n is simply K_1, and the reversal fields H_4^{iii} and H_4^{ii} take a simplified form $H_C \pm K_1M$. Actually, this expression is identical as for the reversal fields in the case of two wires H_2^i and H_2^{ii}, and comparing their respective values, we find H_2^i and H_4^{ii} equal to -0.43 Oe and -0.45 Oe, respectively. For H_2^{ii} and H_4^{iii} the obtained values are -1.1 Oe and -1.35 Oe, respectively. Moreover, the first reversal field H_4^i becomes equal to $H_C - 3K_1M$, and substituting the value of K_1M, we find H_4^i equal to 0.17 Oe, which is very close to the measured value, 0.16 Oe. Notice that this field is now positive, i.e., the effective dipolar field is so strong that it overcomes the applied magnetic field. The same analysis can be performed for the fourth jump H_4^{iv}, which turns out in the expression $H_C + 3K_1M$, and results in -1.87 Oe, which, however, differs from the measured value, -2.45 Oe. Thus, using the fact that all K_n's have the same strength, the predicted fields to H_4^i, H_4^{ii}, and H_4^{iii} (in exception of H_4^{iv}) are in very good agreement with experiments.

Let us now analyze the demagnetization curves of arrays with an odd number of wires, starting with the case of five wires, and assuming again that all K_n's are equal to K_1. As before, we can compare the predicted and measured values of the reversal fields. It is remarkable that the expression of the third step H_5^{iii} is oversimplified to give simply H_C, and the measured values of $H_5^{iii} = -0.73$ Oe and $H_C = -0.85$ Oe are rather close. The first and second steps, H_5^i and H_5^{ii}, with corresponding expressions, $H_C - 4K_1M$ and $H_C - 2K_1M$, respectively, result in 0.51 Oe and -0.17 Oe, which are also close to the measured values, 0.69 Oe and -0.13 Oe, respectively. The fourth and fifth steps, H_5^{iv} and H_5^{v}, with opposite increments in K_1M are positioned after H_C, and are given by $H_C + 2K_1M$ and $H_C + 4K_1M$, respectively. Comparing their expected values (-1.53 Oe and -2.21 Oe) with the measured ones (-1.9 Oe and -3.0 Oe) one finds that the agreement is not as good as in the previous case of four wires.

In conclusion, comparing the reversal fields predicted according to the model with measured values for four and five wires, a good agreement is obtained mainly for fields near and below H_C, while for fields well above H_C the agreement is poor.

The particular situation of three wires, contrary to other arrays with two, four, and five wires, is characterized by the absence of one of the jumps. This situation has been exhaustively tested for different samples both in the SQUID and in the flux integrator, but we could not obtain the missing jump. Actually, all samples measured are in the condition $r_{ij} \ll L$, where all K_n's have the same strength. Hence, it is possible that the geometry of an array of three wires, where K_1 and K_2 have the same approximate value, should be equivalent to three wires placed as a triangle. This configuration can favor the occurrence of frustration of magnetic interactions, and might prevent the formation of an intermediate configuration. On the other hand, the elimination of the condition $r_{ij} \ll L$ requires either the increase of r_{ij} in a controllable way or the decrease of L to order of a few tenths of micrometers; however, both are quite difficult to attain experimentally and are not in the scope of our present study. Our model seems not to be applicable to three wires under the condition $r_{ij} \ll L$ possibly because of the existence of frustration.

Let us finally discuss the demagnetization process for a large number of wires. It is clear that extending the reasoning developed above for a still larger number of wires the calculation of reversal fields becomes increasingly tedious. Therefore, we have used the Monte Carlo (MC) method based on a one-dimensional modified classical Ising model. We have considered a one-dimensional array of magnetic moments interacting through the long-range dipole-dipole interaction. In our model, the Hamiltonian takes a simple form,

$$H = M^2 \sum J_{ij}\sigma_i\sigma_j - (H + H_{ani}) \sum \sigma_i, \qquad (9)$$

where the variable σ_i takes the values ± 1 on a site i on a one-dimensional array, allowing the magnetic moments to point up ($\sigma_i = +1$) or down ($\sigma_i = -1$) along an axis perpendicular to the axis of the array. The first summation in Eq. (9) denotes the dipole-dipole interaction acting over all pairs of magnetic moments. The constant of coupling J_{ij} is identified with $1/K_n$ [see Eq. (5)], and the distances between the magnetic moments, r_{ij}, are measured in units of the lattice constant a. Note that the magnetization, **M**, of a wire is given by $M\sigma_i\mathbf{z}$ (**z** is a unitary vector perpendicular to the axis of the array). The second term denotes the interaction between the magnetic moments and an external magnetic field (H), H_{ani} being a fixed bias field representing the magnetic anisotropy of one wire, i.e., the reversal field of one wire. It is easy to realize that the field H_{ani} can be recognized as H_C.

Note that in the experimental case, the wires are glass coated, inhibiting any possibility to interact through ex-

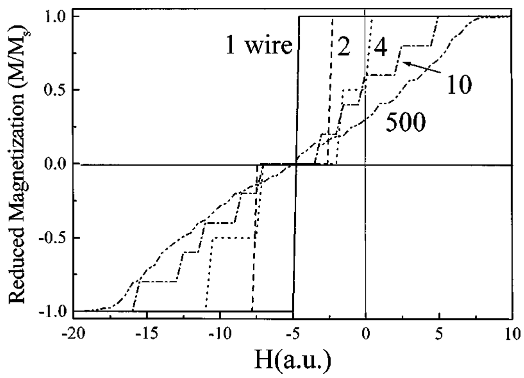

FIG. 7. Demagnetization region of hysteresis loop calculated using the Monte Carlo method for 1 wire and for arrays of 2, 4, 10, and 500 wires.

change interaction, and therefore, the constant J_{ij} contains only the dipole-dipole interaction. Another point to remark is that since J_{ij} is positive, the first term favors an antiparallel alignment among the magnetic moments.

We used the single-spin-flip Metropolis dynamics and open boundary conditions (details of calculations are given in a previous publication).[4] The hysteresis loops were calculated changing the field H with a sweep rate of 10 MC steps for each magnetization value. The temperature (T) was considered low enough in order to be well below the antiferromagnetic-paramagnetic phase transition. The values of parameters M,H,T, are chosen arbitrarily. Notice that what is here mostly relevant is the relative intensity among the terms of the Hamiltonian. In that way, we determine trends and not absolute values; thus our results calculated from the MC method may be qualitatively compared with experiments. We used M^2, H_{ani}, and T equal to 5, 5, and 1, respectively. This trial of values is good enough to discuss the role played by the number of wires on the demagnetization process.

Figure 7 shows hysteresis loops for 1 wire and for arrays of 2, 4, 10, and 500 wires calculated using the MC method. As observed in experiments (see Figs. 2–5) the reversal fields for an array of multiple wires are distributed around the reversal field of 1 wire (H_C), and enlarging the number of wires the width of plateaux decrease. This agreement confirms the idea that spin models can be used to study the magnetic properties of macroscopic systems like an ensemble of microwires. In addition, for 500 wires the system demagnetizes monotonically with small jumps and plateaus, which should correspond in real systems to microscopic Barkhaunsen jumps. Notice the presence of a clear anisotropy field, even for 500 wires (Fig. 7). Although the underlying physical meaning of this field is still unknown, and needs further experimental and theoretical investigations, it can be referred to as a ''long-range effective interaction anisotropy,'' which is generated by the intricate superposition of dipolar fields from many wires in a specific array.

IV. CONCLUSIONS

In this work we have presented experimental hysteresis loops of sets of long microwires arranged parallel in a dense packing configuration. Owing to the protective insulating glass-coating the magnetic microwires are nevertheless not touching each other. The hysteresis loops are characterized by well-defined Barkhausen jumps corresponding each to the magnetization reversal of individual microwires that are separated by horizontal plateaux. As discussed in the text, these jumps are theoretically interpreted according to a model based on the nucleation of closure domains at the ends of the wires and the subsequent depinning and propagation of a domain wall. The dipolar field acting on each individual microwire due to all surrounding wires is responsible for the actual value of its observed reversal field. The plateaux have been proved to be determined by the dipole-dipole interaction as well. It has been pointed out how the peculiarity of the coupling between the wires, namely, the independence of distance from the magnetic coupling transforms it in a very interesting system.

One main achievement of the present work is that although the array of microwires is macroscopic, the dipolar interaction among them has a similar effect on the magnetic properties as classical spins interacting throughout long-range interactions. Therefore, we believe that the studied system can be regarded as a standard system to verify the influence of dipolar interactions in the magnetic response of an array of dipoles, being possible to test micromagnetic predictions and verify the best conditions to optimize the macroscopic magnetic behavior for specific applications.

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