Combined Ferromagnetic Resonance and Magnetic Force Microscopy 
Studies in Arrays of Magnetic Nanowires

M. Vázquez, C. Ramos*, E. Vassallo*, M. Jaafar and A. Asenjo
Instituto de Ciencia de Materiales de Madrid, CSIC., 28049 Madrid, Spain
* Centro Atómico Bariloche e Instituto Balseiro, 8400 Bariloche, Argentina

Abstract.- Present study reports on magnetostatic interactions in highly-ordered arrays of Ni nanowires embedded in nanoporous alumina membranes. We use two techniques supplying complementary information: ferromagnetic resonance, FMR, studies from which we derive information of the whole array of nanowires, and magnetic force microscopy, MFM, that informs us about the magnetic state of individual nanowires. From FMR study of the angular dependence of resonance field and its line-width it is concluded that the magnetostatic interaction plays an important role to decrease the effective anisotropy field of individual nanowires. This is confirmed by analysis of MFM images at remanence and its comparison with vibrating sample magnetometer measurements.

Keywords: magnetic nanowires, ferromagnetic resonance, magnetic force microscopy, magnetostatic interactions, nanoporous membranes.

1. Introduction

Highly-ordered arrays of magnetic nanowires are of interest in a number of particular applications as magnetic units in perpendicular recording media1) and including microwave and sensing devices. Nanowires are typically fabricated out of magnetic elements as Fe, Ni and Co and their alloys. There are a number of methods to produce such arrays, some of them involving costly and complex technologies as nanolithographies2). Other techniques still allowing us the preparation of similar arrays of nanowires are actually offering much expectation because of their more reasonable economical approach and still effective results. This is the case of magnetic nanowires embedded in nanoporous membranes that exhibit outstanding magnetic ordering which is induced by self-organization during anodization of highly pure Aluminum disks3).

In these systems, the magnetic interaction among nanowires plays a decisive role since it determines actually the magnetization process of individual nanowires but also the macroscopic magnetic behavior of the array. As studied earlier3), nanowires are magnetostatically coupled with different strength depending on the geometric characteristics as nanowires diameter and lattice parameter. In the present work, we study these magnetic interactions among nanowires by using two techniques supplying complementary information: ferromagnetic resonance, FMR, studies from which we derive information of the whole array of nanowires, and magnetic force microscopy, MFM, that informs us about the magnetic state of individual nanowires.

2. Preparation of highly-ordered arrays of nanowires

Alumina, Al₂O₃, nanoporous membranes have been firstly produced by two-step anodization process. Pores self-organize into highly ordered geometrical structure of hexagonal symmetry. Later on, nanopores are filled with metallic magnetic (Ni in the present case) elements by electrodeposition. Ordering degree as well as diameter of pores and interpore distance can be tailored by the parameters of fabrication3-5).

On the other hand, magnetization and hysteresis loops studies have been performed by vibrating sample magnetometer, VSM. From these studies, the nanowires length, L, of the samples S1, S2 and S3 estimated from high-field magnetization, are 0.66, 1.05 and 2 μm, respectively. All mentioned geometrical details should play a significant role in the final strength of magnetostatic interactions4,5).

3. Ferromagnetic Resonance

FMR experiments were performed at frequencies of 9.4 and 34 GHz as a function of the applied biasing field with a Bruker ESP300 Spectrometer. Figure 1 shows a typical FMR signal indicating the resonance field and the peak-to-peak linewidth. Particularly the angular dependence of the resonance field, θ, has been studied in detail. It has been fitted to the expression 6):

\[(\omega \gamma)^2 = [H_R \cos(\theta - \theta_0) + H_N \cos^2 \theta] [H_R \cos(\theta - \theta_0) + H_N \cos 2\theta]\]

(1)
where \( \omega = 2\pi v, \nu = 9.4 \) or \( 34 \) GHz for \( X \) and \( Q \) bands respectively, \( \gamma = g\mu_B / h \), \( \theta \) denotes the angle between applied field and the wires axis, \( \theta_e \) is the equilibrium angle between the magnetization and the wire axis (determined by minimizing the free energy, \( dE/d\theta = 0 \)), and \( H_A \) is an effective anisotropy constant. From the angular dependence, as observed in Fig. 2(a), it is possible to evaluate the effective magnetic anisotropy field, \( H_A \). The anisotropy field, as determined from this angular variation at \( Q \) band turns out to be \( 2.56 \pm 0.08 \) kOe, \( 2.46 \pm 0.04 \) kOe, and \( 2.09 \pm 0.20 \) kOe for samples S1, S2 and S3 respectively. Therefore the least ordered array, which contain the shortest wires yield the largest effective anisotropy.

The origin of the anisotropy of individual nanowires is mainly shape anisotropy given by \( 2\pi M_sH_{A0} = 3.05 \) kOe. The \( H_A \) values obtained by FMR shows a reduction of the \( H_{A0} \) up to 20\% assumed to be due to dipolar interactions. The effect of the dipolar field would be to decrease the single-wire anisotropy, \( H_{A0} \), by an amount \( 4\pi M_f \), where \( f \) is the filling factor of the wires (the average area of the wires over the area of the sample). From the structural characterization the filling factor can be estimated to be \( f = 0.109 \) yielding an estimated effective anisotropy of \( H_{A0} (1 - 2f) \) and thus explaining roughly the observed values of \( H_A \).

The peak-to-peak line-width (see Fig. 2(b)) of the FMR signal shows angular variations with pronounced minimum at \( \theta_b = 0 \) (the external magnetic field applied at 0 degrees off the wire axis). If the wires were slightly (randomly) disoriented around an average orientation then a maximum instead of a minimum would be expected at this orientation. This confirms a structural fact clearly observed by SEM pictures on the edge of the alumina showing extremely well oriented columns (see Figure 3). Furthermore, a variation of the anisotropy field would yield maximum at \( \theta_b = 0 \) and \( \pi/2 \). If a Gaussian anisotropy disorder distribution of width \( \sigma_H \) is assumed, then a symmetric line would be expected and its effect of the line-width would be such as to produce a maximum at \( \theta_b = 0 \) with amplitude \( \sigma_H \), a minimum at \( \theta_b = \pi/2 \), and a second maximum at \( \theta_b = \pi/2 \) of amplitude \( \sigma_H/2 \). Fig. 2(b) shows a 0.9-1.0 kOe angle-independent line-width. Subtracting a constant value passing through the minimum of the observed angular variation of \( \Delta H_{pp} \) then the excess linewidth, \( \Delta H_{pp}(\theta_b) \), could be related to this random variation \( \Delta H_A \). Furthermore, the expected value \( \Delta H_{pp}(0) = 2\Delta H_{pp}(\pi/2) \) is only found in one of the samples (S3) which corresponds to the largest long-range order.

We note, however, that the effect of disorder seems to affect more pronouncedly the line-width in the perpendicular direction. A simple picture of the dipolar field caused by the neighbors onto a given wire at its center can explain this feature. When the wires are polarized in the parallel direction the dipolar field of the first neighbors can be pictured (see Figure 4) as the effect of the dipolar field produced by "charged" caps of magnitude \( \pi M_s(D/2)^3 \) generating a field that follows a law

\[
H_{A0}(D/2R)^3 \text{ with } R^2 = L^2 + S^2.
\]

Fig. 1: FMR signal in S3 with \( H \parallel \) to the wires indicating the peak-to-peak linewidth and resonance field.

Thus each of the first neighbors contributes \( H_{A0} \) \( (D/L)^2(1-6(S/L)^2) \), where \( (D/L)^2 \sim 10^{-3} \) and \( (S/L)^2 \sim 10^{-2} \). This is a very small contribution to the total dipolar field \( \sim 2H_{A0} \) and has a negligibly small correction due to disorder in the inter-wire separation \( S \). Thus, the demagnetizing field acting on a given wire at its center is mostly due to the average wire density far from the "test" wire. This can be calculated explicitly and shows that the only effect of disorder would be through variations in the filling factor \( f \), from a given place of the sample to another and the local disorder in the wire position would...
be negligible.

![Fig. 3 SEM image of S3 sample showing the Al₂O₃ columns. Note that the are columns very well aligned.](image)

**Fig. 3** SEM image of S3 sample showing the Al₂O₃ columns. Note that the are columns very well aligned.

**Fig. 4** a) In \( H_y \) to the wires condition, the nearest neighbor contribution is small since the “magnetic charges” are very distant from the center “test” wire. In this case, the field at the center depends weakly on the separation between the wires, \( S \). b) In \( H_z \) condition, the dipolar field is large and strongly dependent on \( S \) (and their diameters). This produces a significant dipolar field at the center wire that traduces in an additional contribution to the FMR line-width.

On the other hand, a similar analysis of the dipolar field caused by the neighboring wires when they are polarized perpendicular to the wire axis gives a completely different result. A straightforward calculation yields that dipolar field calculated at the center of a “test” wire produced by a wire separated a distance \( S \ll L \) is \( H_{\text{dip}}(D/2S)^2 \), that is, the field produced by the neighbors depends critically on the local \( (D/S)^2 \) ratio, a sort of local filling factor.

Thus, besides long-range fluctuations of \( J \), additional dipolar fields can be expected from local variations in the lattice parameter, wire diameters, and defects. An estimation of the local field \( \Delta H_L \) arising from \( \Delta S \) and \( \Delta D \) can be estimated to be \( \Delta H_L \approx 0.28 \) kOe for \( (\Delta S)/(\Delta D) \approx 0.3 \). Therefore, we would expect a larger spread of dipolar fields in the perpendicular direction due to these local variations as confirmed by the FMR line-width.

A note of caution should be made as the lineshapes observed are not totally symmetric. Besides possible spin-wave (or surface modes) excitations, the dipolar coupling among the wires would allow new collective excitation modes, similar to the optic and acoustic modes found in exchange-coupled films, which could lead to an apparent line-broadening in our systems. In isolated nanowires of larger diameters electrodeposited into polycarbonate membranes asymmetric lines were also observed while dipolar interactions among the wires should not be present in their case.

### 3. Magnetic Force Microscopy

Magnetic force microscopy experiments were performed in a Nanotec™ microscope. It allows us to reach complementary information on the magnetic state of individual nanowires. Assuming each individual nanowire to behave as a magnetic dipole, its image results with white and black contrast respectively for repulsive and attractive interaction with the magnetic tip and thus, offering a unique view of the local distribution of magnetic nanowires that actually reflects the magnetostatic interaction among nanowires.

As an example, Figure 5 shows the topography (a) and the magnetic moment distribution (b) corresponding to the sample S3 at remanence after saturating under axial magnetic field.

Due to shape anisotropy, the magnetization direction at remanence state is parallel to the wires. As mentioned earlier, the dipolar interaction tends to decrease the anisotropy in this direction, however the dipolar interaction is not fully sensitive to the neighboring wires magnetization so allowing the situation shown in Fig. 5(b) were nanowires magnetized in one direction are surrounding by nanowires in the same and opposite direction, in average, there are 1.8 neighboring nanowires with the magnetization pointing in the same direction.

![Fig. 5 Topography (a) and MFM (b) images of Ni nanowire array S3 at remanence after saturating in axial direction. Image size 4.2µm x 3.9µm.](image)

After careful analysis of MFM images, we have obtained the remanent magnetization values by subtracting the number of nanowires with the magnetic moment pointing in each direction. The remanent magnetization value corresponding to the MFM image in
Fig. 5(b) is $M_r = 0.3 M_s$. This value obtained for a local region, does not agree with the remanence value measured for the whole array by VSM, $M_r/M_s = 0.8$. Some reason is the influence of the magnetic MFM tip that causes irreversible changes in the magnetic state as confirmed by analysis of successive images obtained in the same region.

In conclusion, the effect of magnetostatic interactions derived from FMR and particularly from the angular dependence of resonance field and the line-width has been reported and correlated with MFM images at remanence states. A distinction between the local order and the long-range order reflects in the angular dependence of the line-width.

Acknowledgements
The work has been supported by projects CAM-GR/MAT/0423/2004 and CAM-GR/MAT/0437/2004 in Spain, and ANPCYT (PICT 03-13297) in Argentina. E.V. acknowledges his fellowship from CONICET.

References
8) We have used two different methods: by counting individual nanowires and by fitting the MFM data to two gaussian distribution, A. Asenjo, M. Jaafar, D. Navas and M. Vazquez (unpublished data).

Received May. 12, 2005; Accepted Aug. 24, 2005