Study of Magnetic Interactions in Metallic Nanowire Networks

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Nanowire arrays are characterized using ferromagnetic resonance (FMR) experiments. The dipolar interactions between nanowires are studied by investigating the angular variation of the FMR resonant field. Two qualitatively different angular variations in the resonant field are experimentally observed and explained using the interaction field. The experimental data are explained using a theoretical model that considers the interaction field in nanowire networks as arising from magnetic charges at the wire’s surface (wire’s extremities and lateral cylindrical surface) and takes into account the finite wire length and porosity of the sample.

Index Terms—Ferromagnetic resonance, magnetic nanowires.

I. INTRODUCTION

Nanowire arrays have recently attracted a lot of attention as potential materials for advanced data storage and microwave applications. The possibility to fabricate uniform magnetic nanowires with controlled diameter and distance between wires motivated a large number of studies. Besides the practical aspect, nanowire networks constitute one of the important theoretical model systems for studying the magnetic interactions in ordered magnetic systems.

For an isolated long wire, due to shape anisotropy, the magnetization direction is aligned along the wire axis. In the case of a system of wires, the interaction field between wires can significantly affect the magnetic properties of the assembly. Studies on single wires are crucial to understand the mechanism by which the magnetization of a single wire reverses, but for possible device applications it is important to quantify the distribution of the internal fields in wire arrays containing a large number of wires. Knowledge of the coupling mechanism between wires could be useful in tuning the magnetic properties of the system. Recent papers investigated the dipolar interaction in nanowire arrays related to the reversal mechanism [1], [2]. The finite length of the wires, the curling mode of magnetization, the domain-wall nucleation, and the depinning fields are only a few of the supplementary problems that make this analysis difficult. The high-frequency ferromagnetic resonance (FMR) techniques for magnetically saturated samples overcome some of these problems, being a useful tool for dipolar interaction studies [3]. The uniaxial anisotropy field can be derived using a phenomenological mean field approach and increases almost linearly with the porosity of electrodeposited nanowire arrays. In this paper, the angular dependence of the FMR resonance field of different Ni nanowire arrays embedded in alumina membrane was analyzed. For the first time experimentally, the existence of two qualitatively different behaviors for the angular dependence of the resonance field was proved. Experimental data are explained using a theoretical model that considers the interaction field in nanowire networks as arising from magnetic charges at the wire’s surface (wire’s extremities and lateral cylindrical surface) and takes into account the finite wire’s length and porosity of the sample.

II. EXPERIMENT

Ni nanowire arrays with a nominal radius \( a \) of 145 nm and different lengths and porosities were prepared by standard electrochemical deposition at room temperature using commercial alumina membrane as templates. The length of the wires was controlled by using different deposition times. The obtained samples constitute an almost cylindrical and parallel set of ferromagnetic Ni nanowires embedded in alumina membrane with an average interwire distance (center to center) of 340 nm. For this study, we selected two samples of different nanowire lengths \( h_i \), labeled Ni3 (0.8 \( \mu \)m) and Ni6 (3.0 \( \mu \)m). As will be shown later, in addition to different wire lengths, the samples have different porosities due to the incomplete filling of alumina membrane channels for short electrodeposition times. The FMR experiments were performed at room temperature, the microwave-pumping field frequency being 9.8 GHz. The angle \( \theta \) between the applied field \( H \) and nanowire’s axis was changed in the domain (0.180°) with \( \theta \approx 0° \) for \( H \) parallel to the Oz axis (nanowires direction) and \( \theta = 90° \) for \( H \) perpendicular to the Oz. The FMR spectra were subsequently recorded while sweeping \( H \). The angular dependence of the resonance field \( H_r \) obtained for samples Ni3 and Ni6 is displayed in Fig. 1(a) and (b), respectively. While the variation of resonance field for the Ni3 sample was usually observed and reported for Ni nanowire systems [4], the results for sample Ni6, where at \( \theta = 90° \) the resonance field is minimum, are quite unusual. In the following analysis, this difference in the angular variation of the resonance field for the two samples is explained by evaluating the difference of the internal effective fields associated with each sample. Initially, we consider our analysis investigated the case of an...
isolated ferromagnetic wire. An isolated Ni wire can be considered as a cylinder with the anisotropy direction parallel to the cylinder axis (Oz axis). The samples are magnetically saturated at resonance so that the magnetization vector \( \mathbf{M} \) is parallel to the external field \( \mathbf{H} \). For this configuration, the uniform resonance condition is given by

\[
\frac{\omega}{\gamma} = \left[ \left[ H + [H_k + 4\pi M(N_x - N_z)] \cos(2\theta) \right] \right]^2 \times \left[ \left[ H + [H_k + 4\pi M(N_x - N_z)] \cos^2(\theta) \right] \right]^{\frac{1}{2}}
\]

with \( \gamma \) as the gyromagnetic ratio, \( \omega = 2\pi f \), \( f \) is the frequency of the microwave pumping field, \( M \) is the magnetization of the sample, \( H_k = 2K/M \) is the anisotropy field, and \( N_x \) and \( N_z \) are the demagnetizing factors perpendicular and along the cylinder axis, respectively [4]. For the particular cases when the static field is applied parallel (\( \theta = 0^\circ \), respectively, perpendicular (\( \theta = 90^\circ \)) to the cylinder axis, the resonance condition becomes

\[
\frac{\omega}{\gamma} = \left[ H || + H_k + 4\pi M(N_x - N_z) \right]
\]

(2)

\[
\frac{\omega}{\gamma} = \sqrt{H_L[H_L - H_k - 4\pi M(N_x - N_z)]},
\]

(3)

Equations (2) and (3) show that the resonance condition for one direction is a function not only of the magnetic field in that direction but also, through demagnetizing factors, of the magnetic field perpendicular to that direction. In the case of a nanowire assembly, a wire is not only in the external field but also in the effective field created by neighbor wires, so the resonance condition has to include this interaction field. The nanowire samples can be modeled as a two-dimensional (2-D) network of equidistant cylinders that have the axis parallel to the Oz axis. The interaction field for this system can be computed along two directions: parallel and perpendicular to the cylinder axes. The interaction field is expressed in terms of magnetization \( 4\pi M \), so we will obtain the interaction fields between cylinders in terms of the supplementary demagnetizing factors for considered directions \( N_{x_e} \) and \( N_{x_p} \). So, for a system of nanowires, the angular dependence of the resonance field can be determined using (1), in which instead of isolated wire’s demagnetizing factor one considers a total demagnetizing factor that takes into account the effect of interwire interaction \( N_{x_e} = N_x + N_{x_e} \) and \( N_{x_p} = N_x + N_{x_p} \). For a uniform magnetized infinite cylinder, \( N_x = 1/2 \) and \( N_z = 0 \). Equation (1) can be used even for a finite long cylinder if the corresponding demagnetizing factors are used.

The experimental angular variation of the resonance field for both samples is fitted using (1) having \( 4\pi M(N_{x_e} - N_{z_e}) \) as the fitting parameter. The saturation magnetization value (Ni bulk value \( M = 485\ \text{emu/cm}^3 \)), the anisotropy fields for each sample \( H_{KNi3} = 75 \text{ Oe} \), \( H_{KNi6} = 170 \text{ Oe} \) [as determined from magnetization measurements using the first-order reversal curve (FORC) protocol [1]], and the resonance field for parallel and perpendicular configurations for each sample \( H_{L1N3} = 5360 \text{ Oe} \), \( H_{1N3} = 2380 \text{ Oe} \), \( H_{L2N6} = 2800 \text{ Oe} \), \( H_{2N6} = 3260 \text{ Oe} \) are considered as input parameters in the fit procedure. The obtained fit parameters are \( 4\pi M(N_{x_e} - N_{z_e})_{Ni3} = 2655 \text{ Oe} \) and \( 4\pi M(N_{x_e} - N_{z_e})_{Ni6} = -477 \text{ Oe} \), which correspond to the total demagnetizing factors \( (N_{x_e} - N_{z_e})_{Ni3} = 0.34 \) and \( (N_{x_e} - N_{z_e})_{Ni6} = -0.08 \), respectively. One observes that these values are significantly different from the isolated infinite wire value \( (N_{z_e} - N_{z_e})_{w} = 0.50 \), so the effect of dipolar interactions is very important. The fit (solid curve in Fig. 1) is very good for the Ni6 sample, while some discrepancies can be noticed for Ni3. In the fit procedure, it was supposed that the demagnetizing factors are independent of the magnetization direction, a hypothesis that is not true for finite cylinders [5]. For shorter nanowires in the sample Ni3, the deviation from the infinite wire case is more important than from sample Ni6, which explains the difference in the fit quality for these samples.

To obtain better insight into the nature of the interwire interaction field, one evaluates the field created by a 2-D array of cylindrical wires that are magnetically saturated. The parallel and perpendicular components of the dipolar field with respect to the cylinder axis are considered to appear as an effect of the magnetic poles at each end of a cylinder and as an effect of the cylinder side surface poles, respectively. The magnetic field created by two opposite magnetic charges situated at the ends of the wires at point P is the superposition of fields created by each charge

\[
\vec{H} = A \left( \frac{\vec{r}_1}{r_1^3} - \frac{\vec{r}_2}{r_2^3} \right)
\]

(4)

where \( \vec{r}_1 \) and \( \vec{r}_2 \) are the distances between each charge and P, and A is a constant. We are interested only in the axial component of this field because only this does not vanish for an assembly of parallel cylinders. The created magnetic field can be expressed in terms of magnetization \( 4\pi M \), and the value of the field can be simply translated in demagnetizing factor terms. It is observed that the field is not constant along the wire axis; so, in cylindrical samples, the demagnetizing field is not uniform. Because the sample is located in a uniform applied field along its magnetization at the midplane perpendicular to the axis) \( N_{Lz} \) to compute the demagnetizing field [5] \( A = N_{Lz}(h/2)^2 \pi M \), where \( h \) is the cylinder length. In order to estimate the field component perpendicular to the cylinder axis, one considers that the sample is saturated along the Ox direction, and the magnetization vector has a constant value inside the cylinder and is oriented along the Ox direction. The field distribution can be determined as a superposition of the fields created by two cylinders of the same radius and opposite volume charge density that are shifted along the Ox direction with a small distance \( I (l \ll a) \), where \( a \) is the cylinder radius [6]. This configuration is able to
simulate a surface magnetic charge distribution that assures a constant field inside the cylinder

$$\vec{H} = \frac{N_{fx} \kappa_1 M}{l} (\bar{r}_1' - \bar{r}_2') = N_{fx} \kappa_1 M \bar{r}. \tag{5}$$

Outside the cylinder, the created magnetic field is

$$\vec{H} = N_{fx} \frac{a^2}{T} \kappa_1 M \left( \frac{\bar{r}_1'}{r_1} - \frac{\bar{r}_2'}{r_2} \right) \tag{6}$$

where $\bar{r}_1'$ and $\bar{r}_2'$ define the distances between the center of each cylinder and the P point where the field is computed and $N_{fx}$ is the fluxmetric demagnetizing factor along the Ox direction.

A square array of finite long wires was considered. The dipolar fields are then summed over all wires of the array using a matrix of $1000 \times 1000$ wires, which guarantees convergence of the dipolar field sum. Fig. 2(a) shows the simulated variation on the total demagnetizing factor $N_t = N_{fx} - N_{fs}$ as a function of aspect ratio $m$, defined as the wire’s length $l$ to wire’s radius $a$ ratio, for different interwire distances $d$. It is observed that the total demagnetizing factor becomes almost constant for long wires, the large variation being observed only for small wire lengths. Also, the value of the demagnetizing factor is strongly dependent on the interwire distance with values in a large interval ($-1, 0.5$) including negative and positive values, as previously reported [7]. As shown earlier in the case of positive values for $N_t$, the angular dependence of the resonance field looks like Fig. 1(a), while for negative values a variation as the one in Fig. 1(b) should be expected.

A linear dependence of the total demagnetizing factor as a function of membrane porosity $P$, defined as $P = \pi a^2 / l^2$, is revealed in Fig. 2(b). The theoretical porosity values obtained from Fig. 2(b) are 0.17 for Ni3 and 0.52 for Ni6. If the porosity value for the longest sample Ni6 is close to the membrane’s nominal porosity of 0.57, the value for Ni3 is much smaller. This is consistent with the observation that for shorter wires the pore’s filling is smaller than 100%, resulting in a smaller apparent porosity. For long wires, the simulated dependence is similar to the results derived using a phenomenological mean field approach $N_t = (1 - 3P) / 2$ [3], some discrepancies appearing only for shorter wires. One must note that, for a specified porosity, one can obtain $N_t = 0$, which corresponds to an isotropic behavior. From the results presented in Fig. 2, one observes that for long wires the total demagnetizing factor is a function of the sample porosity only, while for short wires both the porosity and the wire length are important. As also shown in Fig. 2, the total demagnetizing factor depends only on the geometrical parameters of the wire system: porosity and aspect ratio. As the resonance frequency depends on the total demagnetizing factor, this can be tuned using nanowire assembly morphology with specific wire lengths and interwire distances. The value of the effective interaction field is also dependent on the material by sample magnetization $M$, so this can be tuned by proper selection of materials.

\[\text{III. CONCLUSION}\]

The angular dependence of the ferromagnetic resonance (FMR) resonance field was investigated for Ni electrodeposited nanowire samples. Two different types of angular dependence of resonance field were experimentally observed for wire arrays of different lengths, and this was explained using an effective interaction field approach. The interaction field parallel and perpendicular to the wire axes was modeled taking into account the magnetic charges at the ends of the wires and on their lateral surface, respectively. A linear dependence of the interaction field with the sample porosity was found for long wires. By tuning porosity and the wire’s aspect ratio, it is possible to explore a large interval of interaction fields from negative to positive values.

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\[\text{REFERENCES}\]


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