An experimental analysis from the magnetic interactions in nanowire arrays

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Abstract
We studied the magnetic interactions experimentally in nanostructures of nano-wire arrays. The intensity value obtained for the interactions provides information about their magnetic behavior. Such behavior can be demagnetized or magnetized. Our approach represents the first experimental way to analyze magnetic interactions considering their magnetic dependence, which is very important for sensor applications, for example.

Keywords Energy · Experimental · Interactions · Nanostructures · Nanowires

Nanowires of magnetic materials have always been sources of research by the scientific community. Many research groups investigate the magnetic properties of nanometric systems (Zhang et al. 2019; Charilaou et al. 2018; Holanda et al. 2014, 2015; Masuda and Fukuda 1995; Cvelbar 2011; Stoner and Wohlfarth 1948; Landeros et al. 2007). Such interest is due particularly to the magnetic interactions that influence the properties of nanostructures (Wang et al. 2020; Shevchenko and Barabash 2022; Lavín et al. 2009; França et al. 2017; Encinas-Oropesa et al. 2001). As it is well known, magnetic interactions lead to complex phenomena that are far from well understood (Larsson et al. 2021; Honda et al. 2021; Zhou et al. 2014). One of the methods used to analyze these effects is the magnetization process. Such a process produces the remanent magnetization used as a source of information about the intensity value from the interactions (Lv et al. 2020; Liu et al. 2019; Kelly et al. 1989; Henkel 1964; Klik et al. 1997; Mayo et al. 1991). One can manipulate the magnetic interactions using the remanent state by the \( \Delta m \) curves. Such \( \Delta m \) curves are comparisons between isothermal remanent magnetization (IRM(\( H \))) and direct current demagnetization (DCD(\( H \))) curves (Estrada and Holanda 2022; Buehler and Mayergoyz 1996; Wohlfarth 1958; Holanda 2021; Hernández et al. 2009; Cornejo and Padrón-Hernández 2007; Escrig et al. 2008).

In this paper, we present an experimental analysis to determine the intensity value from the magnetic interactions in nanowire arrays electrodeposited on anodic aluminum oxide (AAO) membranes. We electrodeposited the nanowires of different materials (permalloy, iron, and cobalt) and interpreted the experimental results considering the angular dependence from the interactions. Through our analysis, we detected two types of magnetic behavior: demagnetized and magnetized. The demagnetized state refers to the process in which the predominant interactions are demagnetizing (PID). On the other hand, the magnetized state is when the predominant interactions are magnetizing (PIM). This type of analysis is of fundamental importance for applications in devices dependent on magnetic behavior (Zhang et al. 2019; Holanda et al. 2014, 2015).

In the Fig. 1, we present an illustration of a hexagonal distribution of nanowire arrays electrodeposited in membranes of anodic aluminum oxide (AAO), as in Refs. Holanda et al. (2014), Masuda and Fukuda (1995) and Cvelbar (2011).
electrodeposition method is well-known in the literature (Holanda et al. 2014; Masuda and Fukuda 1995; Cvelbar 2011; Lavín et al. 2009; França et al. 2017; Cornejo and Padrón-Hernández 2007). We also define in Fig. 1 the $t$ and $H$ angles, which are the angles that the magnetization and magnetic field, respectively, make with the axis of the nanowires during the measurements of IRM($H$) and DCD($H$) curves, which were performed by using a Vibrating Sample Magnetometer (VSM) model EV7 at room temperature.

The polycrystalline nanowire (permalloy, iron, or cobalt) arrays were electrodeposited onto AAO membranes. We manufacture some samples, i.e., electrodeposited membranes with pore diameters of $D = 18$ nm and a pore center-to-center distance of $d = 56$ nm, which we call NiFe-A (permalloy), Fe (iron), and Co (cobalt). We manufacture another sample, i.e., an electrodeposited membrane with a pore diameter of $D = 44$ nm and a pore center-to-center distance of $d = 98$ nm, which we call NiFe-B (permalloy). All electrodeposited nanowires have a length on the order of 1–5 μm.

In Fig. 2a-d we show the maps of experimental interactions in $θ_H = 00^\circ$, where the hatched areas represent the intersection of the curves defined by the equations

\[ m_{d2}(H) = \Delta m_{\text{Exp}} + \left[ 1 - 2m_r(H) \right], \]

and

\[ m_{d1}(H) = 1 - 2m_r(H). \]

Here $m_{d2} = \frac{\text{DCD}(H)}{\text{IRM}(H_{\text{Max}})}$, $m_{d1} = \frac{\text{DCD}(H)}{\text{IRM}(H_{\text{Max}})}$, and $m_r = \frac{\text{IRM}(H)}{\text{IRM}(H_{\text{Max}})}$ are the direct current demagnetizations (DCD($H$)) and isothermal remanent magnetization (IRM($H$)) curves, all normalized by the maximum value of the isothermal remanent magnetization (IRM($H$)) curve for the maximum magnetic field $H = H_{\text{Max}}$. The experimental term $\Delta m_{\text{Exp}}$ represents the magnetic interactions. In the Fig. 2a, we observe only PID interactions, which convey the influence of the amount of electrodeposited magnetic material. On the other hand, in the experimental interaction maps presented in Fig. 2b–d, we illustrate the evidence of PID and PIM interactions for each material (iron, cobalt, and permalloy). In the Table 1, we present the intensity values found for the PID and PIM interactions using the Eqs. (1) and (2) in $I = \lim_{\delta m_{\text{Exp}} \rightarrow 0} \sum_{i=1}^{N} |\Delta m_{\text{Exp},i}| \delta m_r(H)$ (Holanda 2021), where $\Delta m_{\text{Exp},i} < 0$ for PID and $\Delta m_{\text{Exp},i} > 0$ for PIM. The values

Fig. 2 a NiFe-A, b Fe, c Co, and d NiFe-B show the experimental interactions maps at $θ_H = 00^\circ$ for the different materials. e $θ_H = 30^\circ$, f $θ_H = 60^\circ$ and g $θ_H = 90^\circ$ show the angular dependence of experimental interactions maps for the NiFe-B sample, which has the largest amount of electrodeposited magnetic material.
Table 1  Show intensity values from the magnetic interactions of the PID and PIM interactions for each sample (NiFe-A, Fe, Co, and NiFe-B) at  θH = 0°

| Sample         | PID       | PIM       |
|----------------|-----------|-----------|
| NiFe-A         | 0.43 ± 0.003 | 0         |
| Fe             | 0.41 ± 0.004 | 0.00093 ± 0.000002 |
| Co             | 0.32 ± 0.003 | 0.00018 ± 0.000005 |
| NiFe-B         | 0.43 ± 0.004 | 0.00029 ± 0.000004 |

show the behavior from the magnetic interactions in each sample defining an intrinsic characteristic that can be used to define the behavior of interactions in devices.

In Fig. 2d–g, we show the behavior of the angular dependence of the experimental interaction maps of the NiFe-B sample for θH = 0°, θH = 30°, 60° and 90°. These maps show the variation in the intensity of the experimental term Δm_{Exp}. We observe from the experimental interaction maps of the Fig. 2d–g, that the PID and PIM interactions decrease as the angle θH increases. Such behavior is a result of the decrease in energy balance during the IRM and DCD measurements.

The mean-field approach introduced by Ref. Encinas-Oropesa et al. (2001) is an estimation of the dipolar energy in real nanowire arrays, which is an aspect important in this type of sample. Even in electrodeposited membranes with equally long nanowires, the dipole field is not uniform along the length of the nanowire. The inhomogeneous dipolar field leads to dipolar interactions between nanowires; the situation is even more complicated here because the length of the nanowire is not uniform. In general, the analysis of the angular dependence of the PID interactions for nanowire arrays needs to consider the energy density of packing of the nanowires in the array (Encinas-Oropesa et al. 2001), which may be written as \( E_{\text{PID}}^{NW} = -3\pi PM^2 \sin^2(\varphi_{\text{PID}} + \theta_H) \), where \( P = (\pi/2\sqrt{3})D/d^3 \) is the packing factor of the nanowires in the array, \( d \) is the interwire distance and \( D \) the diameter of nanowire and \( \varphi_{\text{PID}} \) is the PID angle defined by \( \varphi_{\text{PID}} = \theta_{\text{PID}} - \theta_H \). In this way, the angular dependence of intensity value for the PID interactions is described here for nanowire arrays by

\[
I_{\text{PID}} = I_{\text{PID}}^{NW}(0) \cos(\theta_H) + I_{\text{PID}}^{NW}(0) \sin^2(\varphi_{\text{PID}} + \theta_H),
\]

where \( I_{\text{PID}}^{NW}(0) \) and \( I_{\text{PID}}^{NW}(0) \) refer to the maximum values obtained for the intensities of interactions for the individual nanowires (NW) and the nanowire arrays (NWA) (Holanda 2021). In the Fig. 3, we present the angular variation of the PID and PIM interactions of the NiFe-B sample obtained through the experimental interaction maps using the same procedure realized to obtain the values in Table 1. We chose to analyze this sample, because it has the largest amount of electrodeposited magnetic material. Fitting the data of the Fig. 3a with Equation (3), we found \( I_{\text{PID}}^{NW}(0) = 0.42 \), \( I_{\text{PID}}^{NW}(0) = 0.35 \) and \( \varphi_{\text{PID}} = -7° \). The values obtained for the intensities \( I_{\text{PID}}^{NW}(0) \) and \( I_{\text{PID}}^{NW}(0) \) are in good agreement with the values of the Table 1 for PID interactions.

According to Fig. 3b, the NiFe-B sample exhibits PIM interactions. The PIM interactions are associated with the exchange interaction between grains or nanowires. The exchange energy density can be considered constant in the nanowires and for nanowire arrays can be written as \( E_{\text{Exc}} = -A \cos(\varphi_{\text{PIM}} + \theta_H) \), where \( A \) is the exchange constant (Holanda et al. 2014; Stoner and Wohlfarth 1948; Landeros et al. 2007; Lavín et al. 2009; França et al. 2017; Wohlfarth 1958) and \( \varphi_{\text{PIM}} \) is the PIM angle defined by \( \varphi_{\text{PIM}} = \theta_{\text{PIM}} - \theta_H \). Hence, the angular dependence of intensity value for the PIM interactions is written as Holanda (2021):

\[
I_{\text{PIM}} = I_{\text{PIM}}^{NW}(0) + I_{\text{PIM}}^{NW}(0) \cos(\varphi_{\text{PIM}} + \theta_H),
\]

where \( I_{\text{PIM}}^{NW}(0) \) and \( I_{\text{PIM}}^{NW}(0) \) represent the maximum value found for the intensities of interactions for the nanowires (NW) and nanowire arrays (NWA). Considering the data of the Fig. 3b and its respective fit with Eq. (4), we obtained \( I_{\text{PIM}}^{NW}(0) = 0.00049 \), \( I_{\text{PIM}}^{NW}(0) = 0.00052 \) and \( \varphi_{\text{PIM}} = 114° \).

The values obtained for the intensities \( I_{\text{PIM}}^{NW}(0) \) and \( I_{\text{PIM}}^{NW}(0) \) are in perfect agreement with Table 1 for PIM interactions. The angles \( \varphi_{\text{PID}} = -7° \) and \( \varphi_{\text{PIM}} = 114° \) reveal the positions of maximum equilibrium of the spins and its liquid magnetic moment associated during the experimental measurements. We observed a \( \varphi = -7° + 114° = 107° \) phase difference between the maximum equilibrium positions of the PID and PIM interactions. The observed phase difference is unequivocal evidence that we can separate magnetic interactions. Furthermore, the results show that magnetic interactions in nanostructures are complex (depending on material, shape, experimental configuration, and excitation parameters), and its analysis is fundamentally necessary for applications. The research supported by the experimental results presented here does not converge to the dependence of any magnetic instabilities in applications.

![Fig 3](image-url) Shows the angular dependence from the magnetic interactions PID (a) and PIM (b) for the NiFe-B sample.
Nanostructures, such as nanowires, are used in a diversity of applications spreading from nanoscale optoelectronic devices (such as sensors, for example) to high-density data storage media. The remnant state offers a fundamental and natural way of studying magnetic interactions for applications. In summary, the approach we present here incorporates the measurement of magnetic interactions experimentally. Furthermore, it represents a way of analyzing the value of the intensity of interactions considering them as PID and PIM, which is of fundamental importance to describe the behavior of magnetic interactions in devices.

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Data Availability Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Declarations

Conflict of interest There are no conflicts of interest to declare.

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