Synthesis and magnetism of modulated FeCo-based nanowires

Ester M Palmero‡, Cristina Bran, Rafael P del Real and Manuel Vázquez*
Institute of Materials Science of Madrid, CSIC, 28049 Madrid, Spain

E-mail: ‡ epalmero@icmm.csic.es, * mvazquez@icmm.csic.es

Abstract. FeCo based nanowire arrays have been proposed for different applications as high-density magnetic storage or spintronics. Depending on the application different magnetic properties are required and the electrochemical techniques are low-cost routes to tailor them, by tuning the nanowires composition and geometry. In this work two different types of nanowires are studied: multisegmented nanowires and nanowires with modulated diameter. The magnetic properties of multisegmented [FeCoCu(\(y\))/Cu(\(x\))]\(_{10}\) nanowire arrays have been studied considering different Cu layer thicknesses (\(x\)) and FeCoCu segment lengths (\(y\)). The obtained results show that the hard magnetic properties of these nanowire arrays present a higher coercivity and remanence comparing to the continuous nanowires, for thicker Cu layers and shorter FeCoCu segments. On the other hand, for the nanowires with modulated diameter it has been stated that the magnetization reversal process takes place by a vortex domain wall and with the tailored modulations along the nanowire it is possible to induce the domain wall pinning. This opens the possibility of controlling the domain wall motion along magnetic nanowires.

1. Introduction

Novel nanoscaled magnetic systems are attracting much interest in basic research and for their potential in advanced technologies as high-density magnetic storage, spintronic media, magnetotransport, logic circuits, sensing devices and biomedicine [1-6]. The importance of the increased packing density of integrated circuits and functional nanodevices in future technologies has called for advanced research in nanowires [7-10]. Particularly, the template-assisted electrodeposition of metallic elements and alloys as highly ordered nanowire arrays has been proved to be an interesting and low-cost alternative to enhance the magnetic data storage capability in perpendicular recording media [11, 12].

Different alternatives have been proposed to tune, according to the application, the magnetic properties of the nanowires and, consequently, of the nanowire array. Essentially, we can gather them into two main groups: tailor (i) the composition (single element, alloy or multilayer/multisegmented nanowires) and (ii) the geometry (modulation in diameter) of the nanowires. Considering the first group, Co, Fe and CoFe based nanowire arrays are being investigated due to their relevant magnetic and magnetotransport properties [13-17]. They have been proposed as a novel family of rare-earth free permanent magnets as they present a high saturation magnetization as well as high Curie temperature, which implies a high working temperature [18, 19]. It is well-known that the addition of a small amount of elements (e.g. C,
Cr, Cu, B, P, Mn, or V) as alloy doping can modify the mechanical, electrical, thermal or magnetic properties of the alloy [20-25]. Previous reports show that for FeCo nanowires the highest values of coercivity and magnetization at remanence are obtained for around 65-70% of Co in the alloy [17]. In the particular case of these magnetic FeCo nanowire arrays, it has been reported that the doping with a small amount of Cu, followed by suitable thermal treatment, induces relevant magnetic hardening [14, 26, 27].

On the other hand, adding non-ferromagnetic elements to the nanowires not only as a component into the alloy but as interfacial layers between ferromagnetic segments has been also studied [28-36]. Such multilayer systems include usually Cu, Pd, Pt and Au as non-ferromagnetic elements, showing interesting results in the way of tailoring the magnetic properties of the nanowire arrays, like magnetic hardening or their functionalization. The magnetic behavior of the multilayer/multisegmented nanowire arrays depends on the non-ferromagnetic and ferromagnetic layers/segments thicknesses and the ratio between them [28, 29, 31, 36, 37]. The magnetic behavior will be determined by the net interactions in the nanowire array: (i) intrawire interactions generated between the magnetic segments coupled by the non-ferromagnetic layers along the nanowire; and (ii) interwire interactions among neighbor nanowires induced by the stray fields generated by the magnetic segments [28, 31].

An alternative way to tune the magnetic properties of the nanowires is to tailor their geometry by modulating their diameter along the nanowire length (i.e. segments with different diameter along the nanowire) [38-42]. The fabrication of anodic aluminum oxide (AAO) templates by hard anodization process has been proved to be a suitable alternative fabrication method which optimizes the nanopores growth rate and allows for a fast hexagonal highly ordering [43, 44]. For the nanopores with modulated diameter, the combination of mild and hard anodization is used, which allows us to obtain segments with different diameter along the nanopores [39, 41-43, 45]. Tailoring the diameter and length of the different segments is a promising new route which provides the possibility of control the domain wall displacement along the nanowire [42, 46-48].

In this article we review recent results obtained for FeCo-based nanowires with: (i) modulated composition (i.e. multisegmented nanowires) and (ii) modulated diameter along the nanowire length. We show how it is possible to tune the magnetic properties of FeCo-based nanowire arrays by tailoring their composition and geometry. We overview the nanowire geometrical and crystallographic structure as well as the magnetic properties of the nanowire arrays and the magnetization reversal process of individual FeCo-based nanowires with modulated diameter. We have paid particular attention to the influence of the ferromagnetic/non-ferromagnetic segments/layers thickness on the multilayer nanowire arrays behaviour and the influence of the tailored periodical diameter modulations.

2. Synthesis of FeCo-based nanowires into Anodic Aluminium Oxide (AAO) membranes

2.1. AAO membranes fabrication

The AAO templates were produced by different anodization techniques as they present different geometries. The templates used to grow the multisegmented nanowires were fabricated by a two-step anodization process [49]. Those used to grow the modulated diameter nanowires were fabricated by hard [43, 44] and pulsed anodization [40, 41].

Previous to the anodization, the high purity (99.999%) Al foils were ultrasonically degreased in acetone for 10 min followed by 10 min in ethanol. The clean Al foils were electropolished in a mixed solution of perchloric acid and ethanol (1:3 in volume), under a constant voltage of 20 V for 5 min. Then, the polished foils were anodized.
The two-step anodization was carried out using a 0.3 M oxalic acid aqueous solution under a constant voltage of 40 V at 3 °C for 24 h and 20 h, first and second anodization step duration, respectively. The alumina barrier layer formed after the first anodization step was chemically etched by a mixed solution of 0.18 M CrO$_3$ and 0.72 M H$_3$PO$_4$ [17].

Templates with modulated diameter nanopores were fabricated by pulsed anodization. Additionally, hard anodization was used to fabricate the templates with non-modulated pores, to grow the non-modulated nanowires to be used as reference sample. The hard and pulsed anodization processes were both carried out using 0.3 M oxalic acid aqueous solution and 5% ethanol in volume at 0-1 °C. In the case of hard anodization, a pre-anodization was performed to create an alumina protective surface to avoid burning the Al foil. A constant potential of 80 V was applied for 5 min. Then, the voltage was increased using a voltage ramp (0.08 V/s) until reaching a voltage of 140 V which was kept constant for 1 h [50].

The pulsed anodization was performed in two different ways to obtain two different types of modulations. For both, firstly a pre-anodization was carried out (for the first type, constant voltage of 80 V for 15 min, followed by 5 min at 140 V; and 80 V for 10 min and after that 6 min at 100 V for the second one) and then pulses with different durations in time (pulses of 10 s at 80 V and 30 s at 140 V for the first type; and pulses at 130 V for 5 s and 150 s at 100 V for the second one). The modulations in the nanowire are obtained by controlling the duration and the amplitude of the hard anodization pulses [42, 50].

Once the porous membranes were obtained, they needed to be open at both sides to proceed with the nanowire electrodeposition. The residual Al was chemically etched by a mixed solution of 0.1 M CuCl$_2$·2H$_2$O and 1.6 M HCl. The alumina barrier layer was chemically removed and the modulated nanopores were enlarged by an aqueous H$_3$PO$_4$ solution (5 wt%).

2.2. Nanowires growth
Previous to the nanowire growth, a Au layer was sputtered at the bottom of the pores followed by Au electroplating into the pores in order to serve as a working electrode.

All the nanowire arrays reviewed in this work were grown in a three-electrode cell using a single Watts-type bath which composition was 0.12 M CoSO$_4$·7H$_2$O, 0.05 M FeSO$_4$·7H$_2$O, 0.01 M CuSO$_4$·5H$_2$O, 0.16 M H$_3$BO$_3$, and 0.06 M C$_6$H$_8$O$_6$, and the pH was 3.0.

FeCoCu/Cu multilayer nanowires were grown by pulsed electrodeposition. The potential used to grow the ferromagnetic segments (FeCoCu) was -1.5 V and -0.3 V for the non-ferromagnetic layers (Cu), both versus Ag/AgCl reference electrode. Two series of multilayer nanowire arrays were prepared, where each nanowire is composed by ten FeCoCu/Cu bilayers: (i) FeCoCu segment thickness was kept constant (25 s electrodeposition time) and the pulses of Cu electroplating were varied between 5 and 60 s; and (ii) constant Cu layer thickness (15 s) and the FeCoCu electroplating pulses were varied between 10 and 60 s. Additionally, a continuous FeCoCu nanowire array was prepared to be used a reference sample. It was electroplated using the same composition bath and applying a voltage of -1.5 V for 6 min [51].

The modulated nanowires were grown under an electroplating potential of -1.8 V vs. Ag/AgCl reference electrode at room temperature [50].

3. Geometrical, compositional and microstructure characterization
The nanowire geometrical characterization was performed by a Nova Nano 230 High Resolution Scanning Electron Microscope (SEM), the composition was determined by Energy
Dispersive X-ray Spectrometer (EDS) and the morphology and microstructure characterization was carried out by High-Resolution Transmission Electron Microscopy (HRTEM) and Selected Area Electron Diffraction in an image-corrected FEI Titan Cube 60–300.

3.1. Multisegmented nanowires

All the multisegmented nanowire arrays presented a hexagonal highly ordered structure where the nanowire diameter ($d$) had a constant value of 35 nm and the distance between nanowire centres ($D_{int}$) was 105 nm (Figure 1(a)). The first set of multisegmented [$FeCoCu/Cu(x)_{10}$] nanowire arrays were fabricated with constant FeCoCu segment length of 300 nm and with Cu layer thickness ($x$) ranging between 7 and 40 nm. The second series of multisegmented [$FeCoCu(y)/Cu_{10}$] nanowire arrays where grown, keeping constant the Cu layer thickness with a value of 15 nm and varying the FeCoCu segment length ($y$) from 120 to 900 nm. An example is shown in Figure 1(b). The nanowire total length ($L$) for the [$FeCoCu(300 nm)/Cu(x)_{10}$] series varies from 3.07 to 3.40 µm, and for the [$FeCoCu(y)/Cu(15 nm)_{10}$] series ranges between 1.35 and 9.15 µm. The EDS analysis confirmed that the composition of the continuous FeCoCu nanowires and, consequently, that of the FeCoCu segments in the multilayer nanowires, was $Fe_{30}Co_{44}Cu_{6}$ [51].

The nanowires present a polycrystalline structure as is concluded from the granular-like contrast in the bright field image (see Figure 1(c)). Figure 1(d) shows a HRTEM image of a Cu layer. In this image multiple sets of fringes are found in different regions, related to the presence of grains with different crystallographic orientations. To determine the crystal structure of the FeCoCu segment and the Cu layer, it was performed a local Fourier analysis. Both present a polycrystalline structure. The Fast Fourier Transform (FFT) in the Cu area presents reflections at approximately 2.08 and 1.80 Å corresponding to $fcc$ $(111)$ and $(200)$ planes (Figure 1(e)). The FFT for the FeCoCu area present reflections at around 2 Å, associated with a $(110)$ $bcc$ structure (Figure 1(f)). The detailed analysis of the chemical composition of the multilayer nanowires was performed by Scanning Transmission Electron Microscopy (STEM). The combination of High-Angle Annular Dark Field (HAADF) and Electron Energy Loss Spectroscopy (EELS) was used to acquire spectrum images (SI) of the different regions. The chemical map of a [$FeCoCu(300 nm)/Cu(7 nm)_{10}$] multilayer nanowire is shown in Figure 1(g). We observe that the Cu layers (green colour) are perfectly segregated from the FeCoCu segments (red colour), and they present an irregular and rough shape, probably caused by their polycrystalline nature, the large grain size, and possible inhomogeneities during the growth. Additionally, an oxidation layer is observed all around the nanowire (see blue colour at the surface), evidenced by the high oxygen content at the nanowire surface. It was determined that the oxidation layer present a thickness of 9 nm at the FeCoCu surface, while at the Cu surface the oxidation layer thickness decreases to less than 4 nm [51].
meter modulations were fabricated, namely 2,3: wide segments (equation not shown) of the multilayer nanowires inside the AAO membrane. TEM images of \([\text{FeCoCu}(300 \, \text{nm})/\text{Cu}(15 \, \text{nm})]_{10}\) multilayer nanowires: (c) Bright field image of an individual nanowire; (d) HRTEM image of a Cu spacer; (e) and (f) FFT at Cu and FeCoCu regions of the HRTEM image, respectively. (g) STEM-EELS chemical mapping of \([\text{FeCoCu}(300 \, \text{nm})/\text{Cu}(7 \, \text{nm})]_{10}\) nanowires: low magnification SI of one of the nanowires, including the HAADF and the RGB composition of the Co L\text{2,3} \,(red), \, \text{Cu L}_{2,3} \,(green), \, \text{and O K} \,(blue) integrated intensities. TEM images adapted from Palmero et al. [51].

### 3.2. Nanowires with modulated diameter

In order to characterize individually the modulated diameter nanowires, they were released from the templates by chemical dissolution of the membranes (see Figure 2). Firstly, the Au layer was chemically etched by a mixture of iodine and potassium iodide. Then, the alumina template was dissolved by a mixed solution of CrO\text{3} and H\text{3}PO\text{4}. After that, the modulated nanowires were cleaned, immersed in ethanol and dispersed on Si a substrate.

Nanowires with constant diameter (as reference sample) and two types of nanowires with two types of diameter modulations were fabricated, namely \textit{Modulated A}: wide segments (\(D_1\) in diameter and \(L_1\) in length) shorter than the narrow ones (\(D_2\) in diameter and \(L_2\) in length); and \textit{Modulated B}, with the narrow segments shorter than the wide ones (see Figure 2). The geometrical parameters (i.e. segment diameters and lengths, and nanowire total length, \(L_f\)) were measured by SEM and the values are collected in Table 1. The composition of the modulated nanowires was confirmed to be Fe\textsubscript{36}Co\textsubscript{63}Cu\textsubscript{7} by means of EDS technique [50].

![Figure 1](image-url)
The magnetic characterization of single nanowires with modulated diameter was performed by Magneto-Optical Kerr Effect (NanoMOKE™ 2), applying a maximum magnetic field of ±500 Oe in parallel (|| to the nanowires) or perpendicular (⊥ to the nanowires) configuration. On the other hand, the magnetic characterization of single nanowires with modulated diameter was determined by measuring the hysteresis loops using a Vibrating Sample Magnetometer (VSM), ADE system EV7 KLA-Tencor, applying a maximum magnetic field of ±18 kOe in parallel (|| to the nanowires) or perpendicular (⊥ to the nanowires) configuration.

**Table 1.** Geometrical characterization of the FeCoCu nanowires shown in Figure 2. It also includes the fitted exchange constant, $A_{exc}$ (see Section 4.2 in the text).

| Sample | Type         | $D_1$ (nm) | $L_1$ (nm) | $D_2$ (nm) | $L_2$ (nm) | $L_T$ (μm) | $A_{exc} \cdot 10^6$ (erg/cm) |
|--------|--------------|------------|------------|------------|------------|------------|-----------------------------|
| S1     | Constant diameter | 150        | -          | -          | -          | 10         | 3.45                        |
| S2     | Modulated A (a) | 170        | 50         | 150        | 400        | 14         | 3.65                        |
| S3     | Modulated A (b) | 170        | 50         | 150        | 800        | 13         | 3.09                        |
| S4     | Modulated B   | 130        | 1000       | 100        | 300        | 17         | 2.24                        |

**Figure 2.** SEM images: cross-section of nanowires embedded into AAO membranes with (a) constant diameter and (b) modulated diameter, sample S2; single nanowires on silicon substrate: (c) constant diameter, sample S1; (d), (e) and (f) modulated diameter nanowires, samples S2, S3 and S4, respectively. Figures (d) to (f) adapted from Palmero et al. [50].

**4. Magnetic characterization**

The magnetic properties of the multisegmented nanowire arrays were determined by measuring the hysteresis loops using a Vibrating Sample Magnetometer (VSM), ADE system EV7 KLA-Tencor, applying a maximum magnetic field of ±18 kOe in parallel (|| to the nanowires) or perpendicular (⊥ to the nanowires) configuration.
Each MOKE hysteresis loop was the result of 1000 averaged loops, in order to reduce the noise to signal ratio.

4.1. Magnetic behaviour of multisegmented nanowires

The normalized hysteresis loops (i.e. fractional magnetization \(M/M_s\)) vs. applied magnetic field \((H)\) of \([\text{FeCoCu(300nm)/Cu(15nm)}]_{10}\) and \([\text{FeCoCu(y)/Cu(15nm)}]_{10}\) multilayer nanowire arrays and of the FeCoCu alloy nanowire array are plotted in Figure 3.

![Figure 3](image)

Figure 3. Hysteresis loops measured in parallel field configuration: (a) \([\text{FeCoCu(300nm)/Cu(15nm)}]_{10}\) series for different Cu layer thicknesses and (b) \([\text{FeCoCu(y)/Cu(15nm)}]_{10}\) series for different FeCoCu segment lengths. Adapted from Palmero et al. [51].

From the hysteresis loops, we determined the coercivity \(H_c\), fractional remanence \(M_r/M_s\) and differential magnetic susceptibility around the coercivity \((\chi=dM/dH\text{, for parallel field configuration})\). The values for both series of multilayer nanowire arrays as a function of the Cu layer thickness and FeCoCu segments length are plotted in Figure 4. The data for continuous FeCoCu nanowire array are also included for comparison. For the continuous FeCoCu nanowires, it was calculated a value for the saturation magnetization, \(M_s\), of 1448 emu/cm³, while for the multilayer nanowire arrays a maximum reduction of 11% in \(M_s\) was determined from the comparison with the continuous nanowires.

A magnetization easy axis parallel to the nanowire axis is determined according to the high values of the fractional remanence under parallel configuration and the vanishing values for the perpendicular configuration (Figure 4). All the magnitudes (i.e. coercivity, \(H_c\), fractional remanence, \(M_r/M_s\), and susceptibility, \(\chi\)) show a general trend to increase with the Cu layer thickness for parallel field configuration, while for perpendicular field configuration, both \(H_c\) and \(M_r/M_s\) show small values (see Figure 4(a)). On the other hand, \(H_c\) and \(M_r/M_s\) when increasing the FeCoCu segments length for constant the Cu layer thickness \((x=15\text{nm})\) present a moderate and relatively complex variation (see Figure 4(b)). It is worth mentioning that the susceptibility shows a significant reduction for FeCoCu segment up to around 300 nm long while it remains almost constant for larger thicknesses [51].
Figure 4. Coercive field, $H_c$, and fractional remanence, $M_r/M_s$, in parallel (||) and perpendicular (⊥) field configuration, and differential susceptibility, $\chi$, for (a) [FeCoCu(300nm)/Cu(x)]$_{10}$ and (b) [FeCoCu(y)/Cu(15nm)]$_{10}$ series. The single scatters represent the data for continuous FeCoCu alloy nanowires. (c) Henkel plots for different [FeCoCu(y)/Cu(x)]$_{10}$ multilayer nanowires. The black line shows the behaviour of non-interacting nanocylinders. Adapted from Palmero et al. [51]

Henkel plots were obtained for FeCoCu/Cu multilayer nanowire arrays in order to get more information about the magnetic interactions between nanowires in the array. Henkel plots represent the values of dc-demagnetization (DCM) as a function of isothermal remanent magnetization (IRM), both normalized. A more detailed description of the measurement process can be found elsewhere [52]. In Figure 4(c) the Henkel plots are shown for several [FeCoCu(y)/Cu(x)]$_{10}$ nanowire arrays for parallel field configuration. The values for $x$ and $y$ for each nanowire array are indicated in the graph. A black line has been added to the graph, which represents a theoretical system of non-interaction nanoparticles (Wohlfarth model) [53-54].

In a multilayer nanowire array, we can consider two types of interactions: (i) intra-wire (positive) interactions between adjacent magnetic layers along each nanowire which favour the parallel alignment of the magnetization within the wire; and (ii) the inter-wire (negative) magnetostatic interactions between magnetic layers of adjacent nanowires which increase the effective demagnetization factor [28, 31]. According to the Henkel plots in Figure 4(c), the net magnetostatic interactions in all the multilayer nanowire arrays are demagnetizing since all the curves fit below the Wohlfarth model line. For nanowire arrays with the same FeCoCu segment length ($y = 300$ nm), the one with thickest Cu layer ($x = 40$ nm) is closer to the non-interacting line. On the other hand, for constant Cu layer thickness ($x = 15$ nm), the nanowire array with the shortest FeCoCu segments ($y = 120$ nm) is closer to the Wohlfarth line. According to these results, we can conclude that thicker Cu layers and shorter FeCoCu segments promote a decrease of the dipolar interaction field in the nanowire array [51].

4.2. Magnetic behaviour of individual modulated diameter nanowires

Magneto-Optical Kerr Effect (MOKE) hysteresis loops measurements were used to characterize isolated nanowires with modulated diameter. Firstly, for each type of nanowire the hysteresis loop was obtained by focusing the laser spot on the centre of the nanowire (see Figure 5). For all the nanowires, the normalized longitudinal Kerr effect signal at remanence is close to 1, suggesting the existence of a nearly single domain structure with magnetization easy axis lying along the nanowire. In the case of the nanowires with constant diameter (Figure 5(a)), we observed a squared hysteresis loop with a sharp transition between two stable magnetic states at remanence, a single giant Barkhausen jump [44, 55]. In the same way, only one sharp transition is observed for the Modulated A (a) nanowire with shorter thin segments (Figure 5(b)). In contrast, for the Modulated A (b) nanowire with longer narrow segments, two abrupt and symmetric magnetization jumps are observed in each branch of the hysteresis loop (Figure 5(c)). In the case of the Modulated B nanowire, the hysteresis loop presents a main Barkhausen jump.
together with several additional ones of less amplitude (Figure 5(d)). The hysteresis loops measured for *Modulated A* (b) and *Modulated B* nanowires suggest the existence of metastable magnetic states during the magnetization reversal process, which can be correlated to their particular diameter modulations [38, 50].

The variation of the magnetization process was also studied performing the MOKE measurements along the nanowire, obtaining the hysteresis loops at different positions along the nanowires length (see the obtained profile in Ref. [50]). The measurements were performed along the nanowire from one end to the other using steps of 1 µm. It was observed that the MOKE electrical signal obtained at the ends of the nanowire was several times smaller than when the measurement was performed focusing the laser spot at the nanowire centre. Along the nanowire, again several steps are observed that suggest metastable states in the magnetization reversal process that can be correlated to pinning centres for the domain wall propagation at local diameter modulations. For comparison, additional local MOKE measurements were carried out along a nanowire with constant diameter. In this case, the hysteresis loops present square shapes along the nanowire with single Barkhausen jumps. Similar coercivites were obtained at the different positions along the nanowire although, as similar to the modulated nanowire, at the ends the MOKE signal was reduced seemingly as a consequence of the formation of closure domain structures. The similar values of coercivity and hysteresis loop shape indicate that the magnetization reversal process takes place uniformly along the nanowire with constant diameter [56], allowing us to ascribe the small Barkhausen jumps observed in modulated nanowires to pinning sites correlated to diameter modulations [50].

A method to determine the coercivity mechanism of magnetic nanowire is the quantification of the angular dependence of the magnetization process [57]. Previous works about demagnetization process in nanowires by means of micromagnetic simulations proposed that
this process in nanowires with constant diameter and effective longitudinal axial anisotropy takes place by the depinning of a domain wall from one nanowire end followed by its propagation along the wire [58]. The hysteresis loops obtained from the angular measurements performed on the Modulated B nanowires are shown in Figure 6(a). It was observed a similar behaviour for all the samples, obtaining an increasing switching field, $H_{sw}$, with the angle, $\theta$ (Figure 6(b)). Note that for $\theta > 60^\circ$, the maximum magnetic field available in the setup was not enough to give rise to the reversal process.

The increasing coercivity with the angle of the applied magnetic field with the nanowire axis as it is observed in Figure 6(b) can be ascribed to the propagation of a vortex domain wall [59]. In the case of a vortex magnetization reversal mode, the angular dependence of the coercivity for an isolated nanowire with high aspect ratio is given by the following expression [60]:

$$H_{sw} = \frac{8q^2A_{exc}}{M_s D^2} \left(2\pi - \frac{4q^2A_{exc}}{\pi M_s D^2}\right) \sqrt{\frac{16q^4A_{exc}^2}{\pi^2 M_s^2 D^4} \sin^2 \theta + \left(2\pi - \frac{4q^2A_{exc}}{\pi M_s D^2}\right)^2 \cos^2 \theta}$$

(1)

In this equation, the parameter $q^2$ takes a value of 1.08$\pi$ for a cylindrical geometry [61], $D$ is the nanowire diameter, $A_{exc}$ is the exchange constant and $M_s$ is the saturation magnetization, which for this particular FeCoCu alloy is $M_s(Fe_{70}Co_{30}Cu) = 1448 \text{ emu/cm}^3$ [51]. The experimental data obtained for the angular dependence of the switching field for the different nanowires were fitted using Equation 1 (dashed lines in Figure 6(b)). For the modulated wires, the best fitting curves were obtained for the wide segments diameter ($D_s$). By fitting the experimental data, reasonable values of $A_{exc}$ were obtained (see Table 1) according to previous data for the nanowire alloy [62].
5. Conclusions

This work reports two different ways to tune the magnetic properties of nanowires by tailoring their composition or geometry. Both alternatives can be controlled by low-cost electrochemical processes modifying the fabrication parameters. For the first group, multilayer \([\text{FeCoCu}(y)/\text{Cu}(x)]_{10}\) nanowire arrays were fabricated with different FeCoCu segment lengths and Cu layer thicknesses, and constant diameter of 35 nm. The segments and the layers present both polycrystalline cubic structures, \(\text{fcc}\) and \(\text{bcc}\) structures, respectively. For all the samples, it was determined a magnetization easy axis parallel to the nanowires. For constant FeCoCu thickness, the coercivity, remanence and susceptibility increase with Cu layer thickness, while for the series with constant Cu layer thickness, a significant decrease of susceptibility with FeCoCu thickness was observed. A complementary Henkel curves study indicates that the net inter/intra nanowires magnetostatic interactions always contribute to demagnetization of nanowires. The results show a decrease in the effective magnetostatic interactions for multilayer nanowires with thicker Cu and thinner FeCoCu layers arising from stray fields at the surface of intra-wire and adjacent inter-wires magnetic layers. The hard magnetic characteristics of the multilayer nanowire arrays present a moderate improvement with regards to the continuous nanowire array in the case of thicker Cu layer and shorter FeCoCu segments.

For single modulated nanowires we can conclude from the MOKE measurements that the magnetization reversal process involves a giant Barkhausen jump preceded or followed by smaller jumps, which can be ascribed to the pinning of the domain wall at the diameter modulations as the smaller jumps are not present in the nanowires with constant diameter. Additionally, the experimental results from the angular dependence of the switching field and its analytical calculations, allow us to conclude that the coercivity mechanism corresponds to the propagation of a vortex domain wall. The domain wall is eventually pinned at local modulations along the nanowire resulting in metastable magnetic states during its propagation. This work opens new opportunities to further control the motion of domain walls through a further tailoring of nanowire diameter modulations.

Acknowledgments

This work was supported by the Spanish Ministerio de Economia y Competitividad under Project MAT2013-48054-C2-1-R, by the European Community’s 7th Framework Program under Project REFREEPERMAG, Grant Agreement 280670, and by the Spanish National Research Council under project 201460E014.

References

[1] Mourachkine A, Yazyev O, Ducati C and Ansermet J-P 2008 Nano Letters 8 3683
[2] Gao N, Wang H and Yang E-H 2010 Nanotechnology 21 105107
[3] Kou X, Fan X, Dumas R K, Lu Q, Zhang Y, Zhu H, Zhang X, Liu K and Xiao J Q 2011 Adv. Mat. 23 1393
[4] Chen X, Wong CK, Yuan CA and Zhang G 2013 Sens. Act. B: Chem. 177 178
[5] Lavrijsen R, Lee J-H, Fernández-Pacheco A, Petit DC, Mansell R and Cowburn R P 2013 Nature 493 647
[6] Lee D J, Kim E, Kim D, Park J and Hong S 2013 ACS Nano 7 6906
[7] Allwood D A, Xiong G, Faulkner C, Atkinson D, Petit D and Cowburn R 2005 Science 309 1688
[8] Terabe K, Hasegawa T, Liang C and Aono M 2007 Sci. Tech. Adv. Mater. 8 536
[9] Parkin S S, Hayashi M and Thomas L 2008 Science 320 190
[10] Chałupniak A, Morales-Narváez E and Merkoçi A 2015 Adv. Drug Deliv. Rev. 95 104
[11] Losic D and Losic D Jr 2009 Langmuir 25 5426
[12] Sousa C, Leitao D, Proenca M, Ventura J, Pereira A and Araujo J 2014 App. Phys. Rev. 1 031102
[13] Gandha K, Elkins K, Poudyal N, Liu X and Liu J P 2014 Sci. Rep. 4 5345
[14] Bran C, Palmero E M, del Real R P and Vazquez M 2014 Phys. Status Solidi A 211 1076
[15] Kuz’min M, Skokov K, Jian H, Radulov I and Gutfleisch O 2014 J. Phys. Condens. Matter 26 064205
[16] Gandha K, Tsai P, Chaubey G, Poudyal N, Elkins K, Cui J and Liu J P 2015 Nanotechnology 26 075601
[17] Bran C, Palmero E M, Li Z-A, del Real R P, Spasova M, Farle M and Vazquez M 2015 J. Phys. D: Appl. Phys. 48 145304
[18] Coey J 2011 IEEE Trans. Magn. 47 4671
[19] Lewis L H and Jiménez-Villacorta F 2013 Metall. Mater. Trans. A 44 2
[20] Chen Y, Tzeng H, Wei L, Wang L, Oung J and Shih H 2005 Science 310 1001
[21] Fu J, Yan Z, Xu Y, Fan X and Xué D 2007 J. Phys. Chem. Solids 68 2221
[22] Sharif R, Shamaila S, Ma M, Yao L, Yu R, Han X, Wang Y and Khaleeq-ur-Rahman M 2008 J. Magn. Magn. Mater. 320 1512
[23] Baker T 2009 Mater. Sci. Tech. 25 1083
[24] Liu Z, Li W, Jin P and Fei W 2013 J. Magn. Magn. Mater. 345 96
[25] Hussein M A, Mohammed A S and Al-Aqeeli N 2015 Materials 8 2749
[26] Bran C, Ivanov Y P, García J, del Real R P, Prado V, Chubykalo-Fesenko O and Vazquez M 2013 J. Appl. Phys. 114 043908
[27] Rodríguez-González B, Bran C, Warnatz T, Rivas J and Vazquez M 2014 J. Appl. Phys. 115 133904
[28] Carignan L-P, Lacroix C, Ouimet A, Ciureanu M, Yelon A and Ménard D 2007 J. Appl. Phys. 102 023905
[29] Béron F, Carignan L-P, Menard D and Yelon A 2008 IEEE Trans. Magn. 44 2745
[30] Jeon I T, Yoon S J, Kim B G, Lee J S, An B H, Ju J-S Wu J H and Kim Y K 2012 J. Appl. Phys. 111 07B513
[31] Krimpalis S, Dragos O-G, Moga A-E, Lupu N and Chiriac H 2011 J. Mater. Res. 26 1081
[32] Elbaile L, Cubero I, Crespo R, Vega V and Garcia J 2012 J. Alloy Compd. 536 S359
[33] Qi K, Li X, Zhang H, Wang L, Xue D, Zhang H, Zhou B, Mellors N J and Peng Y 2012 Nanotechnology 23 505707
[34] Jaleh B, Koosha F and Dezfuli A O 2014 J. Supercond. Nov. Magn. 27 1065
[35] Yang W, Cui C, Liu Q, Cao B, Liu L and Zhang Y 2014 J. Cryst. Growth 399 1
[36] Hnida KE, Żywczak A, Gajewksa M, Marciszko M, Sulka G D and Przybylski M 2016 Electrochim. Acta 205 29
[37] Clime L, Zhao S, Chen P, Normandin F, Roberge H and Veres T 2007 Nanotechnology 18 435709
[38] Pitzsche K, Bachmann J, Martens S, Montero-Moreno J M, Kimling J, Meier G, Escrig J, Nielsch K and Görlitz D 2011 J. Appl. Phys. 109 033907
[39] Esmaeily A, Venkatesan M, Razavian A S and Coey J 2013 J. Appl. Phys 113 17A327
[40] Salem M S, Sergelius P, Corona R M, Escrig J, Görlitz D and Nielsch K 2013 Nanoscale 5 3941
[41] Minguez-Bacho I, Rodríguez-López S, Vázquez M, Hernández-Vélez M and Nielsch K 2014 Nanotechnology 25 145301
[42] Bran C, Berganza E, Palermo E M, Fernandez-Roldan J, del Real R P, Aballe L, Foerster M, Asenjo A, Fraile-Rodríguez and Vazquez M 2016 J. Mater. Chem. C 4 978
[43] Lee W, Ji R, Gösele U and Nielsch K 2006 Nat. Mater. 5 741
[44] Vega V, Böhmer T, Martens S, Waleczek M, Montero-Moreno J M, Görlitz D, Prado V M and Nielsch K 2012 Nanotechnology 23 465709
[45] Pitzschel K, Montero-Moreno J M, Escrig J, Albrecht O, Nielsch K and Bachmann J 2009 ACS Nano 3 3463
[46] Yuan H and Wang X 2014 Phys. Rev. B 89 054423
[47] Chen T-C, Kuo C-Y, Mishra AK, Das B and Wu J-C 2015 Physica B 476 161
[48] Lage E, Urs N O, Siddiqui S, Baldo M, McCord J and Ross C A 2016 IEEE Magn. Lett. 7 1
[49] Masuda H and Fukuda K 1995 Science 268 1466
[50] Palmero E M, Bran C, del Real R P and Vázquez M 2015 Nanotechnology 26 461001
[51] Palmero E M, Bran C, del Real R P, Magen C and Vazquez M 2014 IEEE Magn. Lett. 5 6700304
[52] García-Otero J, Porto M and Rivas J 2000 J. Appl. Phys. 87 7376
[53] Wohlfarth E P 1958 J. Appl. Phys. 29 595
[54] Samwel E O, Bissel P R and Lodder J C 1993 J. Appl. Phys. 73 1353
[55] Vilanova-Vidal E, Ivanov Y P, Mohammed H and Kosel J 2015 Appl. Phys. Lett. 106, 032403
[56] Burn D M, Arac E and Atkinson D 2013 Phys. Rev. B 88, 104422
[57] Kronmüller H and Fähnle M 2003 Micromagnetism and the Microstructure of Ferromagnetic Solids, Cambridge Univ. Press, Cambridge
[58] Vázquez M (ed) 2015 Magnetic Nano- and Microwires (Cambridge: Woodhead) ch 14, 22, 25
[59] Tejo F, Vidal-Silva N, Espejo A P and Escrig J 2014 J. Appl. Phys. 115, 17D136
[60] Aharoni A 1997 J. Appl. Phys. 82, 1281
[61] Shtrikman S and Treves D 1963 Magnetism, Vol. 3 (Eds: G.T. Rado, and H. Suhl), Academic, New York
[62] Liu X, Sooryakumar R, Gutiérrez C J and Priz G A 1994 J. Appl. Phys. 75, 7021