Magnetic properties of Ni–Fe nanowire arrays: effect of template material and deposition conditions

S Aravamudhan1,4, J Singleton2, P A Goddard3 and S Bhansali1

1 Department of Electrical Engineering, Nanomaterials and Nanomanufacturing Research Center (NNRC), University of South Florida, Tampa, FL 33620, USA
2 National High Magnetic Field Laboratories (NHMFL), Los Alamos National Laboratory, Los Alamos, NM, USA
3 Clarendon Laboratory, Department of Physics, University of Oxford, Oxford, UK
E-mail: saravamu@gatech.edu and bhansali@eng.usf.edu

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Abstract
The objective of this work is to study the magnetic properties of arrays of Ni–Fe nanowires electrodeposited in different template materials such as porous silicon, polycarbonate and alumina. Magnetic properties were studied as a function of template material, applied magnetic field (parallel and perpendicular) during deposition, wire length, as well as magnetic field orientation during measurement. The results show that the application of magnetic field during deposition strongly influences the c-axis preferred orientation growth of the Ni–Fe nanowires. The samples with magnetic field perpendicular to the template plane during deposition exhibit strong perpendicular anisotropy with greatly enhanced coercivity and squareness ratio, particularly in the Ni–Fe nanowires deposited in polycarbonate templates. In the case of polycarbonate template, as magnetic field during deposition increases, both coercivity and squareness ratio also increase. The wire length dependence was also measured for polycarbonate templates. As wire length increases, coercivity and squareness ratio decrease, saturation field increases. Such magnetic behaviour (dependence on template material, magnetic field, wire length) can be qualitatively explained by preferential growth phenomena, dipolar interactions among nanowires and perpendicular shape anisotropy in individual nanowires.

1. Introduction
In recent years the increasing interest in highly ordered artificial magnetic nanostructures has been driven not only by a desire to understand the fundamental properties of these materials but also by the diversity of their potential applications. Such applications range from magnetic recording to sensors and bio-magnetism [1–3]. Nanoscale magnetic arrays are attractive as ultra-high density storage media. The magnetic density in conventional longitudinal recording is typically less than 50 Gb inch−2, limited by thermal instability [38]. However, nanoscale magnetic arrays have the potential to produce recording up to 100 times greater than existing random access memories [4–6]. The other field of extremely promising applications is bio-magnetism, as the magnetic nanowires can be manipulated and probed by magnetic interactions [7]. The spectrum of applications in bio-magnetism includes cell separation [9], bio-sensing [8], cellular studies [10, 11] and a variety of other therapeutic applications [7]. Holmgren et al performed both high yield (>90%) and high purity single step cell separations on NIH-3T3 mouse fibroblast cells by applying magnetic forces through nanowires [12]. These nanostructures have also been

4 Author to whom any correspondence should be addressed. Now with Nanotechnology Research Center (formerly Microelectronics Research Center), Georgia Institute of Technology, Atlanta, GA 30332, USA.
explored for use in drug delivery and gene therapy. Further, as nanowires are quasi-one-dimensional, high-aspect ratio (>100) structures they have a large surface to volume ratio. Thus, nanowire-based sensors allow for higher sensitivity, higher capture efficiency and faster response time, due to their large adsorption surface and small diffusion time [13]. Many types of magnetic nanowire arrays (metals, alloys or multi-layer structures) have been previously investigated [16]. Amongst the various materials studied, Ni–Fe is attractive because of its superior ferromagnetic properties, high magnetization behaviour and invar effect in certain compositions [17, 18].

One-dimensional nanostructures can be produced by a variety of techniques such as molecular beam epitaxy, nanolithography, vapour–liquid–solid growth and electro-deposition. Electrodeposition of metals into the pores of nanoscale templates (such as alumina membranes, nuclear track-etched polymer membranes, mesoporous silica or porous silicon) has been particularly attractive [19, 20] because (a) it is a simple, low-cost, high-throughput technique for fabricating large arrays of nanowires with monodisperse diameter and length, (b) it provides the ability to tailor size, length, shape and morphology of the material deposited by controlling the template morphology and the synthesis parameters and (c) it provides the ability to introduce composition modulation along the wire length, which in turn enables precise control on architecture and magnetic properties. For example, Reich et al showed selective binding of two different ligands onto two-component Ni/Au nanowires, thus enabling spatially modulated functionalization schemes [1]. Such properties can potentially give rise to improved performance in bio-magnetic applications.

The magnetic properties of nanowire arrays are directly related to the template properties—pore dimensions, relative pore orientation, pore size distribution and pore surface roughness. To date, most of the research work has focused on studying the magnetic properties of nanowires by either changing their electrodeposition parameters or their template parameters such as pore diameter and inter-pore spacing [21, 22]. In this work, in addition to the comparative study of magnetic nanowires deposited in different templates, we also investigate the influence of applied magnetic field during electrodeposition of the Ni–Fe nanowires on their crystallographic and magnetic properties. Furthermore, in addition to the traditional templates such as porous alumina and polycarbonate, which have been studied exhaustively in the literature [23–25], the magnetic properties of the Ni–Fe nanowires deposited in porous silicon were also investigated. In a previous work, we demonstrated the ability to control the porous silicon dimensions (pore diameter, 40–290 nm and length, up to 240 µm) and then successfully electroplated metal ions into the pores [26]. Furthermore, in order to investigate the magnetostatic coupling effect on the overall magnetic properties, nanowires of different wire lengths were studied.

2. Experimental details

The magnetic nanowire arrays are prepared by electroplating Ni–Fe into the pores of Anopore® alumina membranes5, Nuclepore polycarbonate track-etched membranes3 and in-house prepared porous silicon templates. The alumina and polycarbonate membranes are thoroughly cleaned in de-ionized water and subsequently dried prior to use. The porous silicon template is prepared in-house by electrochemical etching of silicon substrate [26, 27]. N-type 2” silicon substrate (resistivity: 0.4–0.6 Ω cm) is etched in a mixture of 1 : 1 : 49% HF : ethanol at a constant current density of 35 mA cm−2. Ethanol is added to the HF solution to (a) increase the wettability of porous silicon surface and (b) to remove hydrogen evolved during etching.

A film of aluminium (~1 µm) is evaporated on one side of all the templates to serve as the working electrode. This is followed by the electrochemical deposition of Ni–Fe into the templates from a sulfate based electroplating bath (200 g L−1 NiSO4 · 6H2O, 8 g L−1 FeSO4 · 6H2O, 5 g L−1 NiCl2 · 6H2O, 25 g L−1 H3BO3, 3 g L−1 saccharin). As the stoichiometry of the Ni–Fe nanowires is significantly affected by plating temperature, pH, agitation conditions, current and additives, all the parameters have been maintained constant, except for the electroplating time. In the polycarbonate template, varying lengths of nanowire are deposited (up to 5 µm) so that the length dependent magnetic properties can be studied. Ni foil is used as anode to maintain constant metal-ion composition and the electroplating is performed under a current density of 3 mA cm−2 at room temperature (20 °C). The applied magnetic field during electroplating can be oriented either perpendicular or parallel to the template plane. Note that throughout the paper the orientation of applied magnetic fields will be described with respect to the template plane rather than the nanowire axis. This is because, although in general the wires are perpendicular to the plane of the template, some samples exhibit a degree of misalignment. This point will be discussed in detail later.

The structure and morphology of the nanowires are analysed under a scanning electron microscope (SEM). Energy dispersive spectroscopy (EDS) and x-ray diffraction are used to investigate the composition and crystallographic structure of the electrodeposited Ni–Fe. The x-ray diffraction is performed using an X’Pert PRO x-diffraction system (XRD) from Philips Analytical with a monochromatized Cu Kα (λ = 15.4 nm) radiation in a Bragg–Brentano arrangement. A Physical Property Measurement System (PPMS) and Superconducting Quantum Interference Device (SQUID) magnetometer from Quantum Design are used to measure the magnetic properties of the nanowires embedded within the templates.

3. Results and discussion

3.1. Microscopy and structural characterization

Figure 1(a) shows the top and cross-sectional SEM micrograph of the silicon template after electrochemical etching for

5 Alumina and polycarbonate membranes were manufactured by Whatman Inc., NJ, USA.
Figure 1. SEM images of the starting templates. (a) n-Type silicon substrate (diameter—290 ± 10 nm) (inset) cross-sectional view of 145 µm deep Si pores. View of the pores in (b) the alumina template (diameter—200 nm, inter-pore spacing—285 ± 15 nm) and (c) the polycarbonate template (diameter—200 nm, inter-pore spacing—520 ± 125 nm). The average pore diameter is 300 ± 10 nm with an inter-pore distance of 850 ± 50 nm. The pores are 145 µm in length (see inset) and suffer from irregular walls and branching. More SEMs describing this phenomenon can be found in [27]. Figures 1(b) and (c) show the SEM micrographs of the top surface of the alumina and polycarbonate templates of thicknesses 60 µm and 6 µm, respectively. The pores are 190 ± 10 nm in diameter and have an inter-pore distance of 285 ± 15 nm and 520 ± 125 nm, respectively. Table 1 summarizes the template and pore characteristics for the three templates, as measured with the SEM. It is to be noted that the lattice parameter or inter-pore spacing (distance between two adjacent pores) for polycarbonate (520 ± 125 nm) and porous silicon (850 ± 50 nm) templates are much larger in comparison with the inter-pore spacing of alumina templates (285 ± 15 nm).

Figures 2(a)–(c) show the SEM images of the Ni–Fe nanowires electrodeposited in the porous silicon, alumina and polycarbonate templates, respectively. Figures 2(a) and (c) show partially etched template with nanowires projecting outwards from the template. In the case of figure 2(b), partial etching was not possible so the template was fully etched and nanowires were imaged by dispersing them. The nanowires deposited in porous silicon are found to be 275 ± 25 nm in diameter, while those deposited in both the alumina and polycarbonate are 190 ± 10 nm in diameter. The length of the nanowire, which is initially estimated from the deposition charge and time, is later verified using the SEM. The Ni–Fe nanowires deposited in porous silicon exhibit a textured and highly faceted wire surface with multiple grain boundaries, wire breakage and branched growth of wires. This is probably due to the nature of the porous silicon etching [26, 30]. In contrast, the nanowires deposited in the alumina and polycarbonate templates have smooth and uniform surface morphology. However, the wires deposited in the polycarbonate templates are found have an angle between the wire/pore axis and the normal to the plane typically between 0° and 34° [28, 29]°.

Table 1. Template parameters and characteristics.

| Parameters                  | Porous silicon | Polycarbonate | Alumina |
|-----------------------------|----------------|---------------|---------|
| Pore size (nm)              | 300 ± 10       | 190 ± 10      | 190 ± 10|
| Inter-pore distance (nm)    | 850 ± 50       | 520 ± 125     | 285 ± 15|
| Pore density (pores cm⁻²)   | about 10⁷      | about 10⁸     | about 10⁹|
Figure 2. (a) SEM image of a cluster of 275 ± 25 nm Ni–Fe nanowires partially released from porous silicon. (inset) Magnified view of nanowires in porous silicon. (b) SEM view of fully released nanowires electrodeposited in alumina in perpendicular magnetic field. (c) SEM view of partially released nanowires electrodeposited in polycarbonate in perpendicular magnetic field. The alumina and polycarbonate nanowires wires are 190 ± 10 nm in diameter, regular and uniform.

A quantitative EDS spectrum was taken to determine the elemental composition of the Ni–Fe nanowires deposited in the porous silicon, alumina and polycarbonate templates. The results are summarized in Table 2. EDS analysis demonstrates that the atomic ratios of Ni and Fe in the nanowires formed in porous silicon, alumina and polycarbonate templates are close to 77 : 13, 85 : 14 and 84 : 15, respectively. A small amount of oxygen is seen in all the spectra, indicating a modicum of absorption from air. Lower elemental composition of Ni–Fe in the porous silicon template is due to the formation Si–O impurity phases [26]. By standardizing for elemental Ni–Fe in the EDS data, all samples demonstrate an atomic ratio of 84 : 16 for Ni and Fe. The only difference is in the amount of oxygen absorbed in each template due to the variable oxidation rate.

Figure 3 shows the x-ray diffraction patterns from the Ni–Fe nanowires deposited in polycarbonate template (a) without magnetic field and (b) in the presence of a magnetic field (320 Oe) applied perpendicular to the template plane during electrodeposition. Significant differences in the crystalline structure are observed. The diffraction patterns further confirm the electrodeposition of Ni–Fe alloy along with the pure Ni. In the absence of magnetic field, the pattern (figure 3(a)) shows a strong peak for (1 1 1) FeNi$_3$ and (1 1 1) Ni along with the other lesser peaks at (2 0 0), (2 1 1) for FeNi$_3$ and Ni. A strong peak at (1 1 1) for Ni–Fe and Ni indicates grain orientation along the preferred (1 1 1) direction, but the other peaks suggest an overall polycrystalline nature. Al peak in the XRD spectra could be from the back-contact deposited on the template. Similar XRD diffraction peak intensities are obtained for the Ni–Fe nanowires in alumina template in the absence of magnetic field. However, in the case of porous silicon, in addition to Ni–Fe peaks, there is formation of Ni–Si–O impurity phases. This is described in more detail in [26]. Note that all the samples measured have the same mass of Ni–Fe electrodeposits.

When the nanowires are deposited with a perpendicular magnetic field (figure 3(b)), along with Ni–Fe (1 1 1), Ni–Fe grains with the (2 0 0) texture also become dominant. This indicates a difference in crystal structure for nanowires grown in polycarbonate with an applied magnetic field. Furthermore, SEM images (figure 2(c)) show significant morphological changes such as smoother walls for this type of nanowires. This is in accordance with the earlier reported data of uniform morphology of the electrodeposited films obtained in an applied magnetic field [34]. Importantly, the applied magnetic field seems to have enhanced the growth of the Ni–Fe (2 0 0) textures compared with the (2 0 0) textures, when no magnetic field was applied. As suggested by Devos et al [34] and Tabakovic et al [31], this may be a consequence of induced convective solution flow due to magnetohydrodynamic effect near the template’s vicinity. This in turn may cause decrease in the thickness of the diffusion layer and therefore an increase

| Element | In porous silicon (at%) | In alumina (at%) | In polycarbonate (at%) |
|---------|------------------------|-----------------|-----------------------|
| O       | 9.77                   | 1.21            | 1.03                  |
| Fe      | 12.93                  | 14.23           | 14.85                 |
| Ni      | 77.30                  | 84.56           | 84.12                 |
| Total   | 100.0                  | 100.0           | 100.0                 |

Table 2. EDS elemental composition of the Ni–Fe nanowires.

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in the mass transport of active species. Furthermore, in the presence of applied magnetic field, enhanced Ni–Fe (2 0 0) texturing indicates towards forced growth of the Ni–Fe grains with their c-axis parallel to the orientation of the applied field [34]. This result is consistent with published results for Co nanowire arrays [29]. It seems, however, that the applied field is not strong enough to totally force the Ni–Fe c-axis to align perpendicular to the plane of the template. Therefore, the Ni–Fe (1 1 1) textures do not disappear.

3.2. Magnetic characterization

Next, we compare the magnetic properties of the Ni–Fe nanowires deposited in the three different templates (porous silicon, alumina and polycarbonate) with/without a magnetic field of 320 Oe applied perpendicular to the plane of the template during electrodeposition. The saturation magnetizations of Ni–Fe were measured to be about 1 T. The magnetization hysteresis loops, which display the magnetic response of a material to an external field have been used to characterize the Ni–Fe nanowires. The hysteresis loops may generally depend on the material, size and shape, microstructure and the orientation of applied magnetic field with respect to the sample. In the case of nanowires, the key dependent property is magnetic anisotropy, which is the sum of different contributing factors such as shape anisotropy, magnetocrystalline anisotropy, magnetostatic coupling and other morphological characteristics. It should be noted that in nanowires with no preferential orientation, the magnetocrystalline anisotropy can compete with the shape anisotropy. However, if the easy axis is aligned along the wire axis both shape and magnetocrystalline anisotropies will add up. Lastly, magnetostatic coupling will always reduce both coercivity and effective perpendicular magnetic anisotropy [35].

Figure 4 depicts typical magnetic hysteresis curves of the Ni–Fe nanowires deposited without magnetic field in (a) porous silicon, (b) alumina and (c) polycarbonate templates. The magnetization curves both parallel and perpendicular to the template plane are shown. The quasi-one-dimensional structures such as the Ni–Fe nanowires are expected to behave like infinitely long, magnetic cylinders. If so, they should exhibit strong anisotropy, with the magnetic easy-axis aligning parallel to the wires. In addition, if the magnetocrystalline anisotropy is small compared with the shape anisotropy, square hysteresis curves are expected when the magnetization is measured along the cylindrical axis [32]. However, it is clear from figure 4 that these nanowires exhibit little or no magnetic anisotropy. This is in agreement with our earlier publication for porous silicon in which we suggested that (a) the presence of branched and rough wire surfaces may reduce the shape anisotropy term and (b) competition between this reduced shape anisotropy and magnetocrystalline anisotropy (with no preferential orientation along the easy axis, as seen in figure 3 (a) may result in zero overall magnetic anisotropy [26].

The coercivity and squareness ratio (defined as ratio of the remanent magnetization to the saturation magnetization) are in the range 50–100 Oe and 0.1–0.18, respectively for all the samples deposited in the absence of a magnetic field (see table 3). We note that a similarly weak magnetic anisotropy is shown by nanowires deposited in a small magnetic field of 320 Oe applied parallel to the template plane.
Figure 4. Typical magnetic hysteresis curves of the Ni–Fe nanowire arrays electrodeposited in the absence of magnetic field in (a) porous silicon, (b) alumina and (c) polycarbonate templates (average of three samples measured). Magnetization measured both parallel and perpendicular to the template plane are shown.

Table 3. Magnetic characteristics (coercivity and squareness ratio) for the Ni–Fe nanowires in different templates and magnetic field during deposition (data from three samples each).

| Wire length during deposition (µm) | Magnetic field during deposition (Oe) | Coercivity (Oe) | Squareness ratio |
|-----------------------------------|--------------------------------------|----------------|-----------------|
|                                   | (a) Porous silicon template           |                |                 |
| 2–3                              | 0                                    | 80–100         | 0.18            |
| 2–3                              | 320                                  | 100–130        | 0.2–0.22        |
|                                   | (b) Alumina template                 |                |                 |
| 2–2.3                            | 0                                    | 60–80          | 0.15            |
| 2–2.3                            | 320                                  | 200–220        | 0.25–0.28       |
|                                   | (c) Polycarbonate template           |                |                 |
| 2–2.2                            | 0                                    | 50–65          | 0.12            |
| 2–2.2                            | 320                                  | 400–425        | 0.58–0.60       |

A very different behaviour is exhibited by the nanowires electrodeposited in the presence of a magnetic field of 320 Oe applied perpendicular to the template plane. Figure 5 shows the typical magnetic hysteresis curves for these samples in the three different templates. The coercivities and squareness ratios are tabulated in table 3. It is seen that for all the samples, the magnetic anisotropy is enhanced compared with those deposited in zero field. In all cases, the coercivity and squareness ratio is larger for the magnetization measured perpendicular to the template plane (i.e. roughly parallel to the nanowire axis), but the precise value of these parameters depends on the template material.

Figure 5(a) and table 3(a) show the data for wires deposited in the porous silicon template. Although there is an enhancement of the perpendicular squareness ratio and coercivity when the sample is deposited in an applied field, this increase is smaller compared with the other two templates. Given the discussion on wire morphology above and by Aravamudhan et al [26], it seems likely that further enhancement of these parameters is hindered by the...
imperfections and surface roughness inherent in nanowires formed using the silicon templates.

In the case of the alumina template (figure 5(b) and table 3(b)), because of small magnetocrystalline anisotropy (both the Ni–Fe(1 1 1) and (2 0 0) textures equally being dominant), the net magnetic anisotropy is mainly due to two terms: (a) shape anisotropy induced due to the magnetic easy axis parallel to the wire axis, (b) magnetostatic coupling between wires, which develops an easy axis perpendicular to the wire axis. Because of higher pore density in alumina template (about 10^9 pores cm^{-3}) compared with polycarbonate (less than 10^8 pores cm^{-3}), the net contribution from dipole field (aligned perpendicular to wire) is to reduce the effective anisotropy field given by [21, 22]

\[ H_k = \frac{6.3M_s r^2 L}{d^3}, \]

where \( M_s \) is the saturation magnetization, \( r \) is the wire diameter, \( L \) is the length and \( d \) is the inter-pore distance.

The squareness ratios and coercivities in this case (for three different samples) were, however, improved to 0.25–0.28 and 200–220 Oe, respectively, from greater oriented growth of nanowires. Finally, in the case of polycarbonate (figure 5(c) and table 3(c)), a remarkable perpendicular anisotropy is exhibited. It can be seen that the maximum squareness ratio of 0.58–0.60 and coercivity of 400–425 Oe were observed (from three samples) when the measuring magnetic field is perpendicular to the template plane. This suggests that the application of a perpendicular magnetic field during electrodeposition in polycarbonate template results in the highest perpendicular magnetic anisotropy. However, the slight shearing of the hysteresis curve may be due to the (a) 34° (maximum) deviation between the pore axis and the surface normal and (b) dipole interactions between the wires (inter-pore distance is 520 ± 125 nm), as stated before. This is interesting because even though the average inter-pore distance in polycarbonate is much larger compared with alumina, according to Maeda et al, wire interactions (magnetostatic coupling) will still occur for spacings up to 1.5 \( \mu \)m [33]. This dipole wire interaction tends to align perpendicular to the wire axis, resulting in a decrease in both squareness ratio and coercivity. The other reason for the loss of perpendicular anisotropy in the case of polycarbonate is its random angle variation (within the template and from template to template) [29]. Detailed micromagnetic simulations and magnetic force microscopy (MFM) could resolve their individual contributions and also correlate angle variation with the observed perpendicular anisotropy [39].

Next, the effect of varying the magnetic field (270–1060 Oe) perpendicular to the polycarbonate template during electrodeposition was investigated. Figure 6 and table 4 show the measured average coercivity and squareness ratio \( (M_r/M_s) \) as a function of the perpendicular magnetic field during electrodeposition. With an increase in the applied magnetic field during electrodeposition both coercivity and squareness ratio increase significantly. A squareness ratio of about 0.76 was observed for perpendicular magnetic field of 1060 Oe, indicating greater Ni–Fe growth with the c-axis parallel to the nanowire axis and hence enhanced perpendicular magnetic anisotropy. However, this is still a lower squareness ratio than the expected theoretical values for the above stated reasons.

Lastly, the length effect was examined by depositing Ni–Fe nanowires of varying lengths (2–5 \( \mu \)m) in polycarbonate template in the presence of a perpendicular magnetic field of 320 Oe during deposition. Figure 7 and table 5 show the measured average coercivity and squareness ratio as a function of wire length. For magnetic field applied perpendicular to the template plane, as the wire length is increased, according to infinite long magnetic cylinders model [32], the shape anisotropy should also increase. But our experiments show
that both coercivity and squareness decrease monotonically with increase in wire length. This may be caused by the length dependence of dipole interactions among wires, given as \[ H_d = \frac{4.2 M_r r^2 L}{d^3} \] (2)
where \( M_r \) is the saturation magnetization, \( r \) is the wire diameter, \( L \) is the length and \( d \) is the inter-pore distance. In addition, as wire length increases, saturation magnetization also increases.

The magnetization properties of the Ni–Fe nanowires electrodeposited in different templates showed remarkable variation and possibility for control of coercivity and squareness ratio in nanowire arrays. These require further investigation in terms of studying the variation in magnetization and magnetic (in)homogeneity. In future, ferromagnetic resonance (FMR) study could be performed to obtain valuable information on magnetization dynamics, anisotropy, magnetic (in)homogeneity, Landé splitting, \( g \)-value and spin–spin relaxation times for the different templates [37, 38].

4. Conclusions

In summary, in this work, a systematic investigation was performed to study the structural and magnetic properties of the Ni–Fe nanowires as a function of (a) template material (porous silicon, alumina and polycarbonate), (b) applied magnetic field during electrodeposition (0–1060 Oe), (c) wire length (2–5 \( \mu \)m) and (d) field orientation (parallel/perpendicular to the template plane) during measurement. The applied magnetic field during electrodeposition was shown to have a strong influence on the crystallographic and magnetic properties of the Ni–Fe nanowires; in particular, in the case of polycarbonate template, Ni–Fe nanowires of diameter 190 \( \pm \) 10 nm and length 2 \( \mu \)m fabricated in the polycarbonate template with a 1060 Oe applied magnetic field showed the highest coercivity of 530 Oe and squareness ratio of 0.74. The application of magnetic field perpendicular to the template plane during deposition tends to force the Ni–Fe grains with the \( c \)-axis along the orientation of the applied field, thereby resulting in perpendicular shape anisotropy. Further, the influence of applied magnetic field strength and nanowire length on magnetic properties was also studied. It was shown that with an increase in magnetic field during deposition both coercivity and squareness ratio increased significantly, while coercivity and squareness decreased monotonically with an increase in wire length because of the length dependence on dipole interactions. The promising aspect of this work was the ability to tailor the magnetic and structural properties of the Ni–Fe nanowires by the application of a strong magnetic field during electrodeposition and by the selection of template material. Further optimization of fabrication process to create high-density, isolated and vertical ferromagnetic nanowire arrays comparable to the theoretical expectations (based on coherent rotation theory) is currently underway. This is a key requirement for applications in ultra-high density magnetic storage and bio-magnetics.

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Table 5. Magnetic characteristics (coercivity and squareness ratio) for the Ni–Fe nanowires of varying lengths in polycarbonate template with fixed magnetic field (320 Oe) during deposition.

| Nanowire length (\( \mu \)m) | Coercivity (Oe) | Squareness ratio |
|-----------------------------|----------------|-----------------|
| 2–2.2                      | 400–425        | 0.58–0.60       |
| 2.5–2.75                   | 387            | 0.54            |
| 3–3.2                      | 370            | 0.5             |
| 4–4.25                     | 360            | 0.48            |
| 5–5.3                      | 350            | 0.47            |
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