**ABSTRACT**

BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers have been successfully prepared by an electrospinning method and calcination process, and their morphology, chemistry, and crystal structure have been characterized at the nanoscale. It is found that individual BaFe$_{12}$O$_{19}$ nanofibers consist of single nanoparticles which are found to stack along the nanofiber axis. The chemical analysis shows that the atomic ratio of Ba/Fe is 1:12, suggesting a BaFe$_{12}$O$_{19}$ composition. The crystal structure of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers is proved to be M-type hexagonal. The single crystallites on each BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers have random orientations. A formation mechanism is proposed based on thermogravimetry/differential thermal analysis (TG-DTA), X-ray diffraction (XRD), and transmission electron microscopy (TEM) at six temperatures, 250, 400, 500, 600, 650, and 800 °C. The magnetic measurement of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers reveals that the coercivity reaches a maximum of 5943 Oe and the saturated magnetization is 71.5 emu/g at room temperature. Theoretical analysis at the micromagnetism level is adapted to describe the magnetic behavior of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers.

**KEYWORDS:** BaFe$_{12}$O$_{19}$ · electrospinning · single-particle-chain nanofibers · formation principle · CBED · EDX elemental mapping · high saturation magnetization · magnetic reversal mechanism

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Nanoscale magnetic ferrite materials have attracted much attention in recent years due to their unique magnetic and electrical properties and chemical stabilities. These properties are significant not only from a fundamental point of view, for example, blocking behavior, nanoscale confinement, and nanomagnetism, but also for their potential applications, such as high-density data storage, spin-electronics, bioseparation, magnetic resonance imaging, and magnetically guided drug delivery systems. Barium ferrite (BaFe$_{12}$O$_{19}$) is one member of the ferrite family with significant material qualities such as high Curie temperature, large magnetization, large magnetocrystalline anisotropy, high coercivity, and excellent chemical stability. It has been widely adopted as a traditional permanent magnet and also recently used as high-density magnetic and magneto-optical recording media and microwave filters. Since the magnetic properties of BaFe$_{12}$O$_{19}$ strongly depend on their particle size, shape, and homogeneity, various methods, including microwave-induced, laser deposition, microemulsion, and nanopatterning technique, have been used to prepare nanoscale BaFe$_{12}$O$_{19}$ to improve their magnetic properties. These manufacturing techniques have tended to focus on nanoscale particles. There are few reports on one-dimensional (1D) BaFe$_{12}$O$_{19}$ nanowires which were mainly fabricated by a template method using nanoporous anodic aluminum oxide films as the template. However, the diffusion of aluminum ions in BaFe$_{12}$O$_{19}$ nanowires often causes heterogeneous impurities, and nanowires often display a low aspect ratio. It is also difficult to realize a practical industrial production and currently lack sophisticated nanotechnologies to develop these free-standing nanowire building blocks into functional nanodevices. The ever-increasing applications of magnetic nanowires in the new field of biomagnetics and high-density data storage media demand novel fabrication methods which have a promising potential to realize large-scale production of high-quality free-standing 1D magnetic nanowires. Electrospinning is believed to provide this possibility.
Electrospinning is a process by which very fine fibers (with diameter on the micro- or nanoscale and lengths up to kilometers) are drawn from a liquid by an electrical charge. The first significant report of electrospinning to produce fibers dates from 1934 when a patent filed by A. Formhals was issued which described electrospinning as a process for forming fine textile fibers. Electrospinning combined with heating treatments has been widely adopted to prepare various 1D nanomaterials because of the simple manufacturing method, low cost, and relatively high production rate. The applicability of many types of materials include metals, metal oxides, and ferrite nanofibers. However, there are rarely reports on M-type BaFe\textsubscript{12}O\textsubscript{19} nanofibers. It is believed to be because forming 1D M-type BaFe\textsubscript{12}O\textsubscript{19} nanofibers involves a very high temperature heating treatment under zero local spatial confinement, which is extremely not conducive to forming a 1D structure whether at the microscale or nanoscale.

In this work, we present a fabrication method of BaFe\textsubscript{12}O\textsubscript{19} single-particle-chain nanofibers prepared using a combined technique of electrospinning and high-temperature heating treatment for the first time. The morphology, structure, chemical and magnetic characterization, and growth mechanism of the BaFe\textsubscript{12}O\textsubscript{19} single-particle-chain nanofibers have been systematically investigated. It is believed that the new structural form of the single-particle-chain nanofibers is significant and will contribute to expanding the applications of BaFe\textsubscript{12}O\textsubscript{19} into the new field of biomagnetics and high-density data storage media.

RESULTS AND DISCUSSION

Morphological and Chemical Analysis of BaFe\textsubscript{12}O\textsubscript{19} Single-Particle-Chain Nanofibers. The morphologies of BaFe\textsubscript{12}O\textsubscript{19} nanofibers calcined at 800 °C for 2 h were observed by SEM and TEM. Figure 1a shows a representative SEM image of the calcined BaFe\textsubscript{12}O\textsubscript{19} nanofibers. Continuous structure and virtually uniform diameter can be seen in each nanofiber after the PVP was removed by the calcination process. The average length for the majority of the nanofibers is approximately 150 μm, while the average diameter is for 70 nm. The quantitative analysis (inset of Figure 1a) shows that the diameter of the BaFe\textsubscript{12}O\textsubscript{19} nanofibers, measured on average 70 nm, ranges from 50 to 100 nm.

Figure 1b displays a TEM image of several BaFe\textsubscript{12}O\textsubscript{19} nanofibers, which provides a further insight into their microstructure. It is clearly seen that individual BaFe\textsubscript{12}O\textsubscript{19} nanofibers consist of single nanoparticles stacked along the nanofiber axis. Therefore, the nanofibers are named BaFe\textsubscript{12}O\textsubscript{19} single-particle-chain nanofibers in this work. Individual BaFe\textsubscript{12}O\textsubscript{19} single-particle-chain nanofibers have a continuous structure and uniform diameter, which is in good agreement with the SEM results.
with the above SEM observation. It is known that the critical single-domain radius of BaFe12O19 particles is approximately 290 nm, which suggests that each particle on the BaFe12O19 single-particle-chain nanofibers is a magnetically single domain.

Figure 1c shows a lattice-resolution HRTEM image of the single nanoparticle marked by red square in Figure 1b, revealing a single-crystalline structure. The interplanar spacing is measured to be 0.263 nm, consistent with the (114) crystallographic orientation of M-type hexagonal BaFe12O19. The SAED experiments which are presented later demonstrate that the M-type hexagonal structure is preserved in the BaFe12O19 single-particle-chain nanofibers. The crystal structure was further investigated by XRD technique. Figure 1d shows a typical XRD spectrum of the BaFe12O19 single-particle-chain nanofibers calcined at 800 °C for 2 h. The corresponding XRD diffraction peaks can be indexed to (006), (110), (107), (114), (201), (203), (116), (205), (206), (1011), (209), (300), (217), (304), (2012), (220), (2111), (2014), and (317) planes. This suggests that the hexagonal structure of bulk BaFe12O19 is preserved in the BaFe12O19 single-particle-chain nanofibers, which is consistent with the crystal characterization using TEM. There is no impurity phases presented in this spectrum, indicating a pure chemical phase of BaFe12O19.

The chemistry of the BaFe12O19 single-particle-chain nanofibers was characterized using EDX and STEM mapping on a 300 kV HRTEM. The inset of Figure 2a shows a representative EDX spectrum obtained from the corresponding area in Figure 1b. The barium, iron, and oxygen peaks come from the nanofiber specimen. As the EDX technique is not accurate for analyzing the low atomic number (low Z), only the atomic ratio of barium and iron was simulated in this spectrum in order to avoid an error. Quantitative analysis of this spectra indicates a 1:12 atomic ratio of Ba/Fe, inferring a BaFe12O19 composition for the nanofibers prepared under our experimental conditions. The copper and carbon come from the holey carbon coated copper grids, which was confirmed by EDX of an empty holey carbon coated copper grid.

The chemical element distributions of BaFe12O19 nanofibers were further studied by HAADF-STEM and EDX elemental mapping analysis (Figure 2) techniques. Figure 2a shows a representative HADDF-STEM image of a single BaFe12O19 single-particle-chain nanofiber. The contrast of incoherent high-resolution HAADF-STEM images depends directly on the sample atomic number Z and thickness for the materials; in the nanofiber image, a pure chemical phase is revealed, and the individual BaFe12O19 nanofiber is composed of single crystals of various sizes stacking along the nanofiber axis. Figure 2b–d displays the corresponding EDX mappings of oxygen (Kα, 0.52 keV), iron (Kα, 0.64 keV), and barium (Lα, 4.47 keV) elements, respectively. It is seen that the elements O, Fe, and Ba are evenly distributed throughout the whole nanofiber, revealing a uniform chemical phase.

Figure 3 shows a detailed structural investigation of the BaFe12O19 single-particle-chain nanofibers using TEM and convergent beam electron diffraction (CBED) techniques. The large-magnified TEM image (Figure 3a) reveals that the individual BaFe12O19 nanofiber is composed of single nanocrystallites stacking alternatively along the nanofiber axis. The size of these nanocrystallites ranges from 40 to 80 nm confirmed by the TEM observations. CBED using a 0.5 nm spot size configuration is claimed to be used for the first time to analyze the crystal structure of single BaFe12O19 crystallites on a single nanofiber. The top-left inset shows the CBED pattern of the particle marked by a red circle in Figure 3a, revealing a hexagonal close packing (hcp) structure with ⟨110⟩ orientation. The bottom-right inset shows the CBED pattern of a particle marked by a green circle, revealing a ⟨100⟩ orientation of the hcp structure. The representative lattice-resolution HRTEM image of the interface between the two neighbor particles is shown in Figure 3b, indicating consistent crystal orientations and serial planes also confirmed by CBED analysis. More boundary HRTEM results (see Figure S2 in the Supporting Information for details) prove that the single crystallites of the BaFe12O19 single-particle-chain nanofibers have a random orientations, which is not consistent as previously reported.

Formation Principle of the BaFe12O19 Single-Particle-Chain Nanofibers. The formation mechanism, including chemical reactions and phase transformations, of the BaFe12O19 single-particle-chain nanofibers were analyzed by TG-DTA, XRD, and TEM. Figure 4 illustrates the typical TG-DTA curves from the transformation of the
electrospun PVP/barium nitrate/iron nitrate nonahydrate polymer composite nanofibers to BaFe_{12}O_{19} single-particle-chain nanofibers. Limited to the length of this paper, the detailed description and explanations of Figure 4 are presented in the Supporting Information. Combining the measurements of crystal structures of the nanofibers by XRD at seven temperature stages (see Figure S3 in the Supporting Information for details), it is suggested that the following reactions occur during the calcination process:

\[ 2\text{Fe(NO}_3\text{)}_3 \rightarrow \text{Fe}_2\text{O}_3 + \text{NO}_x \]

\[ \text{Ba(NO}_3\text{)}_2 \rightarrow \text{BaO} + \text{NO}_x \]

\[ \text{BaO} + \text{CO}_2 \rightarrow \text{BaCO}_3 \]

\[ \text{BaCO}_3 + \text{Fe}_2\text{O}_3 \rightarrow \text{BaFe}_2\text{O}_4 + \text{CO}_2 \]

\[ \text{BaFe}_2\text{O}_4 + 5\text{Fe}_2\text{O}_3 \rightarrow \text{BaFe}_{12}\text{O}_{19} \]

This observation is consistent with the reported BaFe_{12}O_{19} nanoparticles.28,29

To further understand the formation mechanism of the BaFe_{12}O_{19} single-particle-chain nanofibers, the morphologies and crystals of the electrospun PVP/barium nitrate/iron nitrate nonahydrate polymer composite nanofibers calcined at six different temperatures (250, 400, 500, 600, 650, and 800 °C) were observed (Figure 5) by TEM and SAED. This provides a direct insight of the formation of individual BaFe_{12}O_{19} single-particle-chain nanofibers during the calcination. Figure 5a shows the nanofibers calcined at 250 °C, revealing that their surface morphology does not appear to change

Figure 5. TEM images showing the morphology evolution during the process of calcination at six different temperatures and the inset showing the corresponding SAED: (a) 250 °C; (b) 400 °C; (c) 500 °C; (d) 600 °C; (e) 650 °C; (f) 800 °C.
from their amorphous nature. The corresponding SAED pattern shows fuzzy rings, suggesting an amorphous structure. When the temperature increased to 400 °C, particle-like structures on each nanofiber were formed (Figure 5b). This is probably due to the crystallization of Fe₂O₃ which came from the decomposition of iron nitrate confirmed by TG-DTA (Figure 4) and XRD (Figure S3). After 500 °C annealing, the grain sizes (Figure 5c) are larger than the size shown in Figure 5b, which is attributed to a coalescence of the small crystal grains of Fe₂O₃. The nanofiber surfaces also became much rougher. After calcination at 600 °C (Figure 5d), it is clearly seen that most of the nanoparticles have an approximate 20 nm size, much larger than the size in Figure 5c, and the average diameter of the nanofibers reduced to 80 nm. Combined with the TG-DTA (Figure 4) and XRD results (Figure S3), it is believed that a continuous nucleation of Fe₂O₃ nanocrystallites, formation of barium oxide and BaFe₁₂O₁₉ appears to accompany the BaFe₂O₄ generation at this temperature. Further annealing of the nanofibers at 650 °C for 2 h caused primary BaFe₁₂O₁₉ formation (Figure 5e). Both SAED patterns (the inset of Figure 5e) and XRD shown in Figure S3 proves that the hcp crystal structure of BaFe₁₂O₁₉ nanofibers has been formed. However, the nanofiber is not pure BaFe₁₂O₁₉, and the morphology is not a single-particle-chain-like structure. The final calcination at 800 °C for 2 h clearly caused the removal of all intermediate products and a further nucleation of individual BaFe₁₂O₁₉ nanoparticles on each nanofiber, which formed a single-particle-chain-like structure (Figure 5f). Their crystal structures detected by SAED (the inset of Figure 5f) and XRD (Figure S3) confirmed that pure BaFe₁₂O₁₉ nanofibers were obtained.

On the basis of these experiments and observations, a formation mechanism of the BaFe₁₂O₁₉ single-particle-chain nanofibers in this work is proposed, outlined in the schematic diagrams illustrated in Figure 6. It started from a sol–gel solution composed of PVP, DMF, DIW, barium nitrate, and iron nitrate nonahydrate prepared for electrospinning (Figure 6a). The solvents of DIW and DMF are believed to speed up the evaporation process before (Figure 6b) and after (Figure 6c) the PVP/barium nitrate/iron nitrate nonahydrate polymer composite nanofibers are electrospun and placed on a collector. At the preheating stage, the iron nitrite nonahydrate (Fe(NO₃)₃·6H₂O) loses its water of hydration and the PVP starts to decompose (Figure 6d). When the specimen is calcined at a moderate temperature, the PVP is exhausted, and the Fe(NO₃)₃ decomposes into Fe₂O₃ and forms nucleations of ultrafine sizes (Figure 6e). When the heating temperature subsequently increases, the large Fe₂O₃ nucleations engulf their surrounded smaller crystallites (Figure 6f). Various sizes of crystallites are formed on a single nanofiber, as evidenced in Figure 5c. Simultaneously, the Ba(NO₃)₂ decomposes into BaO and reacts with the CO₂ and Fe₂O₃, which forms BaFe₂O₄ nanoparticles. The BaFe₂O₄ crystallites also begin to form, and the Fe₂O₃ grains increase their size (Figure 6g). During these processes between preheating and moderate temperatures (Figure 6d–g), the randomly unburned PVP pieces deriving from an uneven deposition velocity of PVP from the outside to inside of individual nanofibers form local spatial confinement with various sizes for the growth of crystallites. The various energy barriers of these confinements then lead to the formation of random orientations of the crystallites. At the same time, the nanofiber morphologies change from smooth to rough. As the temperature increases to a high calcination temperature for 2 h, the BaFe₂O₄ and Fe₂O₃ crystallites transform into
BaFe$_{12}$O$_{19}$ crystallite. Simultaneously, the large crystals keep devouring their surrounding small crystals until eventually BaFe$_{12}$O$_{19}$ single-particle-chain fibers (Figure 6h) are formed and the metallic salt and polymer have been fully exhausted.

**Magnetic Properties of the BaFe$_{12}$O$_{19}$ Single-Particle-Chain Nanofibers.** SQUID technique was employed to investigate the dynamical magnetic properties of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers. Figure 7a shows a typical hysteresis curve of the BaFe$_{12}$O$_{19}$ nanofibers measured at room temperature, indicating a coercivity of 5943 Oe. This value is larger than that of the BaFe$_{12}$O$_{19}$ nanowires prepared by AAO templates (2371 or 5760 Oe), hollow fibers (2952 Oe), thin films (3350 Oe using sol−gel processes, or 5100 using laser deposition), nanoscale powders (5500 Oe), and nanoparticles (approximately 3000 Oe). Shape anisotropy derived from very large length-to-diameter ratios and high magnetocrystalline anisotropy are believed to be the main reasons for large coercivity force in the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers. This curve also shows that the saturated magnetization ($M_s$) of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers at room temperature is 71.5 emu/g. This value is larger than that of the BaFe$_{12}$O$_{19}$ nanowires prepared by AAO templates (58.26 or 56.14 emu/g), hollow fibers (51.56 emu/g), nanoscale powders (59.36 emu/g), and nanoparticles (51.9 and 56.5 emu/g). Figure 7b shows a field-cooled curve of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers measured at temperature ranging from 5 to 300 K with an applied magnetic field of 6 T.

BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers have a random orientation and each particle is a single domain. That is, the easy axis of the individual particles on the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers is 35 nm, determined by TEM observation, which is larger than the coherence radius. According to the criteria of coherent radii, our BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers should have a curling mechanism for magnetization reversal as illustrated in Figure 8.

For the curling process, the coercivity of the nanowire structure can be theoretically obtained from eq 2:

$$H_c = \frac{2K_1}{\mu_0M_s} - NM_s + \frac{cA}{\mu_0M_sR^2}$$

where $A$ is the exchange constant, $-6.1 \times 10^{-12}$ J·m$^{-1}$ for BaFe$_{12}$O$_{19}$ and $M_s$ is the saturated magnetization. The exchange length of BaFe$_{12}$O$_{19}$ is calculated to be approximately 5.9 nm. A 21.5 nm coherence radius for BaFe$_{12}$O$_{19}$ fibers is then calculated. In our case, the radius of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers is 35 nm, determined by TEM observation, which is larger than the coherence radius. According to the criteria of coherent radii, our BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers should have a curling mechanism for magnetization reversal (as illustrated in Figure 8).

Figure 8. Schematic illustration of the magnetization reversal mechanism.
nanofiber length axis as suggested using the hypothesis of eq 2. Therefore, eq 2 requires a modification for a better fit with our case. The first term of eq 2 represents a contribution of the magnetocrystalline anisotropy. When the angle between the easy axis(s) (or c-axis) of uniaxial single domain particle(s) and the applied field is only for $\tau$, the constant is 2. $^{26}$ When their angles are randomly distributed, the constant becomes 1, which is more appropriately fit with our case. The second term is attributed to the shape anisotropy. Due to the nanofibers’ random orientation, the shape anisotropy of the nanofibers is equivalent to the nanoparticles that make up the nanofibers. $^{26}$ In our case, each particle on the nanofiber could be treated as a sphere for simplification, although it is not ideal in geometry. The third term represents a contribution of exchange energy which then stays the same. Therefore, eq 2 can be modified into (see Supporting Information for details):

$$H_{ex} = \frac{K_1}{\mu_0 M_s} - \frac{1}{3} \frac{1}{\mu_0 M_s} + \frac{cA}{\mu_0 M_s R^2} \quad (3)$$

Using the geometry and saturation magnetization of the measured nanofiber, a calculation for the coercivity yields a value of 7131 Oe. This value is larger than the experimental findings of 5943 Oe, revealing a large discrepancy. Several reasons for this difference include a neglect of magnetostatic and exchange interaction between the neighborhood BaFe$_{12}$O$_{19}$ nanoparticles, too much simplification of particle’s geometry, and the surface effect of individual particles. Nevertheless, the theoretical analysis still gives a preliminary insight of the magnetic origins of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers.

**CONCLUSIONS**

In conclusion, we have demonstrated a fabrication method for BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers using an electrospinning technique. Individual BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers are found to have a continuous structure and uniform diameter, of which nanoparticles stacks side by side along the nanofiber axis. The hexagonal structure of bulk BaFe$_{12}$O$_{19}$ is proved to be preserves in the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers, and individual single crystallites on each BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers have a random orientation. The experimental results reveal that the formation of BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers mainly involves chemical reactions and phase transformations, and a formation mechanism is then proposed. The saturated magnetization of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers is measured to be 71.5 emu/g at room temperature. The magnetization reversal mechanism of the BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers is theoretically analyzed to fit a curling model. This work opens a new route for preparing large-scale production of various magnetic ferrite nanofibers with a high quality and length-to-diameter ratio. The new structural form of the single-particle-chain nanofibers is expected to have applications in the fields of biomagnetics, high-density data storage media, magnetic separation, microwave absorbers, switches, magnetic nanosensors, etc.

**EXPERIMENTS AND METHODS**

BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers were prepared using the electrospinning techniques as follows. In a typical synthesis, 0.1 mmol barium nitrate (Ba(NO$_3$)$_2$, A.R., Alfa-Aesar Inc., USA), 1.2 mmol iron nitrate nonahydrate (Fe(NO$_3$)$_3$·9H$_2$O, A.R., Alfa-Aesar Inc., USA), and 0.18 g of poly(vinyl pyrrolidone) (PVP, $M_w \approx 1$ 300 000, Sigma-Aldrich Inc., USA) were dissolved into a mixed solution of 1.25 mL of deionized water (DIW) and 1.25 mL of N,N-dimethylformamide (DMF, A.R., Tianjin Chemical Corp., China) in a 5 mL vessel. The solution was continuously and vigorously agitated by a magnetic stirrer for 4 h. A homogeneous PVP/barium nitrate/iron nitrate precursor sol–gel solution was formed and then transferred into a syringe for electrospinning. The electrospinning process was performed by a dedicated electrospinning facility at 18.4 kV DC voltage, 15 cm spacing between needle tip and collector, and a feed rate was fixed with 0.4 mL/h. In comparison with traditional electrospinning methods, a special heating body was mounted in the end of syringe (see Figure S1 in the Supporting Information for details) to help the solubility of the Ba(NO$_3$)$_2$. The electrospun polymer composite fibers were collected using alumina crucibles and then calcined at 300 °C for 2 h, and then the temperature was increased to 800 °C for 2 h with a heating rate of 1 °C/min in air. The sample was finally allowed to cool to room temperature with the same heating rate of 1 °C/min in order to obtain a high level of crystalline structure.

The morphology, crystal structure, and chemical characterization of individual BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers were analyzed at the nanoscale using a field-emission scanning electron microscope (FSEM, Hitachi S-4800, Japan), high-resolution transmission electron microscopy (HRTEM, Tecnai G2 F30, FEI, USA) equipped with energy-dispersive X-ray analysis (EDX, Oxford Instrument, UK), high-angle annular dark and scanning transmission electron microscope (HAADF-STEM), and an X-ray diffraction instrument (XRD, Philips Xpert Pro MPD, The Netherlands). The transformation of the precursor nanofiber to BaFe$_{12}$O$_{19}$ single-particle-chain nanofibers was verified by a commercial thermogravimetry/differential thermal analysis (TG-DTA, Diamond, USA) with a heating rate 1 °C/min, XRD, and TEM techniques. Magnetic properties of the BaFe$_{12}$O$_{19}$ nanofibers were measured by superconducting quantum interference device (SQUID, MPMS-XL, Quantum Design, UK).

**Conflict of Interest:** The authors declare no competing financial interest.

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REFERENCES AND NOTES


