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Fabrication of constricted compositionally-modulated Ni_xFe_{1-x} nanowires

H F Liew, S C Low and W S Lew*
School of Physical & Mathematical Sciences,
Nanyang Technological University, 21 Nanyang Link, Singapore 637371

*E-mail: wensiang@ntu.edu.sg

Abstract We demonstrate the fabrication of compositionally-modulated Ni_xFe_{1-x} nanowires using templated growth electrodeposition techniques. The composition of the Ni and Fe in a grown magnetic layer was modulated by varying the deposition potential during growth. Periodic constrictions were created along the Ni_xFe_{1-x} nanowires via diluted nitric acid etching. Conceptually, the constrictions created along nanowires may induce a low energy well which has an advantage as a potential barrier to trap domain walls in magnetic storage application.

1. Introduction

Magnetic nanowires have received strong interest recently because it has promising potential for application in magnetic solid state memory devices[1]. For instance, IBM has proposed the magnetic domain-wall based “racetrack memory” that uses planar and cylindrical magnetic nanowires as the storage medium for horizontal and vertical memory design, respectively[2]. The vertical “racetrack memory” design has the advantage of higher density but the implementation is extremely challenging. Generally, a magnetic domain-wall based memory device works by controlling the movement of the domain wall. When a nanosecond pulsed current is applied, the domain wall propagates along the nanowire until it meets an obstacle where it requires higher energy to overcome the barrier. The movement of domain wall enables binary data stored in the ferromagnetic nanowire be retrieved or written by a magnetic recording head. To precisely control the movement of the domain wall intentional defects[3-10] is usually created along the nanowires. Such defect acts as a low energy well that is readily to trap the moving domain wall. Systematic creation of such intentional defects so that domain wall can be effectively trapped at this region for planar nanowires is considered established; however, the technique required for making similar defects in cylindrical nanowire is still to be explored[11].

A significant number of dry and wet chemical deposition methods of producing magnetic nanowires have been reported in literature. Template-assisted electrodeposition is one widely-used technique because of its simplicity and flexibility, specifically in making multilayered structures. Here, we demonstrate the fabrication of constricted cylindrical Ni_xFe_{1-x} nanowires, which consist of alternate layers of Ni_xFe_{1-x} with two different of *x* values. The constrictions are created along the nanowires by etching the as-deposited nanowires in diluted HNO_3.

2. Experimental

Compositionally-modulated Ni_xFe_{1-x} nanowires were fabricated by using templated growth pulse electrodeposition technique. The deposition cell consists of 0.5 M nickel sulfate, 0.01 M iron sulfate and 0.5 M boric acid. Figure 1 shows the step-by-step fabrication process of the constricted Ni_xFe_{1-x} nanowires. A 200-nm-thick aluminium layer was first deposited on one side of an anodized aluminum oxide (AAO) template (Anodisc 13, Whatman). The Ni_xFe_{1-x} nanowires were alternately deposited between –1.0 V and –1.4 V vs SCE for a period of 50 sec using similar pulse potential, as shown in Figure 2. The pH and temperature during the growth were maintained at 4 and 40 ^{o}C, respectively. The length of the alternating segments is determined by the electrodeposition time. Upon the completion of growth, the nanowires were released from the AAO template by dissolving them into 3M NaOH solution for 30 minute. Then, the nanowires were thoroughly cleaned from the AAO template by using deionized water, with the assistance of ultrasonic agitation. The Ni_xFe_{1-x} nanowires segment that grown at potential –1.0 V (higher Fe composition) were then selectively etched by 1% HNO_3 for 40 sec. The segment deposited at a reduction potential of –1.0 V has a higher etching rate compared to that of the segment deposited at potential –1.4 V. Thus, the depth of the constriction can be controlled by altering the concentration of the HNO_3 and the etching time.

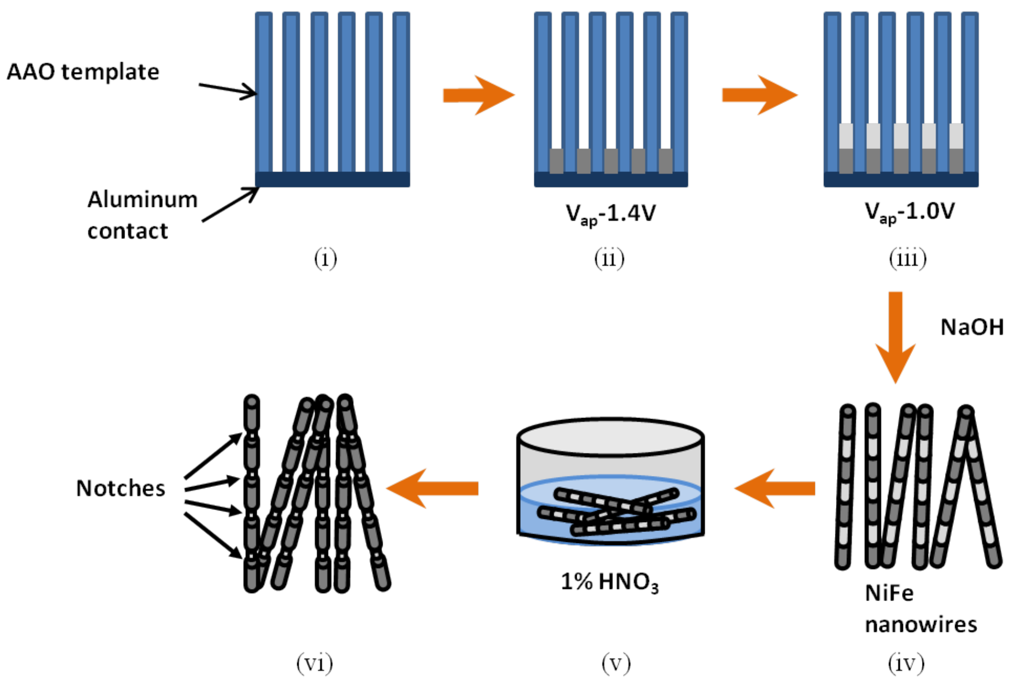

Figure 1. Schematic diagram illustrating the fabrication process of notched Ni_xFe_{1-x} nanowires

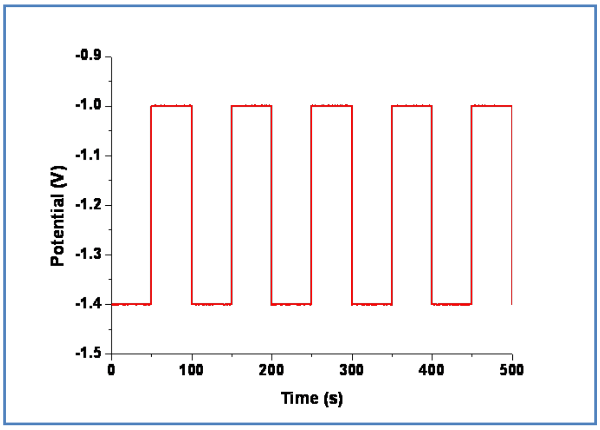

Figure 2. The pulse potential applied during the growth of compositionally-modulated Ni_xFe_{1-x} nanowires.

3. Results and Discussion

Field emission scanning electron microscopy (FE-SEM) imaging was carried out by using a JEOL JSM-6700F operated at 10kV. Figure 3 shows the bamboo like feature of the Ni_xFe_{1-x} cylindrical nanowires with alternate constrictions along the nanowires. The constrictions obtained at potential –1.0V are well defined and uniform in shape and size. The constrictions are clearly distinguishable and orderly formed along the nanowires. In addition, the bath contains Ni^+ and Fe^+ ions in a single bath which produced the multilayered nanowires in an ordered fashion when compared with separate bath deposition. A close-up view of the image (Figure 4) revealed that the segments grown at potential–1.4V have a length of 1.5μm and diameter of 350 nm, while segments growth at potential of –1.0V have a length of 100 nm and a diameter of 150 nm. The above multilayered nanowires with optimized diameter of 150 nm which produces the constrictions easily and mechanically stable. Figure 5 shows transmission electron microscope (TEM) image of a released Ni_xFe_{1-x} nanowire with constrictions. The Ni and Fe composition along the two different potential segments were determined by elemental analysis by using energy dispersive X-Ray spectroscopy (EDX). EDX result shown in Figure 6 indicates that higher atomic percentage of Fe (13%) was obtained in the constriction and less trace of Fe (5%) was analysed in the non-constriction region. The variation in the measured Ni and Fe compositions confirms the modulation of the composition in the Ni_xFe_{1-x} nanowires.

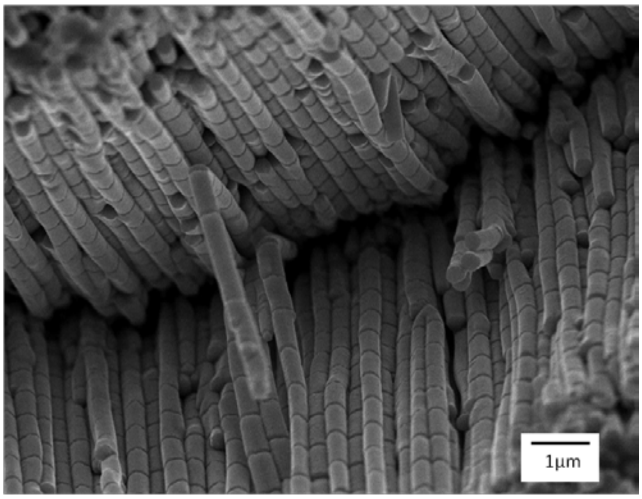

Figure 3. SEM image of compositionally-modulated Ni_xFe_{1-x} nanowires with notches along the nanowires.

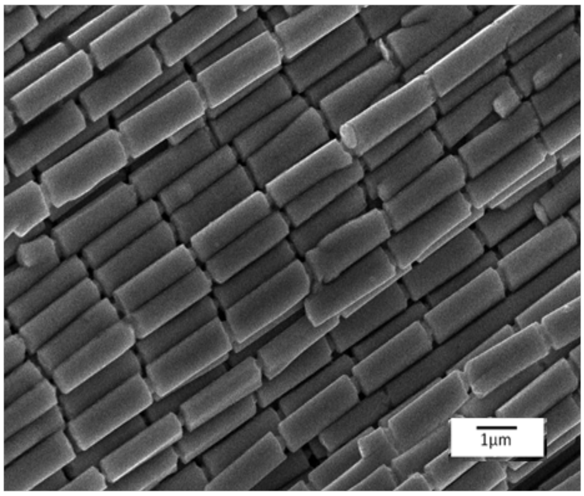

Figure 4. A close-up view of well defined notches structure along the Ni_xFe_{1-x} nanowires.

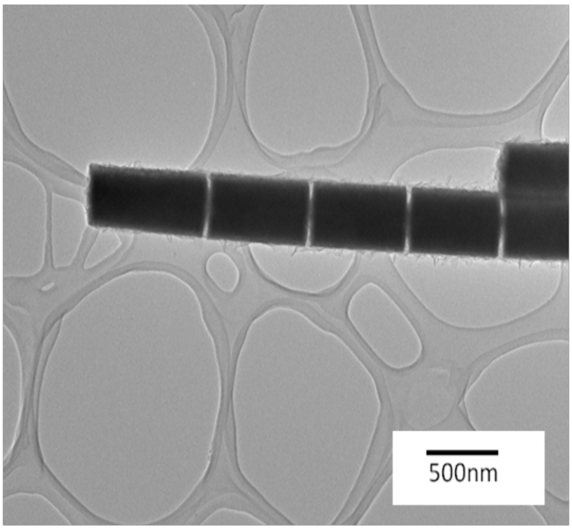

Figure 5.TEM image of single notched Ni_xFe_{1-x} nanowires.

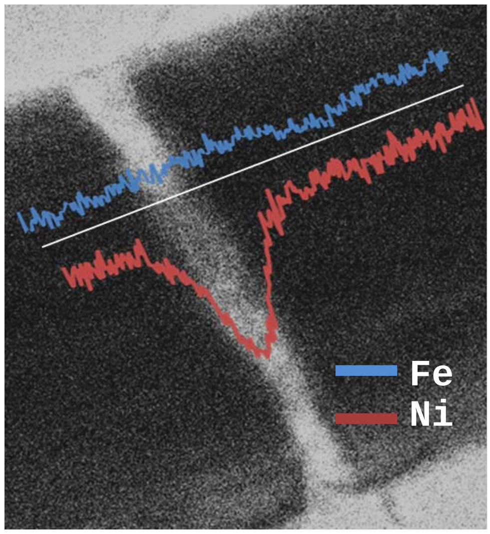

Figure 6. TEM elemental line scanning of Ni and Fe elements (Ni red, Fe blue) along the compositionally-modulated Ni_xFe_{1-x} nanowires.

The magnetic properties of the notched Ni_xFe_{1-x} nanowires with alternately different composition were measured using an alternating gradient force magnetometer (AGFM). The hysteresis loop of the released Ni_xFe_{1-x} nanowires sample is shown in Figure 7, where $H^{//}$ and $H^{\perp}$ represent the applied field, H being parallel and perpendicular to the nanowire axis, respectively. The coercivity $H_c(//)$ and ratio of the remnance to the saturation magnetization $(M_r/M_s)(//)$ are 77 Oe and 0.27, respectively compared to $H_c(\perp)$ at 118 Oe and $(M_r/M_s)(\perp)$ at 0.10. The squareness ratio in the parallel direction is higher than the perpendicular direction which indicates that the easy axis is parallel to the orientation of nanowire direction. The hysteresis measurement indicates the fabricated Ni_xFe_{1-x} nanowires are of soft ferromagnetic material due to its high magnetic saturation and low coercivity. The magnetization contributions from the contricted segments could have been negligible as the length of the contrictions is insignificant compared to the other segment.

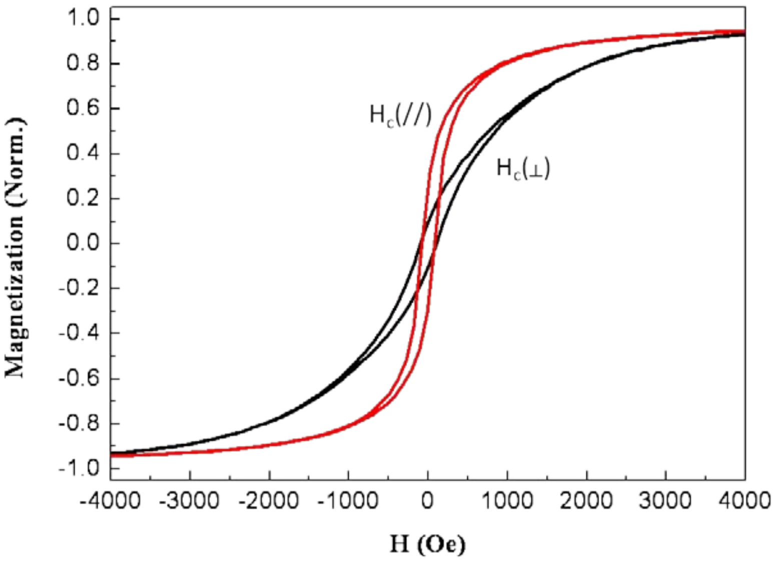

Figure 7. Hysteresis loop for the compositionally-modulated Ni_xFe_{1-x} nanowires with notches at room temperature.

4. Conclusion

We have successfully fabricated constricted Ni_xFe_{1-x} nanowires with different composition of Ni and Fe by using pulse electrodeposition techniques. By selectively chemical etching, the diameter of the Ni_xFe_{1-x} nanowires at constriction region reduces from 350 nm to 150 nm. EDX measurement confirms the variation percentage of Fe along the compositionally-modulated Ni_xFe_{1-x} nanowires. The constricted Ni_xFe_{1-x} nanowires have an easy magnetization axis parallel to the nanowire axis. This constricted nanowire has the potential to be used as the storage medium for magnetic domain-wall memory device.

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