

## Self-assembled magnetic nanowire arrays

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Different self-assembled magnetic nanowire arrays were achieved with  $\sim 100\%$  trapping rate on templates with nanomagnet arrays under a low external magnetic field ( $\sim 10$  Oe). The principles of magnetic charge matching and dimension matching between the magnetic nanowires to be assembled and the gaps between two nanomagnets were proposed and demonstrated to be crucial for achieving low magnetostatic energy and high trapping rate. This templated self-assembly technique and the proposed template design principles have great potential for nanomanufacturing of regular arrays of magnetic nanostructures. © 2007 American Institute of Physics.

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Self-assembly is a process by which small-scale components spontaneously assemble into functional systems, and has emerged as a particularly promising technology for fabricating nanometer-scale functional devices and for achieving affordable nanomanufacturing.<sup>1–17</sup> Different driving forces have been used to control the self-assembly process, such as magnetostatic forces,<sup>4–11</sup> capillary forces,<sup>12–16</sup> electrostatic forces,<sup>17,18</sup> van der Waals forces,<sup>19</sup> biospecific interactions,<sup>20</sup> etc. The use of templates is known to be able to provide a certain level of control over the driving forces for self-assembly processes and has been shown to be an important way to achieve self-assembly.<sup>2,4–8,20</sup> Magnetic interaction is particularly promising for templating in self-assembly processes<sup>4–10</sup> for several reasons. First, the wide variety of magnetic materials and the capability of manipulating their magnetic properties such as anisotropy, magnetization, coercivity, etc., provide flexibilities in designing diverse self-assembly processes and nanosystems through magnetic interactions. Second, the dipole nature of magnetism enables both attractive and repulsive forces on the magnetic elements, which add more control knobs over the self-assembly processes.<sup>6,7</sup> Third, magnetic interactions have a long range of interaction that typically does not interfere with the biological and chemical interactions, which is crucial for real applications. Last, magnetic templates can be used many times without concern of poisoning unlike some of the biologically or chemically active templates, and they are easy to refunctionalize with a magnetization process.

Compared to other self-assembly processes that typically have limited control over the self-assembly processes, magnetic force driven self-assembly processes on magnetic templates have the flexibility of controlling many of the parameters. For example, the geometry and magnetic properties of the magnetic nanoelements and the nanomagnets on magnetic templates, as well as the nanomagnet array on the magnetic templates, can be readily tuned. This flexibility of controlling the self-assembly process of the magnetic nanoelements on magnetic templates enables diversified applications of the self-assembly processes, such as biological applications,<sup>5,6</sup> nanocontacts,<sup>4</sup> etc.

Significant achievements have been made in the self-assembly process by using magnetic templates. Reich and co-workers used Ni micromagnet pairs with an elliptical shape for the purpose of trapping magnetic nanowires.<sup>4,5</sup> Yellen *et al.* used magnetic templates with an array of bar micromagnets and morphological microwells, and achieved programmable self-assembly of superparamagnetic microbeads and nonmagnetic nano/microstructures with a rotating magnetic field.<sup>6,7</sup> Roberts *et al.*<sup>8</sup> used an array of thin film bar-shaped micromagnets to trap superparamagnetic microbeads. From these published results,<sup>6–8</sup> it can be concluded that magnetostatic force needs to be balanced with another kind of constraint, so that a self-assembly process with a low defect density can be possibly achieved. Two different additional interactions and constraints were used in achieving self-assembly of superparamagnetic microbeads, microwells with complementary shape to the microbeads,<sup>6,7</sup> and fluid drag force from a controlled liquid flow in a microfluidic channel.<sup>8</sup> In this work, by using a combination of the external magnetic field and the local dipolar magnetic field, we experimentally demonstrated magnetic template controlled one-dimensional and two-dimensional self-assemblies of magnetic nanowire arrays.

Ni nanowires with a diameter of 200 nm were grown on nanopores of alumina membrane by electrodeposition, using a Cu film sputtered on one side of the template as a working electrode.<sup>4,21,22</sup> The alumina membrane filled with a cylindrical and parallel set of ferromagnetic Ni nanowires is shown in Fig. 1(a) with the average wire density of

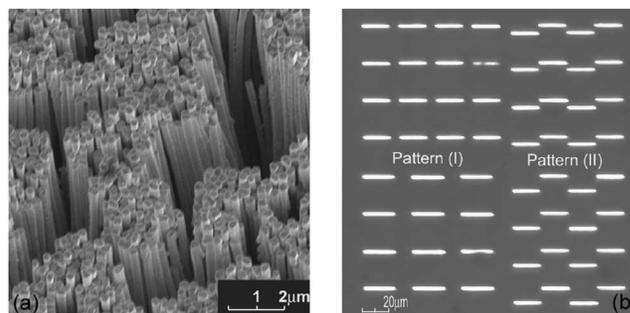


FIG. 1. Scanning electron micrograph (SEM) image of the Ni nanowires with diameter of 200 nm (a) and image of the template with nanomagnets which have a width of 100–400 nm and a thickness of 100 nm (b).

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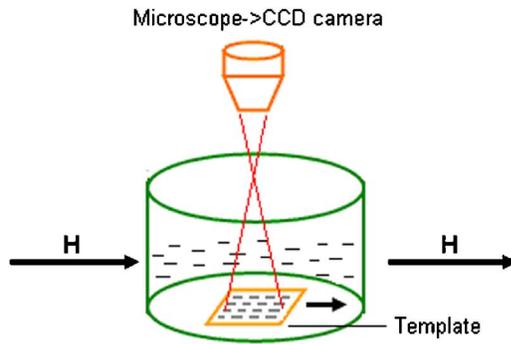


FIG. 2. (Color online) Schematic of the arrangement used in the self-assembled magnetic nanoarray.

$\sim 6.0 \times 10^8/\text{cm}^2$  and a length of  $10 \mu\text{m}$ . The Ni nanowires were extracted from the alumina membrane by etching away the Cu film and then dissolving the membrane into warm KOH solution. Alcohol solutions with a suspended magnetic nanowire concentration of  $2.0 \times 10^5/\text{mL}$  were prepared for the self-assembly process.

Templates of cobalt nanomagnet arrays were e-beam patterned from Co full films with a thickness of 100 nm, which has Co nanomagnets with different lengths of 20–25  $\mu\text{m}$  and widths of 100–400 nm, as shown in Fig. 1(b). Pattern (I) was designed for applied parallel external field and pattern (II) was designed for perpendicular external field. The gaps between nanomagnets in patterns (I) and (II) were 5 and 10  $\mu\text{m}$ . The template was magnetically initialized by applying 5 kOe magnetic field along the long axis of magnets.

Self-assembled magnetic nanowire arrays were achieved by immersing the template with Co nanomagnet arrays in the alcohol solution of suspended magnetic nanowires with a diameter of 200 nm and a length of  $10 \mu\text{m}$  under a parallel or perpendicular external magnetic field, as shown in the schematic in Fig. 2. The self-assembly process was monitored through a charge-coupled device camera mounted on a microscope.

Because of the dependence of the dipolar magnetic interaction between nanowires on their relative orientation, applying an external field can suppress the tendency of aggregation, prealign the initially random nanowires, and lead to the formation of extended head-to-tail nanowire chains. As illustrated in Fig. 3, the uniform Ni nanowire chain with a length of  $60 \mu\text{m}$  was formed under an external field of 10 Oe, as was reported before.<sup>4,5</sup>

When a 10 Oe external magnetic field was applied parallel to the magnetization vector direction of the nanomagnets on the template [pattern (I)], the suspended magnetic nanowires will first be aligned by the applied magnetic field, and then attracted and trapped in the gap of the two nanomagnets by the local dipolar magnetic field generated by the nanomagnets. Figure 4 shows the image of a Ni nanowire array self-assembled between the gaps of Co nanomagnet pairs with a Co nanomagnet width of 100 nm. (The width of the Co nanomagnets appears wider than 100 nm in Fig. 4 due to the fact that an e-beam photoresist was left on the Co nanomagnet arrays on the templates to minimize the damage on the Co nanomagnets.) It is interesting to note that only one Ni nanowire was trapped in each gap of the Co nanomagnet pairs, of which the width is patterned to be 100 nm. The magnetic charge of a bar magnet magnetized along the length direction can be expressed by  $M_s A$ , where

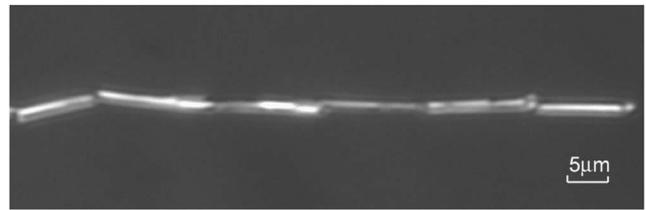


FIG. 3. Optical micrograph of a chain with head-to-tail connected Ni nanowires.

$M_s$  is the saturation magnetization and  $A$  is the cross-section area. The magnetic charge for a 100 nm wide Co nanomagnet is  $1.4 \times 10^{-8}$  A m, which is close to that of Ni nanowires,  $1.6 \times 10^{-8}$  A m, assuming that both the nanomagnets and Ni nanowires have 100% remanence under the applied magnetic field. The nearly equivalent magnetic charges for the Co nanomagnets and the Ni magnetic nanowires lead to nearly full compensation of magnetic charges when one magnetic nanowire is trapped at the gap of the nanomagnet pair, and therefore a low magnetostatic energy compared to the case when no nanowire got trapped or when two or more magnetic nanowires are trapped in one gap.

Nanowire trapping probability was also studied on magnetic templates with different gaps of the nanomagnet pairs and different distances between the two nanomagnets. It was also found that Ni magnetic nanowires with a length of  $10 \mu\text{m}$  have a significantly higher probability of getting trapped in the nanomagnet gaps with a width of  $10 \mu\text{m}$  compared to the nanomagnet gaps with a width of  $5 \mu\text{m}$ . This is believed to be due to the fact that the matched dimension of the magnetic nanowire and the gap of a nanomagnet pair leads to lower magnetostatic energy compared to an unmatched dimension between the nanowire and the gap.

These findings on the nanowire trapping probability indicate that lowered magnetostatic energy is an important guide for designing nanomagnet array templates for achieving high trapping probability of the magnetic nanowires or a low defect rate in the self-assembled magnetic nanowire arrays. The principles of magnetic charge matching and dimension matching between the magnetic nanowires and the nanomagnet arrays on the templates can lead to a low magnetostatic energy state and are crucial for achieving defect-free self-assembled magnetic nanowires.

When the external magnetic field was applied perpendicular to the magnetization of the magnet template [pattern (II)], another self-assembled nanowire array pattern was achieved with a  $\sim 100\%$  trapping rate, as shown in Fig. 5. Since the gaps between magnet pairs show magnetic fringing fields that are antiparallel to each other, only one of the two

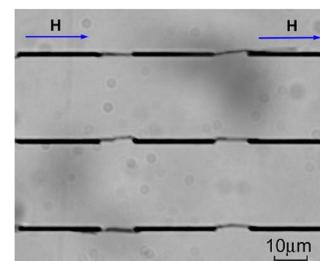


FIG. 4. (Color online) Optic micrograph of self-assembly nanowire arrays when an external magnetic field (10 Oe) was applied parallel to the magnetization direction of the magnet template (pattern I).

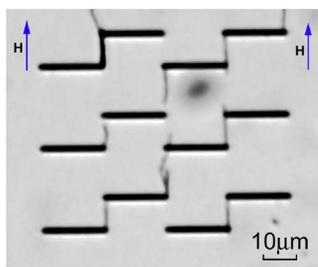


FIG. 5. (Color online) Optic micrograph of self-assembly nanowire arrays when an external magnetic field (10 Oe) was applied perpendicular to the magnetization direction of the magnet (pattern II).

magnetic gaps that has a fringing field parallel to the external field can be filled with one magnetic nanowire when 10 Oe external field perpendicular to the magnet is applied. The gaps for trapping the magnetic nanowires were designed to be 10 and 15  $\mu\text{m}$ . These 10  $\mu\text{m}$  gaps are all filled with one magnetic nanowire, while the 15  $\mu\text{m}$  gaps are either filled with one nanowire or two nanowires due to the mismatch of the dimensions between the magnetic nanowires and the gaps. This observation again confirmed that the dimension matching between the nanowires and the gap was important for achieving a low magnetostatic energy and therefore a high trapping rate for one nanowire per gap.

In addition to achieving self-assembly nanowire arrays by applying an external field on the magnetic nanowire template, the programmability of self-assembly can also be realized by changing the external field orientation. This demonstrates the feasibility of achieving programmable defect-free self-assembled magnetic nanowire arrays through proper design of the nanomagnet templates.

With the magnetic template design and an external magnetic field, magnetic manipulation and self-assembly techniques for magnetic nanowires were demonstrated and self-assembly magnetic nanowire arrays were achieved with  $\sim 100\%$  trapping rate. Novel magnetic template design principles of matched magnetic charges and matched dimension were proposed and demonstrated. This templated self-assembly process for magnetic nanowires and the proposed template design principle have great potential for nanomanufacturing of large-scale arrays of magnetic nanostructures

which can be potentially used in biology as well as in other nanotechnologies.

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