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Wafer-scale synthesis of monodisperse synthetic magnetic multilayer nanorods

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Abstract

A double exposure technique has been used to fabricate nanoimprint stamps for making monodisperse nanorods with controllable lengths. The nanorod length is defined by a normal photolithography projection process whereas the nanorod width is defined by an edge-lithography process using a soft polydimethylsiloxane (PDMS) contact mask. Taking advantage of edge-lithography, the nanorod width can be less than the diffraction limit of the exposure light. Using these nanorod stamps, synthetic magnetic multilayer (SMM) nanorods have been fabricated using nanoimprint lithography, resulting in a length variation of ~3%. Nanorod magnetic properties have been characterized in both longitudinal and in-plane transverse directions of the nanorods. A theoretical model has been established to explain the magnetic responses and has revealed that both shape anisotropy and interlayer interactions are important in determining the properties of SMM nanorods.

Keywords

Nanorod; magnetic; synthesis; nanoimprint lithography; nano-patterning

Anisotropic nanoparticles^{1–4} can have very special properties, different from their spherical counterparts. As one example, nanorod synthesis using various chemical methods^{5–7} has received much recent attention and, consequently, major progress in controlling nanorod shapes has been made. However, in many cases, problems still remain in obtaining monodispersity or creating internal structure. Recently, monodisperse synthetic nanoparticles have been fabricated using nanoimprint lithography^{8–14} (NIL) over the full area of Si wafers. However, due to the limited stamp-making strategies and the costs of using e-beam methods over large areas, only disk-shaped nanoparticles have been fabricated over full Si wafer areas using this method.

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Author Contributions

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Supporting Information. Experimental details; theoretical calculation based on single domain model; edge lithography using PDMS contact phase mask; patterning nanorod pillars; hysteresis loop measurements of magnetic nanorods patterned on Durimide layer for both longitudinal and in-plane transverse magnetic field directions. This material is available free of charge via the Internet at <http://pubs.acs.org>.

Here, we further advance this technology by fabricating NIL stamps with uniform nanorod-shaped pillar structures over entire wafers using a novel optical double-exposure strategy. With these newly developed stamps, monodisperse nanorods with controllable aspect ratios and internal layer structure are successfully synthesized by depositing materials on NIL patterned substrates. Unique from other template methods, such as anodic alumina oxide (AAO) templates^{15–17}, our method can fabricate nanorods comprised of materials layered parallel to the substrate surface.

Consequently, magnetic multilayer nanorods with a monodisperse size distribution were fabricated and are hereafter referred to as synthetic magnetic multilayer (SMM) nanorods. These magnetic nanorods offer the advantage of a controllable rotational response to an external magnetic field^{18–21}, in addition to the translational movement of spherically isotropic nanoparticles in response to the field gradient²². The magnetic properties of SMM nanorods are then characterized, illustrating how shape anisotropy introduces a magnetic response which is very different along the longitudinal and transverse in-plane directions of the nanorods. A magneto-static model has been established to explain the magnetic response, where the shape anisotropy and the inter-layer interaction play deterministic roles.

The nanorods fabricated here have a length controlled between 250 nm and 1.5 μm , and a width of ~ 100 nm. The length scale can be achieved with normal optical lithography. However, the width is well below the diffraction limit of the illuminating ultraviolet (UV) light, and therefore a more advanced lithography technique must be involved. Edge lithography has been adopted as a useful tool to pattern features with critical size below the diffraction limit^{23, 24}. Inspired by this, a double exposure procedure has been developed (Figure 1A). First, a normal photolithography process is conducted to expose parallel lines with “top to bottom” orientation using a Cr mask. The width of the lines defines the length of the final nanorod structures. Then, an edge lithography process is conducted using a patterned polydimethylsiloxane (PDMS) contact mask as a phase-shift mask²³ to pattern parallel lines with “left to right” orientation. This PDMS contact mask is transparent to UV light over the entire area except the “edge” regions, where long thin lines can be patterned with a positive photoresist. Taking advantage of edge lithography, the widths of the patterned lines stay well below the diffraction limit, defining the widths of nanorod structures. After the second exposure the resist coated wafer is developed, leaving nanorod-shaped photo-resist patterned on unexposed regions of the wafer.

The PDMS contact phase-mask is 4" in diameter and ideally has parallel lines over the entire mask (Figure 1B), and lines of different widths and pitches have been fabricated (Figure S1, Supporting Information). A small pitch size is always desired since it leads to high nanorod patterning density. However, edge lithography using PDMS stamps of pitches less than 1.5 μm was found to cause side-wall connections between neighboring lines on patterned wafers (Figure S1F). For the rest of the paper, the width and pitch of the lines on PDMS phase masks are maintained at 1 μm and 2 μm respectively. The width of photoresist lines on the patterned wafer after edge lithography depends on the exposure dosage. If only the edge lithography step was conducted, the smallest width we can achieve using the current setup is approaching 100 nm. Further increasing the exposure dosage has caused the collapse of the resist.

In the double exposure case, it is found that the normal photolithography step will also cause a width reduction in the finally patterned nanorods. Therefore, in order to achieve the same width, the edge lithography exposure dosage for double exposure is smaller than that for only edge lithography. Figure 1C and 1D show the nanorod resist patterns for two different conditions. In Figure 1C, the nanorods have a length of 840 nm and width of 190 nm whereas in Figure 1D, the nanorods have a length of 380 nm and width of 170 nm. Clearly,

the nanorod length can be precisely controlled using different Cr masks. In the current setup, edge lithography is conducted using a light source with an exposure diameter of 3", and therefore nanorods can only be found in the center 3" area (Figure S2, Supporting Information). However, if a more advanced exposure tool is used, features can be patterned on a much larger area.

To convert the doubly patterned resist coated wafer to a nanorod NIL stamp, it is subjected to dry-etching, as shown in Figure 2A. Isotropic etching using O₂ chemistry can effectively reduce the widths of the resist lines, and ultimately of the synthesized nanorods. After O₂ etching, the widths of the resist lines defining the nanorod pillars reduces to ~ 110 nm. Subsequently, Si can be etched using the nanorod resist as an etch mask. Due to the high selectivity of Si reactive ion etching chemistries, C₂F₆ is first used to remove the native oxide layer prior to Si etching, followed by a mixture of Cl₂, HBr and O₂ to etch the Si substrate. After transferring the pattern from photoresist to Si substrate, the photoresist residue is removed and the 4" wafer is cleaved to obtain the center 1.5" by 1.5" area for use as a NIL stamp. Figure 2B shows a photograph of the stamp, where the entire surface is covered by a nanorod array. For a stamp fabricated from the resist pattern shown in Figure 1D, the pitch size is 1 μm in both directions. Therefore, one nanoimprinting process using the current stamp can yield 1.5×10^9 nanorods. Figure 2C and 2D show 45° SEM views of patterns on two different stamps, which are fabricated from the resist patterns shown in Figure 1C and 1D. These nanorod pillars replicate the photo-resist patterns and have pillar heights of ~ 200 nm. A detailed nanorod stamp fabrication procedure is included in Session A, Supporting Information. For simplicity, the two stamps shown in Figure 2C and 2D are later referred to as Stamp L (long) and Stamp S (short).

SMM nanorods are fabricated according to an established method⁹, starting with these as-fabricated stamps. Detailed nanoparticle fabrication information can be found in Session B, Supporting information. The as-fabricated stamps are coated with a perfluorocarbon-silane release agent before being used for nanoimprinting. The release agent modifies the surfaces of the stamps, making them hydrophobic and ensuring that the stamps can be easily separated from the NIL resists after the nanoimprinting step. A substrate wafer is coated with a stack of three NIL resist layers for nanoparticle release from the substrate, undercut profile generation, and thermal nanoimprinting respectively. The substrate wafer is thermally nanoimprinted and the stamp is removed, and then the NIL resist stack is processed to remove residue and to generate an undercut profile. Next, nanorod materials are vacuum-deposited into the holes created in the NIL and undercut resists, and these resists are then removed to lift-off the continuous overlying metal film. Figure 3A and 3B show nanorods right after the lift-off process, for Stamp L and Stamp S respectively. These nanorods are uniform in size, have a well-aligned orientation, and cover the stamp area. They all have a layer sequence of Ti 5 nm/Fe 20 nm/Ti 3 nm/Fe 20 nm/Ti 5 nm. Figure 3C shows the distributions of nanorod lengths for the two different nanorod stamps. Using SEM, the average nanorod length in Figure 3A, for Stamp L, is determined to be 664 nm, with a standard deviation of 17 nm. Significantly, the variation of the nanorod lengths in this case is only 2.6%. For the other case shown in Figure 3B, the average nanorod length for Stamp S is 317 nm, with a standard deviation of 10 nm, leading to a variation of 3.1%. For 664-nm-long nanorods, the pitch size is 1.5 μm in the longitudinal direction and 1 μm in the transverse direction (see schematic in Figure 3D). For 317-nm-long nanorods, the pitch sizes are 1 μm in both directions. These SMM nanorods can be easily released by dissolving the release resist, and then transferred into water for biological applications according to a well-established procedure⁹.

The hysteresis loops of the SMM nanorods in Figure 3A are shown in Figure 3E. Since all nanorods on a wafer are uniform in size and orientation, such hysteresis loops will reflect

the response of single nanorods to the external field, provided the nanorod-nanorod interactions are negligible. Figure 3E shows that the magnetic curves in the longitudinal and in-plane transverse directions are quite different. In the longitudinal direction, there is an abrupt change from the moment from being saturated in one direction to being saturated in the other, and the curve shows relatively large hysteresis, as compared with that in the transverse direction. The most important parameters to characterize in the longitudinal response are the coercivity H_c , which is the applied fields at which the net moment crosses zero, and the remanent magnetization, M_R , which is the magnetization when the field is reduced to zero. For the long nanorods of Figure 3E, the longitudinal coercivity is about 0.4 kOe and the remanence (M_R/M_S) is 0.83. In the transverse direction, the coercivity and remanence are very small and the change of the moment is roughly linear, in the applied field, until the magnetic moment saturates when the field exceeds H_{sat} . The magnetic responses for the short SMM nanorods in Figure 3B, as well as single-Fe-layer nanorods (Ti 5 nm/Fe 20 nm/Ti 5 nm) fabricated by both Stamp L and Stamp S are included in Figure S3, Supporting Information. The magnetic response in the out-of-plane (thickness) direction is not shown, as the saturation field in this case exceeds the range of applied fields available.

A theoretical model based on single domains, similar to one described in literature²⁵, is helpful to understand the magnetic response of both SMM nanorods and single-Fe-layer nanorods. In this model, we assume that the magnetization at every point within each Fe layer has the same orientation (single domain) during the application of external magnetic fields. Provided that the external field is applied in-plane with the substrate, the magnetization is also assumed to be confined in-plane, because the thicknesses of the Fe layers are much smaller than their lengths and widths and therefore the out-of-plane magnetization will be energetically unfavorable considering the demagnetizing factors. Thus, we henceforth use the term transverse to mean transverse to the long axis and in the plane of the layers.

First, the transverse response of the nanorods is studied. In single-Fe-layer nanorods, only the shape anisotropy effect determines the magnetic response. As shown in Fig. 4A, similar to the case of electric charges, the magnetic moment will build up magnetic charges on the surface, leading to a demagnetizing field counteracting the magnetic moment. When the moment stays in the longitudinal direction, the positive and negative charges are accumulated at the left and right ends of the rods, whereas when the moment stays in the transverse direction, the charges are accumulated at the top and bottom sides of the rods. In the former case, the positive and negative charges are much more separated from each other, making a much smaller demagnetizing field, leading to a low-energy state. Consequently, demagnetizing fields favor a magnetic moment aligned along the longitudinal direction and discourage alignment by a transverse external field. As a result, the magnetic moment in the transverse direction is linearly proportional to the external field, until reaching saturation (Session C, Supporting Information). Here, a shape anisotropy coefficient N_0 is defined to characterize the contribution of shape anisotropy effect, which represents the magnetic field generated by magnetic layer itself, and N_0 is in linear relationship with H_{sat} , as shown in Equation 1, where $\mathbf{M}$ is the magnetization of the Fe layer. At a fixed Fe layer thickness of 20 nm, N_0 gradually increases with the nanorod length (Figure 4C).

$$H_{sat} = 2N_0 \cdot |\mathbf{M}| \quad (1)$$

In SMM nanorods, the interlayer interaction plays an important role sometimes exceeding the shape anisotropy effects. As shown in Fig. 4B, without an external field, the moments of the two Fe layers, each confined to the longitudinal direction due to shape anisotropy effect, will stay in the low energy state if they are oriented anti-parallel to each other, because this

will cause an attractive interaction between these two layers, as compared with the repulsive interaction if the moments are pointing in the same direction. The addition of an external field in the transverse direction will compete with both the interlayer interaction and the shape anisotropy effect, and eventually align the two moments with the transverse field direction at the transverse saturation field. Similar to the shape anisotropy coefficient, N_0 , an interlayer interaction coefficient, k_0 , is defined to characterize the contribution of the interlayer interaction (Session C, Supporting Information) of two layers which are separated by a spacer layer, whereas N_0 still refers to shape anisotropy effect within a single magnetic layer. For SMM nanorods, H_{sat} is related to both shape anisotropy and interlayer interaction effects as Equation 2.

$$H_{\text{sat}} = 2(N_0 + k_0) \cdot |M| \quad (2)$$

Figure 4C shows calculated values for k_0 that indicate, at any given nanorod length, k_0 decreases with increasing spacer layer thickness, indicating weakening interlayer interaction. Interestingly, k_0 becomes 3 orders of magnitude lower for 1- μm spacer layer thickness, as compared with a 20-nm thickness. For our nanorod arrays, since the pitch size is at least 1 μm , the small k_0 indicates that nanorod-nanorod interactions can be neglected, unlike in other nanorod patterns^{26,27}. For symmetric disk-shaped nanoparticles, with no shape-preferred axis, $N_0 = 0$ and the interlayer interaction is the only contribution to the saturation field. For large aspect ratio nanorods, both the shape anisotropy effect and the interlayer interaction are significant.

Notably, the dependence of k_0 on the nanorod length varies with the spacer layer thickness. At large spacer thickness, k_0 will increase with the nanorod length whereas at small spacing layer thickness, the trend is opposite. This is a result of the complexity of the dipole-dipole interaction. Figure 4D shows two Fe layers in an anti-parallel magnetic moment configuration. If we focus on the unit volume 'A' in the middle of the lower Fe layer, it has attractive interaction with point 'B', which is in the middle of the upper Fe layer. This attractive interaction greatly reduces the magnitude of interaction energy, counteracting the alignment with external field in the transverse direction. For the case of large spacer layer thickness, as compared with nanorod length, the force between unit volumes in the upper and lower Fe layers is always attractive. Therefore, increasing the nanorod length will make it harder for the moments of the two Fe layers to align in the transverse direction. As a result, the saturation field as well as k_0 increases with nanorod length. The situation will change when the nanorod length is further increased to point 'C', which has a large distance to point 'A' in the length direction compared with the thickness direction. Now, the unit volumes of 'A' and 'C' will repel each, increasing the interaction energy. Therefore, for small spacer layer thickness, as compared with nanorod length, further increasing the nanorod length will weaken the originally strong attraction between the two Fe layers, leading to a decreased saturation field as well as k_0 .

Figure 4E shows the dependence of the transverse saturation fields on the nanorod length in both single-Fe-layer nanorods and SMM nanorods, with theoretical values based on computed N_0 and k_0 . Generally, this saturation field increases with the nanorod length. For a given length and magnetic layer thickness, the saturation field of SMM nanorods is always higher than that of single-layer nanorods, due to the interlayer interaction. Without any fitting, the experimental data follows the trend of the theoretical curve with < 20% deviation. More measurements were conducted to further verify our model. First for single-Fe-layer nanorods, the effect of varying the thickness of the Fe layer is shown in Figure 4F. The theoretical curve demonstrates an increased transverse saturation field with increasing Fe layer thickness, which is a result of an increase in N_0 . This data implies that the

transverse saturation fields of bilayer nanorods are close to those of single layer nanorods with doubled thickness. Second, Figure 4G shows that the saturation field for SMM nanorods decreases with increasing spacer layer thickness due to the decrease of k_0 described above. Experimental data are also marked on the same plots in both cases, demonstrating a good match with the theoretical curve even without any fitting. Therefore, a theoretical model including single domain rotation can satisfactorily describe the magnetic behavior of nanorods in transverse magnetic fields.

However, the single domain model is not sufficient to explain the longitudinal response of these magnetic nanorods. For a single-Fe-layer nanorod in a longitudinal field, the moment aligns along the field in order to stay in the minimum energy state. The moment remains aligned as the field is reduced to zero, as reflected in the longitudinal remanence. When the field is reversed, the minimum energy state shifts to a reversed moment, but the moment reversal, in the single domain model, would require a coercive field, $\sim 2N_0|\mathbf{M}|$, to overcome a large energy barrier that blocks a single domain transition. In practice, the coercive fields needed to achieve zero moment, ~ 900 Oe for 664-nm nanorods and ~ 300 Oe for 317-nm nanorods, are not nearly this large (Figure 5) because reversal usually proceeds through gradual multi-domain processes. Although domain mechanisms are complex, shape effects do play a role and H_c increases with nanorod length. SMM nanorods also show similar coercive behavior, but the incorporation of two Fe layers clearly reduces H_c greatly, by a factor of 2–3 compared with single-Fe-layer nanorods (Figure 5). Details of the longitudinal response for single-Fe-layer and SMM nanorods are under further investigation.

In summary, we have developed a double exposure technique to pattern nanorod shapes onto photo-resist-coated Si wafers, where the lengths of the nanorods are defined by projection-lithography and the widths of the nanorods are defined by edge-lithography. The photo-resist pattern is then transferred into the Si layer to make nanorod stamps, which are then used to fabricate monodisperse nanorods. The length of the nanorods can be controlled anywhere above 250 nm. The widths of the nanorods are typically around 110 nm, well below the diffraction limit of photo-lithography. Using these stamps, SMM nanorods have been fabricated. A theoretical model has been applied to explain the magnetic responses and reveals that both shape anisotropy and interlayer interactions play an important role in determining the transverse saturation field, which is in accord with domain rotation models. The magnetic response in the longitudinal direction is more complex and usually involves multiple domain formation, but multilayer nanorods offer reduced coercivities. Compared with single-Fe-layer nanorods, the incorporation of two Fe layers in SMM nanorods reduces the coercivity by a factor of 2–3. Moreover, before release to water, the bilayer nanorods can be prepared with anti-parallel orientations, by application of a transverse field greater than the transverse saturation field, which is then gradually reduced to zero, which will result in an anti-parallel moment configuration, leading to zero remanence. This helps prevent nanorod aggregation, which is very strong for the fully magnetized nanorods, when they are initially dispersed in water and until a magnetic field is applied. Furthermore, these magnetic nanorods can be easily incorporated with other functionalities, such as for plasmonic and magnetic nanorods, by sequential deposition of additional layers of different materials together with the magnetic material. Therefore, these SMM nanorods offer some unique advantages which are very promising in biomedical applications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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ABBREVIATIONS

SMM	synthetic magnetic bilayer
PDMS	polydimethylsiloxane
NIL	nanoimprint lithography

References

1. Jin R, Cao YW, Mirkin CA, Kelly KL, Schatz GC, Zheng JG. *Science*. 2001; 294:1901–1903. [PubMed: 11729310]
2. González E, Arbiol J, Puntès VF. *Science*. 2011; 334:1377–1380. [PubMed: 22158813]
3. Ghosh A, Fischer P. *Nano Lett*. 2009; 9:2243–2245. [PubMed: 19413293]
4. Kang K, Yoon WS, Park S, Moodenbaugh AR, Lewis LH. *Adv Funct Mater*. 2009; 19:1100–1105.
5. Qiu Y, Liu Y, Wang L, Xu L, Bai R, Ji Y, Wu X, Zhao Y, Li Y, Chen C. *Biomaterials*. 2010; 31:7606–7619. [PubMed: 20656344]
6. Huang X, Neretina S, El-Sayed MA. *Adv Mater*. 2009; 21:4880–4910.
7. Zhang J, Langille MR, Mirkin CA. *Nano Lett*. 2011; 11:2495–2498. [PubMed: 21528893]
8. Zhang M, Xie X, Tang M, Criddle CS, Cui Y, Wang SX. *Nat Commun*. 2013; 4:1866. [PubMed: 23673651]
9. Hu W, Zhang M, Wilson RJ, Koh AL, Wi JS, Tang M, Sinclair R, Wang SX. *Nanotechnology*. 2011; 22:185302. [PubMed: 21415483]
10. Hu W, Wilson RJ, Koh AL, Fu A, Faranesh AZ, Earhart CM, Osterfeld SJ, Han SJ, Xu L, Guccione S, Sinclair R, Wang SX. *Adv Mater*. 2008; 20:1479–1483.
11. Zhang M, Earhart CM, Ooi C, Wilson RJ, Tang M, Wang SX. *Nano Res*. 2013; 6:745–751.
12. Zhang W, Krishnan KM. *J Appl Phys*. 2012; 111:07B509.
13. Wen T, Booth RA, Majetich SA. *Nano Lett*. 2012; 12:5873–5878. [PubMed: 23035797]
14. Kim DH, Rozhkova EA, Ulasov IV, Bader SD, Rajh T, Lesniak MS, Novosad V. *Nat Mater*. 2010; 9:165–171. [PubMed: 19946279]
15. Tanase M, Bauer LA, Hultgren A, Silevitch DM, Sun L, Reich DH, Searson PC, Meyer GJ. *Nano Lett*. 2001; 1:155–158.
16. Schmucker AL, Harris N, Banholzer MJ, Blaber MG, Osberg KD, Schatz GC, Mirkin CA. *ACS Nano*. 2010; 4:5453–5463. [PubMed: 20738131]
17. Lee KB, Park S, Mirkin CA. *Angew Chem Int Ed*. 2004; 43:3048–3050.
18. Mair LO, Evans B, Hall AR, Carpenter J, Shields A, Ford K, Millard M, Superfine R. *J Phys D: Appl Phys*. 2011; 44:125001.
19. Sniadecki NJ, Anguelouch A, Yang MT, Lamb CM, Liu Z, Kirschner SB, Liu Y, Reich DH, Chen CS. *Proc Nat Acad Sci USA*. 2007; 104:14553–14558. [PubMed: 17804810]
20. Tanase M, Felton EJ, Gray DS, Hultgren A, Chen CS, Reich DH. *Lab Chip*. 2005; 5:598–605. [PubMed: 15915251]
21. Liu M, Lagdani J, Imrane H, Pettiford C, Lou J, Yoon S, Harris VG, Vittoria C, Sun NX. *Appl Phys Lett*. 2007; 90:103105.
22. Ho D, Sun X, Sun S. *Acc Chem Res*. 2011; 44:875–882. [PubMed: 21661754]
23. Odom TW, Love JC, Wolfe DB, Paul KE, Whitesides GM. *Langmuir*. 2002; 18:5314–5320.
24. Qin D, Xia Y, Whitesides GM. *Nature Protocols*. 2010; 5:491–502.
25. Worledge DC. *Appl Phys Lett*. 2004; 84:2847–2849.

26. Kou X, Fan X, Dumas RK, Lu Q, Zhang Y, Zhu H, Zhang X, Liu K, Xiao JQ. Adv Mater. 2011; 23:1393–1397. [PubMed: 21400603]
27. Bennett AJ, Xu JM. Appl Phys Lett. 2003; 82:3304–3306.

Figure 1.

Double exposure patterning of nanorod shapes on photoresist. (A), schematic of double exposure. The first column is the plain view of the wafer, the second column is the side view from top to bottom and the third column is the side view from left to right. Here, grey color stands for Si wafer, red and pink color stands for unexposed and exposed photoresist respectively, the yellow color stands for Cr mask and the blue color stands for PDMS mask. (B), a picture of a PDMS phase mask replicated from a 4" wafer. (C) and (D), SEM images of two different resist patterns formed by double exposure. Scale bar: 1 μm .

Figure 2. Fabricating nanorod stamps. (A), schematic of transferring nanorod pattern from photoresist to Si substrate. (B), photograph of 1.5'' by 1.5'' nanorod stamp. (C) and (D), SEM views (45°) of nanorod pillar patterns on the stamps. These two stamps are referred to as Stamp L (long) and S (short) respectively. Scale bar: 1 μm .

Figure 3.

(A) and (B), SMM nanorods fabricated using Stamp L and Stamp S respectively with scale bar 2 μm . The layer sequence is Ti 3 nm/Fe 20 nm/Ti 5 nm/Fe 20 nm/Ti 3 nm. (C), the distribution of nanorod lengths for the two SMM nanorods in (A) and (B). (D), schematic of different directions of applied magnetic field for hysteresis loop measurements. The black arrow denotes the field applied in in-plane transverse (T) direction and the red arrow denotes the field applied in longitudinal (L) direction. (E), hysteresis loops measured with applied magnetic field in in-plane transverse or longitudinal directions for SMM nanorods fabricated using Stamp L. Here, H_{sat} denotes the saturation field in the in-plane transverse field measurement and H_c denotes coercivity in the longitudinal field measurement.

Figure 4.

Theoretical model explaining the observed saturation field in transverse direction. (A), top-view schematic of the shape anisotropy effect. The left image stands for the magnetic moment aligned in the longitudinal direction, i.e. low-energy state, and the right image stands for the moment aligned in the transverse direction, i.e. high-energy state. Color in blue stands for single Fe layer; '+' and '-' signs stand for positive and negative magnetic charges respectively; black arrows stand for magnetic moments; red arrows stand for demagnetizing field. (B), side-view schematic of the interlayer interaction for SMM nanorods. The left image stands for the low-energy state, where the moments of the two Fe layers stay in the longitudinal direction, but opposite to each other. The right image stands for the high-energy state, where the moments point in the same direction, aligned with the transverse external field. Colors in blue stands for Fe layers, black arrows, in-plane or pointing inward, stand for magnetic moments; red arrows indicate attractive or repulsive forces between the two layers. (C), computed values for the shape anisotropy coefficient N_0 and interlayer interaction coefficient k_0 for varying nanorod lengths. k_0 also varies with the spacing layer thickness d . (D), a schematic of the interlayer interaction. Red arrows show how the interactions change from attractive to repulsive. (E), the saturation field plotted versus nanorod length for both single-Fe-layer and SMM nanorods. (F), the dependence of

saturation field on the Fe layer thickness in single-Fe-layer nanorods. (G), the dependence of saturation field on the spacing layer thickness d in SMM nanorods. In both (F) and (G), the nanorods are fabricated using Stamp L. In (E), (F) and (G), the theoretical calculations are all compared with the experimental data.

Figure 5.
Comparison of H_c for single-Fe-layer and SMM nanorods with different lengths.