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## Tailoring the magnetization reversal in antidot nanostructures using lithographically engineered inhomogeneities

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We report on tailoring the magnetization reversal mechanism in engineered permalloy antidot nanostructures by lithographically introducing inhomogeneities in the form of neighboring antidots with alternate dimensions. We observed that the magnetic domain configurations are significantly altered when compared to homogeneous antidots due to the dissimilar size of adjacent antidots. The reversal process also is strongly influenced by the relative difference in the size of adjacent antidots and the thickness of the permalloy film. Our results have been further corroborated by micromagnetic simulations and low temperature measurements. © 2011 American Institute of Physics. [doi:10.1063/1.3537948]

There has been significant interest in the magnetization reversal mechanisms of patterned nanomagnets with precisely controlled geometry and interelement spacing due to potential applications in a wide range of magnetoelectronic devices such as magnetic random access memories,<sup>1</sup> read head sensors,<sup>2</sup> programmable logic devices,<sup>3</sup> and ultrahigh density storage.<sup>4</sup> From a fundamental viewpoint, nanomagnets by virtue of their low dimensionality offer a wide range of magnetic properties which are not observed in their continuous bulk counterparts, especially when the size becomes comparable to or smaller than certain characteristic length scales such as spin diffusion length, carrier mean free path, and magnetic domain wall width.<sup>5</sup> One class of magnetic nanostructures that has received growing attention are antidots, which consist of arrays of “holes” embedded in a continuous magnetic film.<sup>6</sup> The presence of “holes” can also modify the intrinsic magnetic anisotropy of the film, thereby inducing well defined periodic domain structures in the vicinity of the “holes.”<sup>7</sup> With advancements in lithography tools for fabricating nanostructures with precisely controlled dimensions and geometry,<sup>8</sup> it is now possible to create well defined antidot nanostructures with tailor-made physical parameters such as “hole” size and density<sup>9</sup> and lattice geometry.<sup>10</sup> The size and distribution of such engineered “holes” strongly affect magnetic properties such as coercivity, anisotropy, and reversal mechanism. Recently we have demonstrated that the use of two sublattices in bicomponent antidot nanostructures greatly enhances the parameters available for engineering the magnetic properties of antidots.<sup>11</sup>

In this work, we investigate how the relative difference in the size of adjacent “holes” affects the magnetization reversal mechanism in antidot nanostructures as a function of temperature. We demonstrate that the reversal can be con-

veniently tuned by creating a differential in the dimensions of neighboring antidots.

A schematic of our proposed antidot nanostructure is shown in Fig. 1(a). Unlike homogeneous antidots, our structure is patterned such that there is a differential ( $\Delta D = D_1 - D_2$ ) in the diameters of adjacent antidots. The experimental fabrication of such “inhomogeneous” antidots was achieved over a large area ( $4 \times 4 \text{ mm}^2$ ) on commercially available Si substrates using deep ultraviolet (DUV) lithography at 248 nm exposing wavelength, followed by e-beam evaporation of permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) films of varying thickness  $t$  and ultrasonic assisted lift-off in OK73 resist thinner. Details of the fabrication process are described elsewhere.<sup>8</sup> Figure 1(b) shows the scanning electron microscope (SEM) image of two sets of “inhomogeneous” antidot nanostructures:

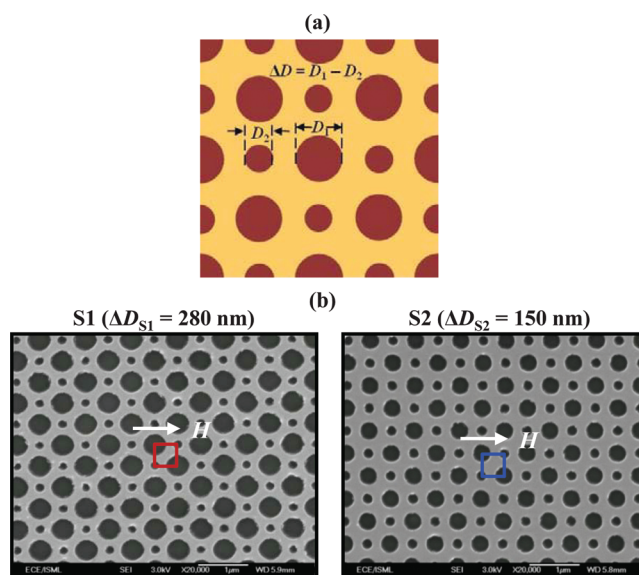


FIG. 1. (Color online) (a) Schematic illustration of the proposed antidot nanostructure with a differential  $\Delta D = D_1 - D_2$  in the diameters of adjacent antidots. (b) SEM image of antidot nanostructures S1 and S2.

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**S1** with alternating diameters  $D_1 = 450$  nm,  $D_2 = 170$  nm,  $\Delta D_{S1} = 280$  nm and center-to-center spacing between adjacent antidots fixed at  $\lambda = 470$  nm; and **S2** with  $D_1 = 350$  nm,  $D_2 = 200$  nm,  $\Delta D_{S2} = 150$  nm, and  $\lambda = 450$  nm. For all the results shown in this work, the orientation of the external magnetic field  $H$  is along the edge of the square unit cell. Detailed insight into the magnetization reversal mechanism in the antidots was facilitated by micromagnetic modeling which was performed using LLG Micromagnetic software.<sup>12</sup>

Figure 2(a) shows the in-plane magnetization curves for antidot array **S1** at room temperature for  $t = 30$  nm and  $t = 80$  nm, respectively. The simulated magnetization curve for  $t = 30$  nm is shown as an inset (i) in Fig. 2(a). Insets (ii) and (iii) show the respective half-loop derivatives of the magnetization curves. The corresponding anisotropic magnetoresistance (AMR) curves in the transverse geometry (field perpendicular to current density) are shown in Fig. 2(b). It is evident from both the magnetization and MR curves that in comparison to homogeneous circular antidot nanostructures of comparable dimensions and film composition,<sup>13</sup> the magnetization reversal mechanism of our “inhomogeneous” antidot arrays is distinctly modified due to the alternating dimensions of adjacent antidots. The reversal occurs via two characteristic switching fields for both  $t = 30$  nm and  $t = 80$  nm, and also manifests itself in the two distinct peaks ( $G_1$  and  $G_2$ ) in the respective derivate loops. The simulated magnetization reversal for both **S1** and **S2** exhibits the same number of transitions [from  $A_1'$  to  $A_4'$  for **S1** as indicated in inset (i) of Fig. 2(a)] as observed in the experimental magnetization curves.

To better elucidate the reversal process, magnetization states obtained from LLG simulation at various stages of reversal are shown in Fig. 2(c) for  $t = 30$  nm. At positive saturation field, all spins are aligned along the field direction. As the external magnetic field is reduced from saturation, domains form via demagnetizing fields due to surface magnetic charges at the boundary between the permalloy film and the antidot edges. Magnetization state  $A_1$  in Fig. 2(c) shows that unlike homogeneous antidots where four wedge shaped domains connect each antidot to its nearest neighbor at each end,<sup>14</sup> the domain patterns for our “inhomogeneous” antidots are altered. We observed that the wedge shaped domains now connect only the larger antidots ( $D = 450$  nm) to their respective closest neighbors of identical dimension instead of the nearest neighbor smaller antidots ( $D = 170$  nm), and the spins are oriented at  $\pm 45^\circ$  to the field direction. The nucleation of wedge shaped domains around the smaller antidots is barely discernible, and they are unable to stretch out and connect to their counterpart antidots. The domain configuration may be ascribed to the additional anisotropy that has been induced in the “inhomogeneous” antidot nanostructures by patterning neighboring antidots with alternate dimensions.<sup>11</sup>

With further reduction in magnetic field, we observed that magnetization continues to decrease gradually until there is a drop of  $\sim 18\%$  at  $H = 30$  Oe. We attribute this behavior to the formation of the domain pattern shown in state  $A_2$ . Compared to  $A_1$ , it can be seen that some of the wedge shaped domains connecting larger antidots have

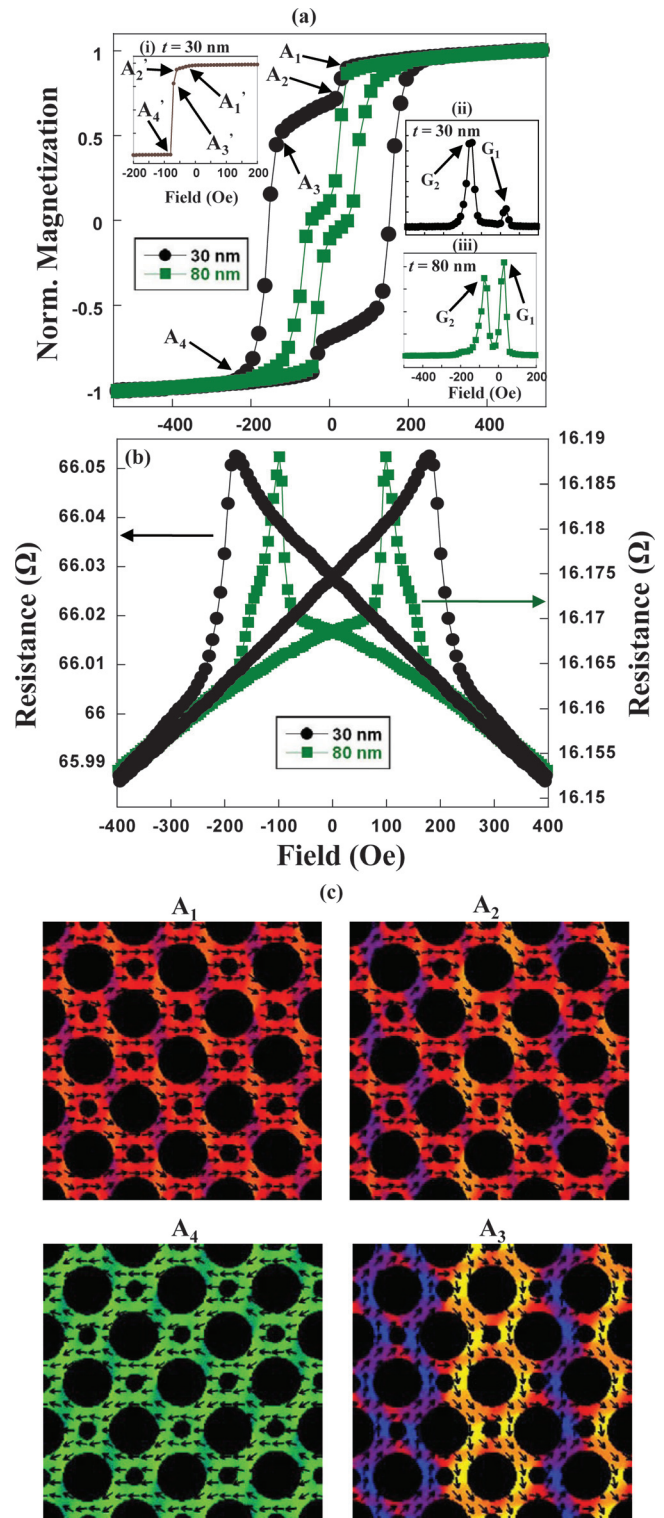


FIG. 2. (Color online) (a) In-plane magnetization curves with insets showing the simulated magnetization curve for  $t = 30$  nm and the respective half loop derivatives. (b) Transverse MR cures for antidot array **S1** at room temperature. (c) Magnetization states obtained from LLG simulation at varying external magnetic fields for  $t = 30$  nm.

increased in area, whereas others have concurrently decreased in area, thereby resulting in a reduction in the area of domains that are parallel to the applied field direction. This drop in magnetization is also accompanied by a change in slope of the MR curve in Fig. 2(b) due to further reduction



in the angle between magnetization and current density. When the field is now increased in the opposite direction, magnetization decreases continuously due to the rotation of domains until state  $A_3$  is formed at  $H = -150$  Oe. It can be seen that the wedge shaped domains from each of the smaller antidots have now coalesced with the adjacent larger domains, thereby resulting in a reduction in the area of domains that are parallel to the applied field direction. Furthermore we also observe that small vertical domains now exist between each pair of large/small antidots in every row of the structure and are oriented at  $\pm 90^\circ$  to the field direction. We also note that for both  $A_2$  and  $A_3$ , the magnetization in the left side of the unit cell reverses slightly differently from the right side. This effect may be attributed to the fact that the SEM image was used to create the mask for the simulations, thereby taking into account the defect distribution at the edges of the “holes.” As the reverse field is increased further, a steep drop in both magnetization and resistance occurs and persists until the stable magnetic state shown as  $A_4$  is formed at  $H = -240$  Oe.  $A_4$  represents the condition where all wedge shaped domains between the larger antidots have completed a  $180^\circ$  rotation from their original orientation in state  $A_1$ , and the spins are now oriented at  $\pm 135^\circ$  to the field direction. Further increase in reverse field signals the completion of magnetization reversal in the antidot nanostructures as all the spins align along the reverse field direction. For  $t = 80$  nm, we observe a similar reversal mechanism with the first switching at  $H = 30$  Oe. However, obvious distinctions were apparent in the considerably larger drop in magnetization ( $\sim 75\%$ ) during the first switching, and the magnitude of the second switching field ( $H = -75$  Oe). This may be attributed to the larger demagnetizing field as a consequence of increased film thickness.

Figure 3(a) shows the transverse MR curves for  $S_2$  at room temperature for  $t = 80$  nm. The difference in diameters ( $\Delta D$ ) of the neighboring antidots for  $S_2$  is  $\Delta D_{S_2} = 150$  nm, while for  $S_1$ , the corresponding value is  $\Delta D_{S_1} = 280$  nm. This suggests that for constant  $t$ , both structures should exhibit different switching mechanisms and magnetization states. We indeed observe that in sharp contrast to the reversal for  $S_1$  (shown in Fig. 2), the reversal for  $S_2$  occurs via three characteristic switching fields and is also evident clearly in the three peaks ( $H_1$ ,  $H_2$ , and  $H_3$ ) in the derivative loop (of the magnetization curve) shown as an inset in Fig. 3(a). This behavior has been attributed to the formation of transitional stable domain states in  $S_2$  during the reversal process. While magnetization states similar to  $A_1$  and  $A_4$  also occur in  $S_2$ , the difference in  $\Delta D$  results in a different reversal mechanism with two intermediate magnetization states.

To eliminate the effects of thermally activated excitations on the reversal process at room temperature, we have also characterized the magnetic and transport properties of the antidot nanostructures as a function of temperature for  $t = 80$  nm. We observed that the key features of the magnetization reversal process which were noticeable at room temperature also manifest themselves in the corresponding measurements at low temperature. The evident difference in the switching field distributions and the magnitudes of the characteristic

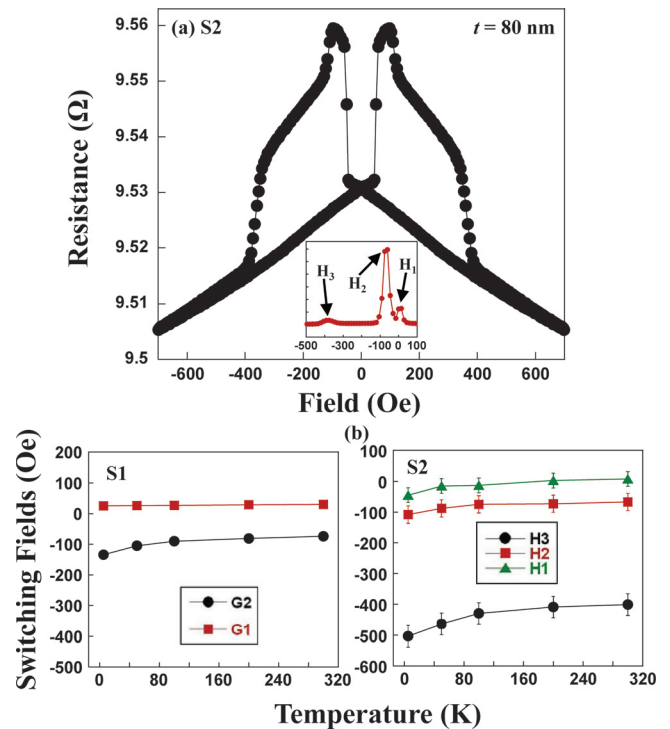


FIG. 3. (Color online) (a) Transverse MR curve with inset showing the half loop derivative for antidot array  $S_2$  for  $t = 80$  nm at room temperature. (b) Temperature dependence of switching fields for  $S_1$  and  $S_2$  corresponding to  $t = 80$  nm.

switching fields ( $G_1$  and  $G_2$  for  $S_1$ ) and ( $H_1$ ,  $H_2$ , and  $H_3$  for  $S_2$ ) has been analyzed by extracting these fields from the half-loop derivatives of the magnetization curve and plotting them as a function of temperature in Fig. 3(b). All switching fields exhibit monotonic temperature dependence and increase noticeably in magnitude below 100 K.

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