Magnetization dynamics and reversal mechanism of Fe filled Ni$_{80}$Fe$_{20}$ antidot nanostructures

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We investigate the magnetization dynamics and reversal mechanism of Fe filled Ni$_{80}$Fe$_{20}$ antidot nanostructures. The mutual magnetostatic coupling between the two ferromagnetic nanostructures leads to a significant modification to the magnetization reversal mechanism and ferromagnetic resonance mode profiles when compared with reference Fe dots and Ni$_{80}$Fe$_{20}$ antidot array. Our experimental results are in qualitative agreement with both the static and dynamic micromagnetic simulations. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4729428]

Magnonic crystals (MCs) conceived as the magnetic microwave analog of photonic crystals are artificial magnetic nanostructures with periodic lateral variations in their magnetic properties, which have received a lot of attention recently due to their potential in a wide range of applications such as microwave resonators, filters, and spin logic devices.\(^1\)-\(^4\) The band spectrum of MC consists of allowed (magnonic bands) and forbidden states (magnonic gaps) that can be tuned by magnetic fields and geometrical parameters.\(^5\),\(^6\)

Magnetic antidots, which consist of a mesh of nonmagnetic “holes” embedded in a continuous magnetic film, represent a two-dimensional (2-D) MC,\(^7\) in which the magnonic band structures can be engineered by varying the periodicity of the holes array. The static and dynamic properties of magnetic antidot nanostructures have been extensively investigated.\(^8\)-\(^14\) Recently, there is interest in matrix antidot structures in which the holes are filled with another ferromagnetic (FM) material.\(^15\) It is expected that the matrix antidot structures will process unique static and dynamic properties due to the mutual coupling between the two ferromagnetic materials that may be exploited in magnonic applications.

In this letter, we investigate the static and dynamic behaviors of Fe filled Ni$_{80}$Fe$_{20}$ antidot nanostructures representing a 2-D MC. Due to the strong coupling between the two FM materials, a drastic modification in the magnetic switching behavior and ferromagnetic resonance (FMR) mode profiles is observed when compared with separate Fe dots and Ni$_{80}$Fe$_{20}$ antidots array due to strong magnetostatic coupling between the two FM materials. Our experimental results are in good agreement with both the static and dynamic micromagnetic simulations.

Periodic arrays of circular holes with diameter $d = 550 \text{ nm}$ were patterned onto Si substrate over a large area ($4 \text{ mm} \times 4 \text{ mm}$) using deep ultraviolet lithography at 248 nm exposure wavelength. Details of the processing steps can be found elsewhere.\(^{16}\) Fe($25 \text{ nm}$)/Au($5 \text{ nm}$)/Al$_2$O$_3$ ($50 \text{ nm}$) films were deposited on the patterned substrate using electron beam (e-beam) evaporation technique followed by lift-off process. The base pressure of the chamber was better than $2 \times 10^{-3} \text{Torr}$. After the lift-off stage, Ni$_{80}$Fe$_{20}$($25 \text{ nm}$)/Au($5 \text{ nm}$) films were then deposited on top of the Fe($25 \text{ nm}$)/Al$_2$O$_3$($50 \text{ nm}$) dots by e-beam deposition. In the final process, the sample was dipped in a AZ photoresist developer solution, which removes the Al$_2$O$_3$ layer and the Ni$_{80}$Fe$_{20}$/Au layer on top of the Fe/Au dots, resulting in Fe filled Ni$_{80}$Fe$_{20}$ antidot nanostructures. We refer to the structure as “Ni$_{80}$Fe$_{20}$/Fe.” The 5 nm Au film is used to protect the FM layers from oxidation during processing. Shown in Fig. 1(a) are representative scanning electron micrographs (SEM) of the Ni$_{80}$Fe$_{20}$/Fe structure. The pitch (center-to-center distance between the nearest neighbor circles) $p$ is 620 nm as depicted in Fig. 1(b). The X and Y of Cartesian frame are along the two orthogonal directions, which are diagonal to the square lattices. The Z axis (out-of-plane) corresponds to the thickness of the nanostructures. We found that there is a tiny gap ($\sim 10 \text{ nm}$) between the Fe dots and the surrounding Ni$_{80}$Fe$_{20}$ antidot structure suggesting that the two FM structures are only coupled magnetostatically (i.e., exchange decoupled). For controlled experiments, we also fabricated reference Fe($25 \text{ nm}$)/Au($5 \text{ nm}$) dots array and Ni$_{80}$Fe$_{20}$($25 \text{ nm}$)/Au($5 \text{ nm}$) antidot array during the same processing steps. In order to fabricate the Fe dots array, we deposited Fe($25 \text{ nm}$)/Au($5 \text{ nm}$)/Al$_2$O$_3$($50 \text{ nm}$) in the same process for the Ni$_{80}$Fe$_{20}$/Fe structure followed by a dip in the AZ photoresist developer solution to remove the Al$_2$O$_3$ layer. To fabricate the Ni$_{80}$Fe$_{20}$ antidots, 70 nm thick Al$_2$O$_3$ dot array was fabricated using the same templates as the Fe dots in the Ni$_{80}$Fe$_{20}$/Fe structure followed by the deposition of Ni$_{80}$Fe$_{20}$($25 \text{ nm}$)/Au($5 \text{ nm}$) films at the same time as the Ni$_{80}$Fe$_{20}$/Fe sample. The Al$_2$O$_3$ dots were then dissolved in the AZ photoresist developer solution, leaving behind array of holes in Ni$_{80}$Fe$_{20}$/Au film.

For FMR measurements, typical coplanar waveguide (CPW) with signal line length of 300 $\mu\text{m}$, width of 20 $\mu\text{m}$ were fabricated on top of the fabricated magnetic structures using optical lithography followed by deposition of Al$_2$O$_3$($50 \text{ nm}$/Au($150 \text{ nm}$) and lift-off process. Shown in Fig. 1(c) is a schematic of Ni$_{80}$Fe$_{20}$/Fe structure incorporating a CPW for FMR measurements.

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The collective magnetic switching behaviors of the fabricated structures were characterized using a focused longitudinal Magneto-Optic Kerr Effect (MOKE) set up with a spot size of about 5 μm. Magnetic force microscopy (MFM) was performed in phase detection mode using a commercial CoCr coated Si cantilever tip scanned at 35 nm lift height. The FMR responses of the fabricated structures were measured using a microwave vector network-analyzer (VNA). The ports of VNA were connected to the CPW using G-S-G-type microwave coplanar probes. The FMR responses were measured at room temperature by sweeping the frequency for fixed applied field ($H_{app}$) in the 1–20 GHz range. This process was repeated for a large number of $H_{app}$ values starting from negative saturation field ($H_{sat} = -1500$ Oe), passing through zero, and then gradually increasing to positive saturation field. The frame of reference used is shown in Fig. 1(b). The $H_{app}$ is applied at an angle $\theta$ relative to the X-axis, while the microwave magnetic field $h_f$ produced by the signal line of CPWs is applied along Y-axis. Understanding of the experimental results was aided using the LLG micromagnetic simulator. Standard parameters for Ni$_{80}$Fe$_{20}$ (gyromagnetic ratio $\gamma = 2.8$ GHz/kOe, saturation magnetization $M_s = 800$ emu-cm$^{-3}$, exchange constant $A = 1.05 \times 10^{-6}$ erg-cm$^{-1}$, and anisotropy constant $K_U = 0$) and Fe ($M_s = 1714$ emu-cm$^{-3}$, $A = 2.1 \times 10^{-6}$ erg-cm$^{-1}$, and $K_C = 0$) were used in the simulation. The damping coefficient is set as $\alpha = 0.008$. The masks used in the simulations were derived from the SEM micrographs using 2-D periodic boundary conditions with a cell size of 7 nm $\times$ 7 nm $\times$ 25 nm. The simulation was carried out in a face-centered square lattice with 256 $\times$ 256 cells in an area about 2 μm $\times$ 2 μm. The spatial characteristics of the different FMR modes were quantified by running time-dependent LLG simulations and analyzing the results using spatially and frequency-resolved fast Fourier transform imaging.

Shown in Fig. 2(a) is the M-H loop of the reference 25 nm thick Fe dots array for fields applied along the X-axis. The Fe dots show a typical dot reversal process, namely, vortex core nucleation followed by core propagation and annihilation. The corresponding hysteresis loop of the reference 25 nm Ni$_{80}$Fe$_{20}$ antidots is shown in Fig. 2(b). The Ni$_{80}$Fe$_{20}$ antidots show a sharp magnetic switching with a coercivity (300 Oe) much larger than that of the corresponding continuous film (23 Oe, see the left inset of Fig. 2(b)) due to pinning effects at the antidot edge and enhanced demagnetization fields. The corresponding M-H loop of the 25 nm thick Ni$_{80}$Fe$_{20}$/Fe structure is shown in Fig. 2(c). Interestingly, we observed three distinct switching steps, corresponding to vortex core nucleation of Fe dots at $H_1$, magnetization reversal of Ni$_{80}$Fe$_{20}$ antidot array at $H_2$ and vortex core annihilation of Fe dots at $H_3$. The switching fields were determined by taking the derivative of the Kerr intensity plot in the ascending sweep direction in order to obtain the peak positions. As the applied field is increased from negative saturation, the

![FIG. 1. (a) Scanning electron micrograph of Fe filled Ni$_{80}$Fe$_{20}$ antidot nanostructures with dot diameter of 550 nm and pitch of 620 nm; (b) Sketch of the structure lattices and the field configuration; (c) Schematics of CPW deposited on top of the Ni$_{80}$Fe$_{20}$/Fe structure for FMR measurements.](image1)

![FIG. 2. Hysteresis loops for (a) Fe dots; (b) Ni$_{80}$Fe$_{20}$ antidots (the corresponding M-H loop of continuous Ni$_{80}$Fe$_{20}$ film is shown in the left inset); and (c) Ni$_{80}$Fe$_{20}$/Fe structure (the interpolate loop assuming no coupling between the Fe dots and Ni$_{80}$Fe$_{20}$ antidots is shown in the left inset) with magnetic field applied along X-axis. MFM images taken at remanence after applying negative saturation field are shown as insets at the right-bottom corner. The corresponding simulated hysteresis loops are shown in (d)–(f), respectively. Also shown as insets at the bottom right hand corners are the simulated spin configurations.](image2)
magnetization is maintained until \( H_{s1} = -80 \) Oe, when a rapid decrease of Kerr intensity occurs, indicating the nucleation process of vortex core in the Fe dots. This is followed by a comparatively slow decrease rate of Kerr intensity at around zero fields, attributed to the propagation of the vortex core in the Fe dots. Further increasing the field up to \( H_{s2} \) results in a sharp switching, corresponding to the magnetization reversal of the Ni\(_{80}\)Fe\(_{20}\) antidots. The last switching process is dominated by vortex core propagation of the Fe dots until the vortex core annihilates at the dot edge at a field \( H_{s3} = 630 \) Oe.

We have compared the switching fields of the reference Fe dots (Fig. 2(a)), and Ni\(_{80}\)Fe\(_{20}\) antidot structures (Fig. 2(b)) with the Ni\(_{80}\)Fe\(_{20}\)/Fe structure (Fig. 2(c)). We observed that the Fe elements in the Ni\(_{80}\)Fe\(_{20}\)/Fe structure show a significant decrease in both \( H_{s1} \) and \( H_{s3} \) from \(-257\) Oe, 960 Oe down to \(-80\) Oe and 630 Oe, respectively, as marked on the dashed lines of Figs. 2(a)–2(c). The reduction in the switching fields in the Ni\(_{80}\)Fe\(_{20}\)/Fe structure is attributed to the direct effects of magnetostatic coupling between the Fe dots and Ni\(_{80}\)Fe\(_{20}\) antidots. Similarly, the formation of vortex core in the Fe dots assists the magnetic switching of the Ni\(_{80}\)Fe\(_{20}\) antidots, leading to a reduction of the switching field from 280 Oe to 177 Oe.

We have further characterized the static magnetic properties using MFM imaging at zero field after first applying a negative saturation field of \(-3\) kOe. The corresponding MFM images taken at remanence for the Fe dots, Ni\(_{80}\)Fe\(_{20}\) antidots, and Ni\(_{80}\)Fe\(_{20}\)/Fe structures are shown as insets in Figs. 2(a) to 2(c), respectively. Interestingly, the Fe dots in the Ni\(_{80}\)Fe\(_{20}\)/Fe structure adopt single vortex core (indicated by the arrows in the lower inset of Fig. 2(a)). This may be due to the modified demagnetization field resulting from surrounding Ni\(_{80}\)Fe\(_{20}\) antidot array in the Ni\(_{80}\)Fe\(_{20}\)/Fe structure. The domain configuration of the Ni\(_{80}\)Fe\(_{20}\) antidots in the Ni\(_{80}\)Fe\(_{20}\)/Fe structure is similar to that of the reference Ni\(_{80}\)Fe\(_{20}\) antidots (inset of Fig. 2(b)).

Shown in Figs. 2(d) to 2(f) are the corresponding LLG simulations for the results shown in Figs. 2(a) to 2(c). The simulated magnetization states at 70 Oe (for the Ni\(_{80}\)Fe\(_{20}\)/Fe sample) and remanence are shown as insets in Figs. 2(d) to 2(f), respectively. There is a good agreement between the experimental results and micromagnetic simulations for the Fe dots and Ni\(_{80}\)Fe\(_{20}\) antidot samples. For the Ni\(_{80}\)Fe\(_{20}\)/Fe structure, there is only qualitative agreement with the experimental results. The difference in \( H_{s1} \) may be attributed to the complex exchange coupling between the Fe dots and Ni\(_{80}\)Fe\(_{20}\) antidot in the Ni\(_{80}\)Fe\(_{20}\)/Fe structure. To evaluate this exchange coupling factor, an interpolated loop from Figs. 2(a) and 2(b) assuming no coupling between the Fe dots and Ni\(_{80}\)Fe\(_{20}\) antidots was shown as left inset in Fig. 2(c). The loop resembles that of the Ni\(_{80}\)Fe\(_{20}\)/Fe structure, suggesting that the two FM structures are exchange decoupled. It is difficult to reproduce the experimental results in the micromagnetic simulation due to the unknown exchange coupling factor.

Next, we investigate the dynamic behavior of the fabricated structures. Shown in Fig. 3(a) are the FMR traces from the Ni\(_{80}\)Fe\(_{20}\)/Fe structure as a function of \( \theta = 0' \). We observed that the number of modes and profiles are markedly different for various magnetic ground states set by the applied field amplitude. At \( H_{app} = -1000 \) Oe the Ni\(_{80}\)Fe\(_{20}\)/Fe structure should be saturated based on the M-H loop shown in Fig. 2(c). The observed two main resonance peaks at 11.4 GHz and 13.5 GHz correspond to modes originating from the Ni\(_{80}\)Fe\(_{20}\) antidot and Fe dots regions, respectively. For the saturated state, it is easy to infer that the resonance peak A with highest frequency is localized in the Fe dots, while the resonance originating from Ni\(_{80}\)Fe\(_{20}\) antidot structure gives rise to the lower frequency peak B due to the lower saturated magnetization (\( 4\pi M_s \)) of Ni\(_{80}\)Fe\(_{20}\) (800 Oe) compared to that of Fe (1714 Oe) based on the Kittel’s equation\(^2^2\) for saturated film. In addition, a weak resonance mode C is also observed at around 10.4 GHz (as indicated by the dashed arrows). The lower absorption and
resonance frequency of this peak suggests that the resonance may come from the edges of the Fe dots and Ni_{80}Fe_{20} antidot due to the strong demagnetizing effect. Only one main peak with wider linewidth (compared with the peak B) can be observed when \( H_{\text{app}} \) is increased to \(-350\) Oe. This observation could be attributed to the fact that the resonance happens in the dot and antidot simultaneously due to the strong magnetostatic coupling between the two FM structures. The higher frequency mode comes out again when the \( H_{\text{app}} = 350\) Oe because of the formation of vortex ground state in the Fe dots as observed in the static results in Fig. 2(c). Interestingly, the FMR resonance frequency for the lower mode is higher than the main mode for \( H_{\text{app}} = -350\) Oe. When \( H_{\text{app}} \) is further increased to 1000 Oe, the magnetization of the Ni_{80}Fe_{20}/Fe structure is saturated along positive X-direction and the FMR curve is identical to the one for \( H_{\text{app}} = -1000\) Oe.

Detailed FMR measurements were performed along the field hysteresis loops as shown in the absorption spectra in Fig. 3(b). Mode profiles transformation can be clearly observed within the full hysteresis loop. We found that the intensity of mode A decreases when the \( H_{\text{app}} \) is increased and disappears at around \( H_{\text{app}} = -400\) Oe even though the magnetization of the Fe dots in the Ni_{80}Fe_{20}/Fe structure has not changed significantly based on the M-H loop in Fig. 2(c). The tilted magnetic configurations near the edge of the Fe dots may be responsible for this observation if we assume that the in-plane demagnetizing field does not change significantly when the magnetization at the edge of dot is slightly tilted. This assumption is reasonable because the accumulated magnetic poles at the boundary of the Fe dot and Ni_{80}Fe_{20} antidot are partially canceled due to the very small gap between them. From this argument, it is plausible that resonance frequency of Fe near the edge of the dot decreases because of the decrease of internal field along the magnetization direction when the spin direction is tilted. Another possible reason may be due to the enhanced spin precession amplitude in Ni_{80}Fe_{20} at lower \( H_{\text{app}} \). The precessions of Fe dots and Ni_{80}Fe_{20} antidots near the boundary will be similar because of the stronger dynamic interaction between the two FM structures. \( \frac{\mu_0 M}{H_{\text{app}}} \) for Ni_{80}Fe_{20} antidot at the adjacent Ni_{80}Fe_{20} antidot. The larger linewidth of the lower frequency peak for \( H_{\text{app}} = -350\) Oe also suggests the coupling between the two FM structures as shown in Fig. 3(a) due to the smaller damping factor \( (\zeta) \) of Fe. We have plotted on the same figure for direct comparison, the measured experimental FMR resonance frequencies of the reference Fe dots and Ni_{80}Fe_{20} antidot array in solid and dashed line, respectively. At saturation state, frequencies of both the Fe and Ni_{80}Fe_{20} peaks in the Ni_{80}Fe_{20}/Fe structure are higher than the reference Fe dots and Ni_{80}Fe_{20} antidot array, respectively. For the Fe dots in the Ni_{80}Fe_{20}/Fe structure, the neutralization of the magnetic poles at the boundary reduces the demagnetizing field along the X-axis and increases the internal field, which in turn pushes the resonance peak to a higher frequency. The internal field in Ni_{80}Fe_{20} is also increased because the direction of total demagnetizing field in the Ni_{80}Fe_{20} antidot array is reversed by the embedded Fe dots. Interestingly, the resonance frequency of Ni_{80}Fe_{20} in the Ni_{80}Fe_{20}/Fe structure gradually decreases and becomes lower than that of reference Ni_{80}Fe_{20} antidot array when \( H_{\text{app}} \) is in a range of \(-400\) Oe to \(-150\) Oe. This may also be attributed to the significant modification of internal field in the Ni_{80}Fe_{20}/Fe structure. The X-component of the internal field in the whole Ni_{80}Fe_{20}/Fe structures will be similar to that of a continuous film, which is shown as dashed-dotted line in Fig. 3(b). When \( H_{\text{app}} \) is further decreased, the stray field of Fe dots is significantly reduced in the X-Y plane due to the formation of the vortex core. A faint Ni_{80}Fe_{20} mode (indicated by the dashed arrow) can be observed at remanence with a similar resonance frequency compared to that of reference Ni_{80}Fe_{20} antidots. When a reverse field is applied, the vortex cores shift to one side and the switched region of the Fe dot may be attributed to the origin of the weak high frequency mode for \( H_{\text{app}} = 350\) Oe. The resonance frequency of the Ni_{80}Fe_{20} antidot array in the Ni_{80}Fe_{20}/Fe structure is higher than that of reference Ni_{80}Fe_{20} antidot array due to the stray field of the switched Fe dots. All of the above analyses are consistent with the M-H loop shown in Fig. 2(c).

To further understand the origin of the resonance modes, we performed quantitative analysis of the dynamic responses on the Ni_{80}Fe_{20}/Fe structure as shown in Fig. 3(c) for \( H_{\text{app}} = -1000\) Oe. There is a good agreement between the experimental results and the simulations for the main peaks in the resonance curve. The resonance mode A in Fig. 3(a), however, splits to a group of small peaks at around 14 GHz in the simulated FMR curve. The difference between the experimental results and dynamic micromagnetic simulations is reasonable because only a limited number of unit cells with periodic boundaries have been considered in the simulation. The assumption that the roughness is uniform across the entire sample may influence the simulation results. A weak mode C is also observed at lower frequency. Shown in Fig. 3(d) are simulated mode profiles, corresponding to the frequencies for the three (groups of) peaks observed in the simulated FMR curve. Clearly, the large spin precession amplitude in the Fe dots is the source of resonance mode A, while mode B originates from the resonance of Ni_{80}Fe_{20} antidot area. Due to dynamic interactions, partial Ni_{80}Fe_{20} or Fe area is also coupled with the other component for these frequencies. The resonance mode C originates mainly from the edge of the Fe dots. Similar to resonance modes A and B, the small Ni_{80}Fe_{20} area between the two nearest Fe dots is also involved in this mode.

In summary, we have probed the static and dynamic properties of array of Fe filled Ni_{80}Fe_{20} antidot nanostructures. We observed a significant modification to the magnetization reversal mechanism and ferromagnetic resonance mode profiles when compared with reference Fe dots and Ni_{80}Fe_{20} antidot array due to the strong magnetostatic coupling between the two ferromagnetic structures. Our experimental results are in quantitative agreement with both the static and dynamic micromagnetic simulations.

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