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Citation: Journal of Applied Physics **113**, 17B901 (2013); doi: 10.1063/1.4794137
View online: http://dx.doi.org/10.1063/1.4794137
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/113/17?ver=pdfcov
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Highly stable signal propagation in a consecutively tuned nanomagnet array

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(Presented 18 January 2013; received 30 October 2012; accepted 28 November 2012; published online 28 February 2013)

A key function of magnetic quantum-dot cellular automata (MQCA) is signal propagation in the nanomagnet array, for which a clocking field is required. However, the misalignment of the clocking field and the resultant low stability for signal propagation is one of the main challenges for its application. Here, we modeled and fabricated a progressively shape-tuned nanomagnet array combined with a reversal clocking field with progressively reduced amplitude. Based on micromagnetic simulations, Fe nanomagnet arrays were fabricated by electron beam lithography and their magnetization states characterized by magnetic force microscopy demonstrated correct signal propagation against clocking field misalignment up to $\pm 5°$. Furthermore, cascade-like signal propagation was observed. This novel design provides high stability and directional control in signal propagation within the nanomagnet array and potentially paves the way for addressing the misalignment issue in MQCA structures. *© 2013 American Institute of Physics*.
[http://dx.doi.org/10.1063/1.4794137]

I. INTRODUCTION

Nano-sized magnetic patterns are candidates for next generation magnetic logic[1] or memory[2] devices. In particular, the recently proposed concept of magnetic quantum-dot cellular automata (MQCA)[3] aims to perform Boolean logic operations through dipole interaction between nanomagnets in a coordinative arrangement. Functioning without electron current, MQCA has many advantages over conventional Si CMOS technology, such as low heat dissipation and high integration density. One of the basic architectures in MQCA logic is a nanomagnet array where the signal propagates down the array with the help of a clocking field to bring the elements to their null state along the hard axis. However, a field misalignment of even $\pm 1°$ would lead to incorrect logic operation 75% of the time, which makes such MQCA logic practically challenging.[3]

To overcome this limitation, many approaches have been tested to enhance the stability characteristics in signal propagation. For example, a biaxial anisotropy was proposed to enhance the hard axis stability.[4] Alternatively, different shaped nanomagnets, such as S-shaped,[5] edge-slanted,[6] and concaved[7] elements, have been proposed. Even though these designs facilitate signal propagation to some extent, they all rely on a highly accurate clocking field alignment.

Here, we propose a structure that would enforce correct signal propagation within a nanomagnet array even with a misaligned clocking field for MQCA. To be specific, a consecutively shape-tuned nanomagnet array was designed and tested through micromagnetic simulations and experiments. A reversal clocking field with progressively reduced amplitude was applied. We modeled clocking field misalignment as high as $\pm 5°$ along the hard axis, demonstrating correct signal propagation. Such an array was fabricated by electron-beam lithography (EBL) and using magnetic force microscopy (MFM), we observed the expected cascade-like signal propagation for the nanomagnet array. A basic MQCA logic array was also modeled, suggesting a correct signal output even under the misaligned field.

II. EXPERIMENTAL DETAILS

Experimentally, we fabricated the nanomagnet array using EBL. Polymethyl-methacrylate (PMMA)/LOR 1A (MicroChem Corp., Newton, MA) bilayer resist was used for undercut profile.[8,9] A magnetic layer, 20 nm-thick Fe, with a 3 nm-thick Au cap were deposited. The magnetic configurations of the array were investigated by MFM with the magnetic field applied parallel to the sample surface using 15 nm CoCr coated low moment probes with a lift height of 50 nm.

III. MAGNETIC MODEL AND SIMULATION

The following parameters were used for all LLG micromagnetic simulations:[10] saturation magnetization, $M_S = 1000$ emu/cm^3, exchange stiffness constant, $A = 2.1\ \mu$erg/cm, magnetocrystalline anisotropy, $K_{mc} = 0$, for each of the $5 \times 5 \times 20$ nm^3 cells due to the polycrystalline structure of nanomagnet array and thickness, $t = 20$ nm. First, we considered a two nanomagnet system with aspect ratios of 2:1 (S_2) and 3:1 (S_3) [Fig. 1(a)]. If an external field with 5° offset from the hard axis is applied, a parallel state (P-state) between S_2 and S_3 is expected after the removal of the clocking field. If the external field goes further negative to the point of $-H_{fl}^{(2)}$, S_2 will flip first owing to its lower shape anisotropy K_S, reaching the antiparallel state (AP-state). The intrinsic barrier for S_2 to flip could be expressed as a field, $H_{bar}^{(2)}$. If we define the dipole interaction between S_2 and S_3 as H_{int}, then we get $H_{fl}^{(2)} + H_{int} = H_{bar}^{(2)}$. The AP-state will be retained after the reversed field is removed. A simulated reversal field ramped from 3000 Oe to −900 Oe then to null [Fig. 1(b)]. Figure 1(c) shows the expected longitudinal and transverse minor loops and indicates the AP-aligned final state.

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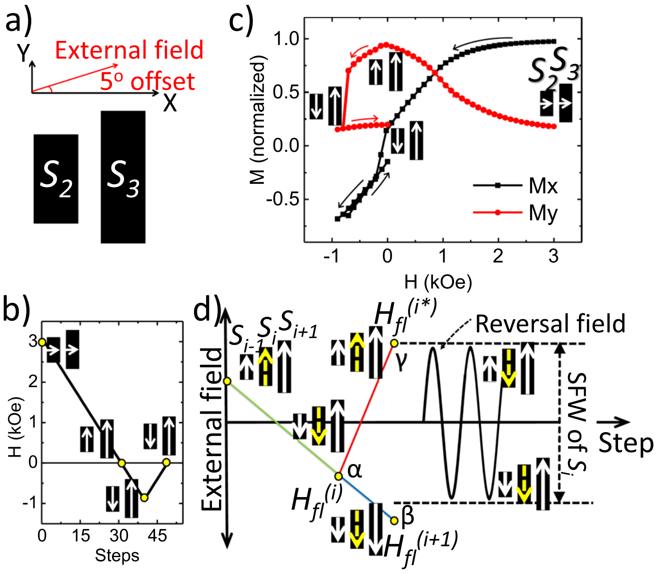

FIG. 1. (a) Schematic of the bimagnet system and the misaligned clocking field. (b) The reversed clocking field applied with 5° misalignment. (c) Hysteresis—minor loops in both longitudinal and transverse modes of the bimagnet system. (d) The array magnetic state (only three elements are shown here). S_i (highlighted with yellow dotted arrow) and its antiparallel state with S_{i+1} will remain if the reversal field is within its SFW. The two cases marked on the right side indicate that S_i and S_{i+1} will stay unchanged.

Next, we studied a nanomagnet array where the shape anisotropy constant, K_S, was progressively tuned by shortening the long axis. A reversal field with 5° offset along the hard axis was applied. For the element S_i, its magnetization would keep flipping and only reach its final state when the reversal field drops to some specific value. Under an increasing field, S_{i-1} with a lower K_S is expected to flip first, such that it is antiparallel to S_i, and the resulting magnetostatic interaction will then hinder S_i from flipping. Considering only the dipole interaction from adjacent elements S_{i+1} and S_{i-1}, we determine the flipping field for S_i from $H_{fl}{}^{(i)} + H_{int}{}^{(i,i+1)} - H_{int}{}^{(i,i-1)} = H_{bar}{}^{(i)}$ [state α in Fig. 1(d)]. After that, there are two possibilities: first, further increased negative field would cause S_{i+1} to flip down at $H_{fl}{}^{(i+1)}$ [state β]; second, the AP-state will be retained when the clocking field is reversed until S_i flips up again at $H_{fl}{}^{(i^*)}$ [state γ]. If we define $H_{int}{}^{(i,j)}$ as the dipole interaction field exerted by S_j, we get

$$H_{fl}{}^{(i^*)} = H_{int}{}^{(i,i+1)} - H_{int}{}^{(i,i-1)} + H_{bar}{}^{(i)} = H_{fl}{}^{(i)} + 2[H_{int}{}^{(i,i+1)} - H_{int}{}^{(i,i-1)}], \quad (1)$$

$$H_{fl}{}^{(i+1)} = H_{bar}{}^{(i+1)} - [H_{int}{}^{(i+1,i+2)} - H_{int}{}^{(i+1,i)}]. \quad (2)$$

Thus, a reversal clocking field in the range $[-H_{fl}{}^{(i+1)}, H_{fl}{}^{(i^*)}]$ will not affect the AP-state between S_i and S_{i+1}; neither of them will flip any more. Furthermore, we could define the stable field window (SFW) as the reversal field with amplitude lower than the minimum of $H_{fl}{}^{(i^*)}$ and $H_{fl}{}^{(i+1)}$, i.e., a reversal field within SFW of S_i will not affect the AP-state between S_i and S_{i+1}. In general, if the amplitude of the reversal clocking field is reduced progressively passing through the SFW of different elements sequentially, the AP-state will be achieved from high anisotropic elements down to the lower ones. The higher the K_S of an element is, the earlier it will become magnetically stable against the clocking field. Thus, the array will realize cascade-like signal propagation.

To demonstrate this cascade-like signal propagation, we modeled a chain of five rectangular elements, with the same short axis length (100 nm), and the long axis length varying from 600 nm to 200 nm corresponding to a gradually decreasing K_S [inset of Fig. 2(a)]. A misaligned reversal field with reduced amplitude was applied as shown in Fig. 2(a). Figure 2(b) (B-F) shows the magnetic state at different steps, suggesting a cascade-like AP-state evolution from right to left. There are three points worth mentioning here. First, only if the clocking field drops into the SFW of S_i can it reach the stable final state, i.e., the amplitude of the reversal field should be smaller than the minimum of $H_{fl}{}^{(i^*)}$ and $H_{fl}{}^{(i+1)}$. Larger amplitude may lead to parallel alignment with S_{i+1} (such as S_2 and S_3 indicated by the field point B, C, and D). Second, the SFW varies for magnets with different K_S and is largest for S_6 (with aspect ratio 6:1 and highest shape anisotropy K_S), and smallest for S_2 (aspect ratio 2:1). Thus, S_6 would be the first to reach its final state with S_2 being the last one. Third, for reversal field smaller than SFW of S_2 (amplitude lower than 1100 Oe), the antiparallel state will remain; clocking fields of -1000 Oe and 900 Oe have been tested, showing no influence on the magnetic configuration.

IV. RESULTS AND DISCUSSIONS

To further demonstrate the progressive switching of elements in this novel architecture, we fabricated and tested Fe nanomagnet arrays. A continuous magnetostatic reversal field with amplitude the same as the simulation [Fig. 2(a)] was applied. Figure 2(b) shows the scanning electron microscope

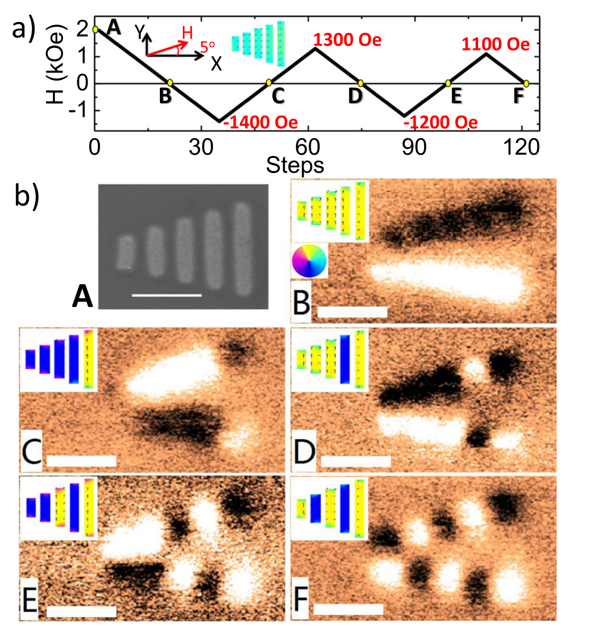

FIG. 2. (a) The reversal clocking field employed for the array with 5° misalignment. Magnetic states at points B-F are shown below. (b) A—SEM image of the patterned array; B-F—simulated magnetic state and the corresponding MFM image for different steps in (a). As the amplitude of the reversal field decreases, elements will be aligned antiparallel with their neighbor and be stable sequentially from right to left. The magnetization direction is indicated by the color wheel or overlaid arrows. The scale bar stands for 500 nm in (b) A-F.

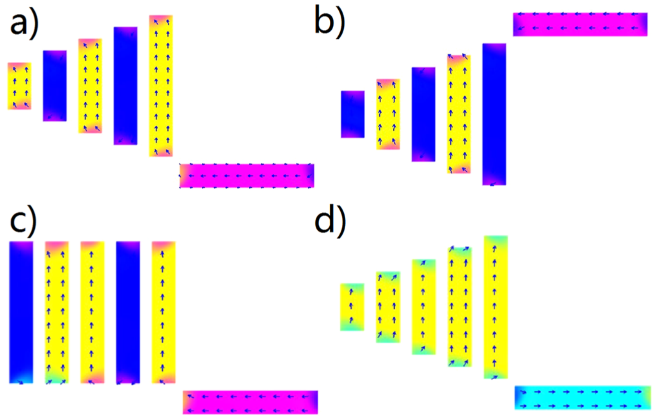

FIG. 3. (a) and (b) Simulated MQCA logic structures with different inputs using the reversal clocking field. (c) and (d) Control architectures of traditional structure and clocking field. There is no shape tuning and no reversal clocking field in (c) and (d), respectively.

(SEM) and the MFM image of the Fe nanomagnet array corresponding to steps B-F. It clearly shows the evolution of the magnetic state to the AP-state, suggesting cascade-like signal propagation. In summary, the reversal clocking field was demonstrated to facilitate signal propagation under a 5° misalignment in this shape-tuned nanomagnet array.

Next, we tested the MQCA logic architecture with a horizontal nanomagnet placed at one end as the input raising only one ground state. The same reversal clocking field as shown in Fig. 2(a) was employed for two structures [Figs. 3(a) and 3(b)] simulating both $\pm 5°$ misalignment. The first turn of the reversal field at -1400 Oe set the input element to the left direction, following the flipping of S_6 to the corresponding state that triggers the signal propagation. After that, the clocking field shows no more influence on S_6 and the input signal is received. Both structures showed the correct signal output disregarding the field misalignment.

We also modeled the traditional logic without shape-tuning or reversal clocking field. First, array with no tuned shape was tested [Fig. 3(c)]. Signal failed to propagate down to the left under the same reversal clocking field. No cascade-like signal propagation was observed. Actually, it is the shape asymmetry that helps the signal move down in one direction, but not in the reverse, guaranteeing the cascade-like signal propagation. Also, a one-shot clocking field with 5° misalignment was tested [Fig. 3(d)] and all the nanomagnets flipped up to the misaligned direction. Thus, it is confirmed that a combination of the shape tuning and the reversal clocking field is critical for signal to propagate against misalignment.

Finally, we would like to discuss the feasibility of the reversal clocking field. Generally, copper wires are embedded underneath the nanomagnets to generate a local clocking field and the misalignment is inevitable during the fabrication process. However, it is estimated[11] that the misalignment angle, θ, between the clocking field and the hard axis should satisfy $\tan\theta < r \ll 1$, where r represents the ratio of the magnetic fields required to magnetize the element along the easy and hard axis, respectively. The above inequality suggests a small value of θ and an extremely low tolerance on misalignment. The $\pm 5°$ misalignment we demonstrated is a case of extreme misalignment that could be generated by a copper wire and our novel architecture overcomes the low tolerance issue for misaligned clocking field. Second, to probe whether θ affects the SFW of elements we tested the bi-magnet system by changing θ from 5° to 3°. The stable field of S_2 increased from 750 Oe (under 5° misalignment) to 900 Oe (3°) due to the reduced Y-component of the clocking field which turns out to be an expansion of the SFW for the nanomagnet array. However, if we apply a reversal field with progressively reduced amplitude within a reasonable range, it is guaranteed that this expanded part will be covered. As a result, the variation of misalignment during fabrication will not affect signal propagation. Third, we can also generate a field pulse instead of the ramping field which is more practically feasible. Similarly, a consecutive field pulse is required for the signal to propagate down the array. Additionally, for larger systems with logic units containing more elements, we can reduce the anisotropy difference ΔK_S between adjacent elements and slow down the amplitude reduction of the reversal field at compensation. However, the integration of larger system may also require signal refreshment connecting different units where signal propagates from a low anisotropic element to an adjacent high anisotropic one. This refreshment could be achieved by using a “granular” clocking scheme where a clock pulse is applied individually to the output element alone through a local current.[11] However, this scheme may require more elaborate fabrication and might only be used for signal refreshment. In summary, the reversal clocking field we proposed is feasible only for signal propagation within a nanomagnet array. Further studies related to the universal gate structure are required to address the misalignment issue in general MQCA logic structures.

ACKNOWLEDGMENTS

This work was supported by NSF-DMR under Grant No. 1063489. Part of this work was conducted at the University of Washington NanoTech User Facility, a member of the NSF National Nanotechnology Infrastructure Network (NNIN). Z.L. would like to acknowledge China Scholarship Council (CSC) for partial financial support. We thank Wei Zhang for help with spin coating and Yufeng Hou for discussions on simulation.

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