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Focused-electron-beam-induced-deposited cobalt nanopillars for nanomagnetic logic

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Abstract

Nanomagnetic logic (NML) intends to alleviate problems of continued miniaturization of CMOS-based electronics, such as energy dissipation through heat, through advantages such as low power operation and non-volatile magnetic elements. In line with recent breakthroughs in NML with perpendicularly magnetized elements formed from thin films, we have fabricated NML inverter chains from Co nanopillars by focused electron beam induced deposition (FEBID) that exhibit shape-induced perpendicular magnetization. The flexibility of FEBID allows optimization of NML structures. Simulations reveal that the choice of nanopillar dimensions is critical to obtain the correct antiferromagnetically coupled configuration. Experiments carrying the array through a clocking cycle using the Oersted field from an integrated Cu wire show that the array responds to the clocking cycle.

Keywords: FEBID, nanomagnetic logic, nanomagnetism, nanofabrication

(Some figures may appear in colour only in the online journal)

1. Introduction

The ever-decreasing scale of electronics comes with ever-increasing challenges in managing byproducts such as heat dissipation and leakage current. To continue the trend of Moore's law, a possible new avenue for computation involves magnetic devices. Specifically, nanomagnetic logic (NML) [1, 2] shows promise as a low-power alternative to perform logic operations with additional advantages such as non-volatility and radiation-hardness. In NML, bits are encoded by the magnetic state of bistable nanomagnets, and information transfers between neighboring magnets through magnetostatic interaction, implying signal transport with in many cases inversion from one magnet to the next (a NOT operation). A magnet that responds to the magnetic state of multiple previously set nanomagnets forms a majority gate, essentially a programmable NAND/NOR gate. These elements together generate a full logic set.

Most commonly, NML systems consist of an array of thin rectangular nanomagnets placed long-edge-adjacent [3]. The two stable magnetization states (that encode a bit) are both in-plane directions along the nanomagnet long axis. Through magnetostatic fields, neighboring nanomagnets

prefer to be in opposite states (antiferromagnetic (AF) coupling) so that the magnetization alternates throughout the array. Majority gates are formed by intersecting a long-edge array with a short-edge array; the magnet at the intersection takes input from three of its neighbors and outputs its response to the fourth. This exposes a problem of in-plane NML: signal transport and magnetostatic coupling behaves differently in long-edge adjacent and short-edge adjacent directions, and majority gates require both.

One way to solve this problem involves nanomagnets with out-of-plane anisotropy, so that bits are now encoded in two directions of out-of-plane magnetization. The magnets can have a square or circular base so that there is no difference between long-edge and short-edge adjacent signal transport. Out-of-plane anisotropy can be achieved by using materials that exhibit perpendicular magnetic anisotropy, such as Co/Pt multilayers [4]. Alternatively, nanomagnets can be tall such that shape anisotropy induces out-of-plane anisotropy [5].

We have used focused electron beam induced deposition (FEBID) [6–9] to fabricate tall nanomagnets for NML. This technique for depositing materials offers a unique and highly attractive possibility of fabricating three-dimensional

nanostuctures [10]. Additional advantages include flexibility in substrate choice, possibility of deposition at predefined location, lateral resolution less than a few tens of nanometers, and *in situ* growth monitoring. FEBID is capable of depositing structures exhibiting ferromagnetism; magnetic structures made using FEBID include extraordinary Hall sensors [11], planar nanowires [12], and 3D nanowires of arbitrary shape [13]. Control of the height of the deposit just by changing the beam dwell time parameter allows altering the shape anisotropy, and in turn the coercivity, in the deposited magnetic structures. Combining the material choice with the ease of simply ‘writing’ by means of FEBID forms a feasible route towards studying NML [14, 15].

Although *on-chip* integration of conventional NML structures and clocking has been widely studied [16–18], this integration has not been studied for FEBID-based NML. This novel combination can lead to the realization of added functionalities in future NML devices and can inspire further research in this area.

Based on this motivation, here we report the successful fabrication of FEBID based Co-nanopillars arranged in an array for NML experiments. We show that the array of nanomagnets responds to the clocking cycle driven by two ways: (1) global magnetic field, and (b) current carrying Cu nanowire lying underneath the nanopillars. In particular, the magnetic nanopillars exhibit AF coupling at correct choices of the aspect ratio and the spacing between the nanopillars.

2. Sample preparation

Cobalt nanopillar samples for the NML experiments were fabricated using a FEI Nova Nanolab 600i dual beam system equipped with a Schottky emitter gun. We chose Co because FEBID Co deposits show the highest metallic content among the other magnetic materials in our system. The base pressure of the chamber was always maintained in the 10^{-7} mbar range before deposition. $\text{Co}_2(\text{CO})_8$ was used as a precursor. Before its insertion to the chamber, the precursor was pre-heated to 26 °C. The deposition was carried out at room temperature, using an electron beam with a beam energy of 30 kV. The beam current varied from 20 to 45 pA in order to tune the diameter of the nanopillars. Oxidized Si wafers, having pre-patterned Au/Ti contacts (fabricated using conventional lithography techniques), were used as substrate. In samples used for current-driven clocking, an additional Cu wire with cross-section $2\ \mu\text{m} \times 250\ \text{nm}$ was fabricated using electron beam lithography and lift-off, connecting two pre-patterned Au/Ti contacts. Arrays with Co nanopillars of various aspect ratios and inter-pillar spacings were deposited on the Cu wires, with diameters ranging from 70 to 150 nm, heights from 80 to 300 nm, and inter-pillar spacing from 15 to 60 nm. Within an array, the inter-pillar spacing as well as the aspect ratio of each nanopillar was maintained uniform. Figure 1(a) shows a scanning electron microscope image of such an array.

Atomic probe tomography (APT) was carried out on a few samples after their exposure to air to determine the atomic

Figure 1. (a) Scanning electron microscope image of an array with pillars of height 126 nm, diameter 79 nm, and separation 71 nm. (b) Atomic force microscopy image of an array with pillars of height between 93 and 119 nm, diameter 68 nm, and separation 75 nm.

composition as well as the spatial atomic arrangement. The APT results give a purity of 97 at% cobalt. Moreover, they indicate that the outer few nm layer of the pillars is oxidized but in the bulk less than 0.1 at% is oxygen, and the remainder is carbon. Such a purity falls in the upper end of purities reported elsewhere [19]. In addition, thin films of cobalt deposited using identical beam parameters were analyzed *in situ* by the integrated energy dispersive x-ray analysis (EDX) detector before exposure to air to determine their elemental composition; the measurement yielded 90 at% cobalt, 4 at% oxygen, and the rest carbon. This corroborates the conclusion that the outer surface of the pillars can contain more oxygen.

Atomic force microscopy (AFM) and magnetic force microscopy (MFM) measurements, as well as clocking experiments were carried out on a Bruker dimension icon machine, outside the dual beam system, using tips coated with magnetic CoCr.

3. Results and discussion

3.1. Simulation results

To transport a bit in a nanopillar NML array, a *clocking cycle* is applied. A field longitudinal or transverse to the chain axis sets all the pillars' magnetizations in the hard-axis (neutral) state. As the field relaxes, the first pillar, biased into a

particular state by a bias field, starts to evolve into that state. Each subsequent pillar evolves according to its neighbor until the signal reaches the end of the chain. The dimensions of the nanopillars have an important impact on the success of signal propagation, just as in in-plane NML [20]. Specifically, the ratio of height to diameter needs to strike a balance between high enough to be perpendicularly magnetized with thermal stability but low enough so the clocking field can be small. Moreover, the aspect ratio has effects on the coupling between pillars and thus on correct signal propagation.

To gain insight in the optimal geometrical parameters for nanopillar NML, we used the micromagnetic simulator OOMMF [21] to simulate signal propagation through clocking cycles in arrays of five nanopillars with various pillar heights, diameters, and spacings. The program numerically solves the Landau–Lifshitz–Gilbert equation, producing the time evolution of magnetization, discretized into cells of $5 \times 5 \times 10 \text{ nm}^3$. The nanopillars were modeled both by an ideal cylinder shape as well as, more true to reality, a half-ellipsoid shape. In a single simulation, a clocking field of 400 mT was applied either transversely or longitudinally to the array for 5 ns (calculations [22] predict that 250–370 mT is necessary depending on the dimensions). For 15 ns thereafter, the field gradually reduced to zero, while a 10 mT field biased the first nanopillar into the up state. If the average out-of-plane components of magnetization finish up-down-up-down-up (AF coupling), the result is considered a success. To obtain statistics, the simulation was run ten times for each particular set of parameters. Stochastic variation was introduced by superimposing a field of randomly oriented vectors of constant magnitude 0.2 mT per cell of the simulation grid.

For every geometrical configuration with cylindrical nanopillars, the proportion of simulations that returned the correct magnetic state is listed in table 1(a) (with longitudinal clocking field). The success rates are 10/10 only in a few specific geometries. We repeated the simulations for the same set of parameters using a transverse clocking field, but only a few parameter sets resulted in success: success rates were 10/10 for (diameter (nm), height (nm), space (nm)) = (60, 160, 30), (60, 140, 40), and (60, 160, 50); 4/10 for (60, 140, 30) and (60, 140, 50); and 0 otherwise. Also, for both clocking directions, success of signal propagation increased with increasing separation.

It is of no surprise that transverse clocking fails more often. Unlike longitudinally magnetized nanopillars, which reinforce each other's magnetization, nanopillars that are magnetized transversely in the same direction oppose each other's magnetization. Consequently the reset state is unstable and the pillars' magnetization will evolve erratically.

One reason that the success rates with cylindrical nanopillars are rather low is that the internal magnetization of the nanopillars had a vortex magnetic texture rather than a single domain, as shown in figure 2(a). As a result of the vortex preference, the overall out-of-plane component of magnetization is rather small—generally less than 25% of uniform magnetization—and thus the coupling between pillars is not very strong. Energy calculations [22] as well as simulation results confirm that the single-domain state only becomes

preferable for much taller nanopillars. While the coupling between pillars is stronger in this case, the high aspect ratio makes the hard-axis magnetization in the reset state highly unstable so that pillars may randomly evolve to one state or the other before the signal arrives and render the operation erroneous.

With half-ellipsoidal nanopillars, the results were more promising: for many configurations with aspect ratios (height to diameter) between about 1.5 and 2.7, the array always ended in the correct state, while for all others no success occurred (see table 1(b)). Additionally, increasing the spacing increased the success rate. The half-ellipsoidal nanopillars generally preferred a vortex configuration near the bottom gradually changing into out-of-plane magnetization near the top (figure 2(b)), with a notable exception of a fully single-domain out-of-plane state for the highest aspect ratio ($240 \times 60 \text{ nm}^2$) configuration.

From simulations, we conclude that the aspect ratio of the nanopillars is critical to correct AF coupling during a clocking cycle. We have fabricated NML arrays using FEBID keeping this in mind, and next we present results of clocking cycles performed on Co nanopillars.

3.2. FEBID-grown nanopillars

Magnetic information about the arrays of nanopillars was obtained using MFM. First, the topography of the nanopillars was traced using a tapping mode AFM. The AFM image shown in figure 1(b) shows that very good quality and highly uniform nanopillars have been fabricated. Due to the nature of AFM, deep trenches between pillars (as seen in the SEM image, figure 1(a)) are hard to image.

Then the tip passed over the array of nanopillars at a fixed height above the features. The magnetic field lines from the nanopillars affect the vibration of the magnetically coated tip in such a way that the phase component of the measurement relates approximately to d^2H_z/dz^2 , where z is the out-of-plane direction. MFM confirms the magnetic nature of the nanopillars. In the resulting image, light (dark) regions indicate magnetization into (out of) the plane. They are accompanied by a halo of the opposite color (exemplified in figure 4(a)), indicating the flux closure lines of the out-of-plane magnetized nanopillars.

MFM was used not only to show the magnetic nature of the nanopillars, but also to observe whether the array responds correctly to a clocking cycle. In our experiments, the nanopillar array stands on top of a Cu nanowire, parallel to the chain axis (see figure 3). Current through this nanowire causes an Oersted field that magnetizes the pillars along their hard axes, transverse to the wire. As the current is removed, the pillars' magnetizations relax to one of the two out-of-plane directions. MFM images were taken before and after the clocking cycle to reveal the resulting magnetic configuration.

Before applying current, we observed whether an array would respond to a clocking cycle by a globally applied field. Figure 4 shows one result of a clocking cycle using in-plane field. It manages to change the magnetic state from incorrect to correct. These pillars were, on average, 183 nm tall,

Table 1. Success rates of simulations of a longitudinally applied clocking cycle on an array of five (a) cylindrical or (b) half-ellipsoidal nanopillars for different diameters, heights, and spacing between them.

(a) Cylinders									
Spacing	Diam.	Height (nm)							
		80	90	100	120	140	160	200	240
30	60	0.1	0	0.6	0.8	1	1	1	0
	80	0	0.6	0.2	0.2	0.2	0.1	0	0
	100					0.2	0	0	0.1
	120					0	0	0	0
40	60	0	0	0	0.5	1	1	1	0
	80	0	0.5	0.6	0.4	0	0.1	0	0.2
	100					0.5	0.5	0	0.4
	120					0	0	0	0
50	60	0.1	0	0	0.5	0.8	1	1	0
	80	0	0.2	0.4	0.2	0.2	0.4	0.5	1
	100					0	0.1	0.4	0
	120					0	0	0.2	0.2
(b) Half-ellipsoids									
Spacing	Diam.	Height (nm)							
		80	90	100	120	140	160	200	240
30	60	0	1	1	1	1	0	0	0
	80	0	0	0	0	0	1	0	0
	100					0	0	0	1
	120					0	0	0	0
40	60	0	1	1	1	1	1	0	0
	80	0	0	0	0	1	1	1	0
	100					0	0	0	1
	120					0	0	0	0
60	60	0	1	1	1	1	1	0	0
	80	0	0	0	0	1	1	1	1
	100					0	0	1	1
	120					0	0	0	0

Figure 2. Internal magnetization state of a (a) cylindrical or (b) half-ellipsoidal nanopillar of diameter 60 nm and height 120 nm. The cylinder's magnetization has a vortex state, and the half-ellipsoid has vortex magnetization near the bottom and out-of-plane magnetization near the top.

Figure 3. SEM image of two nanopillar NML arrays on a copper wire. Current through the horizontal wire provides the Oersted field transverse to the array to perform a clocking cycle. The Oersted field from the vertical wire can send input to the first nanopillar in future experiments. The zoomed-in view shows the magnetic field as a result of the current in the wires.

Figure 4. MFM images before (a) and after (b) a clocking cycle using field, during which the nanopillars' magnetization arranges itself in the favorable antiferromagnetic configuration.

104 nm in diameter (aspect ratio 1.8) and separated by 43 nm as measured by SEM, consistent with those in successful simulations. Other devices with lower aspect ratios or higher spacing did change as a result of a clocking cycle by field, but did not end up in AF alignment.

Next we investigated whether the Oersted field from a current rather than a global applied field can clock the nanopillar array. The nanopillars were initialized using an

Figure 5. MFM images of three arrays of nanopillars before (left column) and after (right column) a clocking cycle using current in a wire parallel to the array axis, during which they alter their magnetic configuration.

external negative out-of-plane field of -200 mT and subjected to the Oersted field generated by a 10 mA current through the Cu wire on which they stand. Figure 5 shows the result for an array with pillars of, on average height 148 nm, diameter 83 nm (aspect ratio 1.8), and separation 38 nm: in all cases, the magnetic configuration changed, with one device becoming magnetized in the AF configuration (although one nanopillar failed to initialize), showing that a nanopillar NML device with integrated clocking is possible.

With the wire running parallel to the chain axis, the nanopillars are reset in the transverse direction, which as previously discussed is less stable than longitudinal clocking; the simulations attested with low success rates. Lining the NML array up perpendicular to the wire axis would yield longitudinal clocking and possibly better results. However, the wire needs to be quite a bit wider than the length of the array, otherwise the ends of the array might feel a large out-of-plane component from the Oersted field. Consequently, higher current would be required. Future experiments will investigate whether this improves the AF alignment after a clocking cycle.

The experiment differs from simulation in another way: the absence of input bias. In simulations, an input signal was given at one end of the array, whereas in these experiments whichever magnet evolves first determines the outcome. Future experiments will include a second current-carrying

wire that can bias the first nanopillar of the array through its Oersted field, as seen in figure 3.

4. Conclusions

Arrays of Co nanopillars were fabricated using FEBID for NML. Measurements using APT show that they have high purity, around 97 at% cobalt. MFM imaging confirms ferromagnetic behavior and shows that they are magnetized out-of-plane.

Simulations show that for cylindrical nanopillars, successful signal propagation depends heavily on the nanopillar dimensions but somewhat on the spacing between them. With half-ellipsoidal nanopillars that more closely approach our structures fabricated by FEBID, we determine that the optimal aspect ratio is between 1.5 and 2.7. When arrays of nanopillars were fabricated on top of a Cu wire and subjected to a clocking cycle using external field or the wire's Oersted field, the nanopillars responded by correcting their magnetic configuration. In some cases, they correctly attained the AF configuration. The results suggest that signal propagation by magnetostatic coupling to neighbors occurs but requires optimization of geometrical parameters for reliability.

The flexibility of the FEBID technique lends interesting prospects for NML. Not only is it suited to create optimized structures, but it integrates easily with magneto-electronic interfaces since the magnetic elements can be grown after the rest of the circuit is made. Finally, NML designs with FEBID are not limited to nanopillars but can for example be a hybrid of in-plane and perpendicular elements.

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