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Shape Anisotropy and Resonance Mode Guided Reliable Interconnect Design for In-plane Magnetic Logic *

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Dipole coupled nanomagnets controlled by the static Zeeman field can form various magnetic logic interconnects. However, the corner wire interconnect is often unreliable and error-prone at room temperature. In this study, we address this problem by making it into a reliable type with trapezoid-shaped nanomagnets, the shape anisotropy of which helps to offer the robustness. The building method of the proposed corner wire interconnect is discussed, and both its static and dynamic magnetization properties are investigated. Static micromagnetic simulation demonstrates that it can work correctly and reliably. Dynamic response results are reached by imposing an ac microwave field on the proposed corner wire. It is found that strong ferromagnetic resonance absorption appears at a low frequency. With the help of a very small ac field with the peak resonance frequency, the required static Zeeman field to switch the corner wire is significantly decreased by ∼21 mT. This novel interconnect would pave the way for the realization of reliable and low power nanomagnetic logic circuits.

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The array of dipole coupled single domain magnetic nanodots is under wide investigation for its digital logic operation or computation.[1−5] This computation paradigm is usually called the nano-magnetic logic technology,[3] which has the potential of radiation hardness and nonvolatility.[4] Thus it is regarded as one of the few mature non-CMOS computing paradigms. In nanomagnetic logic, magnetization orientations along the long axis of the magnet are used to represent binary logic states 0 and 1, and dipole-dipole interaction between magnets is responsible for logic process and information transfer.

By arranging nanomagnets in series, some functional magnetic logic structures have been designed, such as majority logic gate,[6] and interconnect wire.[7] The interconnect is a linear chain of several magnets by fixing the first magnet in the chain as an input. Since the dipole coupling between neighboring magnets is not enough to reverse the magnetization (i.e., from pointing up to down), an external static Zeeman field (the 'clock'[8]) is required to reduce the potential barrier between the neighbors, then the new operation will occur.

In the practical nanomagnetic systems, the static Zeeman magnetic field is generated with on-chip current.[9] This means that a larger static Zeeman field requires larger on-chip current, namely the clock is energy expensive. Therefore, how to decrease the static Zeeman field required for logic re-evaluation also becomes very important for reliable magnetic logic interconnect, which will be discussed in the following.

Although some works have concentrated on magnetic logic interconnect theoretically and experimentally,[10−12] there are still some problems to be well solved. For example, the corner wire interconnect (see Fig. 1(a)) is often error-prone and unreliable due to its spontaneous logic state variations at room temperature.[10,11] To the best of our knowledge, the widely used scheme to overcome spontaneous magnetization flopping comes to the introduction of magnetic material helper or protection blocks[10,12] into the corner interconnect. This method is effective, but rather layout-expensive.

In this Letter, we propose a type of corner wire interconnect with trapezoid-shaped nanomagnets. The trapezoid-shaped magnet, a magnet with a slated edge,[4,13] can give a preferred magnetization without any coupling bias fields due to its shape anisotropy. By micromagnetic simulations we validate this proposal and further explore its dynamic magnetization property. Specifically, we have observed that the magnet edge in the corner precesses to a vortex-like magnetization when a low frequency resonance peak appears. Based on the results, a novel low power switching scheme for the proposed corner wire emerges, which is also applicable for the design of all magnetic logic circuits.

The interconnect 'corner', also called bend wire, is often used to construct the turning in the magnetic logic circuits. Figure 1(a) depicts the corner consisting of regular rectangular nanomagnets, where I and O represent the input and output, respectively,[10] and B is the small driver device used to set the input logic value. Note that the inset in Fig. 1(a) shows the geo-

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metrical long axis (easy axis y) and short axis (hard axis x) directions. Simulated logic state propagation in this corner is shown after initializing it with a large static Zeeman field along the x-axis. After the removal of this field, the system will relax to the ground state due to dipole coupling interactions, and then information is transferred.

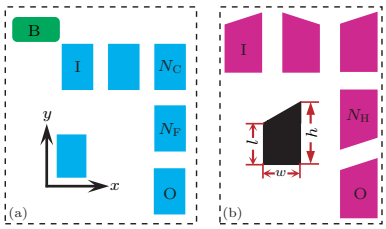

Fig. 1. Magnetic logic corner wire interconnect. (a) Regular rectangular-shaped nanomagnet corner, and (b) trapezoid-shaped nanomagnet corner.

Unfortunately, the magnetization of nanomagnets in the corner does not work like the domino effect. That is, the nanomagnets N_C and N_F usually spontaneously relax to an upwards or downwards magnetization orientation before the actual input arrives N_C. In this case, the corner wire is usually stuck to a metastable state and becomes disabled. Someone may argue that they can adjust the aspect ratio and spacing of rectangular-shaped nanomagnets, or even design symmetrical turning (i.e., the Fanout interconnect[14]), to ensure correct logic propagation in the corner. However, these methods do not appear to be a universal scheme for reliable interconnect design.

We herein utilize two types of trapezoid-shaped nanomagnets to construct corner wire structure with a high reliability and deterministic switching. Figure 1(b) illustrates the corner designed with alternate left slanted-edge magnet and right slanted-edge magnet (namely two types of trapezoid-shaped magnets). Note that I and O represent the input and output of the proposed corner, respectively. The in-plane dimensions of the trapezoid-shaped nanomagnet are set to 90 nm×50 nm×60 nm ($h \times w \times l$), where h and l are the baseline and topline of the trapezoid (see the inset in Fig. 1(b)), and w is the width. Indeed, $(h - l)$ also represents the missing edge amplitude of the trapezoid-shaped magnet.[15] An identical $h \times w$ parameter is used for the regular shape nanomagnet.

An important phenomenon about the slanted-edge magnet is that it favors an upwards magnetization (i.e., left slanted-edge) upon the removal of the clock field towards the right, while to a downwards magnetization upon the removal of the clock field towards the left. Thus logic state switching is deterministic provided a static Zeeman field is applied. Recent work[16] has studied the antiferromagnetic coupling straight wire interconnect based on the trapezoid-shaped nanomagnet from the energy landscape point of view, and obtained enhanced performance. Overall, due to the favorable magnetization effect, the steady logic reevaluation of corner wire interconnect would be feasible, which is validated by micromagnetic software.

We directly reverse the magnetization of the trapezoid-shaped nanomagnet from one binary state to another by increasing the applied static field incrementally to 200 mT, and obtain the critical value needed for state transition (namely the coercive field). The thickness of nanomagnet is set to be 20 nm. Take the right slanted-edge nanomagnet as an example, the normalized hysteresis loops are shown in Fig. 2. We can see that the coercive field (H_C) values vary from 94 mT for the x-axis direction clock to 120 mT for the y-axis direction clock. It is evident that H_C is larger if the static Zeeman field is applied along the long axis (y-axis) of the trapezoid-shaped magnet. This means that an application of a clock along the x-axis may be a more energy-effective method.

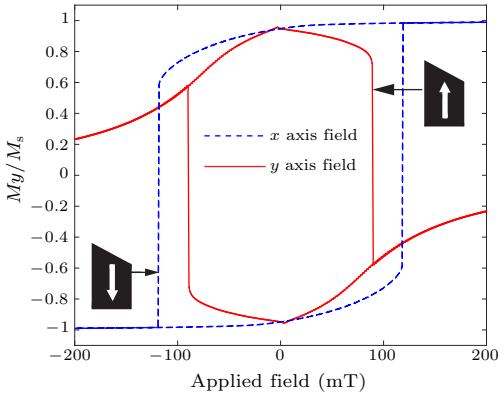

Fig. 2. The static Zeeman field clock required for magnetization reversal along geometrical long axis and short axis, respectively.

To investigate the magnetization reversal mechanism of the proposed corner wire, micromagnetic simulation is performed using the finite element-based OOMMF tool.[17] Specifically, we show the magnetization evolution image of corner switching. In the simulation, the sizes of all the trapezoid-shaped nanomagnets are the same as that which appeared earlier, and they are given a spacing of 20 nm, a damping constant of 0.2, a mesh discretion of 5 nm×5 nm×5 nm, and a saturation magnetization M_s of 850 kA/m. It is very important to note that the system is firstly initialized with an x-axis static Zeeman field toward the right, and then with the same inverse x-axis static Zeeman field toward the left. The key magnetization evolution images are shown in Fig. 3.

In Fig. 3(a), we can see that the binary logic state alternately appears in the corner wire, and the magnet O outputs logic 1 state as the input value. It is evident that the initial logic 1 has been successfully transferred to the output terminal. In the following phase, when the reverse x-axis clock is applied, most of the nanomagnets flop to the null state (see Fig. 3(b)), and have a domain orientation mainly pointing leftwards, while the magnet N_H denotes a transient holding effect in comparison with other magnets. However, as

the static Zeeman field increases further and decreases later, all the magnets begin to switch (see Fig. 3(c)). At last, as shown in Fig. 3(d), the corner wire completes a successful state reversal and a new logic 0 output emerges. The results indicate that the proposal performs well and reliably.

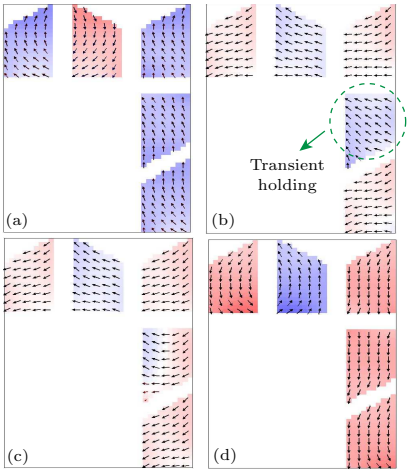

Fig. 3. Magnetization evolution image of the trapezoid nanomagnet corner.

Indeed, the dynamics concerning how the designed corner reaches its new ground state shown in Fig. 3(d) is a complicated process, but one clear fact comes to that it requires a relatively large static Zeeman field, about 112 mT in our simulation. Therefore, decreasing the static magnetic field required for switching of the corner wire becomes significant.

Studies of dynamic magnetization are often made for exploring the properties of magnetic materials[18] but rarely on the interacted logic array except Ref. [19] considering resonant excitation of driver-input magnet pair to show low power programming.

To simulate the ferromagnetic resonance response, time-dependent simulations are performed using a SINC wave excitation

$$H_{\rm ex} = H_0 \cdot \frac{\sin 2\pi f t}{2\pi f t}, \tag{1}$$

where $H_0 = 4\,\mathrm{mT}$, with a gyromagnetic ratio $\gamma = 2.21 \times 10^5\,\mathrm{rad{\cdot}m/A{\cdot}s}$, a frequency $f = 14\,\mathrm{GHz}$ and a damping factor of $\alpha = 0.01$. The SINC microwave field is used in the simulation to yield a uniform excitation across the corner wire. With this excitation, the dynamic response data of the magnetic domain are obtained by OOMMF and stored in the mmData Table, and are further analyzed in the frequency domain after the fast Fourier transform (FFT) processing. The ground state used for microwave excitation is just the relaxation state of the corner structure applied with a 112 mT static Zeeman field toward the right. The ferromagnetic resonance (FMR) spectrum (post-FFT) curve of the proposed corner wire is shown in Fig. 4.

From Fig. 4, four main absorption peaks are generally observed in the spectrum, of which low frequency resonance mode displays the strongest energy absorption. Indeed, at the frequency of the largest absorption peak ($f_{\rm LR} = 5.011\,\mathrm{GHz}$), all the trapezoid-shaped magnets begin to precess at different amplitudes. Specifically, the precessions of the three horizontal magnets weaken, while the magnet $N_{\rm H}$ strengthens, denoting a vortex-like image in its edge, benefiting the reversal. At the other three peak frequencies, the horizontal magnets precess out of the plane. Overall, the ac microwave field excitation allows us to reverse the corner wire having new style.

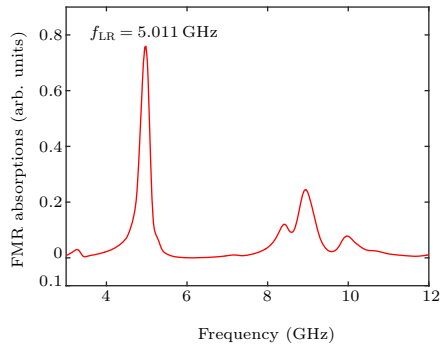

Fig. 4. FMR absorptions spectrum of corner wire interconnect at remanence.

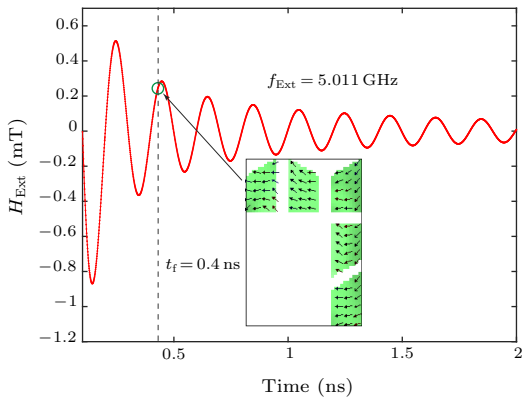

Fig. 5. The ac microwave field with the resonance frequency of 5.011 GHz used to excite the corner wire interconnects.

Next we apply a static Zeeman field of −87 mT (along the x-axis toward the left) in combination with a SINC ac microwave field with the lowest resonance frequency of 5.011 GHz to reverse the corner wire. We are interested in whether the corner wire excited by a very small ac signal and lower static Zeeman field can complete a successful state reversal. Figure 5 shows the waveform of SINC excitation, with the peak value no more than 1 mT. Based on the simulation results, we find that magnetic domain configurations of the corner wire interconnect vary at different times. Specifically, from the inset in the figure, it is evident that the corner wire shows a horizontal magnetization orientation (null state) at 0.4 ns. The transient holding effect of the magnet $N_{\rm H}$ vanishes when compared with the image in Fig. 3(b). Certainly, this attributes to an application of SINC ac microwave field.

Another very important observation from this simulation is that the required static Zeeman field for corner switching significantly decreases, about 21 mT (from 112 mT to 91 mT). Indeed, when the SINC excitation at strong resonance mode is applied, the corner wire experiences a remarkable precession due to various dipolar coupling, which favors the null state magnetization, resulting in reduced effective field H_{eff}. Therefore, the required static Zeeman field is evidently decreased and the corner wire interconnect demonstrates rather low power and reliable magnetic logic operation.

Magnetic logic is an attractive computing paradigm well established by experimental efforts mainly from the Notre Dame university group. However, there are still some roadblocks for this technology, and a reliable and practical corner wire interconnect is one of them.

In summary, we have proposed an interesting corner wire interconnect structure based on the shape anisotropy of trapezoid-shaped nanomagnets. Micromagnetic simulation validates completely correct magnetization reversal of the proposal. We have further observed the FMR response of the proposed corner using a microwave field excitation, and found out the peak resonance frequency. By adopting a very small ac microwave field at the resonance mode as a new excitation to switch the corner wire, the required static Zeeman field significantly decreases. As a result, a novel low power strategy for interconnect wire switching is developed.

Finally, it is important to point out that there are also some other low power clocking schemes to switch the magnetic logic device, for example the strain clocking[20] (not the magnetic field clocking in this study) used for multiferroic nanomagnets, which will be considered in our future work.

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