Critical analysis and remedy of switching failures in straintronic logic using Bennett clocking in the presence of thermal fluctuations

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Critical analysis and remedy of switching failures in straintronic logic using Bennett clocking in the presence of thermal fluctuations

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Straintronic logic is a promising platform for beyond Moore’s law computing. Using Bennett clocking mechanism, information can propagate through an array of strain-mediated multiferroic nanomagnets, exploiting the dipolar coupling between the magnets without having to physically interconnect them. Here, we perform a critical analysis of switching failures, i.e., error in information propagation due to thermal fluctuations through a chain of such straintronic devices. We solved stochastic Landau-Lifshitz-Gilbert equation considering room-temperature thermal perturbations and show that magnetization switching may fail due to inherent magnetization dynamics accompanied by thermally broadened switching delay distribution. Avenues available to circumvent such issue are proposed. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4858484]

Multiferroic devices, consisting of a piezoelectric layer strain-coupled to a magnetostrictive nanomagnet, hold profound promise to replace traditional transistors for our future information processing paradigm. These devices work according to the principle of converse magnetoelectric effect, i.e., when a voltage is applied across the device, the piezoelectric layer gets strained and the strain is elastically transferred to the magnetostrictive layer rotating its magnetization (see Fig. 1(a)). With appropriate choice of materials, such devices dissipate a minuscule amount of energy of ~1 attojoule in sub-nanosecond switching delay at room-temperature. This study has opened up a field called straintronics and experimental efforts to demonstrate such electric-field induced magnetization switching are considerably emerging.

Information processing using Bennett clocking mechanism is an attractive platform for building logic using nanomagnets and dipolar coupling between them. This facilitates avoiding physical interconnects and thus eliminating the energy dissipation due to charging and discharging of interconnect capacitances. Figure 1(b) depicts how a bit of information can be propagated unidirectionally through a chain of energy-efficient stress-mediated multiferroic devices rather than using highly energy consuming magnetic field. Contrary to the steady-state analysis, the investigation of magnetization dynamics has proved to be crucial for achieving sub-nanosecond switching speed making the straintronic logic competitive with traditional charge-based computing. Recent experiments have demonstrated defects and errors in nanomagnetic logic circuits.

Here, we study the source of switching failures in straintronic logic due to thermal fluctuations during the propagation of a bit of information. We solved stochastic Landau-Lifshitz-Gilbert (LLG) equation of magnetization dynamics to understand the critical issues behind the switching failures. As such we would assume that the magnetization of the 2nd nanomagnet in Fig. 1(b) would always switch successfully to the desired state as shown in the last row due to the dipole coupling from the 1st nanomagnet. However, the analysis presented here demonstrates that magnetization’s slight excursion out of magnet’s plane accompanied by the thermal fluctuations can eventually make magnetization backtracking to the wrong direction. This would produce error in propagating a bit of information. Making an approximation by not taking into account the out-of-plane excursion of magnetization would not be able to comprehend such critical reasoning behind switching failures. Noting that it requires a very small bit error rate (<10⁻⁵) for computing purposes, we further suggest a way to tackle such issue.

We model the magnetostrictive nanomagnet in the shape of an elliptical cylinder; its cross-section lies on the y−z plane, the major axis points along the z-direction, and the minor axis along the y-direction (see Fig. 1(a)). Any deflection of magnetization out of magnet’s plane (φ = ±90°) is termed as out-of-plane excursion. The dimensions of the major axis, the minor axis, and the thickness are a, b, and l, respectively (a > b > l). So the volume is Ω = (π/4)abl. We will consider the switching of nanomagnet-2 and the subscript of any parameter will point to the corresponding nanomagnet (1 to 4, see Fig. 1(b)).

We solve the stochastic LLG equation in the presence of thermal fluctuations (details are provided in the supplementary material) and derive the following coupled equations for the dynamics of θ2 and φ2:

\[
(1 + x^2) \frac{dθ2}{dt} = \frac{|γ|}{M_V} \left[ B_{shape, φ2} (φ2) \sin θ2 - 2zB2 (φ2) \sin θ2 \cos θ2 - T_{dipole, θ2} - zT_{dipole, φ2} + (zP_{θ2} + P_{φ2}) \right],
\]

\[
(1 + x^2) \frac{dφ2}{dt} = \frac{|γ|}{M_V \sin θ2} \left[ zB_{shape, φ2} (φ2) \sin θ2 + 2B2 (φ2) \sin θ2 \cos θ2 + zT_{dipole, θ2} + T_{dipole, φ2} - \{\sin θ2\}^{-1} (P_{θ2} - zP_{φ2}) \right] \quad (\sin θ2 \neq 0),
\]
where

\[ B_{\text{shape}, 2}(\phi_2) = \left( \mu_0/2 \right) M_s^2 \Omega (N_{d-xx} - N_{d-yy}) \sin(2\phi_2), \] (3)

\[ B_2(\phi_2) = B_{\text{shape}, 2}(\phi_2) + B_{\text{stress}, 2}, \] (4a)

\[ B_{\text{shape}, 2}(\phi_2) = \left( \mu_0/2 \right) M_s^2 \Omega (N_{d-xx} - N_{d-yy}) + (N_{d-xx} - N_{d-yy}) \cos^2\phi_2, \] (4b)

\[ B_{\text{stress}, 2} = (3/2) \lambda_s \sigma_s^2 \Omega, \] (4c)

\[ P_{\phi_2} = M_V [h_{i,2} \cos \phi_2 + h_{i,2} \cos \phi_2 \sin \phi_2], \] (5a)

\[ P_{\phi_1} = M_V [h_{i,2} \cos \phi_2 - h_{i,2} \sin \phi_2], \] (5b)

\[ h_{i,2} = \sqrt{\frac{2 \alpha kT}{|v| \gamma (1 + \alpha^2)} M_V \Delta \gamma} G(0,1) \quad (i = x, y, z), \] (5c)

\( \alpha \) is the phenomenological damping parameter, \( \gamma \) is the gyromagnetic ratio for electrons, \( M_V = \mu_0 M_s \Omega \), \( M_s \) is the saturation magnetization, \( N_{d-nm} \) is the component of demagnetization factor along \( m \)-direction, which depends on the nanomagnet’s dimensions, \( \lambda_s \) is the magnetostrictive coefficient of the single-domain magnetostrictive nanomagnet, \( \sigma_s \) is the stress on the nanomagnet-2 (note that the product of magnetostrictive coefficient and stress needs to be negative in sign for stress-anisotropy to overcome the shape-anisotropy), \( \Delta \gamma \) is the simulation time-step, \( G(0,1) \) is a Gaussian distribution with zero mean and unit variance, \( k \) is the Boltzmann constant, \( T \) is temperature, \( T_{\text{dipole}, \phi_2} = (1/\sin \phi_2) (\partial E_{\text{dipole}_2}/\partial \phi_2) \), \( T_{\text{dipole}, \phi_2} = \partial E_{\text{dipole}_2}/\partial \phi_2 \), and \( E_{\text{dipole}_2} \) is the dipole coupling energy from the neighboring nanomagnets 1 and 3. Note that in a very similar way, the equations of dynamics for the other three nanomagnets can be derived.

The magnetostrictive layer is considered to be made of polycrystalline Terfenol-D, which has the following material properties—Young’s modulus (Y): 80 GPa, saturation magnetization (\( M_s \)): 8 \times 10^5 A/m, Gilbert’s damping constant (\( \alpha \)): 0.1, and magnetostrictive coefficient ((3/2)\( \lambda_s \)): +90 \times 10^{-5} (Refs. 5 and 27–29). The dimensions of the nanomagnet are chosen as \( a = 100 \text{ nm}, b = 90 \text{ nm}, \) and \( l = 6 \text{ nm} \), ensuring the validity of single-domain assumption.25,30 The center-to-center distance between the nanomagnets is chosen as \( R = 120 \text{ nm} \).

The piezoelectric layer is made of lead magnesium niobate-lead titanate (PMN-PT),31 which has a dielectric constant of 1000 and the layer is assumed to be four times thicker than the magnetostrictive layer. Assuming that maximum strain that can be generated in the piezoelectric layer is 500 ppm,32,33 it would require an electric field of \( \sim 0.4 \text{ MV/m} \) because \( d_{31} = 13 \times 10^{-10} \text{ m/V} \) for PMN-PT.31 The stress generated in the Terfenol-D layer is the product of strain and Young’s modulus. Hence, 4.6 mVs of voltages would generate 20 MPa stress in the Terfenol-D layer.

Figure 2 shows that upon application of stress, different trajectories of magnetization of nanomagnet-2 reaches \( \theta = 90^\circ \) at variable times in the presence of thermal fluctuations. We take the distribution of initial orientation of magnetization due

**FIG. 2.** Distribution of switching delay when magnetization of nanomagnet-2 reaches at \( \theta = 90^\circ \) from \( \theta \approx 180^\circ \) upon application of 20 MPa stress at 100 ps ramp period. A moderately large number (10000) of simulations have been performed in the presence of room-temperature (300 K) thermal fluctuations to generate this distribution. This wide distribution is caused by the following two reasons: (1) thermal fluctuations make the initial orientation of magnetization a distribution, and (2) thermal kicks during the transition from \( \theta \approx 180^\circ \) to \( \theta = 90^\circ \) make the time-period a distribution too. The mean and standard deviation of this distribution are 0.232 ns and 0.056 ns, respectively.

FIG. 1. Bennett clocking mechanism for unidirectional information propagation in straintronic logic. (a) A voltage-controlled strain-mediated multiferroic device and axis assignment. Magnetization is bistable along the \( \gamma-z \)-axis, which stores a bit of information 0 or 1. (b) Unidirectional information propagation through a horizontal chain of straintronic devices. The nanomagnets are stressed separately using different voltage sources. Note that the dipolar coupling between the neighboring nanomagnets is bidirectional and hence we need to impose the unidirectionality in time (using a 3-phase clocking scheme to apply stress on the nanomagnets subsequently) to propagate a bit of information through the chain. The magnetization of the 1st nanomagnet is flipped, and the 2nd and 3rd nanomagnets are stressed to align their magnetizations along the hard-axis. Then stress is released/reversed on the 2nd nanomagnet to relax its magnetization along its desired state.
to thermal fluctuations into account. If we release/reverse the stress on nanomagnet-2 ahead of time, then magnetization may not be able to switch successfully rather it will backtrack to the same easy axis it started. This is exemplified in Fig. 3(a). Magnetization failed to switch to \( \theta = 0^\circ \), even it could not get past \( \theta \approx 90^\circ \) since stress is kept constant for a short period of time of 100 ps. Out of 10,000 simulations, 16.52% switching failures were observed in this case. If we keep the stress constant longer for 200 ps, it would not necessarily result in reducing the failure rate of switching, which we will discuss later. Figure 3(b) depicts a case when switching failed; magnetization backtracked when stress was ramped down. We keep the stress constant for much longer time (600 ps) to observe whether sometimes switching still fails or not. Fig. 3(c) shows a case when switching fails. Note that magnetization keeps lingering around \( \theta = 90^\circ \) since stress was kept constant for a long time, but magnetization eventually backtracked towards \( \theta = 180^\circ \).

Figure 4(a) depicts the non-trivial dependence of switching failure rate with stress constant time. This can be explained by considering magnetization’s excursion out of magnet’s plane (\( yz \) plane, \( \phi = \pm 90^\circ \)) during switching as shown in Fig. 4(b). Magnetization deflects out-of-plane due to the torque exerted on it in the \( \hat{e}_\phi \) direction and fast (non-adiabatic) ramp of stress. Although the dipole coupling from nanomagnet-1 facilitates the switching of magnetization of nanomagnet-2 towards \( \theta = 0^\circ \), the out-of-plane excursion of nanomagnet-2’s magnetization can hinder the switching. In Fig. 4(b), note that if magnetization resides in the quadrant \( \phi \in (90^\circ, 180^\circ) \) or \( \phi \in (270^\circ, 360^\circ) \), the term \( B_{\text{shape,}\phi}(\theta_2) \) as in the Eq. (3) becomes negative in sign, which would facilitate decreasing the value of \( \theta_2 \) [see Eq. (1)] aiding magnetization rotation in the correct direction. But, if magnetization resides in the other two quadrants \( \phi \in (90^\circ, 180^\circ) \) or \( \phi \in (270^\circ, 360^\circ) \), termed as bad quadrants onwards, the term \( B_{\text{shape,}\phi}(\theta_2) \) would be positive, which would force magnetization backtracking towards \( \theta = 180^\circ \). This inherent motion is generated particularly due to \( \phi \)-dependence of potential energy, which is strong enough to affect the magnetization dynamics. This motion is also responsible for reducing the switching delay by a couple of orders in magnitude and bellied under the fact that \( N_{d-xx} \gg N_{d-yy}, N_{d-zz} \) (\( N_{d-xx} - N_{d-yy} \) is higher than \( N_{d-yy} - N_{d-zz} \) by a couple of orders in magnitude).

When magnetization reaches \( \theta = 90^\circ \), thermal fluctuations can scuttle magnetization in either side of the magnet’s
increasing the stress constant time so that all the trajectories works correctly as long as the stress is ramped down when
We performed simulations to show that internal dynamics
sub-nanosecond switching delay. Some tolerance is nonethe-
perturbation in the nanomagnets turns out to be
switching failures were observed and the mean energy dissi-
pair signal with the sensed signal of the MTJ, the stress
magnetization resides on the
a magnetic tunnel junction (MTJ).22,34–40 Basically, we need
we can ramp down the stress thereafter. The sensing circuitry
detect when magnetization reaches around
h
7%. The reason behind is that ther-
quadrants are causing the switching failures.
Figure 4(c) shows the distribution of switching delay considering such sensing circuitry. No
switching failures were observed and the mean energy dissipation in the nanomagnets turns out to be ~1.5 att joules at sub-nanosecond switching delay. Some tolerance is nonetheless required since the sensing circuitry cannot be perfect.

We performed simulations to show that internal dynamics works correctly as long as the stress is ramped down when magnetization’s orientation is in the interval \( \theta \in (85^\circ, 140^\circ) \), i.e., it does not have to be exactly 90\(^\circ\). This tolerance is due to the motion arising from the out-of-plane excursion of magnetization.

In conclusion, we have performed a critical analysis of switching failures in energy-efficient straintronic logic using Bennett clocking for computing purposes. It is shown that the switching failures are caused by the inherent magnetization dynamics particularly due to out-of-plane excursion of magnetization and thermal fluctuations during switching. We have proposed a remedy to circumvent such basic issue after a thorough analysis. Such methodology can be exploited for building logic gates and general-purpose computing purposes. Bennett clocking based architecture is regular in nature, so that different building blocks for computing purposes can be designed systematically. Such energy-efficient, fast, and non-volatile (that can lead to instant turn-on computer) computing methodology has profound promise of being the staple of our future information processing paradigm. Processors based on this paradigm may be suitable for applications that need to be run from energy harvested from the environment, e.g., wireless sensor networks, medically implanted devices monitoring epileptic patient’s brain to warn an impending seizure.

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