Nanopipelining of NML Using Multiferroic Single-Domain Nanomagnets

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Abstract— A recent technology, multiferroic single-domain nanomagnets are very promising for energy efficient nanomagnetic logic (NML) applications with benefits of ultra-low energy consumption and inherent non-volatility. In this paper we evaluate pipelined signal propagation in fundamental nanomagnetic logic elements using a four phase local clocking scheme. We demonstrate that low energy consuming operation is possible with this technology at single nanomagnet level reaching clock frequency of ~100 MHz while still maintaining ultra-low energy consumption.

I. INTRODUCTION

Nanomagnetic logic has been proposed as an energy efficient computing paradigm alternative to CMOS and has been the focus of many works [1-5]. Multiple nanomagnetic device structures have been proposed in literature. Multiferroic single-domain nanomagnets are recently proposed devices composed of a magnetostrictive layer (Terfenol-D) and a piezoelectric (PZT) layer. The magnetization orientations of these nanomagnets are shown to switch when a voltage is applied to PZT layer. This is a very energy efficient way of switching magnetization [3].

Elliptical multiferroic nanomagnets with uniaxial shape anisotropy have two stable magnetization states representing logic “0” and “1.” Nanomagnetic logic relies on the alignment of nanomagnets when there is magnetization orientation change in one or more of input nanomagnets, thus propagating the logical values. Data propagation is achieved by aligning the nanomagnets with respect to the magnetization orientations of the neighbors. This is accomplished by systematically disturbing the stable state of the nanomagnets by applying a clocking scheme. In multiferroic nanomagnets stress induced anisotropy forces the magnetization to rotate toward hard axis. The magnetization of the nanomagnet can cross the hard axis barrier in this state if the dipole-dipole interactions due to neighboring nanomagnets are favoring the magnetization of the nanomagnet to align to the opposite direction of its initial state when the stress is removed or stress polarity is reversed.

In this paper we evaluate the pipelining performance of these devices in fundamental nanomagnetic logic elements using a four phase clocking scheme. Next section shows the clocking scheme used, data propagation in ferromagnetically and anti-ferromagnetically coupled binary wires, energy dissipation and performance.

II. NANOMAGNETIC LOGIC AND CLOCKING

A. Binary Wires

Basic building blocks of nanomagnetic logic are obtained by arranging the nanomagnets such that they are magnetically coupled to the nearest nanomagnets [2]. Vertical (ferromagnetic) or horizontal (anti-ferromagnetic) arrangements of these wires constitute a “binary wire”. In horizontal arrangement when the number of nanomagnets is odd the same logic value is propagated as the input; when the number of nanomagnets is even an inverter or an “inverting binary wire” is obtained. In vertical arrangement it is not possible to obtain inverting binary wire since the nanomagnets can only align themselves in the same direction as their neighbors.

Binary wires are symmetric in the sense that the data flow can happen in both directions (i.e. from input to output or from output to input). In order to attain unidirectional (input to output) dataflow a clocking scheme is required.

When the magnetization direction of an elliptical nanomagnet is disturbed out of one of its stable states it can align itself with either one of its neighbors when neighbors have opposite magnetization directions because the dipole-dipole interaction torque acting on the nanomagnet due to its neighbors are equal. To ensure that the magnetization of the nanomagnet aligns with the input neighbor, the torque due to output neighbor should be reduced. In order to reduce the torque due to output neighbor, its magnetization can be forced toward the hard axis by an external agent. This can be achieved with adequate clocking schemes.

B. Clocking Scheme

Various global and local clocking schemes have been proposed for nanomagnetic logic in order to allow unidirectional data flow [1] [4]. These schemes are usually grouped into two categories: Local clocking and Global clocking. Global clocking schemes rely on simultaneous alignment of magnetizations of the nanomagnets along the hard axis, to the high energy state via a global agent such as a global magnetic field [5]. When the global magnetic field is removed (global clock is low), nanomagnets switch to one of the lowest energy (stable) states. They are expected to switch to the state that is favored by their input neighbor and enable data propagation. The global clocking schemes are
not yet implemented for large systems. They do not allow pipelining of data and can cause frustrations (wrong switching behavior) for large arrays of nanomagnets if the applied field changes too quickly or the switching field distribution of the nanomagnets are too wide [5].

Local clocking schemes rely on the use of local agents to individually access each nanomagnet, thus altering their magnetization orientations separately. This allows the sequential relaxation of nanomagnets and reduces the chance of frustration dramatically.

In our simulations we used the four phase clocking scheme proposed in [6] to allow pipelining at nanomagnet granularity. Fig. 1 shows the 4-Phase clocking scheme. Compressive stress is applied to multiferroic nanomagnets when the clock signal is high and tensile stress is applied when the clock signal is low. This way the slow self-relaxation of the nanomagnets is paced up to increase the operation speed.

C. Switching Dynamics

In order to obtain the transient switching characteristics of a single domain nanomagnet under external influences Landau-Lifshitz-Gilbert (LLG) equation needs to be evaluated:

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} - \frac{\alpha \gamma}{M_s} \left[ \vec{M} \times (\vec{M} \times \vec{H}_{eff}) \right]$$ (1)

where $\vec{M}$ is the magnetization of the nanomagnet, $\gamma$ is the gyromagnetic ratio, $\alpha$ is the damping factor, and $\vec{H}_{eff}$ is the effective magnetic field on the nanomagnet and is described by the equation:

$$\vec{H}_{eff} = -\frac{1}{\mu_0 \Omega} \frac{dE}{d\vec{M}} + \vec{H}_{ext}$$ (2)

where, $E$ is the total energy of the nanomagnet due to the shape anisotropy, stress anisotropy, and the dipole-dipole interactions. $\vec{H}_{ext}$ is the external magnetic field.

Stress anisotropy energy due to external stress is:

$$E_{stress} = -\frac{3}{2} (\lambda_s \sigma \Omega) \sin^2 \theta_{ij}$$ (3)

where, $\frac{3}{2} \lambda_s$ is the saturation magnetostriction and $\sigma$ is the applied stress. The total energy of the nanomagnet is then given by:

$$E_{total} = E_{dipole} + E_{shape\_anisotropy} + E_{stress\_anisotropy}$$ (4)

In our simulations, we numerically solved LLG equation considering shape anisotropy, applied stress, dipole-dipole interactions and external magnetic field terms to obtain the magnetization orientation change over time. Further information on assumptions and simplifications can be found in [3].

III. SIMULATION RESULTS

A. Pipelined Data Propagation

Fig. 2 and Fig. 4 show pipelined data propagation in antiferromagnetically and ferromagnetically coupled binary wires at finite time steps $t0$ through $t4$. Fig. 3 and Fig. 5 show pipelined data propagation in continuous time steps. In both configurations every nanomagnet is forced toward hard axis once, thus they switch to the opposite state or back to their original state once per clock period. Since a single switching occurs per nanomagnet every clock cycle, a single computation can be completed at each cycle. The initial
alignment of the nanomagnets is picked so that all nanomagnets have to switch as the data is propagated.

Fig. 3 shows continuous change in magnetization angles in anti-ferromagnetically coupled binary wire. In this simulation the clock period is 12ns and the applied stress on the PZT layer is 40MPa.

θ₀ represents the magnetization angle of the input nanomagnet. The input nanomagnet is assumed to have switched to “0” at time t₀ and is not clocked. The nanomagnet which has magnetization angle θ₁ is initially “0” and the remaining nanomagnets are aligned opposite to their neighbors. The nanomagnets which have magnetization angles: θ₂ is clocked with phase 1, θ₃ is clocked with phase 2, θ₄ is clocked with phase 3 and θ₅ is clocked with phase 4. θ₂ switches to “1” (90 degrees) at time t₂, θ₃ switches to “0” (-90 degrees) at time t₃, θ₄ switches to “1” at time t₄ and θ₅ switches to “0” at time t₅.

Fig. 5 shows continuous change in magnetization angles in ferromagnetically coupled binary wire. The clock period and the applied stress are same as in the previous case. Initially all nanomagnets are aligned in “1” direction while input nanomagnet with magnetization angle θ₀ is aligned in “0” direction. As the clock is applied magnetizations of the nanomagnets start rotating. The simulation for the ferromagnetically coupled binary wire indicates that some nanomagnets switch right toward 0 degrees, while the others switch left toward 180 degrees. The final angle of the latter are 270 degrees which is the same as desired “0” (-90 degrees) direction. The final angles indicate if the nanomagnets switched to the left or to the right directions.

Material properties and device parameters used in the simulations are presented in Appendix.

B. Performance

In our simulations we have used various stress amplitudes and performed parametric sweeps to obtain the minimum clock frequency for correct data propagation in each stress case. We observed that the performances of ferromagnetically and anti-ferromagnetically coupled binary wires are different. The performance is also directly related with the device dimensions. We considered elliptical nanomagnets with dimensions ~102nm x ~99nm x 10nm and PZT thickness of 40nm in this paper.

Fig. 6 shows minimum clock periods required for correct data propagation in binary wires. The results show that vertical and horizontal binary wires have similar performances for high stress case. However for low stress case horizontal binary wire performs ~30% better.

With 40MPa stress a clock period of about 10ns is achieved with the applied clocking scheme. With 3MPa stress a clock period of ~130ns is obtained.
C. Energy Dissipation

The energy dissipation per flip is estimated as the energy dissipated during the charging and discharging of the PZT layer since this energy is more than the required energy to switch the nanomagnet. This dissipation is equal to

\[ E_{\text{dis}} = \frac{1}{2} CV^2 \]

where \( C \) is the capacitance of the PZT layer and \( V \) is the voltage required to generate desired strain by the PZT layer [3]. Since the reverse stress is applied to nanomagnet during relaxation, total dissipation becomes \( CV^2 \). Fig. 7 shows energy dissipation per nanomagnet per flip versus applied stress. Power consumption can be estimated as the energy per flip times the clock frequency.

IV. CONCLUSION

This paper has demonstrated the pipelined data propagation for nanomagnetic logic at nanomagnet level using multiferroic single domain nanomagnets. The paper has also showed the operation of ferromagnetically and antiferromagnetically coupled binary wires. We have also provided the minimum clock periods required for correct operation. We evaluated the energy dissipations of these devices under various stress conditions. Our results indicated that at maximum performance condition the minimum clock period required is about 10ns which translates to 100MHz operation frequency. At this condition required energy to flip the magnetization of a single nanomagnet is simulated to be ~23aJ. These results indicate that these devices are very promising for the design of ultralow energy systems with non-volatile logic circuits which can have their use in mobile applications with extremely high energy efficiency requirements.

APPENDIX

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<th>Material and Geometry Parameters</th>
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<td>Magnetostrictive Material</td>
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REFERENCES


