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Landauer Clocking for Magnetic Cellular Automata (MCA) Arrays

Anita Kumari and Sanjukta Bhanja

***Abstract*—Magnetic cellular automata (MCA) is a variant of quantum-dot-cellular automata (QCA) where neighboring single-domain nanomagnets (also termed as magnetic cell) process and propagate information (logic 1 or logic 0) through mutual interaction. The attractive nature of this framework is that not only room temperature operations are feasible but also interaction between neighbors is central to information processing as opposed to creating interference. In this work, we explore spatially moving Landauer clocking scheme for MCA arrays (length of 8, 16, and 32 cells) and show the role and effectiveness of the clock in propagating logic signal from input to output without magnetic frustration. Simulation performed in object oriented micromagnetic framework suggests that the clocking field is sensitive to scaling, shape, and aspect ratio.**

***Index Terms*—Clock, magnetic cellular automata (MCA), quantum-dot-cellular automata (QCA).**

I. Introduction

One of the pioneering efforts in field-coupled cellular automata computing evolved using quantum tunneling interactions of electrons in neighboring cell [1] is the promising phenomenal packing density, and the low power-delay product. In this work, we study magnetic cellular automata architecture, already functionally demonstrated by pioneering efforts of Imre *et al.* [2], [3] that promise stable operation at room temperature alleviating the criticism of some of the other Cellular Automata variations. The salient feature of the magnetic cellular automata architectures are: 1) single-domain structure and the shape anisotropy work magnificently to store Boolean logic as the easy axis (Y-axis in our case) magnetization; 2) magnetic coupling between the interacting neighbors assures anti-ferromagnetic alignments (anti-parallel), thus generating the signal and its inverse next to each other [see Fig. 1(a)] and; 3) since magnetic interactions are direction-insensitive, we need an addition control apart from input to drive the information flow from input to output which is commonly termed as *clock*. We have observed that conventional adiabatic clock, having group of nanomagnets in one clock state [4] does not work well for lengthy magnetic cellular automata (MCA) array. So we propose a spatially moving clock field named as Landauer clock, accomplished by magnetically switching cell from a null state [the state which holds no binary information (“1” or “0”)], through a switching state (in which the nanomagnet state is determined by its neighbor) and finally to a locked state (stable state) (in which the state is independent of the previous neighbor).

We used a micro-magnetic simulator [object oriented micromagnetic framework (OOMMF)] that solves the Landau–Lifshitz equations accounting various energies (zeeman energy, magnetostatic energy, exchange energy, anisotropy energy, demagnetization energy, etc.). We demonstrated the spatial temporal clock known as Landauer clock on different length arrays (8, 16, 32), different shapes (rectangular and oval) and different nanomagnet aspect ratio (AR). The aspect ratio is the width to height ratio.

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The authors are with the Nano Computing Research Group (NCRG), Department of Electrical Engineering, University of South Florida, Tampa, FL 33620 USA (e-mail: akumari@mail.usf.edu; bhanja@eng.usf.edu).

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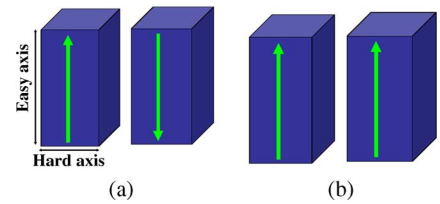

Fig. 1. (a) Definition of logic “1” and “0” for nanomagnets. (b) Metastable states for coupled pairs.

A few observations made by our experimental simulations for the clocking scheme are as follows.

1) Clock field is invariant with length (8, 16, and 32) and works perfectly all the time, yielding anti-parallel cell.
2) Oval shape nanomagnet requires high clock field strength due to high coercivity as compared to rectangular shape nanomagnet. Hence it is not suitable for MCA architecture.
3) Input field required is very low as compared to the null and switch fields and is same for both shapes (rectangle and oval) for aspect ratios under study.
4) Clock field decreases linearly with scaling of nanomagnet.

II. Theoretical Background

Magnetic field coupling is emerging as a promising successor of CMOS. The behavior of magnetic materials is described by the classical theory of micromagnetism. In bulk materials the balance of dipolar coupling and exchange interaction between magnetic moments result in complicated domain structure, opposed to small magnets which exhibit single domain behavior. In single domain, the state is approximately described by a single magnetization vector. The magnetization dynamics of ferromagnetic materials can be described by the well-known micromagnetic equations (1) and (2), describing the time evolution of the magnetization vector field M(r, t) under the influence of an external magnetic field distribution, H(r, t). If the magnetic particle is sufficiently small (i.e. smaller than few times 100 nm), then its magnetization behavior can be approximated by the single-domain Landau-Lifshitz equation.

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M^{(i)}(t)} \times \mathbf{H^{(i)}_{eff}(t)} - \frac{\alpha\gamma}{\mathbf{M_s}}\left[\mathbf{M^{(i)}(t)}\left(\mathbf{M^{(i)}(t)} \times \mathbf{H^{(i)}_{eff}(t)}\right)\right]. \tag{1}$$

Here, M_s is the saturation magnetization of the material, γ is the gyromagnetic ratio, and α is a damping constant. The single-domain approximation assumes that the magnetization is homogeneous inside the particle. Therefore $M^{(i)}(t)$ is a single, time-dependent vector for each particle, and the superscript (i), identifies a specific dot in an array. The effective magnetic field $H^{(i)}_{eff}(t)$ is the average magnetic field experienced by the magnetic moment, and it is the sum of externally applied field (Zeeman field), field originating from the magnetic dot itself (demagnetizing field), and coupling from the dot’s neighbors

$$\begin{aligned}\left(H^{(i)}_{eff}(t)\right) &= H^{(i)}_{\text{Zeeman}}(t) + H^{(i)}_{\text{demag}}(t) + H^{(i)}_{\text{coupling}}(t)\\ &= H^{(i)}_{\text{Zeeman}}(t) + N^i M^i + \sum_{j=ne} C_{ij} M j(t)\end{aligned} \tag{2}$$

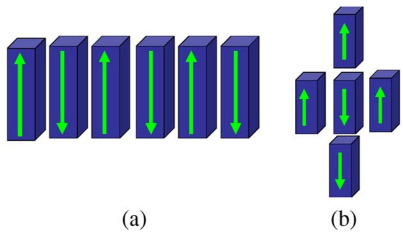

Fig. 2. (a) Inverter. (b) Majority gate.

where N^i is the demagnetization tensor, which takes into account the shape anisotropy. The matrix $C^{i(j)}$ is the coupling between nanomagnets i and j. Both N and C are constant for a given geometry.

III. Review of Magnetic Cellular Automata

The magnetic cellular automata (MCA) concept is a version of the field coupled quantum-dot-cellular automata (QCA) architecture that was first proposed in [1]. The nanomagnets couple to their nearest neighbors through magnetostatic interactions, try to align anti-parallel ground state or minimum energy state Fig. 1(a) or higher-energy metastable state Fig. 1(b). In metastable state the polarity of nearby nanomagnet is in same direction (parallel), which is not desired for correct flow of information. MCA offer very low power dissipation and high integration density of functional devices. In addition, it can operate over a wide temperature range. A nanomagnet logic device consists of a finite number of dots. Fig. 2 illustrates two basic building blocks that would be used to construct MCA circuits.

IV. Clock Structure

In magnetic QCA, first clocking scheme is proposed by Alam *et al.*, where periodically oscillating external magnetic field is applied along the hard axis (X-axis) of group of nanomagnets [4] and is adiabatically removed from all the cells simultaneously.

From our simulation experiments, we observed that even though the previous scheme is easy to implement and works well for short array (upto length 4), larger array of nanomagnets cannot be clocked through the above scheme. Fig. 3 demonstrates the frustrations in 8 MCA array of size $60 \times 90 \times 20$ nm^3 (width $\times$ height $\times$ thickness), using this clock scheme where the entire set was driven to hard axis at the same time and released adiabatically (all of them at the same time). We gave 70 mT field along hard axis and then reduced the field adiabatically and finally to 0 mT. One can easily observe from Fig. 3(d) that magnet (2 & 3) and magnet (7 & 8) are reaching a metastable state which is not anti-parallel.

We realized that releasing field simultaneously from group of nanomagnet, the input output directional information flow is not valid, as not only the input would be driving the output, but the output will have impact over the input making the information reversible. As shown in Fig. 3(c), output (right most) nanomagnet is stronger in polarization and influencing the driver.

The observation led us to design the true spatial Landauer clocking where each releasing clock state would have only one nanomagnet and the clock appears moving from input to the output deriving the directional aspect of conventional logic which is explained in Section IV-A.

A. *Spatially Moving Landauer Clocking Scheme*

We propose a novel clocking scheme for MCA where in essence, we deliver a spatially varying field from input to the output.

The information processing in our scheme requires the interaction of the following three fields.

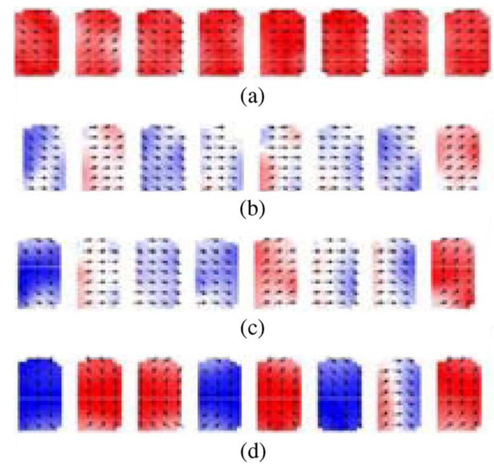

Fig. 3. Conventional clock (Alam *et. al*): simulation result for eight nanomagnet rectangle shape MCA array. (a) Clock field in hard axis is applied to make all the nanomagnet null. (b) Release the clock field adiabatically and input is applied to the left most nanomagnet. (c) The first and last nanomagnet has strong magnetization during releasing hard axis field, hence output also start driving input. (d) Not aligned correctly, frustration at 2 & 3 and 7 & 8 nanomagnet due to the bidirectional flow of information.

1) ***Null Field:*** It is the strong field applied to the hard axis (X-axis) of the nanomagnet, resulting in the Null clock state which holds no binary information ("1" or "0"). A large group of nanomagnets can be placed in null clock state.
2) ***Switching Field:*** It is reduced hard axis (X-axis) field, resulting in switching clock state in which the nanomagnet state is solely determined by its previous neighbor. There is only one nanomagnet in switching clock state.
3) ***Input Field:*** It is the small biased field given to the input nanomagnet in Y-axis to propagate the information down the line.

In this scheme, we drive all the cells initially to null state (hard axis) and then we decrease the field of the input nanomagnet to switching field while the remaining nanomagnets are at null state. In the next time slot we decrease the field of next nanomagnet while rest are still at null state and so on, thereby removing field from the nanomagnet cells one by one.

Fig. 4 illustrates, in more detail the Landauer clocking scheme for MCA. The figure shows an MCA array, implemented with five nanomagnets. The geometry of nanomagnets allows three distinct states of magnetic polarization, which depends on the strength of magnetic field applied to the cell. Fig. 4 illustrates the snapshots of the circuit at different stages as it is clocked using the Landauer clocking scheme. We are giving input to the left most nanomagnet of MCA array and the output signal propagate to the right of the MCA array. The flow of information across the array is controlled by the clocking signal. The purpose of clocking field is to gradually drive the nanomagnets in a particular state, from null to active state. The active state is determined by the state of the neighbor nanomagnet. In this clocking scheme initially all the nanomagnets are in stable antiparallel state. All the nanomagnets then drive into null state by null clocking field in hard axis (X-axis) as shown in Fig. 4(a). Then we move the strong null field from the left most nanomagnet, and give the small switching field in hard axis, which brings it into switching state, and at this point input field is given as shown in Fig. 4(b), while the rest nanomagnets remain at null state. Now clock field is moved from next magnet and it comes into the influence of switching field and hence it moves into the stable state (magnetization in Y-axis) as shown in Fig. 4(c). The nanomagnet

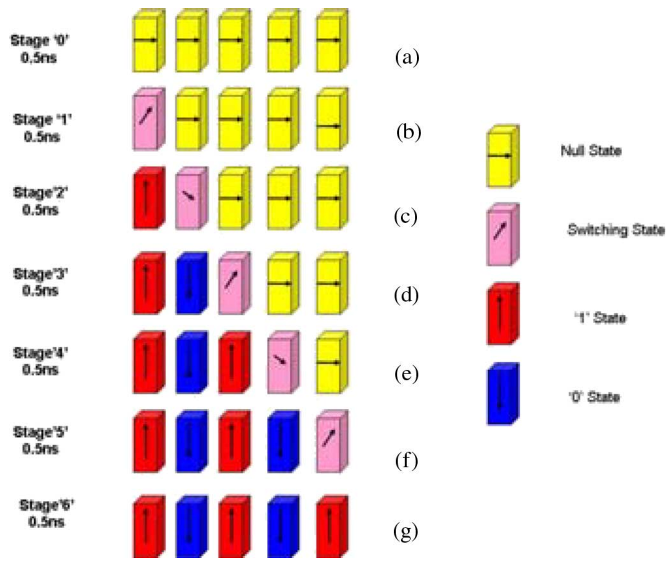

Fig. 4. Landauer clocking: Showing seven stages for five nanomagnet chain. Yellow color shows the null state; pink color is for switching state; red "1" and "0" for blue. Each stage is for 0.5 ns. (a) Null state, all the nanomagnets in the array forced in hard (x-axis) axis. (b) The null-field from the left most nanomagnet is moved, comes under the switching field, at this time input "1" is given. (c) Null-field from the second nanomagnet is moved and comes under the influence of switching field while remaining nanomagnets are at null-field. (d) The second nanomagnet attained the stable state according to the previous neighbor (first nanomagnet) and a third nanomagnet comes under the switching-field.

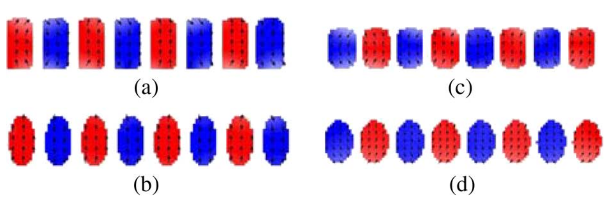

Fig. 5. (a) Simulated eight MCA array of 50 × 100 × 20 nm^3 of rectangle shape. (b) Simulated eight MCA array of 50 × 100 × 20 nm^3 of oval shape. (c) Simulated eight MCA array of 60 × 90 × 20 nm^3 of rectangle shape. (d) Simulated eight MCA array of 60 × 90 × 20 nm^3 of oval shape magnet.

in switching state is influenced by the stable state of the previous nanomagnet as opposed to the following nanomagnet, which is in null state. This is because the magnetization of the null state nanomagnet is in X-axis. In this manner the null field is removed from all the nanomagnets, resulting in directional information flow from input to output as shown in Fig. 4(d)–(g).

We ran various simulations (using OOMMF simulator) and validated the functionality of Landauer clock for different lengths (8, 16, 32) and shapes (rectangular, oval) MCA arrays. Fig. 5 shows the simulated result for eight MCA array. Also experimentally we demonstrated, by moving the strong permanent magnet over the MCA array and looking the array in magnetic force microscopy (MFM) that array aligned antiparallel [5].

To summarize few important features of proposed spatially moving clock scheme, we have the following:

- Landauer clock has directional flow of information from input to output, as output has no impact on driver (input), unlike conventional adiabatic clock;
- our Landauer clock is not similar to Landauer phase clock used for molecular QCA, in which after every fourth cycle first phase repeats [6];
- Landauer clock implies that in every switching (releasing field) clock state there should be one nanomagnet rather than a group of nanomagnets.

V. Simulation Result

In this section, we employed spin dynamics and Landau–Lifshitz–Gilbert equation, which is packeted in OOMMF code to obtain time evolution. We wrote the script for spatially varying field using embedded function Oxs_StageZeeman.

Our main focus is to study Landauer clocking schemes with soft permalloy (80–20) magnetic interconnects under various design scenarios. The parameters values used for the numerical calculations were $Ms(\text{Saturation magnetization}) = 8.5e5$, A (Exchange energy coefficient)$= 13e-12$ and $K(\text{Anisotropy constant}) = 5.0e2$. These parameters are the characteristic property of magnetic material (Permalloy) which are used in calculating various energies (Zeeman energy, magnetostatic energy, exchange energy, anisotropy energy, demagnetization energy, etc). We study the required clocking field strength and switching field strength varying primarily three parameters aspect ratio, shape, and scaling.

A. Aspect Ratio and Shape

It is already demonstrated that the reliability of coupling between nanomagnets is shape dependent [2]. The geometry of the nanomagnet introduces the shape anisotropy term (H_{SA}), which is the source of magnetic field called demagnetizing field. The relation of shape anisotropy and geometry is given by

$$H_{SA} = d \sum_{j} S_j^2. \quad (3)$$

S_j is the magnetic moment of the jth cell. Shape anisotropy is present due to the dipolar interaction between the individual spin within the nanomagnet. The term d is the constant, $d = \mu_0 M_0^2 (\text{w/h})$, calculated by solving the magnetostatic energy [7].

"d" is proportional to the aspect ratio [width (w)/height (h)] and it is evident from the (3) that shape anisotropy is directly proportional to the aspect ratio of the geometry.

We looked into the four different aspect ratios 0.4, 0.5, 0.66, 0.8, utilizing Landauer clock. From our simulation results we found out that shape anisotropy is not only important for reliability of coupling between nanomagnets, but it plays a significant role in clock field strength also. It has been proved that very low aspect ratio requires very high external field due to high coercive field. If we take high aspect ratio, i.e., the more square like structure with smaller coercive field, it prevents magnetic arrays being used for magnetic logic devices.

The nanomagnet array of size 60 × 90 × 20 nm^3 requires less null field (70 mT) for both shapes rectangular and oval as compared the size 50 × 100 × 20 nm^3 and 40 × 100 × 20 nm^3 array. It is depicted from Table I(a) that for rectangle shape, the null field required for aspect ratio 0.4 is more than twice (150 mT) than for aspect ratio 0.6 and for aspect ratio 0.5 it is 30 mT more than that for aspect ratio 0.6. The oval (angular) shape with aspect ratio 0.4 and 0.5 required high null field because of strong demagnetization field (shape anisotropy). The shape anisotropy require high null field because the energy difference between the two states is dependent on the shape and size of the nanaomagnet [2]. Table I(b) shows that oval shape of aspect ratio 0.4 required null field three times more than that for aspect ratio 0.6 and nearly twice that for aspect ratio 0.5. Hence in general oval shape and low aspect ratio requires high null field.

We have also noticed that high aspect ratio (0.8), having square like structure did not work. It did not attain ground state as shown in Fig. 6. The magnetization in X-axis (hard axis) is more comparable to the

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TABLE I
(A) FIELDS REQUIRED FOR RECTANGLE SHAPE NANOMAGNET CHAIN. (B) FIELDS REQUIRED FOR OVAL SHAPED NANOMAGNET CHAIN

(a)

Aspect ratio	Null Field (mT)	Switch Field (mT)	Input Field (mT)
0.4	150	40	3
0.5	100	30	5
0.6	70	20	5

(b)

Aspect ratio	Null Field (mT)	Switch Field (mT)	Input Field (mT)
0.4	170	50	3
0.5	130	40	5
0.6	70	20	5

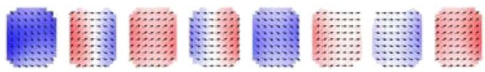

Fig. 6. 8 nanomagnet rectangle shape MCA array with aspect ratio 0.8 ($72 \times 90 \times 20$ nm^3).

Y-axis (easy axis). Hence it is hard to flip the nanomagnet with high aspect ratio.

The switch field is less than the null field as shown in Table I. We have seen similar trend, the Oval shape requiring high switch field which decreases with increase in aspect ratio. The 0.6 aspect ratio require less switch field (20 mT) as compared to the 0.5 and 0.4 aspect ratio.

Through our simulation results we have shown that input field required is very low and is same for aspect ratio 0.5, 0.66 (5 mT) irrespective of the shape as shown in Table I. While the input field required for low aspect ratio 0.4 is less (3 mT) than the other two aspect ratio.

B. Length of Nanomagnets

We also did the clock study on three different arrays lengths (8, 16, 32). The clock field required for $60 \times 90 \times 20$ nm^3 nanomagnet array of 8, 16, and 32 elements is 70 mT null field, 20 mT switch field, and input field is 5 mT. For $50 \times 100 \times 20$ nm^3 MCA array the field required for correct evaluation is 100 mT null field, 30 mT switch field for rectangle shape and for oval shape, 130 mT null field, 40 mT switch field is required which is same for all length arrays (8, 16, and 32). So in general the MCA array length does not matter with regards to the clock field strength.

C. Scaling

From the shape anisotropy study, we concluded that rectangular shape is best for the MCA architecture, as it required less clock field strength as opposed to oval shape. We conceive our next study, i.e., scaling of nanomagnet, with the rectangular shape and

TABLE II
SCALING RESULT FOR $60 \times 90 \times 20$ nm^3 RECTANGLE SHAPED EIGHT NANOMAGNET MCA ARRAY

$Scaling\ factor$	0.8	0.6	0.4
$Null\ field$	50mT	30mT	20mT
$Switching\ field$	15mT	5mT	5mT

$60 \times 90 \times 20$ nm^3 (0.6 AR) size nanomagnet MCA array. It has been demonstrated that MQCA-based logics are scalable. We have scaled the MCA array with different factors and observed that clock field strength decreases with scaling as explained in Table II. This is because as we scale down the size of nanomagnet array the surface volume of the nanomagnet decreases, resulting in small magnetization hence requiring less clock field to reevaluate the array. Thus, we show in this work that spatially moving clocking field is essential for correct logic propagation.

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