Scaling of voltage controlled magnetic anisotropy based skyrmion memory and its neuromorphic application

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Keywords: skyrmion, racetrack memory, magnetic memory devices, magnetic anisotropy

Abstract
Voltage controlled skyrmion memory requires less energy compared to current controlled method where voltage changes magnetic anisotropy (VCMA) and Dzyaloshinskii-Moriya interaction (DMI). Ferromagnetic (FM) and synthetic antiferromagnetic (SAFM) memory devices are simulated using electric field control method where gate and gap width are chosen as smaller than skyrmion size so that skyrmion can feel the change in voltage polarity in the neighbouring gate and moves accordingly. Scaling of memory device is performed which shows SAFM memory can be made much narrower compared to FM memory as skyrmion diameter also depends on width of the structure. Effects of device structure and skyrmion-skyrmion repulsion force on skyrmion diameter variation are shown in cylindrical structure considering effect of demagnetizing field. Apart from these, neuromorphic application is considered where skyrmion moves from central square neuron region to surrounding synapse region or vice versa by the application of voltage. Switching time, voltage range, energy and scaling of device dimensions are shown for synapse-neuron having different number of skyrmions where multiple skyrmions represent different weight in the neuromorphic circuit.

1. Introduction
Voltage or electric field control method of skyrmion requires less energy consumption compared to well known current controlled method. Skyrmion can be created by the application of electric field and skyrmion can also be destroyed by applying electric field of opposite polarity. The electric field creation and annihilation of skyrmion are demonstrated experimentally and theoretically in CoFeB/MgO and in Pt/Co/oxide tri-layer [1–3]. Skyrmion can also be driven by the application of anisotropy gradient in room temperature where varying electric field electronically manipulate the perpendicular magnetic anisotropy (PMA) due to different amount of charge accumulations [2, 4, 5]. Presence of skyrmion in a magnetic material changes the magnetoresistance and electrical detection of magnetic skyrmions is performed by tunnelling non-collinear magnetoresistance (NCMR). NCMR originates from spin mixing effects upon electron hopping between adjacent sites with canted magnetic moments [6, 7]. Skyrmion can also be detected by tunneling anisotropic magnetoresistance (TAMR) in ferromagnet(FM)/semiconductor/normal metal(NM) or FM/insulator/NM magnetic tunnel junctions (MTJs) [8]. MgO having the dielectric breakdown voltage of more than 2 V can be used as insulator material which can used between FM and NM [9].

Neuromorphic circuits are becoming increasingly popular in scientific community which can be used in transistors and various spintronics based devices [10–13]. Ubiquitous von Neumann computer architectures have complex processor cores and follows sequential computation, whereas biological neurons and synapses operate by storing and processing information simultaneously with much less power consumption. Biological Neurons works as a node in the network, axons are like out-going links, and dendrites are like in-coming links. Axons connect to dendrites at synapses. Weighted input spikes form synapses are accumulated, and the neuron is implemented as a threshold detector. Neuron is joined with many synapses. A neuron takes a group of weighted inputs, applies an activation function, and returns an output. Voltage controlled skyrmion motion of
Skyrmion can be used in neuromorphic circuits where single device will operate as synapse and neuron. Conventionally synapse and neuron are made separately and the most common form of synapse is memristor. A memristor is a two-terminal silicon-based electronic device whose conductance can be modulated by charge or flux through it and it requires more energy compared to spintronics based devices like domain wall and skyrmion \[14–18\]. The implementation of an artificial neuron based on silicon-based circuits requires many transistors and requires large amount of area and power \[19\]. Therefore a single device based synapse-neuron is simulated here for designing neuromorphic circuits. Energy requirement is made lower by using voltage controlled method instead of current controlled method and speed is further improved by using synthetic antiferromagnetic (SAFM) material.

2. Device structure

Ferromagnetic and synthetic antiferromagnetic skyrmion can be moved by magnetic anisotropy change (VCMA) from one gate to another gate. Under one gate anisotropy is increased by application of positive voltage while anisotropy is decreased by negative voltage at nearby gate (figure 1(a)). Skyrmion motion due to VCMA method requires very small amount of energy (around 0.1fJ) compared to current controlled method. Skyrmion having diameter of 20 nm is controlled by gates having 10 nm width and two consecutive gates are separated by 4 nm (figure 1(b)). Skyrmion stabilizes at the center of gate having negative voltage. As skyrmion diameter is 20 nm, it marginally touches nearby gate. If voltage polarity at the nearby gate is changed, skyrmion can feel the change and moves accordingly. The proposed structures can work both as shift memory (where only one of the two neighboring cells will have sensing device on top to detect skyrmion to represent 1/0 bit) and race-track memory (where several skyrmions will be driven and skyrmions can be driven as far as necessary. Each skyrmions can be controlled individually).

Voltage controlled skyrmion motion can be used in neuromorphic application where a central metal gate region represents neuron and surrounding metal gate regions are called synapse. Skyrmion will move from synapse to neuron during normal operation (if they are triggered) and MTJ structure of neuron will sense the presence of skyrmions in the neuron. During reset operation, skyrmions will leave from neuron and will wait in the synapse for next trigger signal (figures 2 and 3). Metal gate on top of FM in the surrounding region represents synapse and applied voltage in synapse will move skyrmion towards central neuron region. Metal gate on top of FM in the central region represents neuron. MTJ structure on neuron will sense skyrmion, and voltage can be applied in reset operation to drive skyrmion backwards to synapse region to re-use the device. Central white region contains no FM and it prevents skyrmion not to come to the absolute center, when only one synapse is triggered. Only FM region (no metal on top) represents the gap region between synapse and neuron metal gate.

For experimental realization of the device, there will also be a detecting mechanism to detect the skyrmion \[6–8\]. Skyrmion detection can also be done using probe \[20\]. Skyrmion will be detected at the central neuron region, and the detecting mechanism will be on top of neuron. Spin-polarized scanning tunnelling microscopy can be used to locally probe skyrmion by individual hot electrons \[21\].

3. Theory

To understand the neuron operation with synapse, we start with basic definition of artificial neuron. Artificial neuron general form of equation is as follows:

$$y = f\left(\sum w_i x_i + b\right)$$  \hspace{1cm} (1)
where, \( y \) is the output, \( f \) represents function (here MTJ output is a linear function with skyrmion number and number of points in that line is determined by the total number of skyrmions under neuron), \( x_i \) is \( i \)-th input from previous layer neuron (input voltage at synapse), \( w_i \) is weight for \( i \)-th input (represented by number of skyrmion under a synapse gate) and \( b \) represents bias (synapse without connecting to previous layer neuron). In the proposed model, one synapse has two skyrmions which will represent double weight compared to other synapses.

When more than one skyrmion is present in synapse-neuron or in rectangular VCMA memory or in cylindrical disk, skyrmion-skyrmion repulsion force comes into play. The repulsive force \( F_{ss} \) between two skyrmions can be found from the following equation \([22, 23]\):

\[
F_{ss} = K_1 \left( \frac{d \sqrt{H_k A_{ex}}}{D} \right) \times \left( \frac{A_{ex}}{t} \right)
\]

where \( K_1 \) is the modified Bessel function, \( d \) is the skyrmion separation distance, \( H_k \) is the perpendicular anisotropy field, \( A_{ex} \) is the exchange stiffness, \( D \) is the Dzyaloshinskii-Moriya interaction and \( t \) is the time.

Besides skyrmion-skyrmion repulsion force and edge repulsion force, dipole-dipole interactions also play important role in determining the stability and size of skyrmion. Dipole-dipole interactions (DDI) turn a ferromagnet into a frustrated spin system and generates an effective magnetic field which leads to a new magnetic order with reversed magnetization inside the spot. DDI makes the ground state to have an alternating up-down stripe-domain structure and makes it easier for skyrmion to form \([24]\). In this way DDI helps to stabilize bigger skyrmion.

4. Simulation details

LLG parameters used here are for room temperature interfacial skyrmion hosting material CoFeB and Cobalt where CoFeB is used for FM skyrmion simulation and Cobalt is used for SAFM simulation. When magnetic material is interfaced with heavy metal, interfacial Dzyaloshinskii-Moriya interaction needs to be considered due to broken inversion symmetry \([25]\). Saturation magnetization, exchange stiffness, uniaxial anisotropy
constant in the Z-direction, Landau–Lifshitz damping constant, interfacial Dzyaloshinskii-Moriya strength are used to simulate CoFeB and Co layer. External field is applied only for FM and antiferromagnetic exchange stiffness is used to simulate spacer layer between top and bottom Co layers in SAFM (table 1). For synthetic AFM, opposite polarity of voltage are applied in top and bottom gates so that skyrmion and antiskyrmion move in the same direction. Effect of voltage is incorporated by change in anisotropy and change in DMI where VCMA coefficient of 100 fJ/Vm and voltage controlled DMI change coefficient is 26 fJ/Vm [26–30]. Exchange energy parameters, magnetic anisotropy energy are important in skyrmion based magnetic memory devices, and have been considered in the simulation [31, 32].

5. Results

Switching time of skyrmion (due to VCMA) with applied voltage is plotted considering VCMA coefficient of 100 fJ/Vm. Switching time reduces with increased applied voltage and switching time is less in synthetic AFM compared to FM skyrmion (figure 4). Though mainly anisotropy changes due to voltage, but there is some change of DMI and very small amount of change in saturation magnetization ($M_{sat}$). As variation of $M_{sat}$ is negligible, we neglected this change in our simulation. By applying positive voltage in one gate, both anisotropy and DMI increase under that gate. When incorporating change in DMI with VCMA, switching time increases a little bit as skyrmion prefers to stay in lower anisotropy but in higher DMI (figures 5(a) and (b)).

After that scaling issue of this device is considered. Width of FM region can not be less than 55 nm as FM skyrmion does not move exactly in straight line and gets annihilated at the boundary. But width of SAFM region can be reduced up to 25 nm, as SAFM skyrmion follows straight path. Skyrmion diameter reduces with the reduction of SAFM region width due to repulsion force from the edge (figure 6).

To better understand the skyrmion diameter reduction with device structure, cylindrical structure is also considered. Cylindrical nano-disk is simulated to find the effect of disk diameter on SAFM skyrmion diameter

| Table 1. LLG parameters used in FM and SAFM structures. |
|-----------------------------------------------|
| **Parameter**                                  | **FM (CoFeB) [33]** | **SAFM (Cobalt) [34–36]** |
| Saturation magnetization ($M_{sat}$)           | 0.9 MA/m            | 0.58 MA/m                   |
| Exchange stiffness ($A_{ex}$)                   | 14 pJ/m             | 15 pJ/m                     |
| Antiferromagnetic exchange stiffness ($A_{ex}$)| 0                   | -1 pJ/m                     |
| Uniaxial anisotropy constant ($K_u$)           | 0.779 MJ m$^{-3}$   | 0.8 MJ m$^{-3}$             |
| Landau–Lifshitz damping constant ($\alpha$)    | 0.5                 | 0.3                         |
| Externally applied field ($B_{ext}$)           | 12.5 mT             | 0                           |
| Interfacial Dzyaloshinskii-Moriya strength ($D_{int}$) | 1.68 mJ m$^{-2}$ | 3.5 mJ m$^{-2}$             |

Figure 4. Switching time for VCMA driven skyrmion in FM and SAFM with gate voltage.
Figure 5. Switching time with voltage considering change in VCMA only and considering change in both VCMA and Dind: (a) ferromagnetic system and (b) synthetic antiferromagnetic system.

Figure 6. Diameter variation of SAFM skyrmion with region width.

Figure 7. Diameter variation of SAFM skyrmion in cylindrical region: (a) 1 skyrmion system and (b) 4 skyrmions system.
with and without demagnetizing field. In presence of demagnetizing field, skyrmion diameter increases. Skyrmion diameter is a bit less in cylindrical structure compared to rectangular structure as repulsion force is coming from all directions in cylindrical structure (figure 7(a)). Skyrmion diameter reduces with smaller structure and vanishes when its diameter is very small. Multiple FM and SAFM skyrmions are simulated in a cylindrical structure to see the shrinking effect of skyrmion with the reduction of diameter of outer cylinder where repulsion force from outer edge and inner edge are present along with the skyrmion-skyrmion repulsion force. There is a hollow area at the center of nano-disk which will make additional repulsion force from the center and will stop skyrmion from coming to the central region. Both FM and SAFM skyrmion can be reduced in diameter with the reduction of the size of hosting layer. FM layer can be narrowed down but not as small as SAFM layer. FM skyrmion will shrink until FM cylinder diameter reaches lowest diameter of 95 nm whereas SAFM skyrmion can shrink until cylinder diameter reaches lowest diameter of 65 nm (figures 7(b) and 8).

Voltage controlled skyrmion motion can have application in neuromorphic circuit where skyrmion will move from synapse to neuron or vice versa by the application of voltage. When skyrmions are under neuron region, they will be sensed by MTJ and the sensed output signal from MTJ will be used for next layer in neuromorphic circuit. Switching time with voltage are shown for FM and SAFM neuron. Very low voltage in FM can not overcome the repulsion force from edge and skyrmion can not move from neuron. Also for very high
### Figure 10.
Switching time with voltage for SAFM neuron with 4 and 5 skyrmions.

### Figure 11.
Changing weight of synapse by changing number of skyrmions under gate region.

### Table 2.
Energy, switching time and device dimensions for different number of FM and SAFM skyrmions neuron. Number of skyrmions are shown in parentheses with SAFM and FM.

|                  | SAFM (4) | SAFM (5) | SAFM (6) | SAFM (7) | FM (4) | FM (7) |
|------------------|----------|----------|----------|----------|--------|--------|
| Highest Switching Energy (fJ) | 0.1      | 0.132    | 0.132    | 0.132    | 0.025  | 0.047  |
| Switching Time (ns)      | 1.2      | 1.6      | 1.6      | 1.6      | 5.4    | 11     |
| Neuron Area (nm × nm)   | 95 × 95  | 110 × 110| 110 × 110| 110 × 110| 95 × 95| 130 × 130|
| Widest Synapse Width(nm) | 55      | 110      | 110      | 100      | 55     | 120    |
| Gap between Synapse and Neuron (nm) | 4       | 10       | 10       | 10       | 4      | 15     |
voltage in FM, skyrmion diameter shrinks so much (as there are already a lot of repulsion forces) that it gets destroyed (figure 9). SAFM skyrmion can shrink more compared to FM skyrmion and can sustain in higher voltage (figure 10).

As there can be different weights in different synapses of an artificial neuron, so 5,6,7-skyrmion neurons are simulated where one or more of the four synapses have two skyrmions and will have higher weight (figure 11). Energy, switching time and area required for FM and SAFM neuron having 4 skyrmions up to 7 skyrmions are mentioned in table 2. FM neuron requires larger switching time compared to SAFM and it also requires larger area for having skyrmion Hall angle. FM actually requires higher energy compared to SAFM for similar switching time (in table 2, highest switching energy seems larger for SAFM but actually it is mentioned for SAFM by applying up to 0.5 volt and for FM up to 0.25 volt, as FM skyrmion destroys at 0.5 volt).

To make non-volatile multiple state memory, notch has been given at the joint of neuron and synapse. Notch will prevent skyrmion from coming towards central neuron region when no voltage is present (figure 12). SAFM neuron can work within a range of voltage from 0.125 volt to 0.5 volt. But FM neuron works only near 0.125 volt as higher voltage increases the skyrmion Hall angle and skyrmion hits the boundary region and gets annihilated.

Figure 12. Use of notch to prevent skyrmion from coming back to central region when no voltage is present.
near the notch (table 3). Applied voltage in the proposed devices is maximum 0.5 volt which is even less than the voltage used in current 7 nm CMOS technology, so there should not be any reliability issue in the proposed devices [37]. The proposed device can be integrated with the current silicon-based technology as the demonstration of information storage devices incorporating magnetic wires directly into silicon-based integrated circuits is present in the literature [20].
Energy consumed by current-induced spin-transfer-torques based skyrmion memory is \(\sim 2.5 \text{ fJ per switching}\) [38–40]. The proposed voltage-controlled devices require maximum 0.132 fJ for switching. A comparison with Resistive random-access memory (RRAM), Phase-change memory (PCRAM/PCM), spin transfer torque random access memory (STTRAM) in terms of switching time, energy shows the improved performance in the proposed devices. Write energy/ bit is \(\sim 100 \text{ pJ for PCRAM, } \sim 1\text{ pJ for RRAM, and } \sim 100 \text{ fJ for STTRAM}\). Switching time is \(\sim 50\) ns for PCRAM, \(\sim 10\) ns for RRAM, and \(\sim 10\) ns for STTRAM [38–40]. The proposed synthetic antiferromagnetic (SAFM) memory devices require \(\sim 1.7\) ns switching time.

Next scaling of neuron area is considered for different number of skyrmions (with diameter variation of skyrmion) by using a phase diagram. For 1 and 2 skyrmions, there is no contribution from skyrmion-skyrmion repulsion force. So, relatively larger region is needed as skyrmion hits the central square in smaller structure. For 3, 4 and 5 skyrmions, repulsion force among skyrmions helps them not to hit the central region and neuron size can be made lower. For 3 skyrmions, there is some skyrmion-skyrmion repulsion force which helps skyrmion not to hit the central region in relatively smaller structure. For 4 and 5 skyrmions, there are large skyrmion-skyrmion repulsion force which helps skyrmion not to hit the central region and stabilize in even smaller structure. For 6 and 7 skyrmions, though there is skyrmion-skyrmion repulsion force, but as skyrmion number gets very high, more space is needed to accommodate all of them. Skyrmion-skyrmion repulsion force make skyrmions to stay at a distance from one another and very large number of skyrmions will need larger structure to accommodate all skyrmions (figures 13 and 14). Due to the presence of multiple skyrmions, skyrmion-skyrmion repulsion force needs to be considered. Multiple skyrmions are simulated to address the issue of repulsion and they always stay at a distance from one another due to the repulsion force between skyrmions. Two skyrmions repel each other and stays at a distance which is twice their diameter. To theoretically calculate and determine the maximum number of skyrmions that the proposed device can accommodate, pentagon, hexagon, or larger polygons need to be drawn in the central neuron region where each axis of the polygon should be twice the diameter of a skyrmion.

### 6. Conclusions

Voltage controlled skyrmion motion can offer less power consumption compared to current controlled method. Scaling of the device shows less area is needed for VCMA controlled motion for SAFM skyrmion. This VCMA controlled motion of skyrmion is used in designing synapse and neuron which will require less area, less energy consumption and will help device engineers in designing low power neuromorphic circuits.

### Acknowledgments

This work was supported as part of Modeling and Simulation Program (MSP) grant funded by the US Department of Education under Award No. P116S210002. This work was also supported by the Peach State Louis Stokes Alliance for Minority Participation (PSLSAMP) grant supported by the National Science Foundation under Grant No. 0 503278, and the OSRA FY22 Mini-Grants of Savannah State University.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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