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Invited Paper

Lateral inhibition in magnetic domain wall racetrack arrays for neuromorphic computing

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ABSTRACT

Neuromorphic computing captures the quintessential neural behaviors of the brain and is a promising candidate for the beyond-von Neumann computer architectures, featuring low power consumption and high parallelism. The neuronal lateral inhibition feature, closely associated with the biological receptive field, is crucial to neuronal competition in the nervous system as well as its neuromorphic hardware counterpart. The domain wall - magnetic tunnel junction (DW-MTJ) neuron is an emerging spintronic artificial neuron device exhibiting intrinsic lateral inhibition. This work discusses lateral inhibition mechanism of the DW-MTJ neuron and shows by micromagnetic simulation that lateral inhibition is efficiently enhanced by the Dzyaloshinskii-Moriya interaction (DMI).

Keywords: magnetism, spintronics, lateral inhibition, winner-take-all, domain wall racetrack, spin transfer torque, neuromorphic computing,

1. INTRODUCTION

The von Neumann architecture, as today's mainstream computer architecture, features serial execution mode and physically separated computation and memory locations known as the "memory wall"[1] . Although the computation power of the von Neumann machine has increased tremendously over the past decades, the von Neumann memory wall still limits the computational speed and results in high energy consumption, which calls for a shift in computation paradigm. Biology-inspired neuromorphic computing is promising for addressing the discrepancy between the computation power of the human brain and computers in certain cognitive tasks. In neuromorphic computing, the memory wall dissolves as the neuron is both the computation and data storage unit; also, multiple neurons are connected through numerous synapses that store the weights of connections and can be modified according to synaptic learning rules. The high parallelism and the compute-in-memory nature make the neuromorphic system highly suitable for data-intensive artificial intelligence applications[2,3] .

Signal processing of the nervous system requires the selective firings of a group of neurons in order to distinguish between different stimuli. The firing group selection is based on the winner(s)-take-all (WTA) rule(s) that limit the number of firing neuron(s) (winner) in the population. *Hard*-WTA selects only one neuron with the largest total input stimuli as the winner. In the biologically plausible local neural circuitry model[4] , this type of WTA is most frequently employed. Two other types of WTA, namely k-WTA, in which $k > 1$ winners are chosen, and *soft*-WTA, in which the neuron outputs are analog, have been shown to outperform the classical threshold perceptron[5] . It has also been proposed that the E%-max WTA is a more robust description of the group selection mechanism[6] .

WTA is implemented via neuron inhibition (i.e. the winning neurons exert inhibitory forces on other competitors and prevent their firing). Specifically, *lateral* inhibition is the mutual inhibition of the neurons belonging to the same layer, and is crucial to the auditory cortex, somatosensory cortex and vision.[7] In many biologically plausible models, lateral inhibition is mediated by an interneuron, which performs a surround-type inhibition

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upon other neurons once it receives the output from the winner[48] . The WTA-via-lateral inhibition feature has been realized in the CMOS VLSI platform[9,10] and more recently in a hybrid CMOS-memristor crossbar array.[11] However, these implementations require peripheral circuitry and recurrent connections between the neurons, which greatly increase the area and power overhead of the chip, especially for large-scale networks.

A new form of neuron interaction is the key to an efficient and low-power lateral inhibition implementation. Spintronics based on emerging magnetic materials offers a new arena of novel neuromorphic device development. The domain wall - magnetic tunnel junction (DW-MTJ) neuron is an artificial leaky integrate-and-fire spiking neuron based on the three-terminal MTJ (3T-MTJ) device.[12] It consists of a DW racetrack that performs neuronal integration and an MTJ that outputs the spiking signals. The low power consumption of the DW motion device has been demonstrated in both device- and circuit-level simulations[13,14] ; moreover, the leaking and lateral inhibition functionalities are implemented without extra energy cost: leaking is implemented with a shared fixed ferromagnetic layer[15] or racetrack shape gradient;[16] lateral inhibition originates from magnetostatic interaction[15,17] and is intrinsic to the DW-MTJ neuron. We also showed previously[17] that the magnitude of lateral inhibition is maximized by optimizing the magnetostatic interaction strength and the material parameters of a DW-MTJ neuron pair. Here, we first review the mechanisms of DW-MTJ lateral inhibition; we then show that the Dzyaloshinskii-Moriya interaction (DMI) is highly efficient in further enhancing the lateral inhibition.

2. RESULTS

2.1 Maximized lateral inhibition in a pair of DW-MTJ neurons

In the DW-MTJ neuron, the DW position of the DW racetrack encodes the neuron activity and determines the magnetic stray field of the device; thus in a pair of side-by-side DW-MTJ neurons (Fig. 1(a) cartoon), the magnetic environment experienced by a DW is determined by its position relative to its neighbor. In Fig. 1(a), the two DWs (Neurons) are referred to as $\mathrm{DW_I}$ (Neuron I), the DW (Neuron) of Interest, and $\mathrm{DW_N}$ (Neuron N), the Neighbor DW (Neuron), respectively. The two DWs propagate along $+x$ driven by spin-transfer torque (STT). The less active $\mathrm{DW_I}$ lags behind $\mathrm{DW_N}$ and is thus subjected to a stray field along $-z$ originating from the $+z$ domain of Neuron N; reciprocally, $\mathrm{DW_N}$ experiences a stray field along $+z$ originating from the $-z$ domain of Neuron I.

To show the stray field dependence on the DW positions, we calculate the $z-$ component of the stray field B_z[18] experienced by $\mathrm{DW_I}$ (see Table.1 for parameters). In Fig. 1(b)-(e), $\mathrm{DW_N}$ is located at $X_\mathrm{N} = 1\,\mu$m, $2\,\mu$m, $3\,\mu$m and $4\,\mu$m respectively; for each X_N, B_z is plotted against the $\mathrm{DW_I}$ position X_I. It is seen that B_z is of negative sign when $X_\mathrm{I} < X_\mathrm{N}$ and of positive sign when $X_\mathrm{I} > X_\mathrm{N}$, indicating that the inactive DW experiences a stray field along $-z$ while the active DW experiences a stray field along $+z$. We have shown[17] that only the $-z$ stray field plays a role in lateral inhibition. It is also worth noting that except around the DW racetrack ends and the narrow DW regions, B_z is highly uniform along x. This allows us to conveniently model the influence of Neuron N as a uniform external magnetic field B_ext, its direction dependent on the relative activities of the two neurons.

Lateral inhibition of the DW-MTJ neuron is manifested in DW velocity reduction (Δv_DW). The Landau-Lifshitz-Gilbert (LLG) equation dictates that DW velocity is determined by the combined effects of the electrical charge current density and magnetic field. The STT-driven DW velocity (v_DW) can thus be controlled by an external magnetic field (B_ext): in the v_DW vs. B_ext characteristics[17] , a below- Walker breakdown (WB) regime[19] is observed. This regime is bounded by the low WB field (B_WL) and the high WB field (B_WH), and is characterized by a high DW mobility $\mu = \mathrm{d}v_\mathrm{DW}/\mathrm{d}|B_\mathrm{ext}|$. It is in this regime that v_DW exhibits the largest magnetic field tunability: v_DW decreases with increasing $-z$ external field until it reaches the B_WL. Therefore, the maximum lateral inhibition is achieved with a neighbor neuron stray field of B_WL, which is realized by choosing the optimal neuron spacing s_0. s_0 varies with device material and geometry parameters; for the DW-MTJ neuron with fixed parameters, the maximized Δv_DW is:[17]

$$\Delta v_\mathrm{DW} = -2\pi\gamma\delta M_\mathrm{S} K_\perp$$

where γ is the gyromagnetic ratio, δ the DW width, M_S the saturation magnetization and $K_\perp$ the in-plane magnetic anisotropy.

Table 1. Parameters used in micromagnetic simulations

DW racetrack dimensions ($x \times y \times z$)	$5\ \mu\text{m} \times 50\ \text{nm} \times 1.3\ \text{nm}$
simulation cell size	$2\ \text{nm} \times 5\ \text{nm} \times 1.3\ \text{nm}$
DW racetrack spacing s (Fig. 1(b)-(e))	90 nm
exchange stiffness A_{ex}	$13 \times 10^{-12}\ \text{J m}^{-1}$
saturation magnetization M_{z}	1.6 T
perpendicular magnetic anisotropy (PMA) K_{U}	$10^{6}\ \text{J m}^{-3}$
charge current density J_{e} (Fig. 2)	$2.2 \times 10^{12}\ \text{A m}^{-2}$
Gilbert damping α	0.02
non-adiabaticity β	0.04
spin polarization P	0.72
interfacial Dzyaloshinskii-Moriya interaction (DMI) (Fig. 2)	$-0.5\ \text{mJ m}^{-2}$

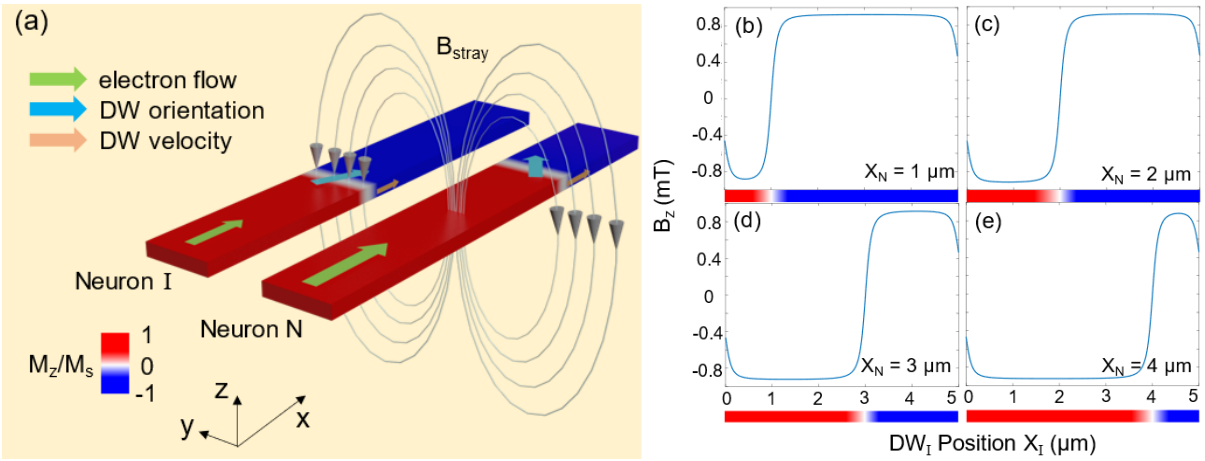

Figure 1. Magnetostatic interactions of a pair of DW-MTJ neurons. (a) Schematics of two side-by-side DW-MTJ neurons, with the coordinate system used throughout the article and magnetic moment defined by legend. Only the DW racetracks are shown. Here Neuron N is more active and impedes the motion of DW_I. (b)-(e) Stray field component B_z experienced by DW_I versus DW_I position X_I, for DW_N located at positions $X_\text{N} = 1\ \mu\text{m}$, $2\ \mu\text{m}$, $3\ \mu\text{m}$ and $4\ \mu\text{m}$.

2.2 Enhanced lateral inhibition with Dzyaloshinskii-Moriya interaction (DMI)

As discussed in 2.1, the maximum lateral inhibition is limited by the WB of the DW. It is therefore possible to further enhance lateral inhibition of the DW-MTJ neuron by suppressing WB. The Dzyaloshinskii-Moriya interaction (DMI) has been experimentally observed to stabilize a chiral Neél-type DW[20] and suppress its WB. Fig. 2 shows the influence of interfacial DMI on the v_{DW} versus B_{ext} characteristics. Here the DW motion of an isolated neuron is simulated using the Mumax^3 micromagnetic simulation package[21] (see Table. 1 for simulation parameters), and the influence of the neighboring neuron is modeled by applying a vertical external field B_{ext}. From here two roles of the DMI can be summarized. First, it increases the WB fields: in the absence of DMI (blue squares), the WB fields are $B_{\text{WL}} = -0.9$ mT and $B_{\text{WH}} = -0.1$ mT; while with DMI (red circles), the WB fields increase to $B_{\text{WL}} = -1.4$ mT and $B_{\text{WH}} = 0.4$ mT. Second, the DMI enhances the field tunability of v_{DW}: in the absence of DMI (blue squares), v_{DW} has the range $[v_{\text{min}}, v_{\text{max}}] = [20\ \text{m s}^{-1}, 120\ \text{m s}^{-1}]$; with DMI, the velocity range is increased to $[-43\ \text{m s}^{-1}, 184\ \text{m s}^{-1}]$. Notably, a negative-sign DW velocity is achieved with DMI, indicating that the lateral inhibition is strong enough not only to delay the neuron firing time but also reverse the direction of DW motion and strictly prohibit the neuron from firing.

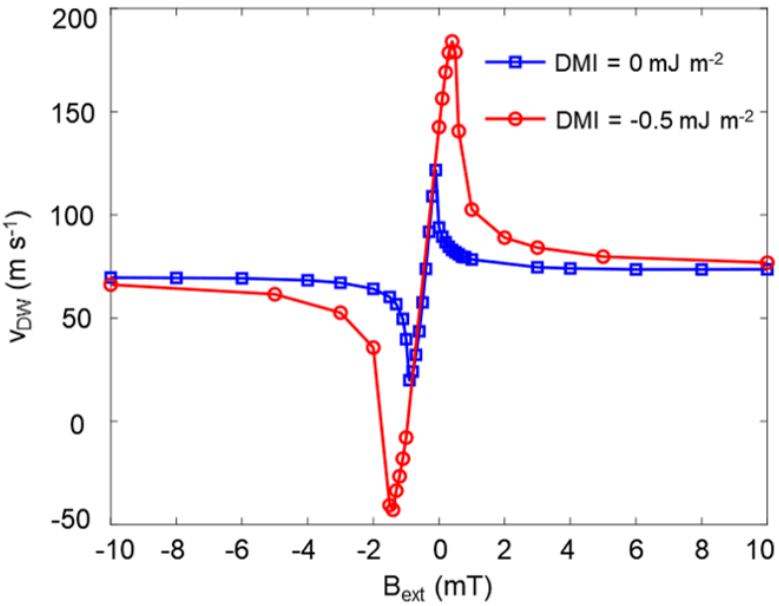

Figure 2. The current-driven DW velocity (v_{DW}) versus external magnetic field (B_{ext}) characteristics of an isolated DW racetrack, with interfacial Dzyaloshinskii-Moriya interaction (DMI) = 0 (blue squares) and DMI = -0.5 mJ m^{-2} (red circles).

3. CONCLUSIONS

This work studies the lateral inhibition characteristics of the domain wall - magnetic tunnel junction (DW-MTJ) neuron. Lateral inhibition of the DW-MTJ neuron is based on the magnetic field tunability of DW velocity. Simulations performed on a pair of DW-MTJ neurons show that the lateral inhibition is maximized for optimal magnetostatic interactions. To overcome the Walker breakdown (WB) limit which is the major bottleneck of the lateral inhibition efficiency, we introduce the Dzyaloshinskii-Moriya interaction (DMI) to the DW-MTJ neuron device and achieve an enhanced field tunability of the DW velocity and lateral inhibition. Such inhibition strength is sufficiently large to reverse DW motion and prevent it from firing altogether. We propose that the large inhibition parameter range is promising for yielding rich neuron firing characteristics in a DW-MTJ neuron array.

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