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Magnetic domain wall neuron with intrinsic leaking and lateral inhibition capability

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ABSTRACT

The challenge of developing an efficient artificial neuron is impeded by the use of external CMOS circuits to perform leaking and lateral inhibition. The proposed leaky integrate-and-fire neuron based on the three terminal magnetic tunnel junction (3T-MTJ) performs integration by pushing its domain wall (DW) with spin-transfer or spin-orbit torque. The leaking capability is achieved by pushing the neurons' DWs in the direction opposite of integration using a stray field from a hard ferromagnet or a non-uniform energy landscape resulting from shape or anisotropy variation. Firing is performed by the MTJ stack. Finally, analog lateral inhibition is achieved by dipolar field repulsive coupling from each neuron. An integrating neuron thus pushes slower neighboring neurons' DWs in the direction opposite of integration. Applying this lateral inhibition to a ten-neuron output layer within a neuromorphic crossbar structure enables the identification of handwritten digits with 94% accuracy.

Keywords: Artificial neuron, leaky integrate-and-fire (LIF) neuron, magnetic domain wall (DW), neural network crossbar, neuromorphic computing, three-terminal magnetic tunnel junction (3T-MTJ)

1. INTRODUCTION

Modern von Neumann computers are able to efficiently solve immensely difficult problems, assuming they are provided with a structured data set. However, if they are provided with a set of unstructured real world data instead, they can be significantly outperformed by the human brain[1-3]. The incredible power of the human brain when dealing with such unstructured problems can be largely attributed to the interactions between neurons and synapses. A neuron is a cell that integrates a series of input current spikes through its axons, and sends output spikes to other neurons through its dendrites. A synapse, on the other hand, electrically connects a dendrite from one neuron to an axon of another neuron.

The primary goal of researchers in the field of neuromorphic computing is to implement these complex neurological systems using electronic components. One of the simplest solutions is to implement such a system using software on a von Neumann computer[4,5]. However, since standard processors are not specifically designed to implement these functions, this method requires considerably more power than the human brain[6]. Neuromorphic systems can also be implemented using specially designed CMOS chips[2,3], but the volatility of CMOS is undesirable, especially due to the memory dependence of a number of neuromorphic functions. To resolve these issues, researchers started developing non-volatile neuromorphic systems using a variety of components, including, but not limited to, memristors[7], magnetic skyrmion devices[8], and three-terminal magnetic-tunnel-junctions (3T-MTJs)[9]. However, most of the resulting circuits were designed to implement synapses. Due to their complexity, fewer neurons have been proposed. These neurons have been demonstrated to successfully implement the required functionalities, but they all require external circuitry to implement several necessary neuronal functions. Limiting, or even completely eliminating, this external circuitry could significantly reduce both the energy consumption and fabrication complexity. To this end, we have developed three separate artificial spintronic neurons using three-terminal magnetic-tunnel-junction (3T-MTJ) neurons that are capable of intrinsically performing the leaking operation[11-13]. In Section 2, we will provide a brief background to neural networking

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and 3T-MTJs. Section 3 will discuss the mechanisms used to implement leaking in each of the three neurons, and conclusions will be provided in Section 4.

2. BACKGROUND

Due to the necessity of neural networks being compatible with standard fabrication processes, researchers developed what is known as the neural network crossbar array, where synapses provide weighted electrical connectivity between two different sets of neurons.

2.1 Neural Network Crossbar Array

An NxM crossbar array contains N input neurons connected to the word lines and M output neurons connected to the bit lines. At each intersection between the word and bit lines exists a single synapse, resulting in the crossbar array containing N*M synapses. These synapses contain an electrical weight between the corresponding input and output neurons.

2.2 Synapse

In biological systems, synapses provide electrical connectivity between the axons of a neuron to the dendrites of other neurons. Synapses in artificial neuromorphic systems perform a similar task – they determine the amount of current to be passed from the input neurons to the output neurons based on their resistance states. These states are determined via trial and error during the training of the network. A number of these synapses have already been proposed, using devices like memristors[14,15] and 3T-MTJ-based devices[9].

2.3 Leaky Integrate-and-Fire Neuron

One of the earliest suggested neurons was the Integrate-and-Fire (IF) neuron[11], which displays two primary functionalities. The device should integrate a series of input current pulses, but once the energy stored in the device reaches a certain point, the device should release this energy in a single output spike. However, improvements to this neuron resulted in the addition of a third functionality – leaking. If such a neuron, known as a Leaky Integrate-and-Fire (LIF) neuron, does not receive any current input, the stored energy will gradually decrease. In general, LIF neurons better represent biological neurons than IF neurons.

2.4 Three Terminal Magnetic Tunnel Junction

When two magnetic domains are separated by a thin insulating tunnel barrier, an effect known as tunneling magnetoresistance (TMR) occurs. If the two domains have a parallel magnetization, the resulting device, known as a magnetic tunnel junction (MTJ) will have an effective low resistance state (LRS). If, however, the two domains have an antiparallel magnetization, the device will have an effective high resistance state (HRS). In order for this to be useful, though, at least one of the magnetic domains needs to exhibit a changeable magnetization state. Generally, only one of these layers, called the 'free' layer, is changeable, while the other one, called the 'pinned' or layer, is fixed to a certain state.

The three-terminal magnetic tunnel junction (3T-MTJ) is a novel idea that is similar to the original MTJ; however, the free layer is stretched along one axis, and contains two antiparallel magnetic domains bordered by a domain wall (DW) instead of just one. The free layer in a 3T-MTJ is known as the DW track. When a current is passed through the DW track, the DW will shift in the opposite direction of the current[16,17]. Therefore, a 3T-MTJ can be used to implement logic[17,18]; whenever the DW moves from one side of the fixed layer to the other, the state will change from HRS to LRS or vice versa. Additionally, since the DW will not shift without external excitation, the device is completely non-volatile.

3. INTRINSICALLY LEAKING 3T-MTJ DEVICES

Although 3T-MTJs are intrinsically capable of integrating current spikes through DW motion, their non-volatility does not allow for intrinsic leaking capabilities. To resolve this issue, researchers in the field of neuromorphic computing proposed the use of a constant current. However, this requires external circuitry to implement, which increases the energy consumption and fabrication complexity. To this end, we have proposed three separate neuron structures that are capable of leaking without any external circuitry.

3.1 Leaking with External Magnetic Field

Whenever a magnetic field is applied in the same direction as the magnetization direction of a magnetic domain, the magnetic domain will tend to expand. Conversely, when a magnetic field is applied in the opposite direction as the magnetization direction of a magnetic domain, the magnetic domain will tend to shrink. Therefore, when a magnetic field is applied along the same axis as the magnetization states of the two domains in a DW track, the DW will shift from one end of the device to the other. This phenomenon can be used to implement intrinsic leaking without any external circuitry by placing an electrically isolated fixed ferromagnet underneath the DW track, as shown in Figure 1.[11]

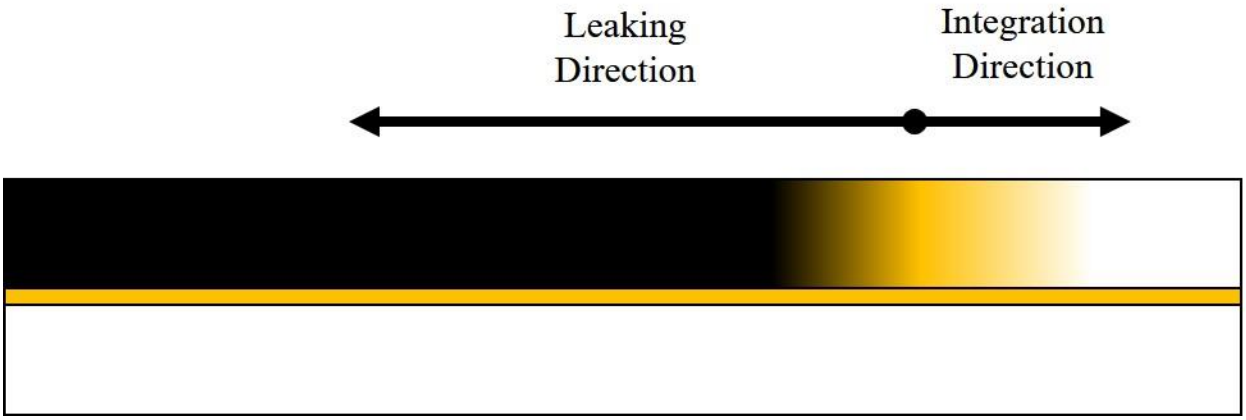

Figure 1. Side view of a DW track with a fixed ferromagnet underneath. Unless the device is integrating, the DW will shift from right to left. Black regions indicate magnetization in the –z direction, and white regions indicate magnetization in the +z direction.

3.2 Leaking with Graded Anisotropy

Alternatively, by introducing a magnetocrystalline anisotropy gradient into a DW track, it is possible to implement an intrinsic leaking functionality without the use of any external excitation. Whenever a DW exists in such a track, it will tend to shift from regions of higher anisotropy to regions of lower anisotropy. Such a DW track can be fabricated by either Ga^+ ion irradiation of the DW track or a TaO_x wedge placed on top of the DW track. Aside from these slight modifications, the device structure is identical to that of a standard 3T-MTJ device. Figure 2 demonstrates this anisotropy gradient.[12]

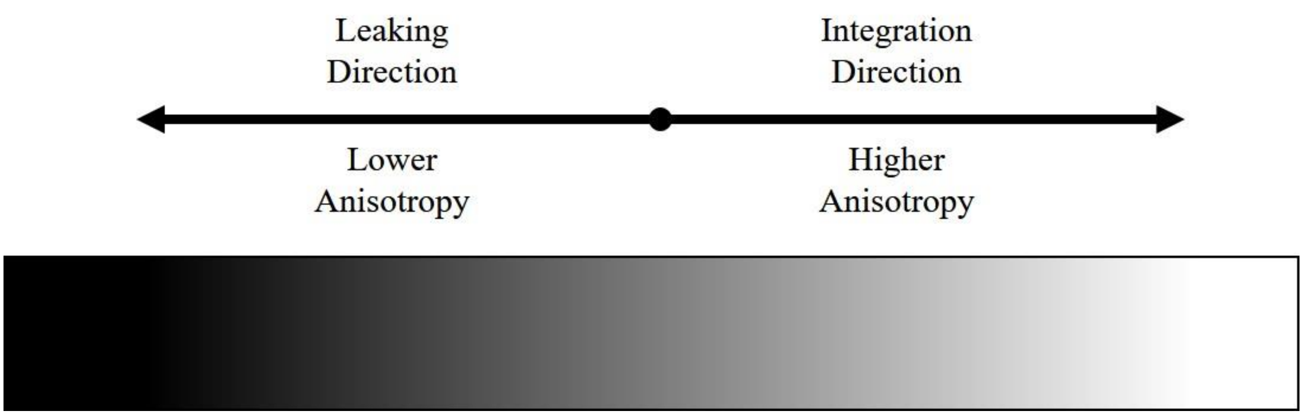

Figure 2. Top view of a DW track showing the anisotropy gradient instead of the magnetization. Lighter regions correspond to regions with higher anisotropy, while darker regions correspond to regions with lower anisotropy.

3.3 Leaking with Shape-Based Domain Wall Drift (SDD)

Typically, a DW exists in a lower energy state when it is in a narrower track than when it is in a wider state. Therefore, altering the width of the DW track creates an energy landscape that is more favorable to the DW existing on one side of the device (the narrow end) than on the other (the wide end). This effect, known as Shape-Based Domain Wall Drift (SDD), can be used to implement an artificial neuron without any external excitation or additional processes. Figure 3 demonstrates the structure of this device.[13]

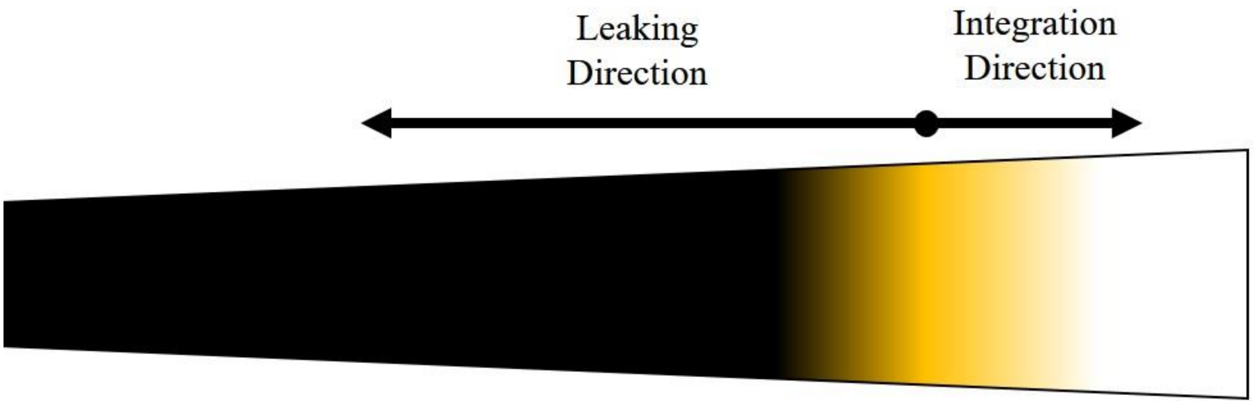

Figure 3. Top view of a trapezoidal DW track. Due to the shape, the DW will shift from right to left during leaking, and from left to right during integration.

4. CONCLUSION

This work discusses the leaking mechanisms utilized by three previously proposed LIF neurons, including the application of an external magnetic field, an anisotropy gradient, or a shape variation. These mechanisms allow for reduced circuit complexity, energy consumption, and fabrication complexity. Because of this, these devices could be important for future work on neuromorphic computing.

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