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Fabrication of Domain Wall based Magnetic Tunnel Junction Devices with Intrinsic Neuromorphic Functionality

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We summarize our progress towards monolithic and analog neuromorphic computing utilizing domain wall-magnetic tunnel junction (DW-MTJ) devices. We have previously shown device performance for binary logic DW-MTJ devices. Here, we expand on that work by demonstrating neuromorphic functionality using shape-dependent tunability. We measure multi-weight synapses and stochastic neurons monolithically fabricated from the same material stack, enabling future integrated neuromorphic circuits. Future work includes fabrication of leaky integrate and fire (LIF) neurons to complete the library of neuromorphic functionality for a full DW-MTJ crossbar array capable of neuromorphic computing.

***Index Terms*— Beyond CMOS, Magnetic domain walls, Neuromorphic computing, Spintronics**

I. Introduction

Domain wall-magnetic tunnel junction (DW-MTJ) devices have been shown to emulate advanced neuromorphic behavior in a single device using simple shape-dependent designs. This three-terminal device shown in Fig. 1a has an extended free layer, referred to as the DW track, which is designed to contain a DW that separates two magnetization states within the free layer. By manipulating the location of the DW, the resistance through the junction can be switched, since the fixed layer stays in a constant magnetization state due to the synthetic antiferromagnet pinning [1]. The DW track and the pinned layer can be geometrically altered to achieve tunable neuromorphic behavior. For example, fabricating notches within the DW track can allow the DW to be pinned in the local potential energy minima. If the pinned layer is extended and notches are fabricated in the track beneath it, multi-weight (MW) switching can be achieved since the DW can be pinned in a nonbinary state between ON and OFF [2]. If the DW track is fabricated in a trapezoidal shape as in Fig. 1b, there is a weight-dependent depinning voltage since the energy required to move the DW will increase as it moves to wider regions. This DW movement can emulate integration. This shows that various neuromorphic functions can be emulated through simple geometric modifications to the DW-MTJ device. Considering this and the fact that each device has the potential to emulate artificial neurons and synapses on a one-to-one basis, spintronic devices offer a compact and energy-efficient alternative to CMOS-based neural networks.

II. Fabrication of DW-MTJ Devices

All neurons and synapses in this work are fabricated on the same thin-film metal stack, grown by Applied Materials: Si(substrate)/ SiO_2(100)/ Ta(10)/ CoFeB(1.2)/ MgO(1)/ CoFeB(1.9)/ [Co/Pt](5)/ Ru(0.9)/ [Co/Pt](6.9)/ Ta(1)/ Ru(3); numbers are in nm and brackets represent multilayers. The devices were fabricated using electron beam lithography and ion beam etching. The non-reactive ion milling is done with low power to preserve the sensitive DW track layer during etching.

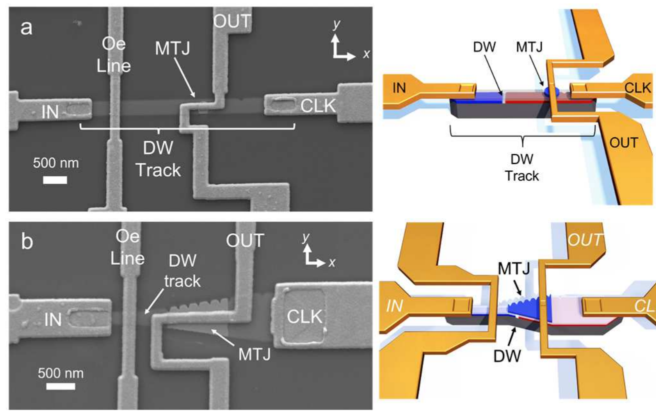

Fig. 1. DW-MTJ devices: a) stochastic neuron Reproduced with permission [262406] copyright 2023 AIP Publishing [3] and b) MW synapse reproduced with permission [202200563] copyright 2022, Wiley-VCH [2].

III. Neuromorphic Functionality

These two devices in Fig. 1 illustrate the tunability of DW-MTJ devices. The IN, OUT, CLK, and Oe Line contacts are identical between the two designs. However, the artificial synapse has a trapezoidal DW track and an extended MTJ with additional pinning notches for MW switching. This is contrasted with the artificial neuron that has a small MTJ at one end of the track and only 2 notches, one directly under the Oe Line and one past the MTJ [3].

A. *Artificial Neuron*

The device in Fig. 1a is operated in three steps. First, the device is saturated in a strong out-of-plane external magnetic field (-200 Oe) to orient the free and pinned layers to be parallel. The field loop is shown in Fig 2a. Second, the magnetic field is reversed to 350 Oe to lower the energy requirements to switch the device using voltage pulses. Finally, constant amplitude voltage pulses are sent from CLK to IN to nucleate and move the DW from left to right shown in Fig 2b for 15 cycles at 1.75 V. The device switches stochastically because the DW is nucleated in a random position each cycle. Each cycle, the number of pulses required to switch the device is tabulated in Fig. 2c, which is used to generate the probability of switching per pulse. This is repeated for 11 different voltage amplitudes and plotted in Fig. 2d. A sigmoid is fit to the data and will be used in the simulation.

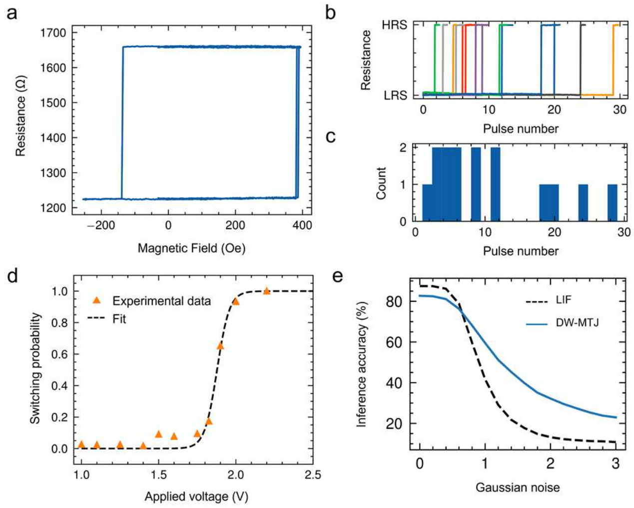

Fig. 2. Stochastic neuron (a-d) experimental and (e) neural network results. Reproduced with permission [262406] copyright 2023, AIP Publishing [3].

This inherent stochasticity has an impact on the performance of the network, shown in Fig. 2e, especially for noisy data. The leaky integrate and fire (LIF) neuron is an idealized benchmark which outperforms the experimental device on ideal data. However, the DW-MTJ neuron outperforms the idealized LIF benchmark if the inference images are noisy, which points to application in edge computing. This occurs since the DW-MTJ device is stochastic and fires probabilistically. If the inference image is noisy it will affect this probability, but not ensure an error. However, the deterministic idealized benchmark will give increasingly erroneous classifications as the images blur.

B. *Artificial Synapse*

Testing the synapse device in Fig. 1b follows the same operation as the neuron, except the voltage pulses are ramped in amplitude from 1 to 4 V each cycle. During the writing an additional resistance state is reached shown in Fig 3a. This MW switching is desirable for synapses. The trapezoidal device also has intrinsic metaplasticity due to its shape. Each switch has low variation since the shape anisotropy gradient within the track requires higher depinning voltages as the DW moves to wider regions. This metaplastic behavior improves stream learning, where information is revealed in subsets during training. Linear synapses struggle with this application due to overfitting information as it is presented and forgetting past information as a result [4].

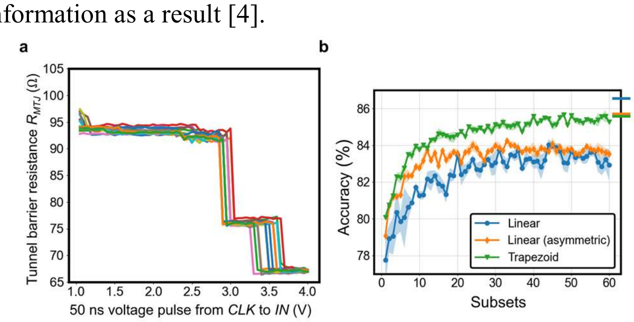

Fig. 3. Metaplastic synapse experimental (a) and neural network (b) results. Reproduced with permission [202200563] copyright 2022, Wiley-VCH [2].

We show the metaplastic synapse outperforms idealized linear synapses at stream learning on the Fashion-MNIST dataset. The horizontal ticks on the y-axis in Fig 3b indicate the performance of each network when trained on the entire dataset at once. The trapezoidal synapse shows no degradation due to stream learning, but the performance of the linear synapses degrades drastically, suggesting they are subject to catastrophic forgetting in the stream learning case. These results indicate that the trapezoidal device has application in online learning and that DW track shape can be manipulated to increase performance without increasing the number of states. A linear DW-MTJ synapse was also fabricated, which was able to achieve 5 highly stable resistance states stochastically [3].

IV. Conclusion and Outlook

In conclusion, DW-MTJ devices can emulate neuromorphic behavior in a single device, such as multi-weight synapses and stochastic neurons. This behavior is tunable via geometry, opening the possibility for fully monolithic neural networks with DW-MTJ neurons and synapses. Future work will seek to emulate leaky, integrate and fire neurons experimentally and increase the number of weights of synapses.

Future work will include prototyping a LIF neuron. A working LIF neuron would complete the preliminary ensemble of neuromorphic devices on a monolithic platform for a fully spintronic crossbar array. A trapezoidal DW track can allow for both integration through DW motion during input pulses and leaking as the DW will spontaneously drift towards the narrow end of the track in the absence of input [5]. This would drastically reduce the required number of devices and allow for fully analog signal propagation through the array while computing matrix multiplications intrinsically through Ohm's law. This breakthrough in neuromorphic computing could significantly reduce the energy and time constraints of conventional simulated neural networks on CMOS hardware for edge computing.

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