Session CC
NOVEL APPLICATIONS OF MRAM: NEUROMORPHIC COMPUTING AND CRYOGENIC MEMORY

Graham Rowlands, Chair
Raytheon BBN Technologies, Cambridge, MA, United States

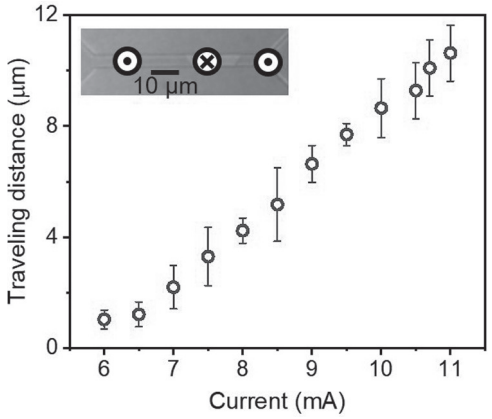
CONTRIBUTED PAPERS

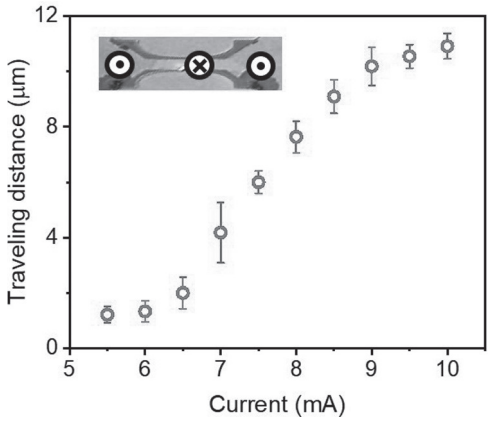
8:30

CC-01. Magnetic Domain Wall based Synaptic and Activation Function Generators for Neuromorphic Accelerators. *S.A. Siddiqui*[1], S. Dutta[1], L. Liu[1], C. Ross[1] and M. Baldo[1] *1. Massachusetts Institute of Technology, Cambridge, MA, United States*

Magnetic domain wall devices are promising candidates for logic [1] and storage class memory [2]. Due to the non-volatility and energy-efficient switching, this type of device is one of the prime candidates for in-memory computing and brain-inspired computing. In-memory computing is a non-von-Neumann architecture where data computation and storage are done locally to reduce the data movement between the processor and the storage memory [3]. The layer-by-layer operations of data require synapses (*i.e.* variable resistors whose resistance vary linearly with the input) and activation function generators between layers (*i.e.* variable resistors whose resistance vary non-linearly with the input current). Domain walls in a magnetic wire exhibit linear motion as a function of applied current due to spin-orbit torque from an adjacent heavy metal (Fig. 1). The current density and spin orbit torque can be modified along the wire by adjusting the width of the heavy metal. The spin orbit torque then becomes a function of the domain wall position, which makes the domain wall motion a nonlinear function of the applied current (Fig. 2). Linear and nonlinear domain wall motion can be detected via magnetoresistance by using a magnetic tunnel junction in which the magnetic wire forms the free layer. The electrical detection is necessary for the analog matrix multiplication in neuromorphic accelerator. However, domain walls are pinned due to the magnetostatic energy minima on the sides of the MTJ. The synaptic and activation function like magnetoresistive behavior can still be generated by using multiple MTJs in parallel. In this work, we demonstrate linear and nonlinear domain wall motion in magnetic wires and modify the design of magnetic tunnel junctions to convert these motions into magnetoresistance. The experimental observations of the device characteristics agree with both analytical and micromagnetic modeling.

[1] J. A. Currivan-Incorvia, S. Siddiqui, S. Dutta, E. R. Evarts, J. Zhang, D. Bono, C. A. Ross, and M. A. Baldo, Nat Commun., 7, 10275 (2016). [2] Stuart S. P. Parkin, Masamitsu Hayashi, and Luc Thomas, Science, Vol. 320, Issue 5873, pp. 190-194 (2008) [3] Jacob Torrejon, Mathieu Riou, Flavio Abreu Araujo, Sumito Tsunegi, Guru Khalsa, Damien Querlioz, Paolo Bortolotti, Vincent Cros, Kay Yakushiji, Akio Fukushima, Hitoshi Kubota, Shinji Yuasa, Mark D. Stiles & Julie Grollier, Nature volume 547, pp. 428–431 (2017).





8:42

CC-02. Neuromorphic Computing with Domain Wall-Based Three-Terminal Magnetic Tunnel Junctions: Synapse. *O.G. Akinola*[1], E. Kim[1], N. Hassan[2], J.S. Friedman[2] and J.C. Incorvia[1] *1. Electrical and Computer Engineering, University of Texas at Austin, Austin, TX, United States; 2. Electrical and Computer Engineering, University of Texas at Dallas, Dallas, TX, United States*

The core building blocks of bioinspired computing are the synapse and neuron. While they have been recently explored using magnetic devices[1,2], we need synapses that have *reliable* weight control and the ability to build *both* synapses and neurons using similar materials. Here, we show through modeling[3] that domain wall (DW)-based three-terminal magnetic tunnel junctions (3T-MTJs)[4] with pinning sites act as a controllable synapse. We find these devices can also act as a leaky integrate-and-fire neuron[5], and thus are a platform for neuromorphic circuits. While 3T-MTJs have been previously modeled as synapses[6], weight control has not been developed and is the focus of this work. The 3T-MTJ synapse has a Ta/CoFeB ferromagnetic

(FM) wire with a *long* MTJ in the center. Spin transfer/orbit torque is used to switch a DW in the FM. By controlling the DW position, we control the MTJ ratio that is parallel and use the conductance levels as gray-scale weights. We model the FM wire as 500 nm x 64 nm x 4 nm, with notches every 64 nm. We find there is a trade-off between notch depth and DW width to determine the depinning current. Using the largest notch at left of 16 nm deep and decreasing notch size by 1.6 nm per notch, we apply 10 ns current pulses to translate the DW. Starting with the DW in the lowest-energy state sitting at the largest notch, we find reliable depinning currents to move the DW to specific pinning sites (Fig. 1, top-down view). Using numbers from our MTJ measurements of TMR = 166% and RA product = 20 Ω-μm^2, we obtain analog MTJ resistance vs. applied current (Fig. 2). Each resistance is a weight controlled by an input current. We see at least 50 Ω between each weight, large enough to distinguish between weights. We will show results on integrating 3T-MTJ synapses and neurons, where firing of the neuron sets the synapse at a given weight. We believe this is an important step forward in building full neuromorphic computers using magnetic materials. While notches are not favorable for scaling, the functionality shown can implemented in other ways, e.g. through voltage-controlled DW traps[7].

[1] S. Lequeux, J. Sampaio, V. Cros, et al. Sci Rep 6, 31510 (2016). [2] J. Torrejon, M. Riou, F. A. Araujo, et al. Nature 547, 428-431 (2017). [3] A. Vansteenkiste, J. Leliaert, M. Dvornik, et al. AIP Adv. 4, 107133 (2014). [4] J. A. Currivan-Incorvia, S. Siddiqui, S. Dutta, et al. Nat. Commun. 7, 10275 (2016). [5] N. Hassan, X. Hu, L. Jiang-wei, et al. Submitted. [6] Q. Dong, K. Yang, L. Fick, et al. IEEE Int. Symp. on Circuits and Systems, 1–4 (2017). [7] U. Bauer, S. Emori, & G. S. D. Beach. Nat. Nanotechnol. 8, 411–416 (2013).

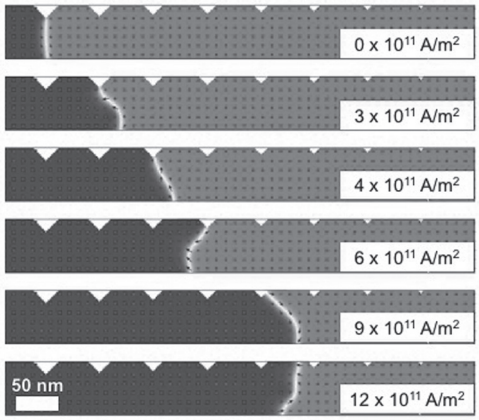
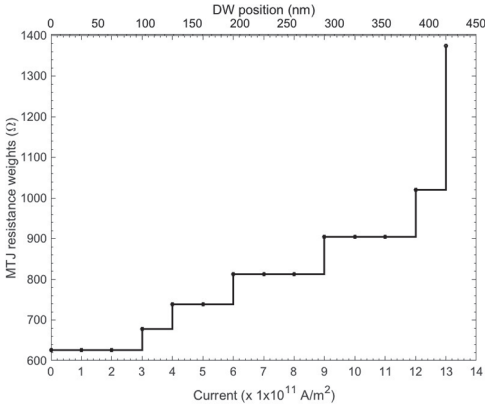


Fig. 1. Micromagnetic images showing domain wall position vs. current.



Analog synapse weights vs. current.

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CC-03. Neuromorphic Computing with Domain Wall-Based Three-Terminal Magnetic Tunnel Junctions: Neurons. *N. Hassan*[1], X. Hu[1], L. Jiang-Wei[2], W.H. Brigner[1], O.G. Akinola[3], F. Garcia-Sanchez[4], M. Pasquale[4], C.H. Bennett[5], J.C. Incorvia[3] and J.S. Friedman[1] *1. Electrical & Computer Engineering, The University of Texas at Dallas, Richardson, TX, United States; 2. Computer Science, The University of Texas at Dallas, Richardson, TX, United States; 3. Electrical & Computer Engineering, The University of Texas at Austin, Austin, TX, United States; 4. Istituto Nazionale di Ricerca Metrologica, Torino, Italy; 5. Centre de Nanosciences et de Nanotechnologies, Université Paris-Saclay, Orsay, France*

The core building blocks of neuromorphic computing systems are neurons and synapses, and it is critical that these bio-inspired device components can be fabricated with compatible material structures. As domain wall (DW)-based three-terminal magnetic tunnel junctions (3T-MTJs) [1] also realize synapse behavior [2], this work proposes a 3T-MTJ artificial neuron [3] that enables the development of an integrated neuromorphic computing system composed solely of 3T-MTJ devices. The proposed spintronic leaky integrate-and-fire (LIF) [4] neuron manipulates the DW position to perform the leaking, integration, and firing functions, while also providing lateral inhibition. Lateral inhibition [5] is critical to the capability of biological systems to prevent neighboring neurons from firing simultaneously, but previous artificial neuron proposals based on emerging technologies require the assistance of external CMOS circuits to provide this lateral inhibition capability [6]–[8]. By exploiting the stray magnetic fields, the proposed 3T-MTJ neuron [3] eliminates the need for CMOS circuitry and intrinsically provides the leaking, integrating, firing, and lateral inhibition capabilities. Input currents applied to the neurons enable integration behavior by pushing the DWs through spin-transfer or spin-orbit torque. The leaking is performed by a hard ferromagnet under the 3T-MTJ neuron tracks that creates a magnetic field to constantly push the neuron DWs opposite the direction of integration. Firing occurs when the DW crosses below the MTJ hard layer, switching the MTJ from the anti-parallel to the parallel state and enabling a large output current. Finally, analog lateral inhibition is achieved by dipolar fields from each neuron that attempt to orient neighboring neurons antiparallel by repulsive coupling. 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 a 94% success rate [3].

[1] J.A. Currivan-Incorvia, S. Siddiqui, S. Dutta, *et al.*, *Nat. Commun.*, Vol. 7, p. 10275 (2016). [2] O. G. Akinola, E. J. Kim, N. Hassan, *et al.*, submitted to *2019 Joint MMM-INTERMAG*. [3] N. Hassan, X. Hu, L. Jiang-Wei, *et al.*, *J. Appl. Phys.* (under review). [4] A. N. Burkitt, *Biol. Cybern.*, Vol. 95, pp. 97–112 (2006). [5] E. Meir, G. Von Dassow, E. Munro, G. M. Odell, *Curr. Biol.*, Vol. 12, pp. 778–786 (2002). [6] A. Jaiswal, S. Roy, G. Srinivasan, K. Roy, *IEEE Trans. Electron Devices*, Vol. 64, pp. 1818–1824 (2017). [7] A. Jaiswal, A. Agrawal, P. Panda, K. Roy, *arXiv*:1705.06942 (2017). [8] A. Sengupta, P. Panda, P. Wijesinghe, *et al.*, *Sci. Rep.*, Vol 6, p. 30039 (2016).

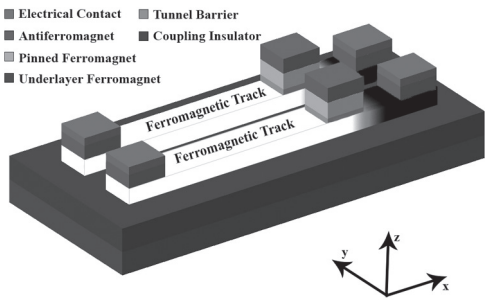

Fig. 1. 3T-MTJ neuron structure with two neurons above a shared ferromagnet.