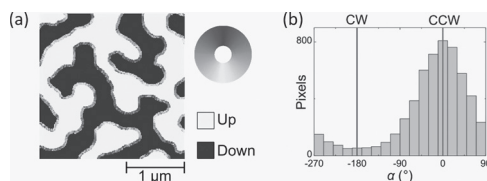


2:54

**HG-06. Tuning magnetic chirality by dipolar interactions.** *J. Lucassen<sup>1</sup>, M.J. Meijer<sup>1</sup>, F. Kloodt-Twesten<sup>2</sup>, R. Frömter<sup>2</sup>, O. Kurnosikov<sup>1</sup>, R. Duine<sup>1,3</sup>, H. Swagten<sup>1</sup>, B. Koopmans<sup>1</sup> and R. Lavrijsen<sup>1</sup>* *1. Applied Physics, Eindhoven University of Technology, Eindhoven, Netherlands; 2. Center of Hybrid Nanostructures, Universität Hamburg, Hamburg, Germany; 3. Institute for Theoretical Physics, Utrecht University, Utrecht, Netherlands*

Chiral magnetism has gained enormous interest in recent years because of the anticipated wealth of applications in nanoelectronics. The demonstrated stabilization of chiral magnetic domain walls and skyrmions has been attributed to the actively investigated interfacial Dzyaloshinskii-Moriya interaction (iDMI). Recently, however, predictions were made that suggest dipolar interactions can also stabilize chiral domain walls and skyrmions, but direct experimental evidence has been lacking. Because the net chirality determines, for example, the interaction of magnetic textures with spin-orbit torques, it is vital that we understand the interplay between the iDMI and dipolar fields. [1] Here, we show that dipolar interactions can indeed stabilize chiral domain walls by directly imaging magnetic domain walls in archetype Pt/CoB/Ir multilayer stacks using scanning electron microscopy with polarization analysis (SEMPA) as shown in fig. 1. [2] The strength of the iDMI and dipolar interactions are systematically tuned by varying the thickness of magnetic Co layer. We find that the competition between the iDMI and dipolar interactions can reverse the domain-wall chirality and verify our interpretation with an analytical model and micromagnetic simulations. Finally, we suggest that this competition can be tailored by an interlayer Ruderman-Kittel-Kasuya-Yosida interaction and provide the first experimental data in this direction. This experimental and modeling work unambiguously confirms that dipolar interactions play a key role in the stabilization of chiral spin textures. This insight will open up new routes towards balancing interactions for the stabilization of chiral magnets.

[1] Legrand, W., Chauleau, J. Y., Maccariello, D., et al. Science advances, 4(7) (2018) [2] Lucassen, J., Meijer M.J., Kloodt-Twesten F., et al. arXiv:1904.01898 (2019)



**Fig. 1** (a) SEMPA image of the multidomain state in [Pt/CoB(0.7nm)/Ir]<sub>66</sub> Pt/CoB(1.0nm). The out-of-plane domains are indicated in black and white. The in-plane magnetization in the domain wall is indicated by the colorwheel. The magnetization in the domain wall systematically points from a down domain towards an up domain revealing the presence of counterclockwise Néel walls. (b) Histogram of the domain-wall angle  $\alpha$  for all pixels in the domain walls where  $\alpha = 0, 180^\circ$  indicates a counterclockwise (CCW) and clockwise (CW) Néel wall respectively.

## INVITED PAPER

3:06

**HG-07. Magnetic domain wall devices for artificial neural network.**

*S. Siddiqui<sup>1</sup>, S. Dutta<sup>1</sup>, A. Tang<sup>1</sup>, L. Liu<sup>1</sup>, C. Ross<sup>1</sup> and M. Baldo<sup>1</sup>*  
*1. Massachusetts Institute of Technology, Cambridge, MA, United States;*  
*2. Argonne National Laboratory, Lemont, IL, United States*

Spintronics promises intriguing device paradigms where electron spin is used as the information token instead of its charge counterpart. In the future cognitive era, nonvolatile magnetic memories hold the key to solve the

bottleneck in the computational performance due to data shuttling between the processing and the memory units. The application of spintronic devices for these purposes requires versatile, scalable device design that is adaptable to emerging material physics. We design, model and experimentally demonstrate spin orbit torque induced magnetic domain wall devices as the building blocks (i.e. linear synaptic weight generator and the nonlinear activation function generator) for in-memory computing, in particular for artificial neural networks. Spin orbit torque driven magnetic tunnel junctions show great promise as energy efficient emerging nonvolatile logic and memory devices. In addition to its energy efficiency, we take advantage of the spin orbit torque induced domain wall motion in magnetic nanowires to demonstrate the linear change in resistance of the synaptic devices. Modifying the spin-orbit torque from a heavy metal or utilizing the size dependent magnetoresistance of tunnel junctions, we also demonstrate a nonlinear activation function for thresholding signals (analog or digitized) between layers for deep learning. The analog modulation of resistances in these devices requires characterizing the resolution of the resistance. Since domain wall in magnetic wires is the nonvolatile data token for these devices, we study the spatial resolution of discrete magnetic domain wall positions in nanowires. A complete neuromorphic hardware accelerator using embedded nonvolatile magnetic domain wall devices can also revolutionize computer architectures by embedding memory into logic circuits in a fine grained fashion.

## CONTRIBUTED PAPERS

3:42

**HG-08. Magnetic Domain Wall Neurons with Intrinsic Leaking.**

*W.H. Brigner<sup>1</sup>, N. Hassan<sup>1</sup>, X. Hu<sup>1</sup>, L. Jiang-Wei<sup>1</sup>, D. Saha<sup>1</sup>, C.H. Bennett<sup>2</sup>, M.J. Marinella<sup>2</sup>, F. Garcia-Sanchez<sup>4,5</sup>, J.C. Incurvia<sup>3</sup> and J.S. Friedman<sup>1</sup>*  
*1. Electrical and Computer Engineering, University of Texas at Dallas, Richardson, TX, United States; 2. Sandia National Laboratories, Albuquerque, NM, United States; 3. Electrical and Computer Engineering, University of Texas at Austin, Austin, TX, United States; 4. Istituto Nazionale di Ricerca Metrologica, Turin, Italy; 5. Department of Applied Physics, University of Salamanca, Salamanca, Spain*

The challenge of developing an efficient artificial neuron for machine learning is impeded by the use of external CMOS circuits to perform both leaking and lateral inhibition. To resolve this issue, we previously proposed a spintronic leaky integrate-and-fire (LIF) neuron with no external circuitry. This was achieved with a three-terminal magnetic tunnel junction (3T-MTJ) device with an externally applied magnetic field that provides a constant leaking force. We also demonstrated that the neurons recognize handwritten digits with an accuracy of 94% when used as the output layer of a neural network [1],[2]. Here, we propose the two alternate LIF neurons shown in Fig. 1, where the leaking capability is implemented by shifting the neurons' DWs in the direction opposite of integration using a non-uniform energy landscape resulting from either shape or magnetic anisotropy variation. First, for anisotropy-gradient-induced leaking, the DW shifts in a standard rectangular DW track, from regions of higher anisotropy to regions of lower anisotropy [3]. Second, for shape-based leaking, we developed a trapezoidal DW track that induces an energy landscape more favorable to the DW existing in the narrower region of the track than the wider region, causing the DW to shift from the wide region to the narrow region in the absence of external stimuli [4]. Fig. 2 demonstrates the combined integrating and leaking functionalities of an LIF neuron using shape-based DW drift. By combining our proposed neurons with 3T-MTJ synapses [5], we aim to develop a monolithic neural network system using only 3T-MTJ devices.

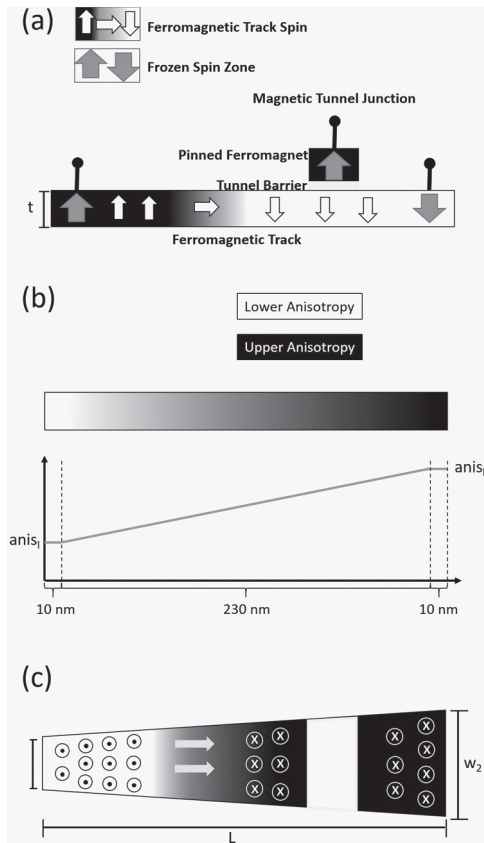


Figure 1. (a) Side view of a 3T-MTJ LIF neuron. (b) Side view of a 3T-MTJ neuron implemented using a magneto-crystalline anisotropy gradient. The DW shifts from right to left in the absence of external stimuli. (c) Top view of a 3T-MTJ neuron implemented using shape variations of the DW track. Again, the DW shifts from right to left in the absence of external stimuli.

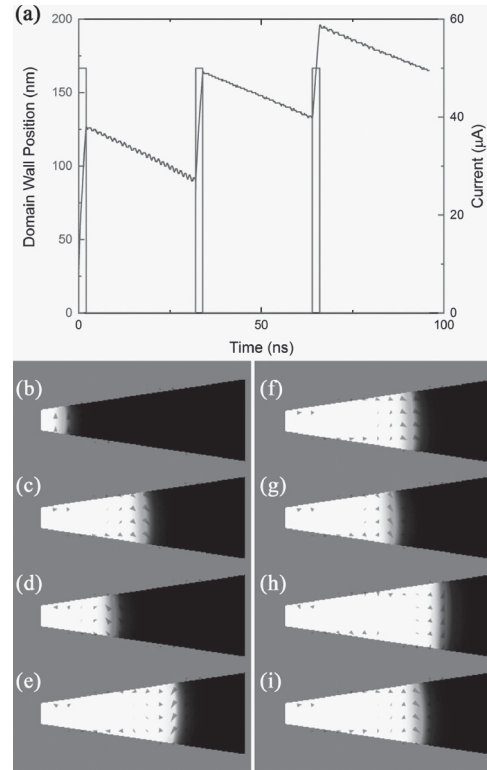


Figure 2. (a) DW position and current versus time. Snapshots during micromagnetic simulations shown for (b)  $t = 0$  ns, (c)  $t = 17$  ns, (d)  $t = 17$  ns, (e)  $t = 32$  ns, (f)  $t = 34$  ns, (g)  $t = 64$  ns, (h)  $t = 66$  ns, (i)  $t = 96$  ns.

3:54

**HG-09. Fast Domain Walls Governed by CErsted Fields in Cylindrical Magnetic Nanowires.** *M. Schöbitz*<sup>1,2</sup>, *A. De Riz*<sup>1</sup>, *S. Martin*<sup>1,3</sup>, *S. Bochmann*<sup>2</sup>, *C. Thirion*<sup>3</sup>, *J. Vogel*<sup>3</sup>, *M. Foerster*<sup>4</sup>, *L. Aballe*<sup>4</sup>, *A. Locatelli*<sup>5</sup>, *T. Mentès*<sup>5</sup>, *F. Genzio*<sup>5</sup>, *L. Cagnon*<sup>3</sup>, *S. Le-Denmat*<sup>3</sup>, *J. Toussaint*<sup>3</sup>, *D. Gusakova*<sup>1</sup>, *J. Bachmann*<sup>2,6</sup> and *O. Fruchart*<sup>1</sup> *1. Univ. Grenoble Alpes / CNRS / CEA, SPINTEC, Grenoble, France; 2. Friedrich-Alexander Univ. Erlangen-Nürnberg, CTFM, Erlangen, Germany; 3. Univ. Grenoble Alpes / CNRS, Institut Néel, Grenoble, France; 4. CELLS, Alba Synchrotron Light Facility, Barcelona, Spain; 5. Elettra-Sincrotrone Trieste, S.C.p.A., Trieste, Italy; 6. Institute of Chemistry, Saint-Petersburg State Univ., Saint-Petersburg, Russian Federation*

Current-induced magnetic domain wall (DW) motion has attracted immense interest, not only in the context of shift registers for futuristic non-volatile 3D data storage concepts, but also from a fundamental point of view. Experimental efforts focused on flat nanostrips which, however, suffer from intrinsic DW instabilities, greatly limiting DW speed and their reliable use in potential applications. In contrast, simulations and theory state that cylindrical nanowires (NWs) should not experience the same fundamental issue and simultaneously give rise to fascinating new physics [1,2]. Key to these predictions is the novel Bloch-point wall (BPW), which is unique to NWs [3]. It has a distinct topology and exhibits azimuthal curling of magnetic moments around a Bloch-point [4], a local vanishing of magnetisation, at the DW core. This feature and its rotational symmetry are at the origin of the steady state dynamics of this DW type, allowing theoretical speeds of over 1000 m/s and the controlled emission of spin waves (spin-Cherenkov effect) [5]. So far, experiments for DW dynamics in NWs are missing. Here we report unprecedented experimental results on current-induced DW motion in NWs [6]. We use magnetic force microscopy and shadow X-Ray Magnetic Circular Dichroism coupled to PhotoEmission Electron Microscopy (XMCD PEEM) to image DWs in 90 nm diameter  $\text{Co}_{30}\text{Ni}_{70}$  NWs before and after the