Spin-orbit torque induced switching using antiferromagnets and its application to artificial neural networks

S. Fukami[1-4], A. Kurenkov[1], W. A. Borders[1], C. Zhang[1,2], S. DuttaGupta[1,3], and H. Ohno[1-5]
[1] Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku University, Sendai 980-8577 Japan
[2] Center for Spintronics Integrated Systems, Tohoku University, Sendai 980-8577 Japan
[3] Center for Spintronics Research Network, Tohoku University, Sendai, 980-8577 Japan
[4] Center for Innovative Integrated Electronic Systems, Tohoku University, Sendai 980-0845 Japan
[5] WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577 Japan

Spin-orbit torque (SOT) induced switching, a magnetization switching technique utilizing spin-orbit interactions in heterostructures with broken space inversion symmetry, offers attractive avenues for high-performance and low-power integrated circuits [1-3]. While the heterostructure considered, in general, consists of a bilayer with a non-magnet (NM), e.g., Pt, Ta, and W, and a ferromagnet (FM), we here show that replacing the NM by an antiferromagnet (AFM) opens up various opportunities beyond the conventional integrated circuits [4-6].

SOT switching in AFM/FM heterostructures can be characterized by the following three effects. The first one is the spin Hall effect (SHE), which manifests in SOT. Several theoretical and experimental works revealed that noncollinear AFMs exhibit direct/inverse SHE. We find that, in a heterostructure consisting of an antiferromagnetic PtMn and a ferromagnetic Co/Ni multilayer, the PtMn exhibits SOT large enough to switch the magnetization of Co/Ni layer. The second effect is the exchange bias, which is known to arise at AFM/FM interfaces and manifests itself in an effective in-plane field. Whereas an application of in-plane field is necessary to achieve bipolar switching of perpendicular magnetization for NM/FM systems, the AFM/FM system allows field-free switching as a result of the exchange bias. The third effect, which arises in polycrystalline systems, relates to a variation of the exchange bias among the polycrystalline grains, which provide fine stable magnetic domain structures [5]. This leads to an analog-like switching behavior as is not usually observed in NM/FM structures. Thanks to these effects, the SOT switching in AFM/FM heterostructures not only offers promising route toward SOT-based magnetoresistive random access memory (SOT-MRAM), but also open unconventional paradigms such as neuromorphic computing.

Taking advantage of the analog nature of the SOT devices with the AFM/FM structure, we have shown a proof-of-concept demonstration of neuromorphic computing [6]. In this work, we have developed an artificial neural network using 36 AFM/FM-based SOT devices with a field-programmable gate array and software implemented on a PC, and have tested an associative memory operation. The Hopfield model [7] has been employed to associate memorized patterns from randomly generated noisy patterns. The learning operation based on the Hebbian rule is performed by changing the Hall resistance of analog SOT devices, which represents a synaptic weight between neurons. We have confirmed that the SOT devices have the expected learning ability, resulting in a successful associative memory operation [6]. Since the spintronics devices have virtually infinite endurance and nonvolatility, the spintronics-based artificial neural networks are expected to realize *edge* artificial intelligence with an on-chip learning capability.

This work is partly supported by ImPACT Program of CSTI, R&D Project for ICT Key Technology of MEXT, JST-OPERA, and JSPS KAKENHI Grant Number 17H06093.

Reference

1) I. M. Miron et al., Nature **476**, 189 (2011).
2) L. Liu et al., Science **336**, 555 (2012).
3) S. Fukami et al., Nature Nanotechnology **11**, 621 (2016).
4) S. Fukami et al., Nature Materials **15**, 535 (2016).
5) A. Kurenkov et al., Applied Physics Letters **110**, 092410 (2017).
6) W. A. Borders et al., Applied Physics Express **10**, 013007 (2017).
7) J. J. Hopfield, Proceedings of the National Academy of Sciences USA **79**, 2554 (1982).