

Pushing the limits of energy efficiency and scaling in spintronics: voltage-control, spin-orbit torques, and microwave dynamics in magnetic tunnel junctions

Pedram Khalili¹

¹Dept. of Electrical Engineering & Computer Science, Northwestern University, Evanston, IL, USA

We will review recent progress and perspectives on future directions of spintronics focusing on two areas: (i) How to build spintronic memory devices with unprecedented energy efficiency, speed, and integration density, with an eye on applications in brain-inspired computing, (ii) How emerging device concepts in spintronics, which frequently emerge from a desire to build better memory elements, can be adapted to other types of devices that are important for IoT, with examples being spintronic oscillators, microwave detectors, and random number generators. We will discuss progress in the development of magnetic tunnel junctions controlled by electric fields, which exhibit the lowest power consumption MRAM cells developed to date (< 5 fJ/bit with write times < 1 ns), and discuss some of the current device and circuit-level opportunities and challenges for these devices [1, 2]. We then discuss random number generators using voltage- and spin-orbit-torque-controlled magnetic tunnel junctions, and some of their potential application areas [3, 4]. Finally, we point out recent results and opportunities in the development of high-performance microwave devices [5], based on engineering of interfacial anisotropy and spin-orbit interaction in nanostructures.

[1] C. Grezes, F. Ebrahimi, J.G. Alzate, X. Cai, J. A. Katine, J. Langer, B. Ocker, P. Khalili Amiri, K.L. Wang, "Ultra-low switching energy and scaling in electric-field-controlled nanoscale magnetic tunnel junctions with high resistance-area product", *Applied Physics Letters*, Vol. 108, No. 1, p. 012403, January 2016.

[2] C. Grezes, H. Lee, A. Lee, S. Wang, F. Ebrahimi, X. Li, K. Wong, J.A. Katine, B. Ocker, J. Langer, P. Gupta, P. Khalili Amiri, K.L. Wang, "Write Error Rate and Read Disturbance in Electric-Field-Controlled Magnetic Random-Access Memory", *IEEE Magnetics Letters*, Vol. 8, p. 3102705, March 2017.

[3] H. Lee, C. Grezes, A. Lee, F. Ebrahimi, P. Khalili Amiri, K.L. Wang, "A Spintronic Voltage-Controlled Stochastic Oscillator for Event-Driven Random Sampling", *IEEE Electron Device Letters*, Vol. 38, No. 2, pp. 281-284, 2017.

[4] H. Lee, F. Ebrahimi, P. Khalili Amiri, K.L. Wang, "Design of high-throughput and low-power true random number generator utilizing perpendicularly magnetized voltage-controlled magnetic tunnel junction", *AIP Advances*, Vol. 7, p. 055934, 2017.

[5] B. Fang, M. Carpentieri, X. Hao, H. Jiang, J.A. Katine, I.N. Krivorotov, B. Ocker, J. Langer, K.L. Wang, B. Zhang, B. Azzerboni, P. Khalili Amiri, G. Finocchio, Z. Zeng, "Giant spin-torque diode sensitivity in the absence of bias magnetic field", *Nature Communications*, Vol. 7, pp.11259/1-7, April 2016.