Prof. Andrei Slavin

Oakland University

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MTJ-based artificial neuron suitable for fully analog machine learning

Magnetic tunnel junctions (MTJs) are nanoscale spintronic devices composed of two ferromagnetic layers separated by an insulating barrier. MTJs are CMOS-compatible and widely used commercially in magnetic memory and sensor technologies, with over 10^8 devices manufactured annually. In this work, we demonstrate a practical analog artificial neuron by pairing a spin-valve/magnetic tunnel junction (SV/MTJ) device with an NMOS transistor. This SV/MTJ-nMOS neuron supports fully analog machine learning and is compatible with conventional electronic systems and neural network architectures.

In a recent theoretical study [1], it was shown that an SV/MTJ device can function as an artificial neuromorphic device replicating fundamental behaviors observed in biological neurons, such as short spike generation, response latency, synaptic integration, refraction, inhibition, adaptation, and spike-train generation. By integrating this SV/MTJ device with an NMOS transistor, both input and output signals become voltage-based. This configuration allows straightforward implementation of synaptic weights through voltage-controlled amplifiers, thus enabling seamless integration into fully analog neural networks.

To validate system-level performance, we constructed a three-neuron SV/MTJ-nMOS neural network in LTspice program, complete with supporting circuitry [2]. A feedforward backpropagation algorithm was employed, performing all learning and synaptic weight adjustments entirely in the analog domain using spike timing (time-encoded signals). An example of realization of an XOR logic gate, a standard neural network benchmark, was used to assess learning effectiveness. After approximately 30 training epochs, the network reliably converged, performing XOR classification successfully. The complete training cycle required less than 2 μs of simulation time. These results confirm the potential of the SV/MTJ-nMOS artificial neuron circuit for fast, low-power, fully analog machine learning, compatible with standard electronic design and established neural network frameworks.

References

[1] S. Louis, H. Bradley, C. Trevillian, A. Slavin and V. Tyberkevych, IEEE Magn. Lett., Vol. 15, p. 1–5 (2024)

[2] S. Louis, H. Bradley, A. Litvinenko and V. Tyberkevych, arXiv preprint arXiv:2503.20813 (2025)

Short Bio

Andrei Slavin received PhD degree in Physics in 1977 from the St. Petersburg Technical University, St. Petersburg, Russia.

Dr. Slavin developed a state-of-the-art theory of spin-torque oscillators, which has numerous applications in the theory of current-driven magnetization dynamics in magnetic nanostructures. His current research support includes multiple grants from the U.S. Army, DARPA, SRC and the National Science Foundation. This research involves international collaborations with leading scientists in many countries, including Germany, Ukraine, France, Italy, and the United States. Dr. Slavin is a frequently invited speaker at international conferences on magnetism around the world.

Andrei Slavin is Fellow of the American Physical Society, Fellow of the IEEE, and Distinguished Professor and Chair of the Physics Department at the Oakland University, Rochester, Michigan, USA.