Self-regulated spintronic long short-term memory for spiking neural networks

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As predictive technologies like real-time language processing, autonomous control, and edge artificial intelligence (AI) continue to expand, the demand for energy-efficient computation has intensified. Spiking neural networks (SNNs) offer a biologically inspired and low-power alternative to conventional AI models, yet their implementation is hindered by the difficulty of reproducing complex temporal dynamics in hardware. A particularly important function is long- and short-term memory handling, essential for tasks involving sequential data. In this work, we demonstrate a spin-orbit torque (SOT)-driven magnetization switching mechanism in the antiferromagnet(AFM)/ferromagnet(FM) heterostructures that mimics leaky neuronal behavior. The device exploits the interplay between SOT and persistent thermally induced spin currents, resulting in post-current pulse magnetization relaxation and controlled temporal decay. While the SOT pulse induces deterministic switching, the thermally generated spin current persists beyond the pulse, exerting a delayed torque on the magnetization. This post-pulse thermal action gives rise to gradual magnetic state evolution, effectively emulating leaky-integrate characteristics. Such a dynamic forms the physical basis of Long Short-Term Memory (LSTM) functionality in spintronic devices, where magnetization decay and memory retention can be tuned through current amplitude and pulse width. This study presents a hardware-efficient, biomimetic approach for neuromorphic computing and paves the way for spintronic architectures capable of real-time, in-memory sequential information processing.

***Index Terms*—Long short-term memory, Magnetic domain walls, Spiking neural networks, Spin-orbit torque.**

I. Introduction

The implementation of neuromorphic functionalities in solid-state devices is increasingly sought to meet the demands of low-power, real-time data processing. While spintronic platforms have shown promise due to their non-volatility and fast switching, most demonstrations remain limited to binary or fixed multistate behaviors. These constraints hinder their application in hardware mimicking the adaptive, time-dependent characteristics of biological systems [1].

In this work, we report a distinct magnetization dynamic in the perpendicularly magnetized antiferromagnet/ferromagnet (AFM/FM) heterostructures, where a leaky, gradual relaxation of the magnetic state occurs following the removal of a spin-orbit torque (SOT) pulse. This behavior arises from the interplay between electrical and thermal spin currents at the AFM/FM interface. Notably, the thermally generated spin current persists after the current pulse ends, driving a delayed torque that gradually restores the magnetization, a process analogous to the leaky integrate-and-fire mechanism in biological neural systems [2]-[3].

This built-in relaxation provides a physical basis for implementing time-dependent computation, crucial for tasks involving memory and temporal correlation. As a result, spintronic devices exhibiting these leaky dynamics offer a promising route toward hardware-efficient emulation of long short-term memory (LSTM) behavior in spiking neural networks (SNNs) [4]. The ability to harness intrinsic physical processes to encode temporal information represents a significant advance for future computing technologies [5]. It opens the door to energy-efficient, compact, and scalable hardware systems capable of learning, forgetting, and adapting in real time—hallmarks of biological intelligence and essential for next-generation artificial intelligence platforms.

II. Results and Discussion

The magnetization dynamics of the AFM/FM heterostructure were investigated using a sequence of current-induced SOT switching pulses and time-resolved anomalous Hall voltage (V_{AHE}) measurements. Fig. 1(a) shows the evolution of V_{AHE} as a function of pulse current amplitude (I_p). As I_p increases, the system transitions from a stable initial state to a fully switched magnetic configuration, with the intermediate states revealing a smooth, non-binary response.

This indicates a multilevel magnetization profile modulated by the applied current. The inset highlights the measurement scheme, where each state is probed 500 ms after the end of the current pulse, capturing the system's response beyond the direct excitation window.

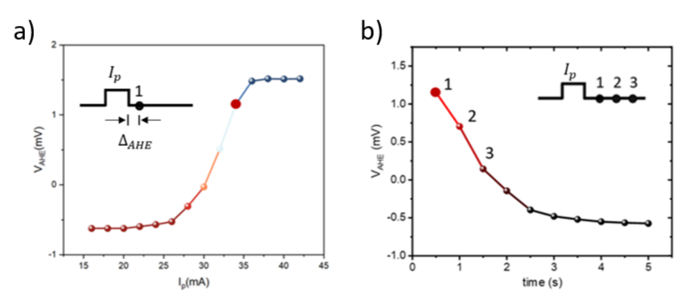

Fig. 1. (a) Anomalous Hall voltage (V_{AHE}) as a function of pulse current amplitude (I_p), showing a smooth transition of magnetic states. (b) Temporal evolution of V_{AHE} for a selected intermediate state, showing a gradual decay over a few seconds. The persistent change is attributed to a thermally driven spin current that continues to influence magnetization after the pulse, emulating leaky neural behavior.

More importantly, as shown in Figure 1b, the temporal evolution of these intermediate magnetization states exhibits an evident post-pulse decay over a few seconds. This behavior arises from the persistent thermal spin currents generated at the AFM/FM interface, which continue to exert torque after the electrical excitation ends. The decay trajectory, following a smooth relaxation curve, mirrors the leaky integration behavior of biological neurons, confirming that the device retains a fading memory of past stimuli. The inset schematic illustrates the temporal reading of each state, underscoring the device's capacity for encoding time-dependent information.

This intrinsic leaky dynamic not only allows for analog multistate behavior but also introduces programmability via pulse amplitude and duration, enabling flexible control over memory decay rates, a critical functionality for neuromorphic operations such as sequence processing or state-based learning. Figure 2 expands upon the device's time-dependent behavior by demonstrating synaptic plasticity through a train of current pulses applied to the device. The anomalous Hall output exhibits distinct temporal evolution depending on the stimulation pattern. Repeated pulses lead to a progressive increase in the resistance state, mimicking long-term potentiation (LTP). In contrast, isolated or sparse pulses result in a gradual relaxation, analogous to long-term depression (LTD). More importantly, the device also exhibits features of short-term plasticity (STP) and short-term depression (STD), where brief or subthreshold pulse sequences induce transient resistance changes that decay back to baseline without consolidation.

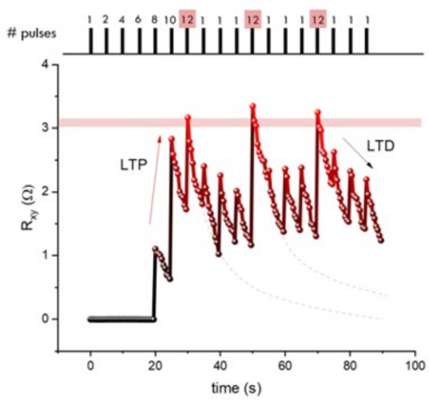

Fig. 2. AHE evolution under sequential current pulse stimulation, showing synaptic-like plasticity. Pulse trains (top) lead to long-term potentiation (LTP), while isolated pulses result in long-term depression (LTD). The system exhibits history-dependent resistance modulation, enabling physical emulation of learning and forgetting dynamics in spintronic devices.

This combination of transient and cumulative magnetization dynamics captures the fundamental ingredients for LSTM behavior: integration, selective memory retention, and controllable forgetting, all realized through intrinsic device physics without complex peripheral circuitry. The capability to realize both history-dependent integration and activity-driven plasticity demonstrates the potential of AFM-enhanced spintronic devices for constructing compact, low-power modules capable of learning, forgetting, and adapting over time, key features for real-time neuromorphic computing platforms.

III. Conclusions

In summary, we demonstrate a spintronic device that harnesses the interplay of electrical and thermal spin currents to generate post-pulse leaky magnetization dynamics. This behavior enables the emulation of biologically inspired temporal processes and provides a hardware-efficient path toward implementing neuromorphic functions such as LSTM in SNN architectures. The observed gradual decay and multistate encoding offer an unprecedented opportunity to develop spin-based systems capable of sequential learning and real-time information processing. These findings mark a step forward in integrating antiferromagnetic materials into neuromorphic in-memory computing platforms, expanding the design space for future intelligent devices.

References

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