Neuromorphic weighted sums with magnetic skyrmions

T. da Câmara Santa Clara Gomes [1,2*], Y. Sassi[1], D. Sanz-Hernandez[1], S. Krishnia[1], M.-B. Martin[1], P. Seneor[1], T. Bhatnagar-Schöffmann[3], D. Ravelosona[3], D. Querlioz[3], L. Herrera-Diez[3], V. Cros[1], J. Grollier[1], and N. Reyren[1]

[1] Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, 91120 Palaiseau, France, [2] INESC Microsistemas e Nanotecnologias, 1000-029 Lisboa, Portugal, [3] Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 91120 Palaiseau, France
*tristan.gomes@inesc-mn.pt

Magnetic skyrmions, which are topological magnetic solitons, exhibit a range of enticing features that make them promising candidates for integration into neuromorphic circuits [1-3], such as stability at room temperature, sub-micron dimensions, non-volatility, particle-like behavior, and motion at low power.

In our study, we exploit the non-volatile and particle-like characteristics of magnetic skyrmions, which makes them countable and hence summable, to perform a basic neuromorphic computing operation: the weighted summation of synaptic signals [4]. We design a device comprising parallel tracks, which act as synapses, connected by transverse electrodes, which act as neurons (Fig 1a). We demonstrate the precise electrical control of skyrmion nucleation and motion in specially designed magnetic tracks, the number of generated skyrmions being determined by the electrical pulse input multiplied by the track synaptic weight. To enable non-volatile control of synaptic weights, we propose using magneto-ionic effects to achieve reversible and persistent modulation of magnetic properties through voltage-gated application. Voltage gating control of magnetic anisotropy is achieved by applying an electric field through an AlO_x layer, enabling the transition from in-plane to out-of-plane magnetic anisotropy in the top Co layer [5]. Detection of the number of skyrmions is accomplished through non-perturbative anomalous Hall voltage measurements. We experimentally validate the weighted sum operation using two electrical inputs in a crossbar array configuration with two tracks, where the measured Hall voltage accurately reflects the cumulative number of skyrmions injected into both tracks (Fig. 1b) [4]. This ensures efficient execution of the fundamental weighted sum operation, a cornerstone for neuromorphic computing. Our experimental demonstration is scalable to accommodate multiple inputs and outputs using a compact crossbar array design, potentially approaching the energy efficiency observed in biological systems.

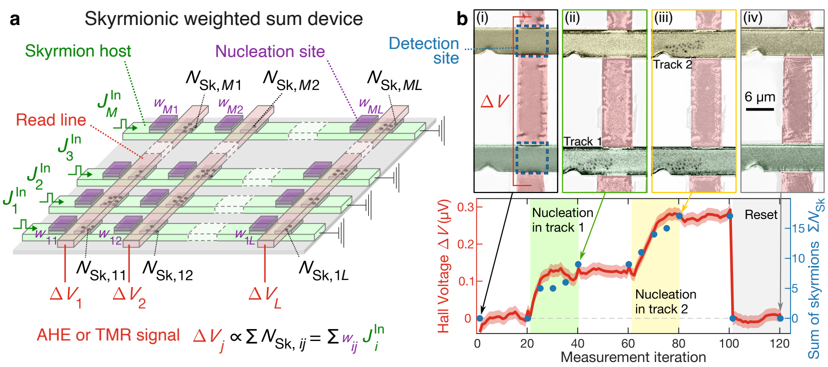

Figure 1. **a**, Scalable device with M tracks (green) in which input currents J_i^{In} generate controlled skyrmion numbers $N_{\mathrm{Sk},ij}$ at nucleation sites (purple) with synaptic weights w_{ij}. These skyrmions are moved into detection zones at the intersection of the tracks and transverse electrodes (red), where their cumulative number $\sum_i N_{\mathrm{Sk},ij}$ is electrically detected by ΔV_j. **b**, Top, Kerr microscopy images showing the skyrmion nucleation in two tracks, before they are erased by a magnetic field. Bottom, the measured Hall voltage ΔV (red) accurately reflects the total number of skyrmions observed $\sum N_{\mathrm{Sk,detec}}$ (blue circles).

References

[1] A. Fert, N. Reyren, and V. Cros; *Nat Rev Mater*, **2017**, 2, 17031.
[2] J. Grollier *et al.*, *Nature Electronics*, **2020**, 3, 148-155.
[3] K.M. Song *et al.*, *Nature Electronics*, **2020**, 3, 148-155.
[4] T. da Câmara Santa Clara Gomes *et al.*, *Nature Electronics*, **2025**, 8, 204-214.
[5] T. da Câmara Santa Clara Gomes *et al.*, *Phys. Rev. Appl.*, **2024**, 21, 024010.