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Demonstration of weighted sum using electrical manipulation and detection of magnetic skyrmions

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Thanks to their original properties, magnetic skyrmions have many promising applications, from memories, sensors to logic operations. In this study, we propose to use fully-electrical manipulation and detection of magnetic skyrmions in multilayer devices to perform a basic unconventional computation operation in hardware. The fabricated devices take advantage of the particle-like nature of the magnetic skyrmions: operations can be applied to a large ensemble of skyrmions using fully-electrical stimuli, while skyrmions can be counted individually by electrical means. Here, we show the nucleation and the motion of a controlled number of magnetic skyrmions in multilayer tracks using electrical current pulse parameters. Then, we show that the number of skyrmions can be directly summed and detected with non-perturbative Anomalous Hall resistance measurements. Magneto-ionic effects are used for the local non-volatile and reversible tuning of the magnetic properties of the tracks.

***Index Terms*— Skyrmions, Spintronics, Magneto-ionics, Unconventional computing.**

I. Introduction

Electrical control of magnetic skyrmions, which are particle-like topological spin textures, holds promise for emerging memory and computing applications such as racetrack memory, logic devices or neuromorphic computing [1-3]. Among the main advantages of magnetic skyrmions are their stability and non-volatility at room temperature, the low energy requirement for their motion, their sub-micronic size and their particle-like behavior. It has been shown, most often separately, that magnetic skyrmions can be experimentally nucleated [4-7], moved [4,7], annihilated [6] and detected electrically using Anomalous Hall effect [8] in metallic multilayers.

In this study, we propose a device design using fully-electrical manipulation and detection of skyrmions to perform basic operations required for unconventional computing. The device is composed of micron-wide lithography tracks with adjustable geometry in optimized skyrmion multilayers made of several repetitions of [Pt(3 nm)|Co(1.2 nm)|Al(3 nm)]. First, using electrical pulses inputs with controlled current density and duration, we show how it is possible to inject a number of magnetic skyrmions that is proportional to the current pulse input J, so that the number of skyrmions in a track is given by wJ , where w denotes the track weight. Secondly, these skyrmions can be detected in real time electrically through measurements of the Anomalous Hall Effect, while also being tracked by magneto-optic Kerr effect microscopy. We demonstrate that the total number of skyrmions detected through the Hall voltage measured by at the edge of the Hall electrodes corresponds to the sum of the number of skyrmions in the parallel tracks crossing the electrodes. Therefore, such device allows to perform weighted sum operation where the total number of skyrmions detected is given by $\sum w_i J_i$. Finally, we investigate how the tuning of the magnetic anisotropy and/or the interfacial Dzyaloshinskii-Moriya interaction of the magnetic multilayers through magneto-ionic effects obtained by electric field gating can be used for non-volatile and reversible control of the nucleation and motion of these magnetic skyrmions in the devices (i.e. the weights). All these basic operations using magnetic skyrmions hold promises for unconventional computing applications such as neuromorphic computing.

II. Results

We demonstrate in a single Hall cross bar that magnetic skyrmions can be selectively nucleated from a notch (see Fig. 1(a)) and moved through the Hall cross using current pulses at room temperature. Fig. 1(b) shows the linear relation between the number of skyrmions and the number of current pulses injected in the track. A regime of one skyrmion per pulse has been obtained for optimized current density and duration, and out-of-plane external magnetic field. The number of skyrmions nucleated per pulse can be adjusted using the current density and duration. The skyrmion velocity is found to vary linearly with the current density within the range of current density used with values ranging from few to few tens of m/s. To avoid perturbing (or even impeding) the skyrmion motion at the Hall cross, we have developed thin Ta-based Hall electrodes connected only at the edge of the track (indicated in red in Fig. 1(a)) that skyrmions are able to cross without reduction of their velocity. We demonstrate that the skyrmions can be counted using anomalous Hall effect. As seen in Fig. 1(c), the Hall resistance variation corresponds well to the number of skyrmions counted by eyes from the magneto-optic Kerr images within the detection zone (taken as the orange square in Fig. 1(a)).

In Fig. 2, we present the Hall resistance variation measured in a device composed of two parallel tracks. Here, skyrmions are successively injected in the “top” and “bottom” tracks using 20 identical current pulses, before being erased using an external magnetic field (reset). The Hall resistance increase

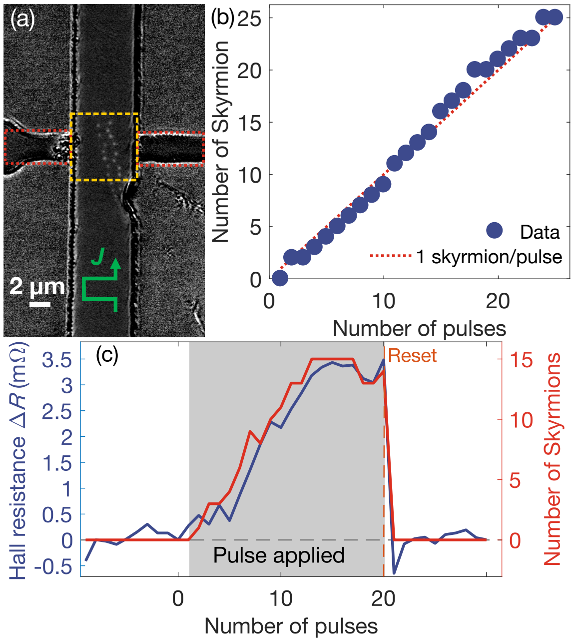

Fig. 1. (a) (b) Linear variation of the number of skyrmions nucleated from a notch in 6 µm wide track with the number of pulses applied for a current density $J = 3.3\ 10^{11}$ A/m^2 and pulse width w = 50 ns under an out-of-plane external magnetic field H = 20 mT. (c) Evolution of the Hall resistance variation and the number of skyrmions for 20 pulses applied (indicated by the grey area). Ten measurements of the resistance are performed before the application of the pulses and after magnetically erasing the skyrmions (reset).

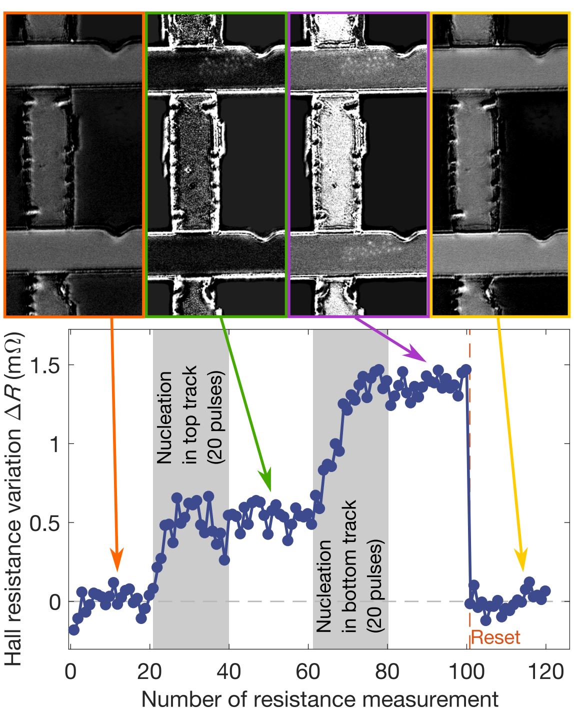

Fig. 2. Hall resistance variation measured in a device composed of two parallel tracks, where 20 nucleation pulses are successively applied to the “top” and “bottom” tracks before erasing the skyrmions using an external magnetic field. 20 measurements of the Hall resistance are taken before nucleation, during and after each nucleation and after the reset of the device. Kerr images corresponding to each situation are also shown.

measured for each nucleation corresponds well to the value expected from individual measurements of the Hall cross. These results demonstrate the possibility to directly obtain an electrical measurement that directly probes the sum of the number of skyrmions N in the two tracks, which depends on the current pulse input parameters sent to each track, J_1 and J_2, with $N = w_1 J_1 + w_2 J_2$, where w_1 and w_2 are the weights of each track. Using a similar device with a given number M of parallel tracks is thus expected to perform a weighted sum of M inputs.

Finally, in Fig. 3, we show the voltage gating control of the magnetic anisotropy of the multilayer stack obtained by magneto-ionic effect. In this system, the top Co layer can be fully switched from in-plane to out-of-plane anisotropy by applying an electric field from an AlO_x layer sputtered on top of the stack, which allows to move oxygen ions in and out of the top Co layer. These changes in the magnetic properties are found to be non-volatile and reversible, as shown in Fig. 3. These results path the way towards gate voltage control of the skyrmion nucleation and motion (i.e. the non-volatile tuning of the track weighs).

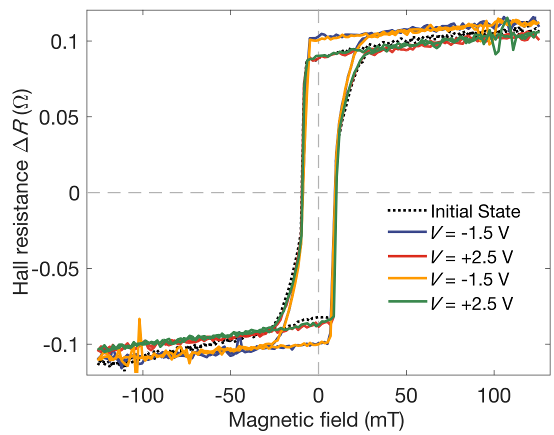

Fig. 3. Hall resistance loops showing the electric field gating control of the magnetic anisotropy of a $[Pt(3)|Co(1.2)|Al(3)]_4|Pt(3)|Co(1.2)|AlO_x(0.8)$ stack, with the dimension in nm, for several voltage applied through the gate resulting in a switching from in-plane to out-of-plane anisotropy of the top Co layer.

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References

[1] A. Fert, N. Reyren, and V. Cros, “Magnetic skyrmions: advances in physics and potential applications”, vol. 2(7), pp. 1-15, 2017.

[2] G. Bourianoff *et al.*, "Potential implementation of reservoir computing models based on magnetic skyrmions." *Aip Advances,* vol. 8(5), pp. 055602, 2018.

[3] K.M. Song *et al.*, "Skyrmion-based artificial synapses for neuromorphic computing.", *Nature Electronics*, vol. 3.3, pp. 148-155, 2020.

[4] W. Legrand *et al.*, "Room-temperature current-induced generation and motion of sub-100 nm skyrmions.", *Nano Letters*, vol. 17, pp. 2703, 2017.

[5] A. Hrabec *et al.*, Hrabec, Ales, et al. "Current-induced skyrmion generation and dynamics in symmetric bilayers.", *Nature Communication*, vol. 8, pp. 1-6, 2017.

[6] S. Woo *et al.*, "Deterministic creation and deletion of a single magnetic skyrmion observed by direct time-resolved X-ray microscopy.", *Nature Electronics*, vol. 1, pp. 288-296, 2018.

[7] S. Woo *et al.*, Woo, Seonghoon, et al. "Observation of room-temperature magnetic skyrmions and their current-driven dynamics in ultrathin metallic ferromagnets.", *Nature Materials*, vol. 15, pp. 501-506, 2016.

[8] D. Maccariello *et al.*, "Electrical detection of single magnetic skyrmions in metallic multilayers at room temperature.", *Nature Nanotechnology*, vol. 13, pp. 233-237, 2018.