Skyrmion Logic System for Large-Scale Reversible Computing

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***Abstract*—Reversible computing is an energy-efficient computing paradigm that conserves the information within the system. While conservative logic is an intriguing approach for reversible computing with no energy dissipation, the large dimensions of information carriers in previous realizations hampered potential improvements to the system efficiency. We have therefore proposed a nonvolatile reversible computing system in which the information carriers are magnetic skyrmions. Fundamental Boolean functions including AND, OR and INV are designed and simulated micromagnetically. The basic Boolean skyrmion logic gates are then directly cascaded to implement larger circuits such as full adders, in which the skyrmions can be transported in a pipelined and nonvolatile manner controlled by notch-shaped synchronizers. This skyrmion logic family has the potential to deliver a scalable high-speed low-power reversible computing system.**

Keywords—Magnetic skyrmion, skyrmion logic, reversible computing, non-volatile, spintronics

I. INTRODUCTION

There is a minimum amount of energy utilized by logic gates which operate through the continuous creation and destruction of information carriers, as defined by Landauer [1]. Reversible computing attempts to overcome this minimum by conserving information, and thus energy, during logical operations [2]. The original thought experiment by Fredkin and Toffoli modeled the information carriers as billiard balls and based logical operations upon their dissipation-free elastic interactions to illustrate the conservative logic paradigm [3].

Magnetic skyrmions are promising candidates for information carriers in reversible computing systems due to their nanoscale (~20 nm) dimensions and the small current required to move them [4], [5]. These quasiparticles, which are stable regions of magnetization with a core that is oriented anti-parallel to the bulk of the surrounding structure, are set into motion by the Spin-Hall effect through the application of an electric current. In motion, skyrmions deviate from the direction of the applied current due to the Skyrmion-Hall effect, which is analogous to the magnus effect. To minimize the impact of the Skyrmion-Hall effect, a track structure has been proposed to restrict the motion of a skyrmion to only one dimension. Although these nanowire track structures have been proposed for memory storage and individual logic gates, the development of a scalable logic system has been impeded by the need to directly cascade gates as well as the large energetic costs for continually creating and destroying skyrmions in previously proposed skyrmion logic gates.

We therefore propose a reversible skyrmion logic system where skyrmions are conserved throughout the system [6], and demonstrate its feasibility through micromagnetic simulations [7]. The logic gates leverage the rich physics of magnetic skyrmions: the Spin-Hall effect, the Skyrmion-Hall effect, skyrmion-skyrmion repulsion, skyrmion-track boundary repulsion, and current-controlled notch depinning [6], [8]. Binary data is encoded as the presence ('1') or absence ('0') of skyrmions, and the output skyrmion of one logic gate is used as the input of the next. These logic gates provide fan-out and can be cascaded into large-scale systems where signal integrity and synchronization are provided by applying global clock pulses across the entire system.

II. REVERSIBLE SKYRMION LOGIC GATES

The geometries of the basic logic gates within our system take advantage of the robust physics of magnetic skyrmions to produce an AND/OR gate, an INV/COPY gate, and a synchronizing element [6]. These gates enable the implementation of any binary logic function and allow the cascading and pipelining of gates.

A. Reversible Skyrmion AND/OR Gate

The reversible AND/OR gate is the most elementary component of the skyrmion logic system [6]. The AND/OR function is performed by the track structure shown in Fig. 1 with the skyrmion trajectories shown. The spin-Hall effect

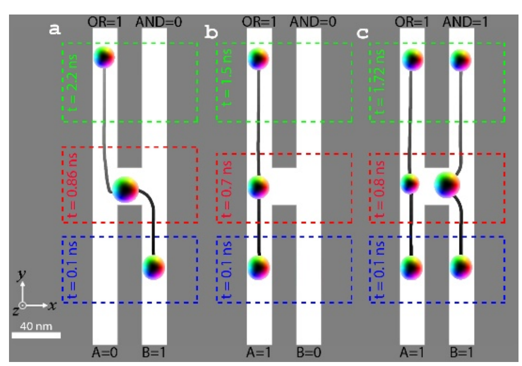

Fig 1. Micromagnetic simulation results for the AND/OR gate for input combinations (a) A = 0, B = 1; (b) A = 1, B = 0; (c) A = B = 1. In this, and subsequent figures, the grayscale line shows the path over time with black at t=0 and the line getting lighter as time passes.

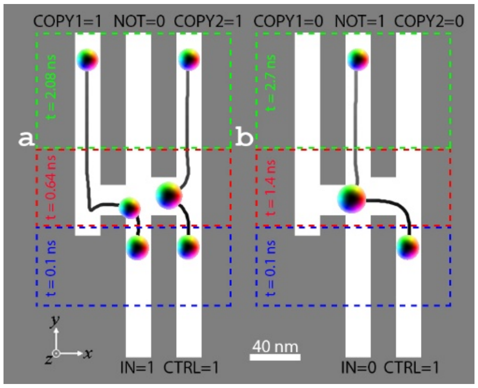

Fig 2. Micromagnetic simulation results for the INV/COPY gate for input combinations (a) IN = 1, CTRL = 1 and (b) IN = 0 and CTRL = 1

forces the skyrmion into motion in the +*y*-direction, while the skyrmion-Hall effect pushes the skyrmions in the -*x*-direction. Countering this skyrmion-Hall effect, the skyrmions are bound within the track due to repulsion from the track boundary.

The central junction of the gate is where the critical interactions defining the logical operation occur. If one skyrmion is input to the gate, it deviates in the -*x*-direction in the junction towards the OR output. In the case where both inputs have a skyrmion, the two skyrmions repel such that one skyrmion goes to the OR output and the other goes to the AND output.

B. *Reversible Skyrmion INV/COPY Gate*

The INV/COPY gate of Fig. 2 enables the logic system to generate all possible logic functions in concert with the AND/OR gate [6]. This INV/COPY gate is similar to the AND/OR gate, but has an additional output track and requires a skyrmion to be present in the CTRL input. This gate generates both the inverse of the input and copies the input. This gate also en ables fanout for cascaded gates as it outputs two copies of the input value, and by cascading multiples of this gate, it is possible to generate a large fanout of a single input skyrmion.

C. *Skyrmion Synchronization and Cascading*

While the basic skyrmion logic gates are interesting in their own right, direct cascading and synchronization of these gates are critical to their use in practical computing applications. Synchronization is achieved with the notch structure of Fig. 3 by applying a pulse of large spin-Hall current to shrink the skyrmion to pass the notch during the duration of the pulse [6]. By applying this current pulse at regular intervals, it can act as a global system clock similar to that of a traditional computing system. These synchronizer gates must be placed between each sequentially cascaded logic gate to ensure that all of the output skyrmions of one gate make it to the input of the next cascaded gate at the same time. This synchronization enables larger, multilevel logic systems such as the full-adder of Fig. 4, and can enable pipelining to increase throughput of these circuits.

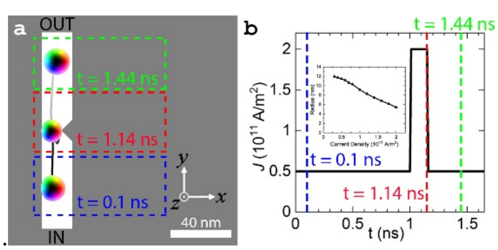

Fig 3. (a) The synchronizer geometry with a 7 nm-wide notch on a 20 nm-wide track which blocks the passage of the skyrmion until a large current pulse is applied. (b) The operational current density for the logic gates is $J = 5 \times 10^{10}$ A/m^2 that is periodically raised to $J = 2 \times 10^{11}$ A/m^2 for 150 ps at 1 ns to allow the skyrmion through.

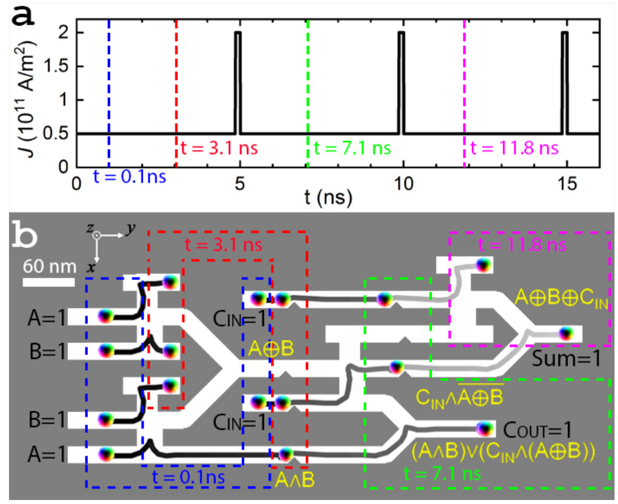

Fig. 4. Cascaded one-bit full adder. (a) Cascaded logic gates are synchronized by large 150-ps-wide electrical pulses applied to the entire structure with a clock period of 5 ns. (b) A one-bit full adder computes the binary SUM and carry-out of two onebit binary numbers, A and B, and a carry-in bit.

III. Conclusions

The proposed skyrmion logic paradigm enables the realization of a conservative, reversible computing system at a nanoscale. The energy required for skyrmion motion through the spin-Hall effect approaches the ideal frictionless information propagation of reversible computing. The proposed logic system takes advantage of the rich physics of magnetic skyrmions to enable cascaded logic circuits where signal integrity can be maintained through synchronization and pipelining. The proposed system for conservative logic thus enables reversible computing that approaches the thermodynamic limits of information processing.

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