Near-Landauer Reversible Skyrmion Logic with Voltage-Based Propagation

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***Abstract*—Magnetic skyrmions are topological quasiparticles whose non-volatility, detectability, and mobility make them exciting candidates for low-energy computing. Previous works have demonstrated the feasibility and efficiency of current-driven skyrmions in cascaded logic structures inspired by reversible computing. As skyrmions can be propelled through the voltage-controlled magnetic anisotropy (VCMA) effect with much greater efficiency, this work proposes a VCMA-based skyrmion propagation mechanism that drastically reduces energy dissipation. Additionally, we demonstrate the functionality of skyrmion logic gates enabled by our novel voltage-based propagation and estimate its energy efficiency relative to other logic schemes. The minimum dissipation of this VCMA-driven magnetic skyrmion logic at 0 K is found to be $\sim$6$\times$ the room-temperature Landauer limit, indicating the potential for sub-Landauer dissipation through further engineering.**

***Keywords*—reversible computing, conservative logic, spintronics, magnetic skyrmion, VCMA, energy-efficient computation**

I. Introduction

The non-volatility and energy-efficient mobility of magnetic skyrmions have made them promising candidates for computation. Previous work has utilized skyrmions in a variety of logical devices [1], and recently skyrmions have emerged as exciting candidates for reversible computing [2], [3], [4]. By conserving information and maintaining logical reversibility in an adiabatic manner, these systems avoid the limits on thermodynamic efficiency intrinsic to traditional computing schemes [5]. Therefore, such reversible computing systems have the potential to outperform the $kT\ln(2)$ limit determined by Landauer [6].

The reversible skyrmion logic system of [2], [3], [4] uses a heavy metal/ferromagnet heterostructure to allow for skyrmion stability within the ferromagnet via the Dzyaloshinsky–Moriya interaction. The spin-Hall effect induces skyrmion propagation with applied electronic current, while the skyrmion-Hall effect and skyrmion-skyrmion repulsion produce billiard-ball-like interactions within the logic gates. Skyrmions can be synchronized through voltage-controlled magnetic anisotropy (VCMA) by modulating the perpendicular magnetic anisotropy (PMA) with the application of a voltage on an electrode [3].

While adiabatic reversible CMOS computing has been well-studied [7], reversible skyrmion logic gets closer to the Landauer limit by directly implementing the elastic billiard ball model proposed by Fredkin and Toffoli [5]. However, the electrical current required by [2], [3], [4] dissipates significant energy. This work therefore proposes a new method of skyrmion propagation that uses voltage-controlled magnetic anisotropy (VCMA) to eliminate the need for current-driven propagation, enabling reversible skyrmion computing to achieve near-Landauer energy dissipation.

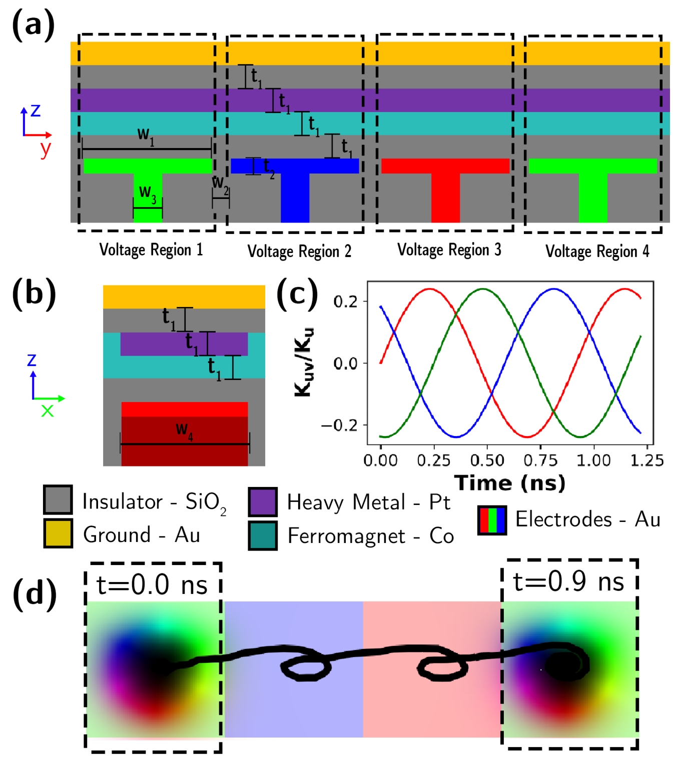

Fig. 1. Skyrmion propagation methodology. An electric field is applied across a heavy metal/ferromagnet interface (teal/purple) via electrodes (red/green/blue) separated by an insulating dielectric (grey). The skyrmion exists in the ferromagnet layer. (a) YZ Device Cross Section (b) XZ Device Cross Section (w_1 = 19nm, w_2 = 1nm, w_3 = 11nm, w_4 = 20nm, t_1 = 0.8nm, t_2 = 0.5nm) (c) VCMA anisotropy waveform applied to electrodes of corresponding color. (d) Micromagnetic simulation of skyrmion propagation; black path indicates skyrmion trajectory.

II. VCMA-Driven Skyrmion Propagation

We propose extremely efficient skyrmion propagation with a three-phase sinusoidal voltage that modulates magnetic anisotropy through VCMA, driving the skyrmions towards regions of lower anisotropy without requiring electrical current [8]. Though previous works modulate PMA periodically in discrete steps [8], the rapid charging of electrode capacitance results in significant energy dissipation. By using three voltage sinusoids each shifted by $\frac{2\pi}{3}$ radians applied to neighboring electrodes (Fig. 1), skyrmions can be controllably propagated with over $\sim$8000$\times$ decrease in electrical energy consumption compared to the square wave clocking of [8] and $\sim$50$\times$ compared to current-driven propagation [3].

As the electronic dissipation is minimal, the magnetic dissipation of this VCMA-driven propagation scheme becomes dominant and can be calculated [9] as

$$\frac{dE}{dt} = -\frac{\alpha\mu_0}{\gamma_0 M_s}\int_V \left(\frac{d\mathbf{M}}{dt}\right)^2 dV.$$

This propagation scheme has also been shown to be thermally robust at non-zero temperatures.

III. Voltage-Based Reversible Logic

By integrating this highly-efficient VCMA-driven propagation into the reversible logic scheme of [2], the energy dissipation is far smaller than required with current-driven propagation. Fig. 2 shows the operation of a physically reversible Ressler-Feynman switch gate and a conservative AND/OR gate, where three clock cycles bring the skyrmions to their respective outputs for the switch gate and two are required for the AND/OR switch gate. The logic processing step takes less than one full clock cycle for both gates, but the difference in skyrmion wire length results in this difference. This VCMA-driven system circumvents the need for synchronizers required in [2], [3], as skyrmion position is directly controlled by the propagation clock.

The system can run from $\sim$100 MHz to $\sim$1GHz, with minimum average dissipation of 102 meV/operation. While the micromagnetic simulations were performed at 0 K, the minimum dissipation is $\sim$6$\times$ Landauer's limit at room temperature. As the skyrmion dynamics are not fully adiabatic, this dissipation remains above the minimum predicted by Landauer. As illustrated in Fig. 3, this is $\sim$9,000$\times$ lower than 8 nm CMOS and $\sim$80$\times$ lower than superconductive logic [10], demonstrating the viability of voltage-based skyrmion logic as a low-energy computation scheme.

IV. Conclusions

The proposed three-phase VCMA-driven skyrmion propagation is far more efficient than previous alternatives. Implementing this propagation mechanism into the reversible skyrmion computing system results in near-Landauer computation, and improvements to the adiabaticity of this scheme could result in sub-Landauer computation.

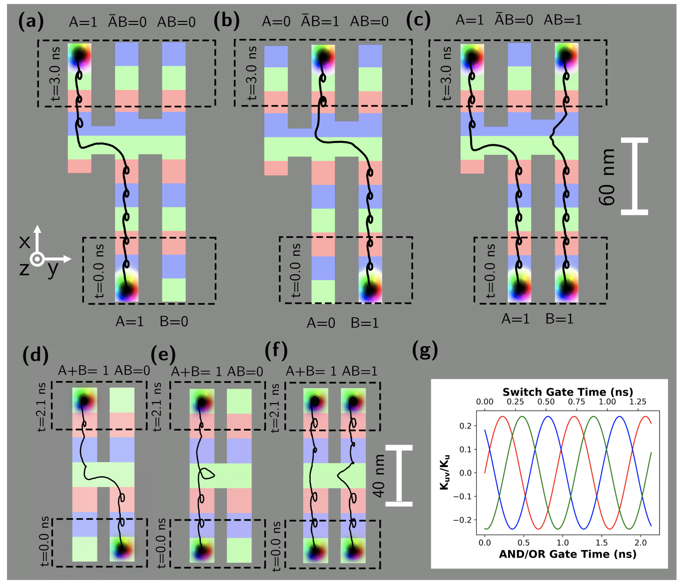

Fig. 2. Micromagnetic simulation results for Ressler-Feynman Switch and AND/OR gate using voltage-based propagation. Skyrmions (colored circles) move in +y as indicated by their trajectory in black. Each colored region represents a VCMA voltage zone, each of which are $\frac{2\pi}{3}$ radians out of phase. Simulations shown for switch gate with input combinations (a) A=0, B=1; (b) A=1, B=0, (c) A=B=1. Simulations shown for AND/OR gate with input combinations (d) A=0, B=1; (e) A=1, B=0, (f) A=B=1. (g) Anisotropy waveform applied to each VCMA region, where $\Delta K_{uv}/K_v$ is the relative change in PMA between when voltage is applied and the baseline anisotropy. Note: the periodic waveform continues for the switch gate until skyrmions reach the end of the track.

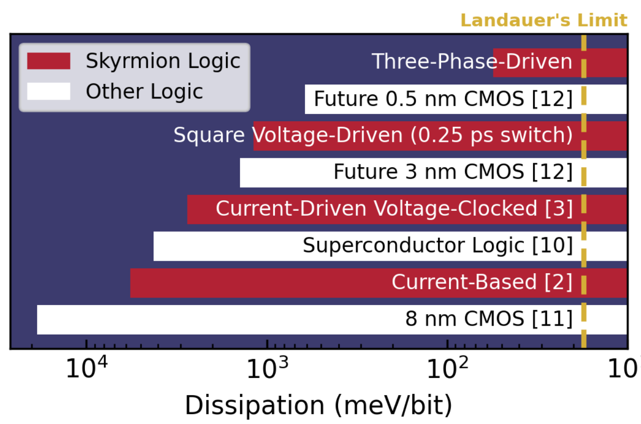

Fig. 3. A comparison of total dissipation per bit processed for skyrmion logic technologies (red) and other logic technologies (white). While temperature is not considered, considerable progress has been made in the efficiency of skyrmion-based logic as it approaches the room-temperature Landauer limit (gold line).

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