Proposal and Micromagnetic Validation of Bipolar Switching in Voltage-Controlled MRAM Devices

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We propose a voltage-controlled MRAM structure with bipolar switching, where opposite voltage polarities write different bit states. A synthetic antiferromagnet (SAF) free layer has the same symmetry as the simultaneous application of electric and magnetic fields. Micromagnetic simulations validate the proposal, and show self-limiting switching.

***Index Terms*—MRAM, voltage-controlled magnetic anisotropy, bipolar switching, micromagnetic simulation, magnetoelectric effect.**

I. Introduction

MAGNETIC random access memory (MRAM) with voltage-control of magnetic anisotropy (VCMA) is promising for higher-level cache and main memory applications [1]. It offers high density and low-energy writing. In the V-MRAM, a voltage pulse lowers the magnetic anisotropy energy of the storage layer momentarily, which drives the magnetization in a precessional trajectory [2], [3]. However, there are multiple challenges with the writing process: for low-energy writing, a large change of magnetic anisotropy by electric field is needed, an in-plane external field is required to break the symmetry and set the precession axis, tight control over the pulse width and shape is needed to achieve a low writing error rate [4]. One major challenge is that the writing process is unipolar, the same writing pulse toggles the bit state. Therefore, a read-then-write sequence is needed to store the proper bit state. In this work, we propose a V-MRAM design that enables bipolar writing using opposite voltage polarities. The switching is self-limiting, and tolerant to pulse width variation.

II. Proposed Bipolar V-MRAM

We base our proposal on symmetry considerations, mainly the space-inversion symmetry (I), time-reversal symmetry (R), and the combined time-space inversion symmetry (IR). Bipolar switching is switching to a '1' or '0' bit state by changing the polarity of the applied electric field. This is similar to the linear magnetoelectric (ME) effect, which requires a spin structure breaking the single I and R symmetries, while keeping the IR symmetry [5]. The reason for unipolar switching in V-MRAM is that all three symmetries are broken. We propose to use a synthetic antiferromagnet (SAF) structure in the free layer of the V-MRAM [Fig. 1]. The SAF with perpendicular magnetic anisotropy breaks the single I and R symmetries, but retains the combined IR symmetry [Fig. 1(a)]. Therefore, a linear ME effect is allowed, a simultaneous application of collinear electric and magnetic fields controls the spin state. The direction of the electric field (E) is opposite on each interface of the free layer. On one side, E increases the magnetic anisotropy energy, while decreasing it on the other. This is illustrated by the arrow size in Fig. 1(b). The stable sublayer magnetization interacts with the stray magnetic field from the reference layer (RL). Depending on E polarity [Figs. 1(b,c)], we can choose either of the stable spin configurations, which is retained after the removal of the voltage. The resistance readout is from the tunneling current in the bottom side between the free sublayer and the reference layer. Thus, we can select the final bit state by the polarity of the writing voltage. Two switching meachnisms are possible: thermally activated and dynamic. In this work, we investigate the dynamic response, and leave the probabilistic (thermal) switching for a future report.

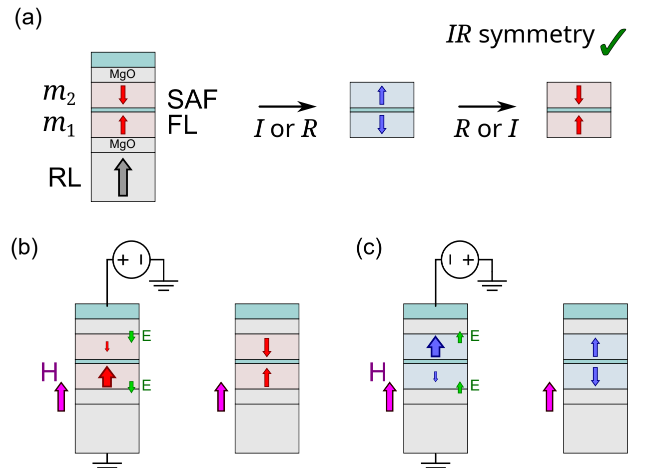

Fig. 1. (a) Schematic of the bipolar V-MRAM with SAF free layer. The SAF is symmetric under IR operation. The writing of bit state by applying a postive writing voltage (b), and a negative writing voltage (c).

III. Micromagnetic Simulation

For verification, we simulate the dynamical switching using the micromagnetics simulation package MuMax3 [6]. We use typical parameters for a $Co_{40}Fe_{40}B_{20}$/MgO interface: saturation magnetization $M_s = 1600$ kA/m, interfacial perpendicular

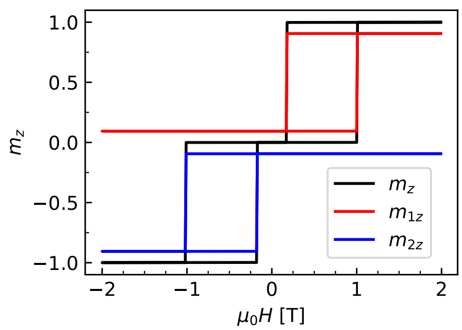

Fig. 2. The hysteresis loop in a magnetic field applied out-of-plane. The sublayer loops are vertically-shifted and scaled for clarity.

anisotropy $K_i = 1.6$ mJ/m^2 [7], Gilbert damping parameter $\alpha = 0.02$, exchange stiffness $A_{\rm ex} = 15$ pJ/m. We simulate an antiferrmagnetically coupled bilayer system of CoFeB (1 nm) / CoFeB (1 nm). The interlayer exchange stiffness $A_{\rm int} = -0.5$ pJ/m, which is equivalent to an interlayer exchange coupling energy $J_{\rm int} = -1.0$ mJ/m^2. We simulate the voltage effect by changing K_i for each sublayer, during time evolution simulations. We introduce a change of ± 1.44 mJ/m^2, corresponding to a VCMA coefficient of 720 fJ/Vm at an $E = 2$ V/nm, which are consistent with reported values [8]. The voltage and VCMA polarities are defined in Fig. 1 The simulation geometry is a cylindrical disk 10 nanometer in diameter, with a discretization cell size of $1.25 \times 1.25 \times 1\text{nm}^3$, representing a 1X MRAM memory element.

IV. Results and Discussion

We show the hysteresis loop simulation result in Fig. 2 in a perpendicular magnetic field. We plot the out-of-plane magnetization component of the normalized magnetization (m_z). The square loops indicate spin-flip switching.

Figure 3 (a) shows the time evolution of sublayer magnetizations under consecutive voltage pulses, highlighted by the shaded spans. We determine the bit state after pulse removal. For an out-of-plane magnetic field $\mu_0 H = +0.2$ T (green-shaded spans), a positive E pulse writes a '1' bit; and a negative E writes '0'. For $\mu_0 H = -0.2$ T (magenta-shaded spans), the relation is reveresed. The pattern is repeatable, and independent of the initial state.

In Fig. 3(b), we show the dynamics near the edges of a voltage pulse. After the onset of the negative voltage pulse, anisotropy of layer 1 is reduced, and enhanced on layer 2. During the voltage application ($t > 30$ ns), layer 1 magnetization tilts towards the inplane direction. Now, two fields are acting on layer 2, the stray out-plane-field, and the larger inplane exchange field from layer 1. After the voltage is removed ($t > 40$ ns), the layer 2 magnetization precesses a half cycle to $+z$ direction. At the same time, the anisotropy of layer 1 returns back, and m_1 is pushed to $-z$ direction. Now, the precession axis becomes the z axis, and the magnetizations quickly damp towards their final position. Notably, the switching is self-limiting and completes without the need for precise timing of pulse width, or an external inplane field.

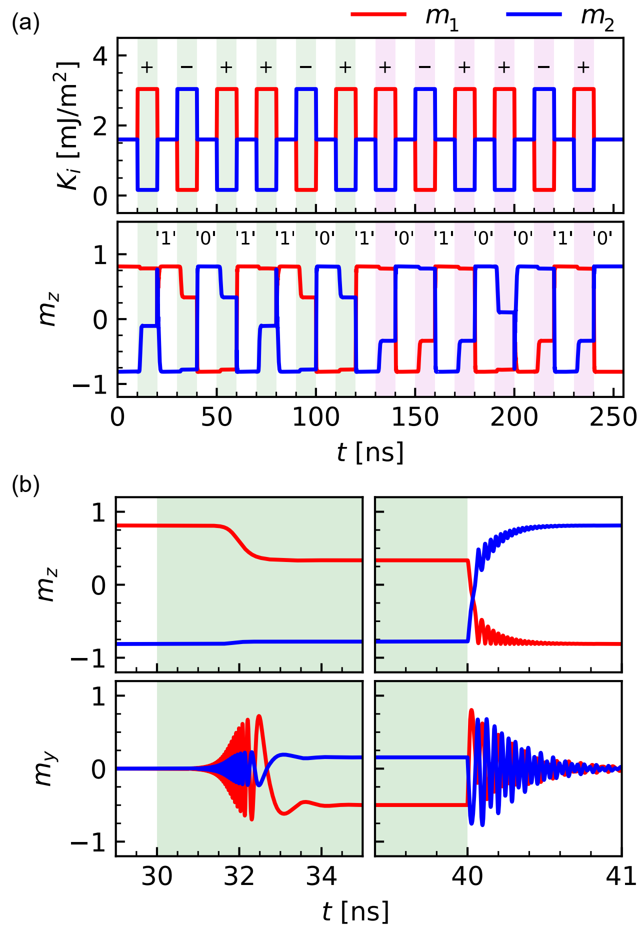

Fig. 3. (a) Bipolar magnetization switching after consecutive voltage pulses, under a positive magnetic field (green-shaded areas), or a negative magnetic field (magneta-shaded). (b) The switching dynamics near the edges of a voltage pulse.

V. Conclusions

We proposed a voltage-controlled MRAM structure based on a SAF free layer, to enable bipolar switching. Guided by symmetry considerations and verified by micromagnetic simulations, the design offers robust and self-limiting switching without precise pulse control or external inplane fields. This proposal offeres a path towards field-free error-tolerant MRAM devices. Furthermore, the use of a SAF free layer is promising for immunity to external field disturbances.

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