FIELD-FREE TOGGLE SPIN-ORBIT TORQUE MRAM WITH PERPENDICULAR MAGNETIC ANISOTROPY

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I. INTRODUCTION

Magnetoresistive random access memory (MRAM) has gained significant traction in the semiconductor industry, being implemented as an embedded nonvolatile memory (eNVM) in low-power applications. At the same time, however, new MRAM device concepts are being explored to achieve broader market adoption, particularly for more advanced technology nodes and for high-performance computing applications. The key requirements to achieve this goal are: 1. The MRAM bits with perpendicular magnetic anisotropy (PMA) that are currently used for STT-MRAM need to be scaled to below ~20 nm, while reducing write currents compared to today's STT-MRAM, 2. These PMA bits need to operate at write speeds below 10 ns with low error rates, e.g. for use in L3 Cache, and 3. For embedded Cache applications, endurance of the bits has to be essentially unlimited, unlike STT-MRAM where higher write currents (needed for fast writing) typically result in limited endurance.

One of the strategies to achieve the above three requirements is the development of spin-orbit torque (SOT) MRAM devices. SOT-MRAM has a three-terminal geometry, separating read and write paths, and thus in principle enables much higher endurance than in STT-MRAM, even for high-speed sub-10 ns writing. The key challenge of SOT-MRAM, however, is that the deterministic directional switching of perpendicular SOT-MRAM bits (which are required for high thermal stability at small device size) requires an in-plane symmetry breaking element, such as an in-plane field, within the device. This complicates the stack design, increases the total device thickness, and potentially reduces the thermal stability of the device.

Here, we instead present a toggle SOT-MRAM device concept where directional switching is not required to switch PMA, thus simplifying the design of the device and eliminating the need for any external magnetic fields [1]. This toggle SOT-MRAM is able to deterministically toggle between PMA states with total directional programming times below 10 ns (including the read step required due to the use of toggle switching) using a simple material stack that can be scaled to small dimensions.

II. TOGGLE SOT SWITCHING OF MRAM WITH PMA

The structure of the toggle SOT-MRAM device [1] is shown in Fig. 1(a), which is a three-terminal magnetic tunnel junction with a simple material stack similar to that of STT-MRAM. The fixed ferromagnet is polarized in the $-z$ direction, and a unidirectional y-directed write current through the heavy metal can cause deterministic toggling of the free ferromagnet between the $+z$ and $-z$-directed stable states. Write current through the heavy metal becomes spin polarized and applies in-plane SOT on the adjacent free ferromagnet, while the compensating ferromagnet cancels the dipolar coupling field from the fixed ferrromagnet. The resistance of the MTJ thus toggles between the antiparallel high and parallel low states in concert with the magnetization of the free ferromagnet, and can be determined using a small perpendicular read current via the tunneling magnetoresistance effect. Separation of the read/write paths contributes to increased endurance, and the use of PMA permits thermal stability at small dimensions.

This field-free toggle switching exploits the precessional nature of field-like SOT to deterministically switch the PMA free ferromagnet [2]. In the transient micromagnetic simulation of Fig. 1(b-c) using the well-established magnetic parameters of [3], the magnetization of the free ferromagnet crosses the hard x-y

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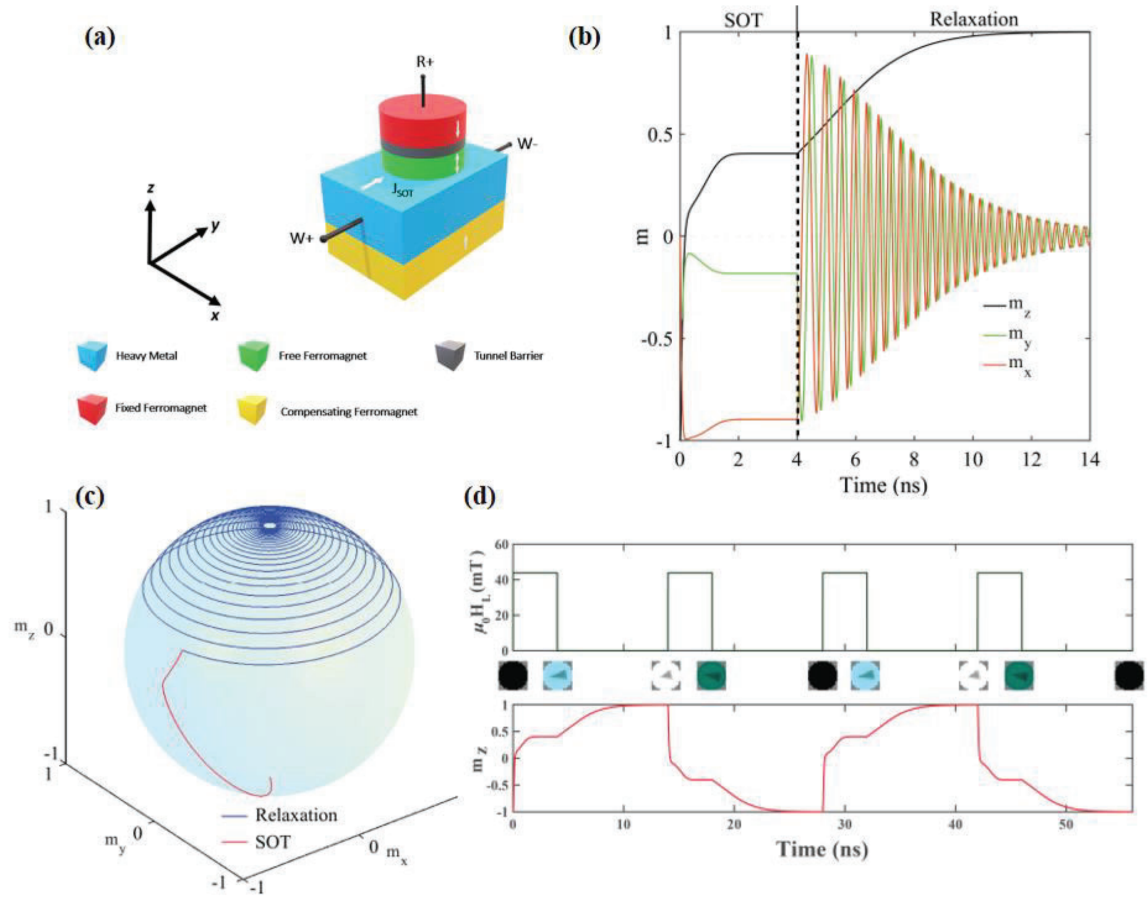

Fig. 1(a) Structure of three-terminal toggle SOT-MRAM. (b) Time vs. free ferromagnet magnetization for single toggle operation. (c) Trajectory of the magnetization in 3D. (d) Consecutive toggle operations.

plane in less than 200 ps and stabilizes at a toggled state in ~2 ns due to interplay between the field-like SOT excitation and PMA [1]. Finally, removal of the SOT excitation quickly relaxes the magnetization along the nearest easy axis direction, thus completing the toggle writing process. The application of consecutive SOT excitations repeatedly toggles the MRAM state, as shown in Fig. 1(d). For directional MRAM writing, the stored bit can be read and compared to the incoming data bit with a simple XOR gate to enable total directional programming times below 10 ns [1].

Robustness analysis from micromagnetic simulations has shown that the proposed toggle MRAM switches deterministically with greater than 50% tolerance to applied SOT current magnitude [1]. Moreover, room temperature simulations indicate that this switching is robust to thermal noise. The proposed toggle SOT-MRAM device therefore provides a promising approach for a new generation of compact, highly-efficient, and robust PMA-MRAM with sub-10 ns writing by field-free SOT switching.

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