

Figure 1. (a) Resistance vs magnetic field at various SOT currents. (b) SOT switching curves for the device with and without Hf interlayers.

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BC-08. Highly Efficient Spin-Orbit Torque Magnetization Switching in a Perpendicularly Magnetized Ferromagnetic-Semiconductor Single Layer: Damping Like Torque and Field Like Torque. *M. Jiang¹, H. Asahara¹, S. Sato¹, S. Ohya^{1,2} and M. Tanaka^{1,2}* *1. Dept. of Electrical Engineering, The Univ. of Tokyo, Tokyo, Japan; 2. Center for Spintronics Research Network (CSRN), Graduate School of Engineering, The Univ. of Tokyo, Tokyo, Japan*

Spin-orbit torque (SOT) magnetization switching, which is induced by a spin current generated by a charge current, is a promising phenomenon that can be used to improve the performance of magnetoresistive random access memory. In our previous study, we achieved a highly efficient full SOT magnetization reversal in a GaMnAs single layer by applying a very low current density (J_c) of $3.4 \times 10^5 \text{ A cm}^{-2}$ [1], which is two orders of magnitude smaller than that required in the conventional SOT systems [2]. According to the Landau-Lifshitz-Gilbert (LLG) equation, the SOT is contributed by two parts; damping like torque (DLT) and field like torque (FLT). By fitting simulated results using the LLG equation to the experimental results, we clarified that the DLT is dominant during the magnetization switching in the 7-nm-thick GaMnAs single layer. Here, we explore the contributions of DLT and FLT by inducing the SOT switching in perpendicularly magnetized GaMnAs single layers with different thicknesses; $d = 5 \text{ nm}$, 7 nm , 10 nm , and 15 nm as shown in Fig. 1. In the GaMnAs single layer with $d = 5 \text{ nm}$, SOT magnetization switching (dominated by DLT) is observed with $J_c = 1.6 \times 10^5 \text{ A cm}^{-2}$, which is even smaller than that of our previous paper [1]. With the increase of d , the FLT starts to act on the magnetization switching and competes with the DLT. When $d < 15 \text{ nm}$, J_c increases as d increases, which is caused by the enhancement of the contribution of FLT. At $d = 15 \text{ nm}$, the switching polarity is totally reversed, indicating that the FLT becomes dominant. This result is understandable, considering that the acting direction of FLT is opposite to that of DLT. Our finding will advance the understanding on the contributions of DLT and FLT during the SOT switching in GaMnAs single layer. This work was partly supported by Grants-in-Aid for Scientific Research (No. 16H02095, No. 18H03860), CREST program of Japan Science and Technology Agency (JPMJCR1777), Spintronics Research Network of Japan (Spin-RNJ), and China Scholarship Council (No. 201706210086).

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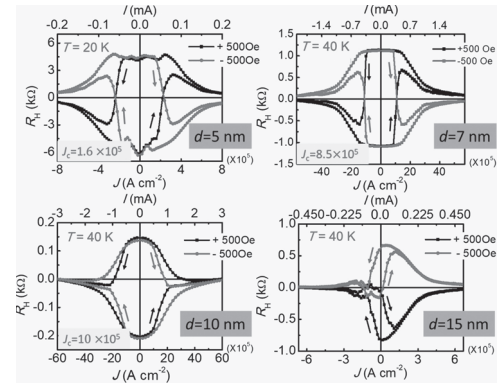


Fig. 1 Thickness dependent spin-orbit torque magnetization switching in a GaMnAs single layer. (The values in the yellow rectangles are J_c of the corresponding samples with a unit of A cm^{-2} .)

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BC-09. Toggle Mode Spin-Orbit Torque Driven Perpendicular Magnetic Anisotropy MRAM. *N. Hassan¹, S.P. Lainez-Garcia¹, F. Garcia-Sanchez^{2,3} and J.S. Friedman¹* *1. Electrical & Computer Engineering, The University of Texas at Dallas, Richardson, TX, United States; 2. Istituto Nazionale di Ricerca Metrologica, Torino, Italy; 3. Dipartimento de Fisica Applicada, Universidad de Salamanca, Salamanca, Spain*

Spin-orbit torque (SOT) is a high speed and energy efficient writing technology for magnetic random-access memory (MRAM) that prevents device degradation by separating the read-write path [1]. However, orthogonality between the in-plane polarized SOT current and thermally stable perpendicular magnetic anisotropy (PMA) inhibits deterministic MRAM switching. Several approaches have been proposed to break this symmetry, including an in-plane magnetic field [2], deformation of the device structure [3], tilted anisotropy [4], an antiferromagnet-ferromagnet bilayer system [5], and competing spin currents [6]. However, all of these approaches increase the fabrication complexity, are highly sensitive to the SOT current duration and magnitude, or increase the switching energy. We therefore propose toggle PMA SOT-MRAM [7], which exploits the precessional nature [8] of field-like SOT to achieve field-free and energy-efficient switching with a simple structure that is robust to the SOT current magnitude and duration. The structure is a three-terminal magnetic tunnel junction that consists of a heavy metal, free ferromagnet, insulating tunnel barrier, and compensating ferromagnet. A unidirectional SOT current applied through the heavy metal causes the free ferromagnet magnetization to stabilize at an excited steady state after crossing the hard axis plane. Switching off the excitation relaxes the magnetization to the nearest easy axis, thus completing a toggle cycle. Application of the next excitatory pulse toggles the magnetization back to its initial state. Micromagnetic simulations demonstrate robust switching, with greater than 50% tolerance to applied SOT current magnitude. This deformation-free structure provides efficient data read-out, and the toggle switching can be leveraged for directional writing through a simple XOR between the current and incoming bits. The proposed device therefore provides a promising solution for compact, highly-efficient, and robust SOT-MRAM with PMA.

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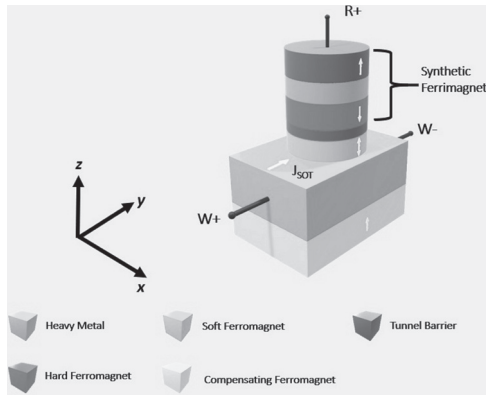


Fig. 1. Schematic of three-terminal toggle SOT-MRAM.

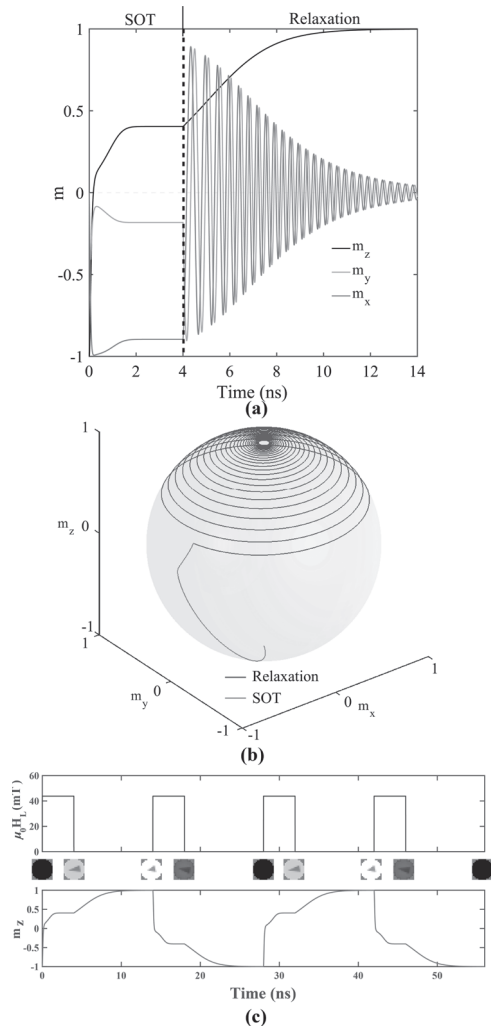


Fig. 2. (a) Time vs. free ferromagnet magnetization for single toggle operation. (b) Trajectory of the magnetization in 3D. (c) Consecutive toggle operations.

BC-10. Materials Requirements of High-Speed and Low-Power Spin-Orbit-Torque Magnetic Random-Access Memory. X. Li^{1,2}, C. Yao², M. DC¹, W. Tsai³, S. Lin³ and S. Wang^{1,2} 1. *Materials Science and Engineering, Stanford University, Stanford, CA, United States;* 2. *Electrical Engineering, Stanford University, Stanford, CA, United States;* 3. *TSMC, Hsinchu, Taiwan*

As spin-orbit-torque magnetic random-access memory (SOT-MRAM) is being intensively researched as the next-generation ultralow-power and high-speed on-chip cache memory solution [1], it is critical to identify the required materials properties to deliver the desired power and performance mandated by on-chip integration based on two transistor-one magnetic tunnel junction (2T-1MTJ) design. In this presentation, we will first discuss the circuit-level goals for replacing different levels of SRAM cache using SOT-MRAM. Then, array- and device-level materials requirement to achieve the above goals will be described, including the SOT material and the magnetic tunnel junction (MTJ). Last, we will briefly present an outlook of promising approaches to realize high-density 2-terminal SOT-MRAM crossbar architecture [2] and accompanying materials requirements. This work will provide important guidelines for SOT-MRAM materials and device research in the future. In particular, the typical 2 transistor-1 SOT-MTJ cell will be modeled in an effective circuit model as shown in Figure 1. Here, we include the parasitic resistance from the metal electrodes and the SOT layer, as well as the transistor itself. We will both analyze the read and write operation of the SOT-MTJ cell and their respective materials requirement. It is worth noting that a few works [3][4] have already discussed the write current shunting effect due to the ferromagnetic free layer (FL) sitting on top of the SOT layer during write operation as shown in Figure 1(a). However, to fully evaluate what are the best materials properties to be used in a SOT-MRAM cell, the transistors resistance and capacitance are also critical parameters to include. We find that to achieve the lowest power and latency, it is crucial to match the SOT layer material properties, such as resistivity, width, and length to that of the transistor if we consider the SOT efficiency of the material remains unchanged. The authors thanks NSF Center for Energy Efficient Electronics Science (E3S) and TSMC for financial support. This research was supported in part by ASCENT, one of six centers in JUMP, a Semiconductor Research Corporation (SRC) program sponsored by DARPA.

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