Multi-bit magnetic memory based on a vertically magnetized pillar on two perpendicularly magnetized pinning layers

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We propose a novel multi-bit magnetic memory structure based on a vertically magnetized pillar placed on two perpendicularly magnetized pinning layers. The magnetization in the pillar is controlled by a spin-polarized current flowing from the pillar into one of the two pinning layers, and its behavior is investigated using micromagnetic simulations. The two pinning layers are magnetized in opposite directions. Depending on the magnetization direction at the bottom of the pillar, a domain wall is formed between the pillar and one of the pinning layers. When a spin-polarized current flows through this domain wall, it expands into the pillar, resulting in reversal of the magnetization at the pillar's bottom. By selecting the pinning layer through which the spin-polarized current flows, domain wall motion can be selectively induced to either reverse or preserve the magnetization direction. This enables control over the magnetization configuration within the pillar, which represents the bit pattern of the stored information. The simulation confirms that two bits of information can be written into a single pillar. This multi-bit memory structure operates with three terminals, and a circuit comprising several such pillars is also proposed.

***Index Terms*— Magnetic memory, Nonvolatile memory, Spintronics, Numerical simulation**

I. Introduction

Vertically magnetized multi-domain nanopillars have attracted attention as promising structures for realizing high-density multi-bit memory devices [1]. In such structures, domain wall (DW) motion is induced by spin-transfer torque (STT) generated by a spin-polarized current (SPC) flowing through the pillar. By shifting domains upward via DW motion, their magnetization directions can be sequentially detected using a magnetic tunnel junction (MTJ) placed at the top of the pillar. One of the major challenges in realizing this type of memory is the reliable control of magnetization at the bottom end of the pillar.

Several structures have been proposed to address this issue. In these designs, magnetization is controlled by passing SPC through the pillar while injecting transverse spins into its bottom end [2]. However, magnetization control using this method has not yet been demonstrated experimentally. Developing an alternative technique for achieving reliable control of pillar magnetization is therefore a critical step.

In this study, we propose a new method that controls pillar magnetization using only current-induced DW motion. The effectiveness of the proposed method is verified through micromagnetic simulations.

II. Proposed Structure

The proposed structure and operation are illustrated in Fig. 1. Two perpendicularly magnetized pinning layers are separately placed beneath the ferromagnetic nanopillar. These pinning layers are magnetized in opposite directions. Although electrically isolated from each other, they are both electrically connected to the lower end of the pillar. Because the pillar is magnetized along its longitudinal axis, one of the pinning layers forms a continuous magnetic domain with the pillar, while a DW appears between the pillar and the other pinning layer. The MTJ includes an additional layer at the top of the pillar, though this layer is omitted in Fig. 1.

The structure allows SPC to selectively flow from the top of the pillar to either of the two pinning layers. By switching the current path, the magnetization configuration within the pillar can be manipulated. When the SPC flows through the side where a DW is present, the DW propagates into the pillar, creating a new magnetic domain at its bottom. Then, the DW splits into an upper and a lower part. The lower DW then moves toward the opposite pinning layer. Simultaneously, the upper DW moves upward. In contrast, when the SPC flows through the side without a DW, the magnetization at the pillar's bottom is preserved, while the DW within the pillar shift toward the top. This mechanism enables control of the magnetization pattern within the pillar via current path selection. The described behavior was validated through micromagnetic simulations.

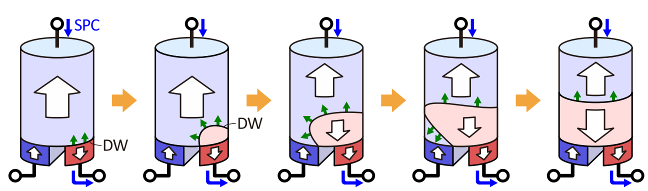

Fig. 1. Schematic of magnetization reversal process of the novel magnetic memory structure of ferromagnetic pillar on two perpendicularly magnetized thin layers. The large white arrows denote the magnetized directions. The direction of each blue arrow denotes the current direction of the SPC. The direction of each green small arrow denotes the direction of the DW motion.

III. Model and Methods

We considered a cylindrical ferromagnetic pillar measuring 50 nm in length along the *z*-direction and 20 nm in diameter. Two 5 nm thick perpendicularly magnetized pinning layers were attached beneath the pillar, as shown in Fig. 2(a). The pinning layers were modeled with semicircular cross-sections to match the pillar's geometry. The separation between the two layers was set at 2 nm. The entire structure was discretized into cubic cells of 1.0 nm³. Magnetization dynamics in each cell were computed using the Landau–Lifshitz–Gilbert (LLG) equation, incorporating the STT term [2,3].

The pillar was assumed to have a saturation magnetization M_s of 100 kA/m, an exchange stiffness constant A of 1.0 pJ/m, and a perpendicular magnetic anisotropy energy density K_u of 0.1 MJ/m³ [3]. The pinning layers shared the same values for M_s and A but had a higher K_u of 2.0 MJ/m³ to stabilize their magnetization. The SPC was applied from the top of the pillar to the left pinning layer. Spin current conversion was modeled assuming a spin polarizability of $P = 0.5$ [3]. The initial magnetic states were set with magnetization along the $+z$-direction in both the pillar and right pinning layer, and along the $-z$-direction in the left pinning layer. The system was then allowed to relax (Fig. 2(b)).

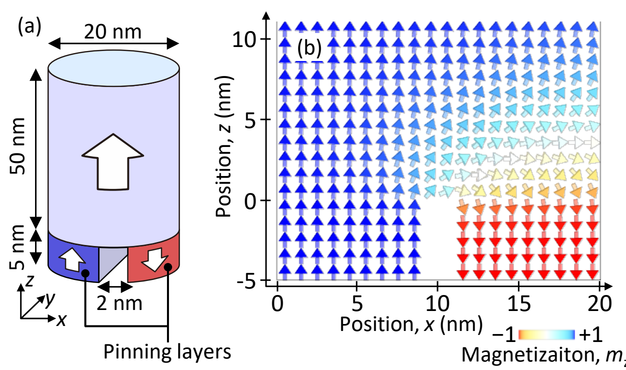

Fig. 2. (a) Structure and (b) initial magnetic state for the micromagnetic simulation. A magnified view of the lower part of the pillar is shown in (b). White arrows in (a) and small arrows in (b) indicate the magnetization direction.

IV. Results and Discussions

A micromagnetic simulation was performed to reverse the pillar's magnetization from the $+z$-direction to the $-z$-direction. A DW formed above the right pinning layer. Figure 3 shows the simulation results when a SPC was continuously applied from the top of the pillar through the right pinning layer. The current density of the SPC was of 5.0×10^{11} A/m² at the top of the pillar. As the SPC started flowing, the DW began moving upward, causing the $-z$-magnetized region to expand (Fig. 3(b)). One end of the DW was pinned at the branching point, where the pillar connected to the two pinning layers, and the DW expanded toward the left side of the pillar (Fig. 3(c)). Eventually, the expanding DW contacted the left surface of the pillar (Fig. 3(d)) and split into upper and lower parts (Fig. 3(e)). The lower part of the split DW stabilized near the right pinning layer, while the upper part continued to propagate upward toward the top of the pillar. Consequently, the entire magnetization of the pillar was reversed in the $-z$-direction (Fig. 3(f)).

When the pillar is magnetized in the $-z$-direction, applying the SPC from the pillar to the $+z$-magnetized left pinning layer causes a magnetization reversal to the $+z$-direction, following a process similar to that of the reversal to the $-z$-direction via the right pinning layer. During this process, the DW initially formed above the right pinning layer shifts above the left pinning layer.

As shown in Fig. 3(e), during the reversal process, the magnetization is vertically divided into upward and downward regions, corresponding to a two-bit intermediate state. Interpreting these magnetization configurations as two-bit states, four distinct states—"00," "01," "10," and "11"—can be realized. In this case, the pillar length was selected to allow the formation of a single DW. However, a longer pillar capable of supporting multiple DWs can store more information.

An example of a circuit comprising a multipillar structure is shown in Fig. 4. Because SPCs must be applied to both pinning layers, each pillar requires three terminals, and two interconnects must be provided at the bottom of each pillar. Additionally, because SPCs flow from the top to the bottom of the pillar, device selection can be achieved using both selector transistors and diodes.

In summary, a novel multi-bit memory structure utilizing a three-terminal pillar has been proposed. Its operations have been demonstrated through the micromagnetic simulations, underscoring its promise for the development of high-density multi-bit memory devices.

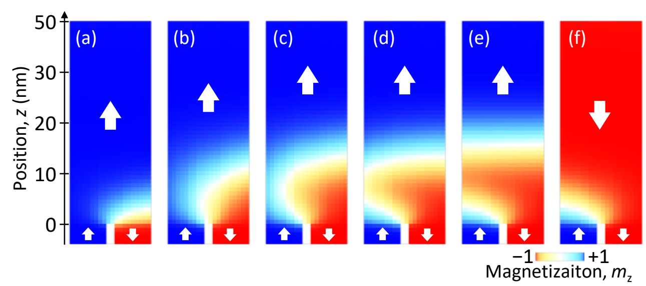

Fig. 3. Snapshots of the magnetic structure in the magnetization reversal prosses at time, t = (a) 0 ns, (b) 8 ns, (c) 16 ns, (d) 17 ns, (e) 18 ns, and (f) 24 ns. Each white arrow denotes the magnetization direction.

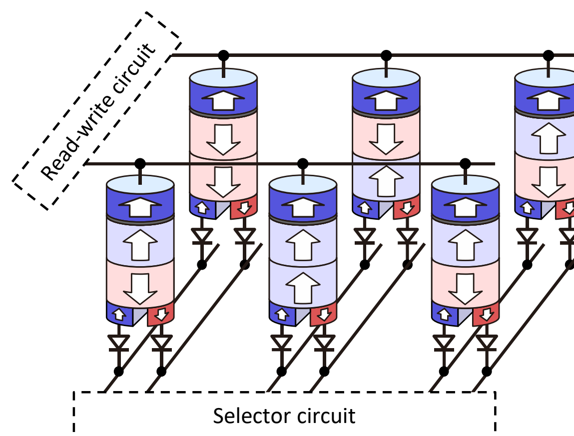

Fig. 4. Example circuit comprising six pillars with MTJ and individual diodes.

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