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Letter to Editor

Experimental demonstration of programmable multi-functional spin logic cell based on spin Hall effect

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ABSTRACT

Confronting with the gigantic volume of data produced every day, raising integration density by reducing the size of devices becomes harder and harder to meet the ever-increasing demand for high-performance computers. One feasible path is to actualize more logic functions in one cell. In this respect, we experimentally demonstrate a prototype spin-orbit torque based spin logic cell integrated with five frequently used logic functions (AND, OR, NOT, NAND and NOR). The cell can be easily programmed and reprogrammed to perform desired function. Furthermore, the information stored in cells is symmetry-protected, making it possible to expand into logic gate array where the cell can be manipulated one by one without changing the information of other undesired cells. This work provides a prospective example of multi-functional spin logic cell with reprogrammability and nonvolatility, which will advance the application of spin logic devices.

1. Introduction

Spin logic is of great interest as its desired property of nonvolatility and subsequentially the potential for realizing the idea of processing in memory architecture which is regarded to play increasingly important role in today's fast-growing volumes of data. Many efforts have been dedicated to explore the prospective candidates of spin logic gate in different systems such as semiconductors [1,2], Oersted-field controlled magnetic tunnel junctions [3], magnetic domain engineered nanowires [4], phase-change material [5], graphene [6,7] and magnetoelectric oxides [8]. However, only a few of them are compatible with complementary metal oxide semiconductor (CMOS) architecture, which limits their practical applications. On the other hand, confronted with huge volumes of data, the demand for high-performance computer naturally becomes an urgency. The traditional solution guided by Moore's law is to miniaturize logic device so as to increase the total number of logic gates, which, however, is hampered by the physical and lithographic restrictions [9–11]. One feasible path is to integrate different logic functions into a single cell, which is nearly impossible for current silicon-based logic device [11]. In this regard, the interplay between orbit and spin has provided new possibilities for electrical manipulation of magnetization. The magnetization switching based on the spin-orbit torques (SOT) induced by spin Hall effect (SHE) has been demonstrated in heavy metal/ferromagnet heterostructures not only with in-plane anisotropy [12,13] but with perpendicular anisotropy [14–18].

Here, we experimentally demonstrate a prototype spin logic cell integrated with five Boolean functions (AND OR NOT NAND and NOR) in perpendicularly magnetized Pt/Co/MgO system. The spin logic cell can be programmed between different logic functions by changing the direction of magnetic field and initial magnetic state. By carefully arranging experimental setup, the robustness of the information stored in cells is intrinsically guaranteed by the symmetry requirements of SOT-induced magnetization switching. This work provides a promising candidate for highly integrated multi-functional spin logic cell with programmability and compatibility with current CMOS architecture.

2. Results

As-deposited Pt(5)/Co(0.8)/MgO(2)/Pt(2) stacks (thickness in nm) have in-plane easy axis which gradually reorients normal to the film plane after annealing above 250 °C under a 7 kOe perpendicular magnetic field. The perpendicular anisotropy of our samples reaches maximum at annealing temperature of 400 °C. Further increase in annealing temperature will result in the degradation of PMA. The following data is based on samples after 400 °C annealing process in a perpendicular magnetic field. Hall measurement of the sample is shown in Fig. 1b. Sharp change of the anomalous Hall resistance R_{xy} was observed for the out-of-plane magnetic field, while it took over 6 kOe to saturate the magnetization for the in-plane field, which

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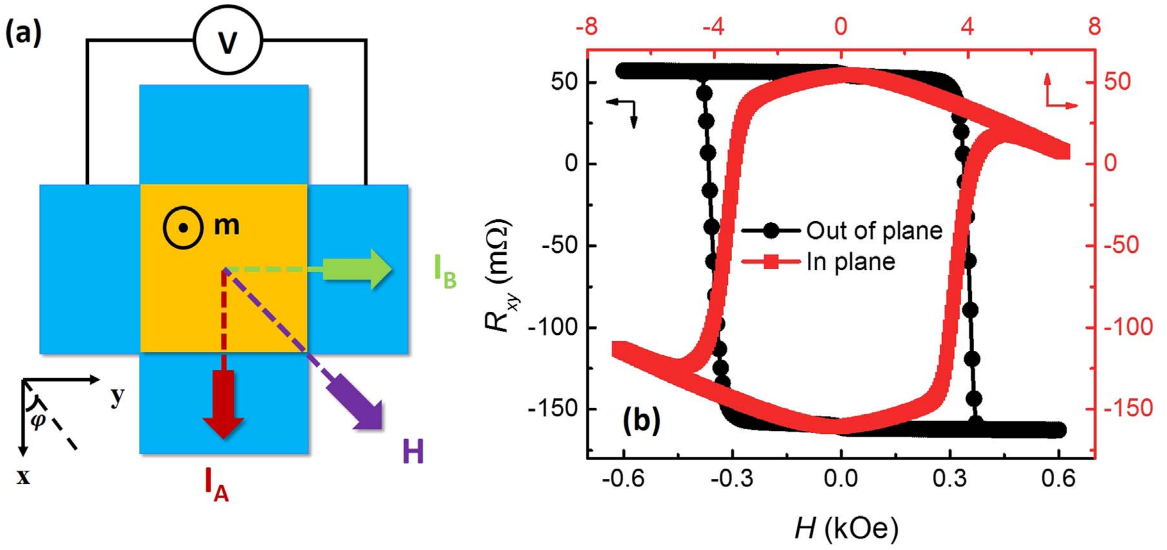

Fig. 1. Measurement setup and magnetic characterization (a) Schematic illustration of experimental setup. I_A is along x direction, I_B along y direction and H along the angle bisector of I_A and I_B. φ is the in-plane angle with respect to $+x$. (b) Hall measurement under out-of-plane field (black circle) and in-plane field (red square). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

confirms the perpendicular anisotropy of the samples.

The film was patterned into cells with cross-shaped Hall bar with 20*20 μm^2 center region, as shown in Fig. 1a. Two currents with identical amplitude, I_A and I_B, which are orthogonal to each other, were applied simultaneously to destabilize the magnetic state of the cell. Then, a small I_A was applied as a read current to pick up the anomalous Hall resistance R_{xy}, which reveals the magnetic state of the system. An in-plane magnetic field H was applied along the angle bisector between I_A and I_B, i.e. φ=45° for $H>0$ and φ=225° for $H<0$. Fig. 2 plots the current-induced switching under different measurement conditions. Before the current sweeping, the system was initialized to $+m_z$ or $-m_z$. Two current configurations were utilized to perform the measurements i.e. I_A and I_B are applied with the same polarity (I_A=I_B configuration) and with the opposite polarity (I_A=−I_B configuration), and the definition of the current polarity is shown in Fig. 1a. Two distinct behaviors are manifested under two kinds of current configurations. For I_A=I_B configuration, complete magnetization switching loop was observed, which is independent of initial magnetic state. The critical current is 50 mA and, importantly, the sequence of magnetic reversal process changed from clockwise to anti-clockwise when H=−120 Oe was switched to the opposite direction H=+120 Oe. On the other hand, for I_A=−I_B configuration, the magnetic state follows its initial magnetization and remains unaffected by changing both the direction of H and the amplitude of applied currents within range of 55 mA.

Based on the different behaviors in two kinds of current configurations, we propose a prototype spin logic cell making use of this symmetry-dependent switching characteristics. Fig. 3 shows the logic performance of this spin logic cell. Five logic functions, i.e. OR, AND, NOR, NAND and NOT, are all realized in the same cell. I_A and I_B serve as two independent input channels and the operation currents are determined to be +55 mA for logic input 1 and −55 mA for logic input 0. The logic output is carried by magnetic state, which in turn is reflected by anomalous Hall resistance R_{xy}. For all five logic functions, the reference R_{xy} is designed to be −300 $m\Omega$ above which we define the logic output 1 ($+m_z$ state) and below which we define the logic output 0 ($-m_z$ state). We adopt two-step operation to execute a single logic test. The first step is initialization, that is, we set the cell to a certain initial state. The second step is logic operation. Four logic input combinations are applied one by one to the programmed cell to check the consistency with the truth tables.

For OR gate (Fig. 3a), H of +1200 Oe is applied and the magnetic state was initialized to $+m_z$ (logic '1' state) before each logic operation. For I_A=I_B configuration, +55 mA, i.e. logic input (1, 1), will select $+m_z$ state leading to logic output 1, while −55 mA, i.e. logic input (0, 0), will reverse the state to $-m_z$, giving logic output 0. For I_A=−I_B configuration, both logic input (1, 0) and (0, 1) cannot drive the cell away from its initial state $+m_z$, exporting logic 1.

For AND gate (Fig. 3b), the same H is applied. The only condition

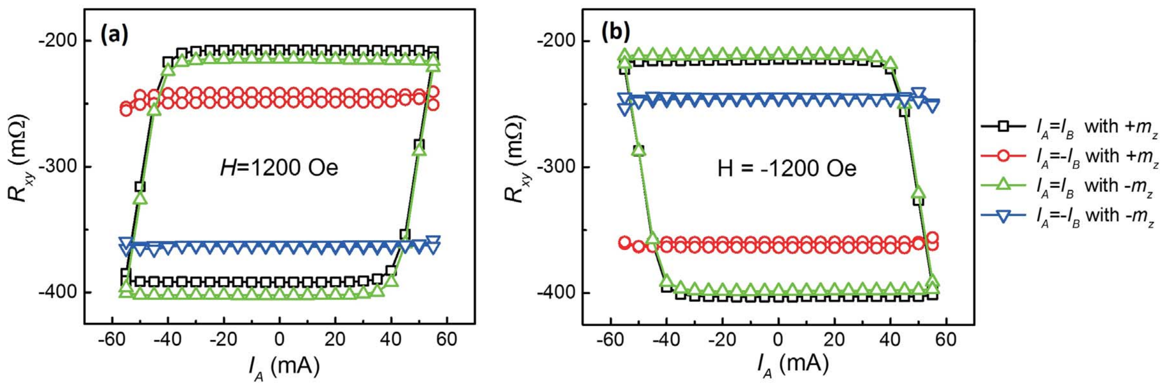

Fig. 2. Current-induced magnetization switching measurements. (a) H=1200 Oe and (b) H=−120 Oe. For each magnetic field, I_A=I_B configuration (black square and green up triangle) and I_A=−I_B configuration (red circle and blue down triangle) were used. Before current sweeping, the system was initialized to $+m_z$ (black square and red circle) or $-m_z$ (green up triangle and blue down triangle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)