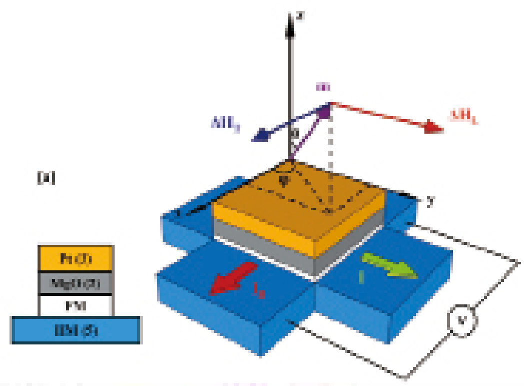
Nonvolatile Multifunctional Programmable Spin Logic Cell

In this era of colossal data, more than 2 quintillion bytes of data were created every day. The huge amount of data brings us not only unprecedented convenience and opportunities but also incomparably severe challenges in data processing at the same time. The processing performance of computers is known to be determined almost entirely by the logic devices. However, the traditional strategy that aims at miniaturization of logic devices to increase the density of integration is going to encounter a ceiling set by the physical and lithographic restrictions. Communities in the field of condensed matter physics, microelectronics and material sciences are thus now urgently searching for probable alternatives. One promising candidate is the spin-based logic device.

The nonvolatile nature of magnetic system is an ideal property for the "processing in memory architecture", which is able to overcome the latency inherent to data transfer between processor and memory, known as the Von Neumann bottleneck, and hence able to improve the efficiency of data processing. In this regard, many spin-logic solutions based on domain wall motion, spin wave propagation or magnetic semiconductor have been proposed and some of them are even experimentally demonstrated. Nevertheless, further application requires the compatibility with complementary metal oxide semiconductor (CMOS) architecture, which can be hardly satisfied by aforementioned proposals. On the other hand, besides reducing the size of logic gates,



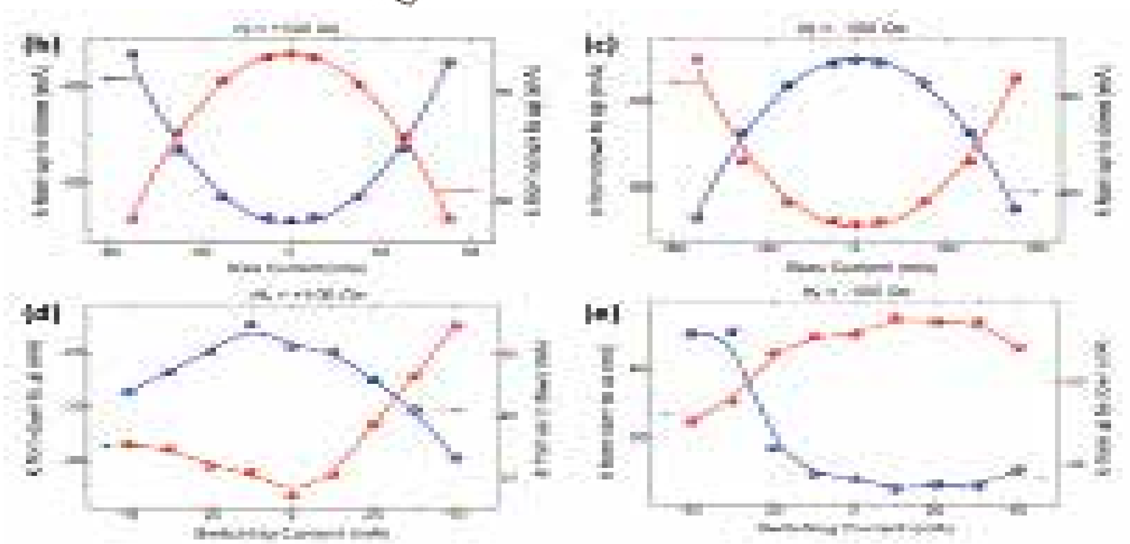


Fig. 1 a. Schematic illustration of measurement setup and film stack where FM is for ferromagnetic layer and HM for heavy metal layer. Bias current dependence of critical switching current for Pt/Co/MgO stack with b. H_y=+100 Oe and c. -100 Oe and for Ta/CoFeB/MgO stack with d. H_y=+100 Oe and e. -100 Oe, respectively.

increasing the number of operations performed per logic cell is one of the most feasible ways to improve the speed of computers, which is inaccessible by current silicon-based logic devices. A natural question arises: can we find such kind of logic cells that combine nonvolatility with multifunctionality and can be blended into CMOS architecture at the same time?

Answering this challenge, the M02 group led by Prof. HAN Xiufeng at the State Key Laboratory of Magnetism, Institute of Physics, CAS broke through in making a novel current-induced spin-logic prototype device based on the spin-orbit torques in the magnetic heterostructures. By means of microfabrication technique, two kinds of samples of typical magnetic heterostructures with perpendicular easy axis, *i.e.* Pt/Co/MgO and Ta/CoFeB/MgO, were patterned into cross-shaped Hall bar (Fig. 1a). The spin-orbit torque of electrical current in these two systems was characterized by lock-in technique. Furthermore, the influence of damping-like torque and field-like torque on magnetization switching was studied by applying two mutual-orthogonal currents (Figs. 1b-1e). Meanwhile, a macrospin model was carried out to provide insight to the experimental results, laying physical foundations for the further experiment of spin-logic prototype cell. In addition, field-free magnetization switching has been achieved by using a FM/AFM exchange bias structure. [Xuan Zhang, C. H. Wan and X. F. Han *et al*., Electrical control over perpendicular magnetization switching driven by spin-orbit torques. *Phys. Rev*. B 94 (2016) 174434; Wenjie Kong, C. H. Wan and X. F. Han* *et al*., Field-free spin Hall effect driven magnetization switching in Pd/Co/IrMnexchange coupling system, *Appl. Phys. Lett*.109 (2016) 132402].

Based on the cross-shaped structure, HAN's team experimentally demonstrates two kind of current-driven spin logic cells induced by spin Hall effect. For the first demonstration, two current sources acting as two logic inputs were applied to one channel of Hall bar. The logic input '1' and '0' are defined by different amplitude of two currents. Meanwhile, a finite auxiliary magnetic field was applied parallel or antiparallel to the current channel (Fig. 2a). The logic output is determined by the magnetic state of the ferromagnetic layer, characterized by anomalous Hall resistance. According to the magnetization switching behavior under different magnetic field and logic inputs, five typically used logic functions (AND, OR, NOT, NAND and NOR) have been realized in a single logic

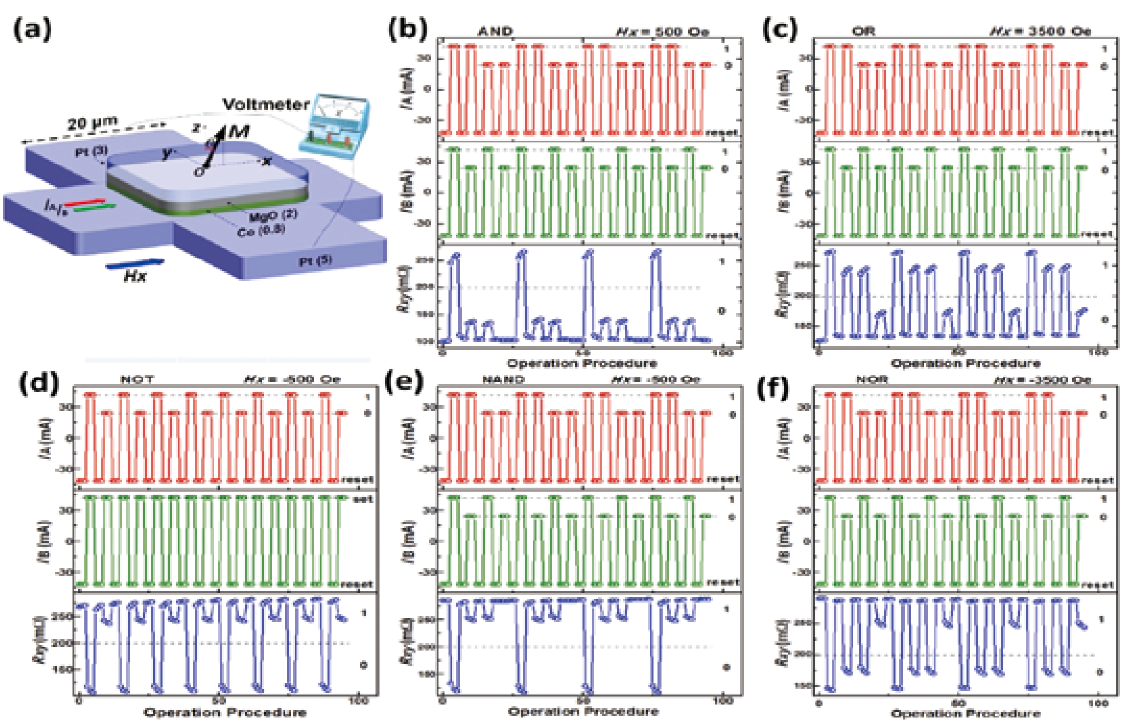


Fig 2a. Schematic illustration of measurement setup and film stack. Logic function test for a single logic cell. b. AND c. OR d. NOT e. NAND and f. NOR

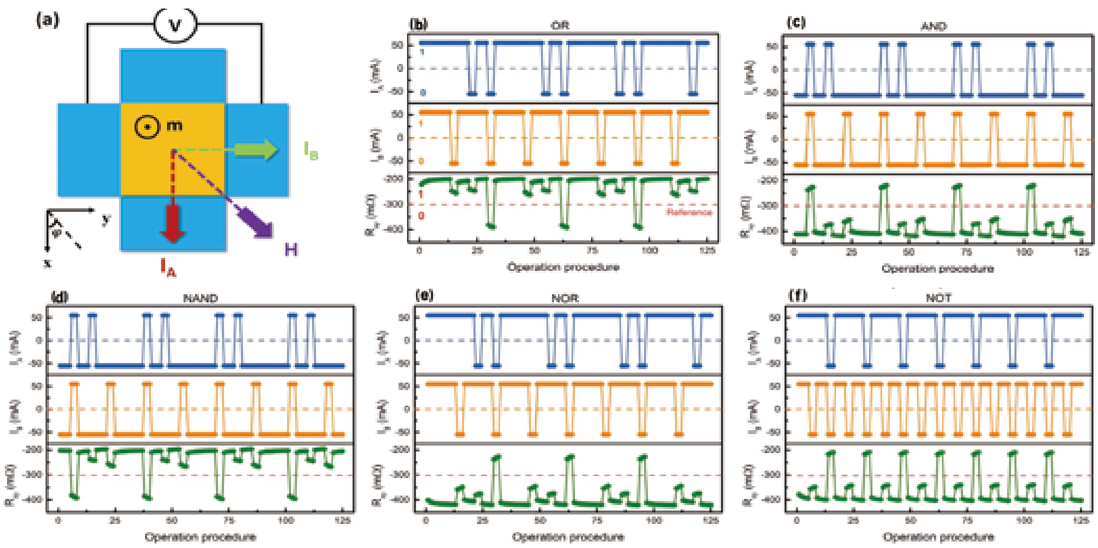


Fig. 3a. Schematic illustration of measurement setup and film stack. Logic function test for a single logic cell. b. OR c. AND d. NAND e. NOR f. NOT

cell. Furthermore, the logic cell can be programmed by applying different magnetic field to perform designed logic function (Figs. 2b-2f). This work has been published in *Advanced Electronic Material* [C. H. Wan, Xuan Zhang and X. F. Han* *et al*., Programmable spin logic based on spin Hall effect in a single device, *Adv. Electron. Mater*. 3 (2017) 1600282].

As for the second demonstration, two currents of the same amplitude were applied separately to two mutual-orthogonal channels of Hall bars as logic inputs. The direction of the current serves as the logic input '1' or '0'. A magnetic field was applied along the angle bisector between two currents (Fig. 3a). Based on the magnetization response to different magnetic field and input currents, five logic functions, *i.e*. AND, OR, NAND, NOR and NOT, can also be implemented in a single cell (Figs. 3b-3f). Programmability lies in the initial magnetic state and the polarity of the magnetic field.

It is worth noting that in the second demonstration, the team takes advantage of the symmetry restrictions of current-induced magnetization switching driven by spin Hall effect. Information stored in such a logic cell is symmetry-protected, which makes the information immune to the stimulation from any single current pulse. On the one hand, it guarantees the robustness of the information in the logic cell during the logic operation. On the other hand, this property makes it convenient to expand this kind of spin logic cells into a programmable logic gate array in which each cell is able to be manipulated precisely, *i.e*., only the desired cell stimulated by two currents can be operated without influencing the rest, which provides possibility to process complicated problems. This work has been published in the *Journal of Magnetism and Magnetic Materials* as a *Letter to Editor*. [Xuan Zhang, C. H. Wan and X. F. Han* *et al*., Experimental demonstration of programmable multi-functional spin logic cell based on spin Hall effect, *J. Magn. Magn. Mater*. **428** (2017) 401, *Letter to Editor*]

In the above-mentioned demonstrations, the nonvolatility, multifunctionality and programmability have all been realized in the spin logic cell. Besides, the adopted magnetic heterostructure is easy to expand so as to meet the compatibility to CMOS architecture. This progress might shed some new light on further scientific research as well as applied research aimed at device application.

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