Computer technology

An electrically operated magnetic logic gate

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Bits of a logic gate can be encoded by differently magnetized regions. A method has been developed in which the walls between these domains are manipulated electrically, rather than magnetically, to produce a logic gate. **See p.214**

Computer logic based on standard electronic components is expected to hit its speed and power limits before long. To get around this, logic devices that use magnetic elements, rather than electronic ones, have been proposed — but these usually require external magnetic fields, which limits their application. A working logic gate that uses magnetic elements and is driven completely electrically, without the need for an external magnetic field, has yet to be demonstrated[1]. However, on page 214, Luo *et al.*[2] report that they have harnessed the chirality ('handedness') of a system to invert the direction of magnetization of domains in a cobalt wire purely by means of an electric current. The resulting inverter device acts as a 'NOT' gate, which they use to build up other logic gates such as NAND and NOR.

First, some background. Magnetic domains are small regions of uniform magnetization in a material. The narrow boundaries separating different magnetization orientations are called domain walls; within the wall, the magnetization must gradually twist around. Such magnetic domains have long been used to encode data bits for storage, such as in hard disk drives, in which mechanical motion is needed to access the data.

By contrast, in magnetic racetrack memory[3] (which is still under development), no mechanical movement is needed. Instead, magnetic domains within hair-thin metal wires are moved by the flow of electric current in the wires. The trick to doing this lies in an interaction — the spin-transfer torque — between the magnetic moments of the domain walls and the spins of the moving electrons. Here, spin refers to a quantum property of the electrons; moment is the magnetic direction and strength; and the torque is a twisting interaction that tends to rotate the moments and thus move the walls.

In spin-transfer systems, the torque arises from current in the magnetic wire itself. But another type of torque, known as spin–orbit torque, is produced when the wire is placed on a layer of a non-magnetic heavy metal such as platinum, and the electric current flows in that layer instead (Fig. 1). In such systems, two effects add to each other to drive twisting in the domain walls more efficiently than in spin-transfer systems[4,5]. The first is that a spin current arises in the non-magnetic heavy-metal layer; the second effect, which is crucial to Luo and colleagues' work, is that an interaction between the two metals forces a specific chirality on the domain walls.

Chirality means handedness: like left and right hands, objects of opposite chirality have mirror symmetry, but cannot be superimposed on each other. Domain walls known as Néel-type walls can exhibit chirality when the direction of their magnetic moment is reversed, because there are two ways in which reversal can happen: the moment can undergo a right-handed twist or a left-handed one. (Moments can also spin in the plane of domain walls known as Bloch walls, but this mechanism is not used in Luo and co-workers' study.)

The chirality is produced by an effect called the Dzyaloshinskii–Moriya exchange interaction (DMI), which acts between the magnetic and non-magnetic metals. The DMI both establishes a specific chirality and favours the generation of the correct type of wall — a Néel wall — in Luo and colleagues' set-up. Researchers have previously recognized that chiral domain walls could be used in logic operations[6], but an all-electrical working logic has been hampered by the lack of a reliable working inverter, the key component for logic operations.

Luo *et al.* have ingeniously invented an inverter that flips the magnetic moments associated with incoming bits of data using spin–orbit torque. Building on their previous

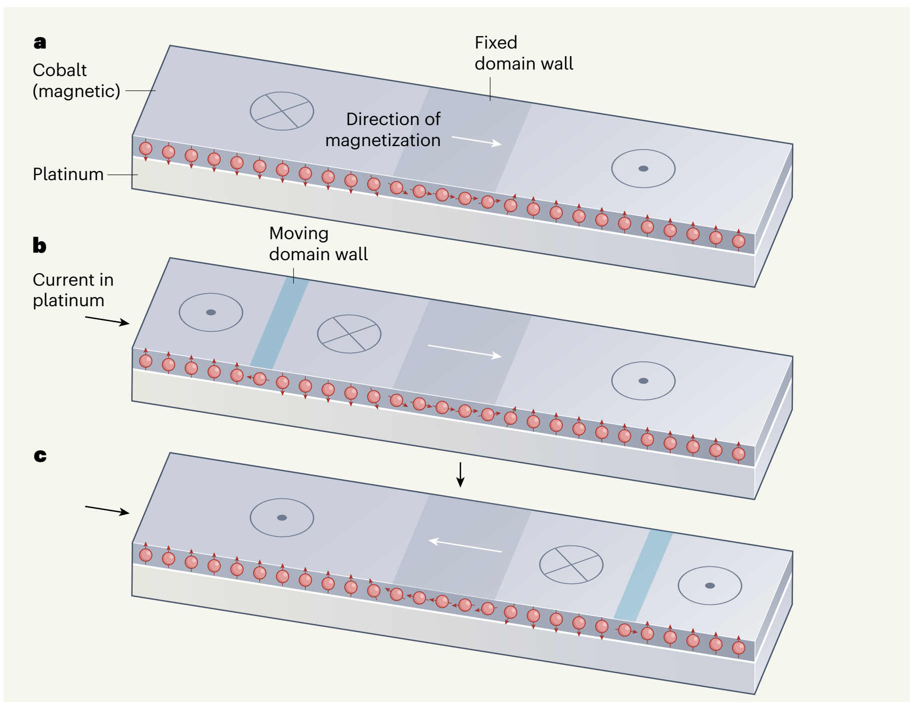

Figure 1 | How to flip magnetic data bits electrically. Luo and co-workers[2] have produced a NOT logic gate that flips the direction of magnetization of magnetic domains by electrical means. In the authors' system, mobile domains of a cobalt wire that have up or down magnetic moments act as data bits. From the side, spheres with arrows represent the direction of magnetization; on the top surface, circled dots and crosses indicate up and down moments, respectively. **a**, The authors fabricated a fixed wall between up and down domains, in which the magnetization direction can rotate in a left- or right-handed direction — a property called chirality. **b**, An electric current in the platinum substrate propels another, moving chiral domain wall (blue) along the wire. **c**, When two opposite magnetic moments collide on the left-hand side of the fixed wall, the direction of the moment in the fixed region switches. A new domain forms on the other side of the wall, in which the moment is reversed, preserving the preferred chirality of the system. Overall, the bit has been flipped. (Adapted from Fig. 1 of the paper[2].)

work on chirally coupled nanomagnets[7], the authors fabricated a sort of artificial, stationary domain wall in a magnetic cobalt wire interfaced with non-magnetic platinum. The magnetization in the cobalt is perpendicular to the plane of the wire, except in the stationary region. There, it is magnetized in the direction of the wire's long axis, like the region in the middle of an ordinary domain wall, but across a much larger width. This is crucial, because it allows smaller coercivity – that is, the magnetization here is easier to switch.

To picture how the inverter works, consider an input consisting of a domain wall that has left-handed chirality (Fig. 1). This mobile wall is rolled along the wire by spin–orbit torque. When it reaches the fixed artificial boundary, two opposite magnetic moments collide, producing a region of the wire in which the moment changes abruptly. According to theories of magnetism, such an abrupt change has a high energy cost. To lower the energy of the system, one of the moments must be switched, or a new magnetic domain must be generated. In this case, the moment in the low-coercivity fixed wall switches to the same direction as that in the incoming wall.

But a chirality effect now comes into play: this switch of magnetic moment produces a right-handed chirality at the other side of the fixed wall that conflicts with the chirality preferred by the DMI. To resolve this, a new domain wall forms on that side (the system is shaped in such a way as to promote this process) and sets off along the wire. The moments in the resulting outgoing bit thus have the preferred left-handed chirality, rather than the right-handed chirality originally produced at the wall.

By integrating their inverters into junctions, Luo *et al.* designed some simple logic gates (NAND and NOR), as well as more-complicated ones (such as exclusive-OR). Each junction has two inputs, an intrinsic bias towards one magnetic moment and one output. The output is determined by the two inverted inputs and by the bias at the junctions (rather like a 'majority gate'[8]). So, when the inputs and bias are (0,0) and 1, respectively, inverters immediately before the junction invert them to (1,1) and 0 at the junction itself, which consequently outputs 1, acting as a NOT gate. But when the inputs are either (1,0) or (0,1), the value of the bias determines whether the gate behaves as a NOR or a NAND. This majority-gate behaviour mitigates the need to precisely synchronize the two inputs, offering reliable logic operations.

This logic system satisfies key criteria known as cascadability and fan-out. Cascadability means that the output of one gate is produced in the correct form and is strong enough to drive the input of the next gate. And fan-out means that one gate output can be connected to several gate inputs[9]. Moreover, the data can be stored in the absence of an external power source, and evade damage by ionizing radiation.

Challenges remain before chips based on Luo and co-workers' system can reach the market. The operating current will need to be reduced so that it can be accommodated by tiny complementary metal oxide semiconductor (CMOS) transistors, which help to pick up inputs and outputs for use in chips. In theory, current decreases as the size of wires and transistors decreases, and so current density (the charge per unit time that flows through a given cross-section of the wire) remains constant with scaling. A reduction in current density will be needed to increase the speed and reduce the energy consumption of the authors' system. Domain-wall velocity does not scale linearly with current, and so new materials might need to be used to reduce the current density[10,11].

Another issue is that the input and output states of Luo and colleagues' system have to be detected by microscopy, rather than by an electrical method. A different read-out system will be needed for practical applications, but this could be technically challenging. An effect known as tunnelling magneto-resistance might offer one solution[12]. The implementation of a domain-wall logic chip that uses an electrically driven read-out system should be the next goal, following on from Luo and colleagues' exciting discovery.

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Neuroscience

Research on the cerebellum yields rewards

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A brain structure called the cerebellum has mostly been associated with learning from errors. The discovery that the cerebellum is also involved in reward-driven learning in monkeys implies a previously unappreciated role in cognition.

People and organizations alike use rewards, from snacks to salary bonuses and frequent-flyer miles, to shape behaviour through a process called reinforcement learning. For example, if a dog receives a treat for rolling over in response to a verbal command, the likelihood of that behavioural response to the verbal cue will increase. Writing in *Neuron*, Sendhilnathan and colleagues[1] describe neuronal signals that could support such reward-driven learning. What is remarkable is where the authors found these signals – not in the brain areas that have long been implicated in reinforcement learning, but in the cerebellum, a brain structure historically associated with error-driven, rather than reward-driven, learning.

The cerebellum is best known for its role in motor-skill learning – the process by which movements become smooth and accurate through practice. Fifty years of research[2] supports the idea that when you practise a movement, such as your tennis backhand, the cerebellum uses feedback about errors to gradually refine the accuracy of the movement by weakening the neuronal connections that are responsible for those errors. It has been widely assumed that the cerebellum uses a similar, error-correcting learning algorithm to support cognition[3], because the regions of the cerebellum that contribute to cognitive functions such as navigation[4] and social behaviour[5] have the same basic circuit architecture as those that control movement.

In the past three years, however, there has been a flurry of studies showing reward-related neuronal activity in the cerebellum[6–12]. What are reward signals doing in an error-correcting part of the brain? Sendhilnathan *et al.* leveraged the rapid learning abilities of monkeys to gain fresh insights into reward-related signalling in the cerebellum.

In each experimental session, the authors presented a monkey with two visual cues it had never seen before on a computer screen.