Memory on the racetrack

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Racetrack memory stores digital data in the magnetic domain walls of nanowires. This technology promises to yield information storage devices with high reliability, performance and capacity.

Magnetic hard disk drives have been the prime repository of digital data for more than half a century. Just over ten years ago the storage capacity of all the world's magnetic disk drives surpassed that of analogue data storage devices, thereby making possible the world of digital data. The technology of the magnetic hard disk drive is two-dimensional (2D); digital data are stored as the magnetization direction of tiny regions on a magnetic thin film that covers the surface of a glass disk. These regions are read and written by a mechanical device — the recording head — that sits just a few nanometres above the surface of the disk. Over the past 50 years, the area of one magnetic bit has decreased in size by about around nine orders of magnitude; it is now so tiny that the technologies needed to find, read and write bits are reaching fundamental limits that are difficult or too expensive to overcome. Today, improvements in the storage capacity of the magnetic disk have slowed to a crawl. A number of alternatives to the magnetic disk drive have been suggested. Among them, racetrack memory[1,2] — proposed ten years ago — seems close to realization, given recent advances in fundamental physics and materials science related to this technology.

Solid-state spintronic memories

In contrast to the magnetic disk drive, racetrack memory is an entirely solid-state device that has no moving parts. It can also be developed as a 3D device, unlike the majority of existing or proposed storage technologies (Fig. 1). Magnetic random access memory (MRAM)[3,4] is an emerging memory technology that, like racetrack memory, is a spintronic device; that is, its operation is based on the creation and manipulation of spin-polarized currents.

The biggest commercial success of spintronics so far has been the development of extraordinarily sensitive detectors of small magnetic fields capable of operating at room temperature and above[4]. These magnetoresistive sensors — known as spin valves — consist of two ultrathin magnetic electrodes separated by a spacer layer;

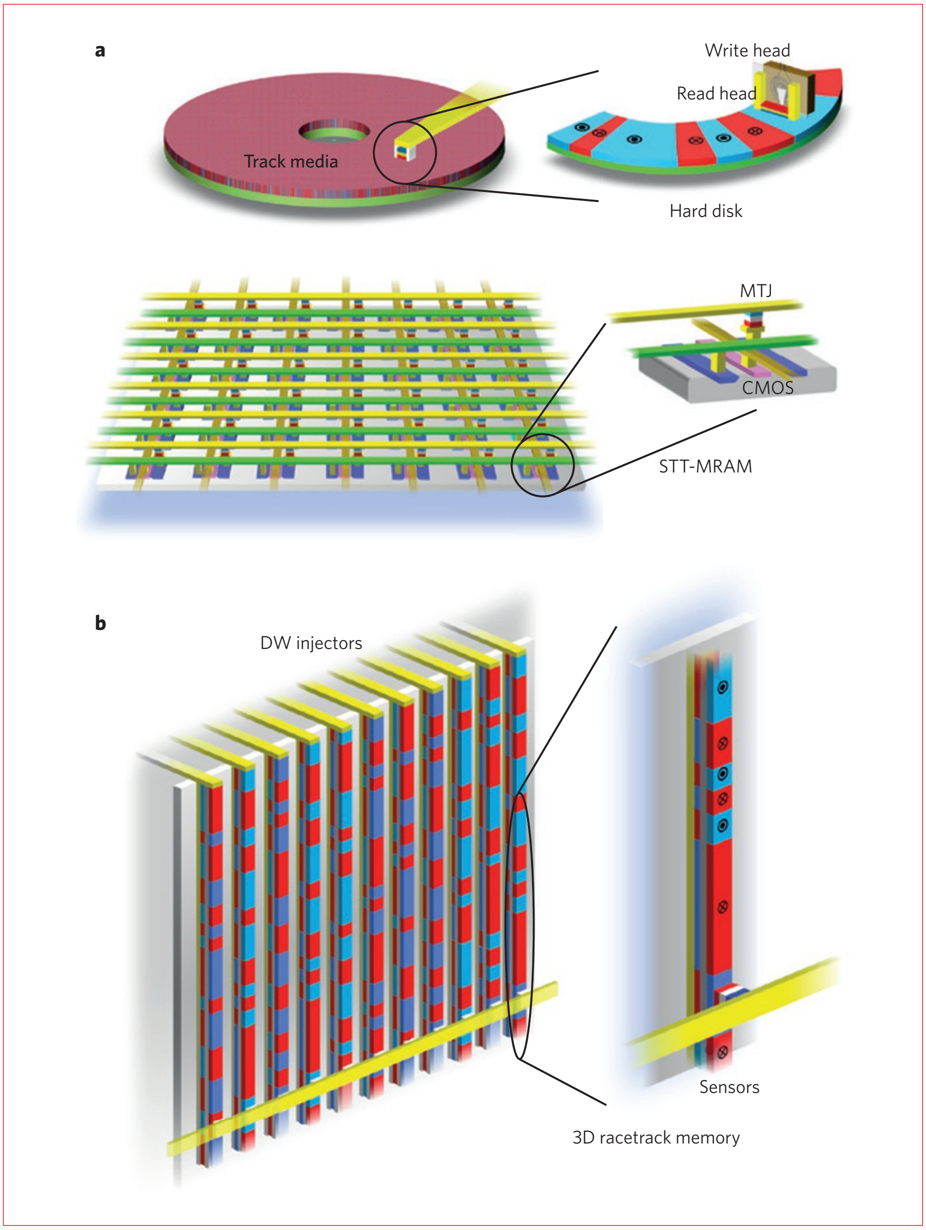

Figure 1 | Three magnetic memory and storage devices. **a**, 2D technologies. Upper panel: The recording head of a magnetic hard disk drive is moved mechanically across the surface of the disk. Lower panel: MRAM, showing an MTJ memory element and a transistor access device. Dark blue regions represent the source and drain; pink regions represent the gate. Yellow and green regions are the bit lines; dark yellow regions are the gate control lines. STT, spin-transfer torque; CMOS, complementary metal-oxide-semiconductor. **b**, 3D technology: Racetrack Memory 4.0. Red and blue regions represent areas that are oppositely magnetized.

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current flowing through the device is spin-polarized due to spin-dependent diffusive scattering and spin-dependent quantum mechanical tunnelling in the case of metallic or insulating spacers, respectively. For insulating spacer layers, these devices are often referred to as magnetic tunnel junctions (MTJs). These sensors enabled the most recent improvements in the storage capacity of magnetic disk drives by making it possible to shrink the magnetic bit area by a factor of 1,000 (ref. 4).

Magnetic tunnel junctions can also be used as non-volatile magnetic memory cells in MRAMs, as originally proposed in 1995[5]; a first device demonstration in 1999[3] showed the potential of MRAM as a high-performance, non-volatile memory. Today, all the world's major memory manufacturers invest in the development of MRAM as a replacement for embedded dynamic RAM, or as standalone memory that could replace dynamic or static RAM. These widely used technologies become increasingly difficult to scale down to device sizes below 10 nm. The information stored in an MTJ memory cell is electrically read via its tunnelling magnetoresistance, which can be very large in certain MTJs[6,7]. This information can be electrically written by the transfer of spin angular momentum from current that is passed through the device[8]. A major challenge in the realization of high-data-capacity MRAM is the development of an MTJ memory cell that can be written by the tiny currents provided by minimum-sized transistors, yet at the same time is sufficiently stable against thermal fluctuations such that the magnetic moments within the MTJ retain their directions for ten years or more. This major obstacle can be overcome in racetrack memory.

Four major steps

The basic structure of racetrack memory is illustrated in Fig. 1. Digital data are stored in a series of magnetic domain walls (DWs) in nanowires that are arranged in a 3D array. The operation of racetrack memory relies on the fact that the DWs can be moved along the nanowires by passing a current through the wire. The current transfers spin angular momentum from the conduction electrons to the magnetic moments within the DWs, which displaces them. This principle was first demonstrated in permalloy nanowires, which are magnetically soft (that is, without significant magnetic anisotropy)[9]. We may call this implementation Racetrack Memory 1.0 (Fig. 2). Surprisingly, the transfer of angular momentum from the current to the DWs is almost perfect[10], and very little spin angular momentum is lost to the lattice through damping. The spin-dependent scattering of the conduction electrons within the bulk of the magnetic layer determines the spin polarization of the current. Given that the spin polarization of the current in permalloy is about 70%[11], the DWs can achieve velocities of around 100 m s^{-1} for current densities in the region of 10^8 A cm^{-2}. Furthermore, the DWs move in the direction of electron flow (that is, opposite to the direction of the current)[10].

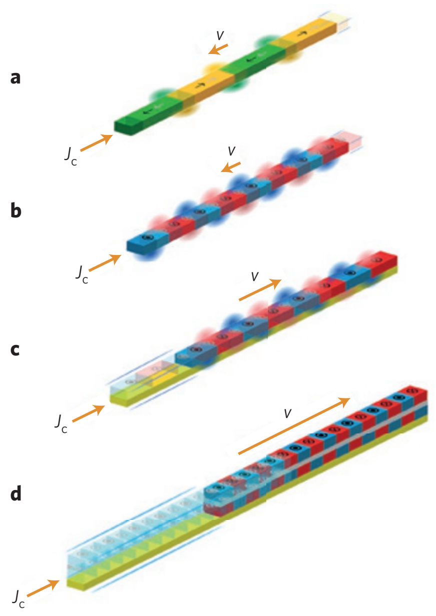

Figure 2 | Evolution of racetrack memory. **a**, Racetrack Memory 1.0, with in-plane magnetized racetracks. **b**, Racetrack Memory 2.0, with perpendicularly magnetized racetracks. Conventional volume spin-transfer torque moves DWs in the direction of electron flow in **a** and **b**. **c**, Racetrack Memory 3.0: chiral spin torque drives DWs at high velocities along the current direction. Note that substantial fringing fields near DWs form in **a**–**c** (shadings). **d**, Racetrack Memory 4.0: a giant exchange coupling torque drives DWs in SAF racetracks at extremely high velocities. J_c, current through the device; v, DW velocity. Red and blue regions represent areas that are oppositely magnetized.

The width of a DW in a soft material is determined by the shape anisotropy of the wire and thus varies approximately with the wire width, which means that the DWs are rather wide. Moreover, the DWs are very flexible and can readily expand to many times their equilibrium size under torques provided by the current. For these reasons, the use of soft magnetic materials is not ideal. Much narrower and more robust DWs are found in materials that exhibit significant magnetic anisotropy, such as Co/Ni superlattices. In technologically relevant materials, the magnetic easy axis must be oriented perpendicular to the plane of the nanowire. This can be accomplished in four major classes of materials: (1) materials with bulk magnetocrystalline anisotropy; (2) magnetic glasses with atomic pair ordering; (3) magnetoelastic materials; and (4) thin layers or atomically engineered multilayers with interface anisotropies. The latter class has so far proven to be the most interesting. In the subsequent development of the device concept — Racetrack Memory 2.0 — the current-induced motion of several DWs via a volume spin-transfer torque was demonstrated in Co/Ni superlattices[12,13]. The DWs in such a device are much narrower than those found in permalloy, yet they move in roughly the same direction and at the same speed.

An important fundamental finding was the discovery, in 2011, that single DWs move much faster (and in the direction of current) in ultrathin layers of cobalt deposited on a platinum layer[14]. The mechanism[15,16] by which the current moves the DWs has turned out to be much more complex and interesting than initially thought. The mechanism involves four distinct phenomena, each derived from spin–orbit coupling. These phenomena are illustrated in Fig. 3. First, the perpendicular magnetic anisotropy exhibited by racetracks formed from single magnetic layers (such as cobalt[14] or CoFeB (ref. 17)) or Co/Ni/Co sandwiches[15,16,18] is derived from strong spin–orbit coupling at the interfaces between these layers and underlying heavy metal layers. Second, a critical contribution is the Dzyaloshinsky–Moriya interaction (DMI) derived from interfaces between the magnetic layers and heavy metal layers, including platinum[15,16,18], palladium[16], iridium[16], tungsten[19] and possibly tantalum[20,21]. The DMI is an exchange interaction that favours perpendicular orientation of neighbouring moments across the DW[22] and thus causes the DWs to exhibit a chiral Néel-type structure[19]. Third, the strength of the DMI is found to be correlated with the magnitude of a proximity-induced magnetic moment within the heavy metal layers at their interfaces with the magnetic layers[16]. Fourth, a spin current is generated within the heavy metal layers by spin–orbit scattering of the conduction electrons through the spin Hall effect[23,24]. A pure spin current without any charge current flows in a direction perpendicular to the charge current towards each surface of the heavy metal layer, where the direction of the spin is perpendicular to both the charge and spin currents (Fig. 3d). The spin Hall effect is the second chiral phenomenon,

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besides the DMI, that contributes to the mechanism of current-induced DW motion. The magnitude of the conversion of charge current to spin current is a subject of considerable debate.

These four phenomena together allow DWs to be moved by a chiral spin torque at much higher velocities (for the same current density) than is possible from volume spin torques. The direction of motion is determined by the subtle interplay of these phenomena[15]. Velocities of around 350 m s^{-1} for current densities of 10^8 A cm^{-2} have been measured[14,15] — this is Racetrack Memory 3.0. The spin current that is generated in the heavy metal layer diffuses into the neighbouring magnetic layer and causes the moments within each DW to rotate towards the spin direction, which is transverse to the length of the racetrack. The DMI exchange field then provides a torque on these rotated moments that causes all the DWs to move in the same direction along the racetrack, as they all have the same chirality. The direction of motion and DW velocity depend, in particular, on the magnitude and sign of the chiral effects, spin Hall effect and DMI. These can be tuned independently by varying the thickness of the heavy metal layers and the composition of the ferromagnetic layer. Despite the greater efficiency of moving DWs in Racetrack Memory 3.0, the demagnetizing fields that each DW produces — which results in interactions between adjacent DWs — remains a limiting factor in the performance of the device. These fields limit the DW density, and therefore the data density, along the racetrack.

In the most recent fundamental development — Racetrack Memory 4.0 — DWs can be moved in racetracks that are formed from synthetic antiferromagnets (SAFs)[25]. The SAF is formed from two perpendicularly magnetized sub-racetracks that are antiferromagnetically coupled via an ultrathin ruthenium layer[4,26,27] (Fig. 2d). The magnetic structure in one sub-racetrack is the mirror-image of the other. By carefully tuning the magnetic moments of each sub-racetrack (including the proximity-induced magnetic moment), the net magnetic moment of the SAF racetrack can be tuned to zero. The DW velocity increases as the net moment of the SAF is reduced to zero; DW velocities of almost 1,000 m s^{-1} have been observed[25]. The DWs move around five times more efficiently, for the same current density, than in an identical structure in which the coupling of the two sub-racetracks is ferromagnetic[25].

In Racetrack Memory 4.0, because the DWs have no associated demagnetizing

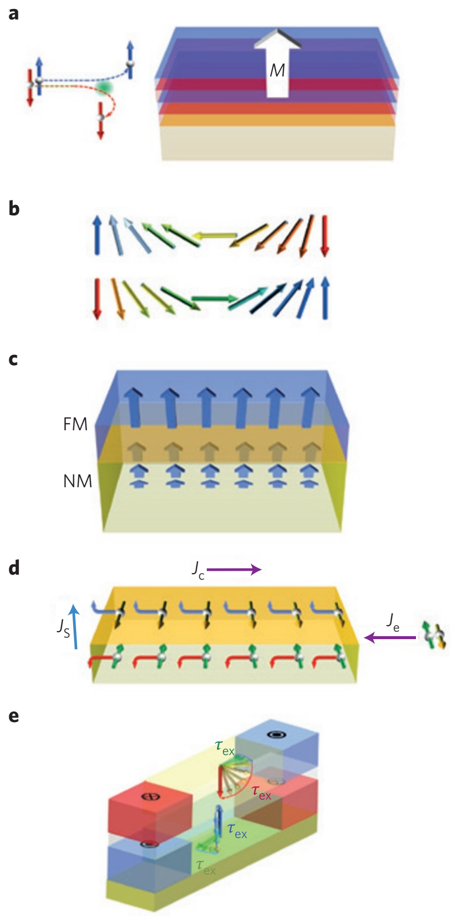

Figure 3 | Key phenomena that contribute to the current-driven motion of DWs. **a**, Perpendicular magnetocrystalline anisotropy derived from interfaces in thin-film magnetic structures. Inset: Spin–orbit coupling that leads to the asymmetric scattering of spin-up and spin-down conduction electrons (blue and red arrows, respectively) from scattering sites (green). **b**, Dzyaloshinsky–Moriya exchange interaction. Upper panel, ↑←↓ DW configuration; lower panel, ↓→↑ DW configuration. **c**, Proximity-induced magnetization in a non-magnetic metal (NM) layer interfaced with a perpendicularly magnetized ferromagnetic layer (FM). **d**, Spin Hall effect, which creates a spin current J_S in a NM layer in the presence of a charge current J_c (electron current J_e). **e**, Exchange coupling torques τ_{ex} are generated by exchange coupling fields in SAF racetracks. The spin Hall torque τ_{SH} rotates the Néel DW magnetizations and thus gives rise to an exchange coupling torque.

fields, the DWs can be packed much closer together. Moreover, owing to the very high efficiency with which the DWs can be moved, very little power is needed to operate the memory. Racetrack Memory 4.0 is a promising solution for delivering high-performance, low-power memory storage devices that can compete in density and cost with magnetic disk drives, but with much smaller physical device dimensions and no obvious wear-out or failure mechanism. To achieve this goal, each SAF racetrack must store about 100 DWs, reaching a density around 100 times higher than that of MRAM. There are many outstanding challenges, particularly related to the fabrication of 3D racetracks and the integration of reading and writing devices. One way to fabricate 3D racetracks is illustrated in Fig. 1b: the racetracks are deposited by, for example, atomic layer deposition, on the patterned side-walls of deep trenches. This is possible because the layers forming the racetracks are just a few atomic layers thick.

Beyond Racetrack Memory 4.0

The 3D implementation of racetrack memory has several interesting properties. First, it makes racetrack memory dynamically reconfigurable in terms of the trade-off between performance and data density. By ensuring that the number of stored DWs per racetrack is smaller than the maximum, the access time to DWs can be reduced proportionally. Thus, one can choose to have memory that is either faster but less dense, or slower but denser, with the same technology and on the same device.

Another important point is that the stability against thermal fluctuations is determined by both the DW size and the DW separation, which can be readily varied by engineering the magnetic structure and the overall length of the racetrack. This is a significant advantage compared with MRAM, where currently known materials will probably not support the development of devices with critical feature sizes below 20 nm.

Racetrack memory has significantly evolved since its first conception, thanks to fundamental advances in spin-transfer-torque and spin–orbit-torque mechanisms. The prospect for racetrack memory is promising, regardless of whether such devices store hundreds of DWs or just one. The technology is extremely flexible and can cover a range of applications, from ultrafast to ultradense memory-storage devices. With increasing effort and resources dedicated to the development of racetrack memory, it is likely that new materials and mechanisms for moving, creating and detecting DWs will soon be discovered. New concepts might also be on the horizon. For example, engineering DMI in atomically engineered magnetic thin-films might allow the creation of complex spin textures that may be more robust and more efficiently manipulated with currents. ❐

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