Spin-transport and spin-torque in antiferromagnetic devices

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Ferromagnets are key materials for sensing and memory applications. In contrast, antiferromagnets which represent the more common form of magnetically ordered materials, have found less practical application beyond their use for establishing reference magnetic orientations via exchange bias. This might change in the future due to the recent progress in materials research and discoveries of antiferromagnetic spintronic phenomena suitable for device applications. Experimental demonstration of the electrical switching and detection of the Néel order open a route towards memory devices based on antiferromagnets. Apart from the radiation and magnetic-field hardness, memory cells fabricated from antiferromagnets can be inherently multilevel, which could be used for neuromorphic computing. Switching speeds attainable in antiferromagnets far exceed those of ferromagnetic and semiconductor memory technologies. Here we review the recent progress in electronic spin-transport and spin-torque phenomena in antiferromagnets that are dominantly of the

relativistic quantum mechanical origin. We discuss their utility in pure antiferromagnetic or hybrid ferromagnetic/antiferromagnetic memory devices.

Introduction

Magnetism and technology have been inextricably linked for centuries - from the navigation compass, to motors and generators, to magnetic data storage. The field of information storage has been dominated by ferromagnetic materials from its inception to the present day. Memories based on ferromagnets, such as magnetic tapes and hard disk drives, have been one of the key factors that enabled the information revolution. Antiferromagnetism, on the other hand, has played fleeting roles in the story of information technology so far, despite the fact that antiferromagnetic order is common in magnetic materials. Most of these roles have been as passive elements, such as for pinning or hardening of ferromagnet layers.

The major obstacle which has kept antiferromagnets away from application is that they are hard to control and hard to read. While ferromagnetic order can be detected by the magnetic fields it creates, and in turn manipulated by an external magnetic field, antiferromagnets produce no fringing magnetic fields and are much less sensitive to them (although they can also be manipulated by large enough magnetic fields). So while antiferromagnets could be used for memories, just like ferromagnets, the difficulty of detecting and manipulating the antiferromagnetic order provided a seemingly insurmountable barrier.

While magnetic fields provide a practical way for detecting and manipulating ferromagnetic order, many other methods have been developed. Perhaps most importantly, electrical currents can now be used both for detection and switching of ferromagnetic order. Utilizing electrical currents instead of magnetic fields is more efficient and more scalable, and thus the latest magnetic random access memories rely entirely on electrical currents.[1] The possibility of using electrical currents instead of magnetic fields for detection and manipulation has inspired a renewed interest in antiferromagnetic materials. Electrical manipulation combined with electrical detection of antiferromagnetic order has been recently demonstrated.[2] This shows that antiferromagnets could be used to store information in electronic memory devices and opens new avenues for fundamental research of antiferromagnetic order and dynamics.

In this article we review recent theoretical and experimental progress on spin-transport and spin-torque phenomena allowing for reading and writing information stored in antiferromagnets. See Fig. 1 for a summary of all proposed electrical reading and writing methods. We also discuss other transport phenomena relevant to spintronics such as the generation of spin currents by antiferromagnets due to the spin Hall effect (SHE).[3, 4]

Nonrelativistic spintronics effects

As discussed in Box 1, antiferromagnetic spintronics initially focused on antiferromagnetic analogues of ferromagnetic spin valves and tunneling junctions. These devices were theoretically proposed to have the same functionality as their ferromagnetic counterparts, but were found to be strongly sensitive to disorder and perfect epitaxy, which prevented their experimental realization.

A more promising approach might be to consider devices which combine antiferromagnets with ferromagnets, where the ferromagnet functions as a spin-polarizer. Gomonay and Loktev[5] showed that a spin-polarized current can efficiently manipulate the antiferromagnetic order, assuming that the torque generated by the spin-polarized current has the same form on each sublattice as is common in ferromagnets, i.e., $T_j \sim M_j \times (M_j \times p)$ (the so-called antidamping-like torque). Here j is a sublattice index, M_j is the magnetic moment on a sublattice j, and p is the direction of the spin-polarization of the current. This form of the torque was subsequently derived in a more rigorous fashion.[6, 7] It is instructive to consider why such a torque is effective for manipulating antiferromagnets. The torque can be thought of as being generated by an effective magnetic field, such that $T_j \sim M_j \times B_j$ with $B_j = M_j \times p$. In a collinear antiferromagnet such a field is staggered, i.e., alternating in sign between sublattices. It is a general principle that staggered fields can efficiently manipulate antiferromagnets, while uniform fields (such as an external magnetic field) cannot. Unlike the spin-transfer torque generated by an antiferromagnet, the torque due to the spin-polarized current is expected to be much more robust against disorder. We refer to the article on dynamics in this focused issue for more details on the phenomenology of the time-dependent phenomena induced by the staggered fields.

The torques acting on an antiferromagnet due to injection of a spin-polarized current have been studied in ferromagnet/antiferromagnet bilayers in which the ferromagnet and the antiferromagnet are exchange coupled. The exchange coupling leads to a shift of the ferromagnetic hysteresis loop, which is known as exchange bias.[8] Several experiments have observed that electrical current influences the exchange bias.[9,10, 11, 12,13,14] This provides indirect evidence that a spin-polarized current can influence antiferromagnets. However, the exact origin of the observed effect is not clear since exchange bias is a complex and not completely understood phenomenon.

The effects we have discussed so far are non-relativistic in origin. In contrast, many of the effects that we will discuss in the following sections are caused by the spin-orbit coupling. This is a relativistic term in the Hamiltonian, which couples the spin and the orbital degree of freedom of an electron. Its significance lies in particular in the fact that it couples spin to the lattice and in this way it lowers the symmetry of the system and can generate a variety of non-equilibrium spin phenomena.

Anisotropic magnetoresistance

The first, and still widely employed, method for electrically detecting a reorientation of the magnetization in a ferromagnet is by using anisotropic magnetoresistance (AMR):[15] the dependence of the resistance on the direction of the magnetization with respect to current or crystal axes.

The AMR tends to be smaller than the giant or tunneling magnetoresistance, however, it is simpler to detect experimentally since it is a bulk effect and thus does not require complex multilayers. Furthermore, since it is an even function of magnetization, it is equally present in antiferromagnetic materials. [16] However, until recently, the effect had remained elusive because of the difficulty in controlling the magnetic moment direction in antiferromagnets. Nevertheless, AMR has now been demonstrated in several antiferromagnets. Marti et al. [17] used antiferromagnetic FeRh for the demonstration of AMR. This material becomes ferromagnetic when heated and responds to applied magnetic fields. By then cooling back into the antiferromagnetic phase with the field still applied, the antiferromagnetic spin direction can be controlled. Other experiments used antiferromagnets exchange coupled to a ferromagnet, [18, 19] large magnetic fields [20,21] or electrical current [2] (as we discuss in depth later) to manipulate the antiferromagnetic moments. The full functional form of AMR, shown in Fig. 2a, was demonstrated by Kriegner et al. [21] in antiferromagnetic MnTe.

AMR has both longitudinal and symmetric transverse components. Historically, the transverse AMR is sometimes called the planar Hall effect but we avoid this terminology since the true Hall effects correspond to the antisymmetric off-diagonal components of the conductivity tensor. Among those the anomalous Hall effect can also be used for detecting the magnetization reversal in ferromagnets. Unlike AMR, the anomalous Hall effect is an odd function of magnetization and thus not present in collinear antiferromagnets. It has, however, been demonstrated in non-collinear antiferromagnets [22, 23, 24, 25] (see Fig. 1c). We refer to the article on topological phenomena in this focused issue for more in-depth discussion of this phenomenon.

The AMR is useful for experimental detection of switching of antiferromagnets, however, its small magnitude limits the possible miniaturization and the readout speed in devices. [15] Significantly larger effects can be achieved by using a current tunneling from an antiferromagnet to a nonmagnetic metal, an effect called tunneling anisotropic magnetoresistance (TAMR) (see Fig. 1d). In antiferromagnets TAMR was predicted by Schick et al. [16] and subsequently demonstrated experimentally by Park et al. [26] who found a very large TAMR effect in a NiFe/IrMn/MgO/Pt tunneling junction. The effect can exceed 160% at low temperature. In this work, the NiFe ferromagnetic layer sensitive to weak magnetic fields and exchange coupled with the IrMn antiferromagnet was used to rotate the antiferromagnetic moments to produce different resistance states. The NiFe/IrMn exchange-spring effect was not robust enough to persist to room temperature. Ralph et al. [27] reproduced the large low-temperature TAMR and highlighted a strong sample dependence of the effect whose detailed microscopic description is still missing.

An alternative TAMR structure of [Pt/Co]/IrMn/AlO$_x$/Pt with a stronger ferromagnet/antiferromagnet exchange coupling used by Wang et al. [28] allowed for the detection of the effect at room temperature. A weak TAMR signal, not exceeding one percent even at low temperatures, was attributed in this structure to the amorphous AlO$_x$ tunnel barrier. Petti et al. [29] demonstrated that the TAMR effect can also exist in structures which contain no ferromagnet using field-cooling from above the Néel temperature. More research is needed to understand precisely the TAMR mechanisms and to optimize the structures, however, these experiments demonstrate that a large magnetoresistance can in principle exist in antiferromagnetic structures.

Spin-orbit torque switching

Spin-orbit coupling allows for the generation of a current-induced torque in a magnet without spin-injection from an external polarizer. The spin-orbit torque occurs because in crystals with broken inversion symmetry electrical current generates a non-equilibrium spin-polarization (see Fig. 2b). This effect is known as the inverse spin-galvanic effect (ISGE) (also called the Edelstein effect). [30, 31, 32, 33] In a magnetic material, the current-induced spin-polarization exchange-couples to the equilibrium magnetic moments and thus generates a torque. The ISGE spin-orbit torque was theoretically proposed [34, 35, 36] and experimentally detected [37, 38] in the ferromagnetic semiconductor GaMnAs and recently also in the room-temperature ferromagnetic metal NiMnSb. [39] For the presence of a net current-induced polarization, the inversion symmetry has to be broken, thus the Edelestein spin-orbit torque can only be used for manipulation of ferromagnets with broken inversion symmetry.

Železný et al. [40, 41] predicted that the ISGE spin-orbit torque will also occur in antiferromagnets with appropriate symmetry and that it can efficiently manipulate the antiferromagnetic order. The reason for the efficient manipulation is that with appropriate symmetry the current-induced spin-polarization contains a component which is staggered. This staggered component in turn generates a staggered effective magnetic field, which can manipulate the antiferromagnetic order efficiently. Železný et al. [40] calculated the spin-orbit torque for antiferromagnetic Mn_2Au, which has the crystal structure shown in Fig. 2c. The nonmagnetic crystal of Mn_2Au has inversion symmetry and, therefore, there is no net current-induced spin-polarizations. The Mn sublattices, however, each have locally broken inversion symmetry. As a consequence there can be a current-induced spin-polarization on each Mn sublattice, but they have to be precisely opposite in the nonmagnetic crystal.

The ISGE spin-orbit torque has advantages compared to the other current-induced torques discussed earlier. Since the torque is generated locally, it is not particularly sensitive to disorder [42] and since it is a bulk effect it does not require special heterostructures and thin-film antiferromagnets. On the other hand it only works in antiferromagnets with the appropriate symmetry. For example, for the presence of the field-like (i.e., independent of the magnetic order) ISGE spin-orbit torque the two spin-sublattices must occupy inversion-partner lattice sites. The switching of an antiferromagnet via this torque was initially demonstrated by Wadley et al. [2] using epilayers of antiferromagnetic CuMnAs which has a symmetry analogous to Mn_2Au. Fig. 2d shows a more recent measurement of this switching phenomenon on CuMnAs grown on Si. In CuMnAs (as well as in Mn_2Au) the efficient torque has a field-like character. Because of the symmetry of the crystal, the field is perpendicular to the electrical current. [41] Thus, by applying perpendicular current pulses, the magnetic moments in CuMnAs can be switched between two perpendicular directions. In the experiment by Wadley et al. [2] the switching was monitored by the AMR. It was shown that the longitudinal and transverse resistances depend on the direction, amplitude and duration of applied current pulses, in a way which is consistent with the expected ISGE spin-orbit torque. Further experiments used x-ray photoemission electron microscopy, combined with x-ray magnetic linear dichroism, to directly image the antiferromagnetic domain configuration following the current pulses, [2, 43] confirming the magnetic origin of the electrical signals due to alignment of antiferromagnetic moments orthogonal to the applied current direction. Recently the spin-orbit torque switching combined with the AMR detection was also confirmed experimentally in sputtered films of Mn_2Au. [44, 45]

Memory devices

Antiferromagnets possess a number of properties that make them highly favourable for memory applications. Like their ferromagnetic counterparts, their magnetic state is inherently non-volatile but with the addition that they are robust to external magnetic fields. The antiferromagnetic spin-sublattices with a compensated magnetic moment give them some intriguing additional benefits. The absence of internal dipolar fields favors multistable antiferromagnetic domain configurations, which can be exploited for integrating memory and logic functionality. The antiferromagnetic exchange is also the origin of the ultrafast reorientation dynamics (in the terahertz regime), as well as making antiferromagnets magnetically "invisible" and enabling denser packing of memory elements.

There have been several demonstrations of antiferromagnetic memory devices based on the concepts we have outlined. The metamagnetic FeRh devices described by Marti et al. [17] demonstrate a memory functionality, where the information bits were represented by perpendicular directions of the antiferromagnetically coupled magnetic moments. Moriyama et al. [46] used the same approach and material system to demonstrate sequential read and write operations of the antiferromagnetic memory stable over a large number of cycles.

The CuMnAs devices described by Wadley et al. [2] demonstrate an antiferromagnetic memory which can be both written (using the spin-orbit torque) and read (using AMR) electrically under ambient conditions (Fig. 3). Olejnik et al. [47] explored the multilevel memory behavior of these devices further and showed that they could be used to write up to thousands of states (Fig. 2e). By applying successive current pulses, progressively higher reproducible resistance states can be reached depending on the number and duration of the pulses. Both pulse-counting and pulse-time-integration functionalities were demonstrated, for pulse lengths ranging from milliseconds down to 250ps, close to the limit of contact current injection with commercial pulse generators (Fig. 2e). The micromagnetic domain origins of these multistable states were imaged by Grzybowski et al. [43] Olejnik et al. [47] also demonstrated their compatibility with conventional microelectronic printed circuit boards (Fig. 3c), and low-temperature-growth and fabrication compatibility of CuMnAs with Si or III-V semiconductors (Fig. 3a). These memory devices have a promising potential for applications based on their multilevel character, such as neuromorphic computing or pulse counters. The readout signals are, at this point, too small for application as a conventional bistable memory. However, with device and materials optimization and utilizing a different readout method such as the TAMR, the readout signals can likely be increased significantly. These memories could then potentially be used as conventional memories in situations where speed is very important, such as the central processing unit (CPU) caches.

Recently, switching by ps-pulses of a THz radiation, combined with the AMR readout, has been demonstrated in the same CuMnAs bit-cells. [48] The switching in these experiments has a multi-level character, similar to the electrical switching. This shows that a non-contact switching of an antiferromagnet is also feasible and opens a path to the development of antiferromagnetic memories for the THz band. In contrast, ferromagnets are limited by the GHz writing speed threshold. For writing speeds up to the GHz scale, weak fields are sufficient for switching ferromagnetic moments and the associated energy cost decreases with increasing speed. Above the GHz threshold, however, the trend

reverses, with both the field and the energy cost increasing proportionally to the writing speed. [49, 50] As a result, current-induced spin-orbit torque switching has not been pushed in ferromagnetic memory devices to writing speeds exceeding 5 GHz. [50]

Another intriguing concept for magnetic memory is a memory based on the movement of magnetic domain walls, the so-called racetrack memory. Antiferromagnets are of interest for such memories since antiferromagnetic domain walls were recently predicted to move much faster than ferromagnetic domain walls. [51, 52] We refer to the article on dynamics in this focused issue for detailed discussion of this topic.

In this review, we have mostly focused on transport phenomena. An exciting possibility is also the control of magnetic order by electric field in magnetic insulators. Such functionality has been demonstrated in magnetoelectric material Cr_2O_3 [53] and in multiferroic materials which combine ferroelectricity and antiferromagnetism. See the review article by Sando et al. [54] for description of recent progress on the most commonly used multiferroic material $BiFeO_3$.

Antiferromagnet/ferromagnet spin Hall structures

When current flows through a material, a spin current appears flowing in a direction transverse to the charge current. This effect is known as the spin Hall effect (SHE). [4,3] It originates due to the spin-orbit coupling, which causes the electrons with opposite spin to deflect in opposite directions thus creating a spin current. The inverse effect also exists: when a spin current is injected into a material with spin-orbit coupling a transverse voltage appears. The direct and inverse SHE are of key importance for spintronics since they allow for transforming between charge currents and spin currents.

The SHE can be used to generate a spin-orbit torque, which can switch a ferromagnet. [55, 56] When a SHE material is interfaced with a ferromagnet and electrical field is applied parallel to the interface a spin current flows into the ferromagnet and generates a torque on the magnetization. It allows, in principle, for a faster and more efficient switching of ferromagnetic layers than spin-transfer torque. [57] Note that the SHE mechanism coexists with the ISGE spin-orbit torque since interfaces break the inversion symmetry of the structure. [4]

The spin-orbit torque due to SHE could also be used to manipulate antiferromagnetic moments [40] (see Fig. 1g). As discussed above, spin current injected into an antiferromagnet generates a torque which can efficiently manipulate the antiferromagnetic order. Such spin current could be injected from a ferromagnet, but the spin current due to SHE could also be used. A spin-orbit torque in a heavy-metal/antiferromagnet configuration has indeed been observed experimentally. [58] However, the difficulty of manipulating the antiferromagnetic order by magnetic fields did not allow for a detailed characterization of the torque which is routinely done in heavy-metal/ferromagnet bilayers. Recently, switching of antiferromagnetic NiO, attributed to the SHE spin-orbit torque, has been observed in Pt/NiO/Pt multilayers. [59]

In the past, research of the SHE focused mostly on non-magnetic materials. It is, however, allowed by symmetry in any material, including antiferromagnetic (and other magnetic) materials. The SHE has been found theoretically and experimentally in several antiferromagnets. [60, 61, 62] Instead of the direct SHE, these experiments demonstrated the inverse SHE, which can be detected electrically by injecting a

pure spin current into the antiferromagnet. The spin current is generated by a ferromagnet either using precessing magnetization (the so-called spin pumping) as illustrated in Fig. 4b, or alternatively using a heat gradient. An example of DC voltages measured in a spin pumping experiment for antiferromagnets MnX, X=Fe, Pd, Ir and Pt (see Fig. 4a) is given in Fig. 4c. Several of the antiferromagnets showed a large SHE comparable to the commonly used non-magnetic heavy metals. In addition the spin Hall conductivities along different crystalline axes are highly anisotropic in these antiferromagnetic alloys as has been demonstrated with measurements of epitaxial films with different growth orientations [63]. This behavior is consistent with intrinsic spin Hall effects as determined by first principle calculations. Furthermore, the spin Hall conductivity seems to be susceptible to manipulation via different magnetic field and temperature cycles resulting in different arrangements of the antiferromagnetic spin structure. [64]

Since antiferromagnets can have a large SHE it is expected that they can also be used to generate a spin-orbit torque on a ferromagnet. This has been confirmed by several experiments for various antiferromagnets. [58, 65, 63, 66, 64, 67, 68, 69, 70, 71] The observed spin-orbit torque can be very large, comparable to the largest values for non-magnetic heavy metals. Switching of ferromagnetic layers by the spin-orbit torque has also been demonstrated. [66, 67, 68, 71] Using an antiferromagnet instead of a non-magnetic metal has some unique advantages. For the spin-orbit torque switching it is preferable to use a perpendicularly magnetized ferromagnet since this allows for faster switching and better scalability. However, in such a case a constant in-plane magnetic field has to be applied to achieve deterministic switching. [72] Conversely, an antiferromagnet can be exchanged coupled to the ferromagnet, thus allowing field-free switching. [66, 67, 68, 71] Another remarkable feature that was observed in antiferromagnet/ferromagnet bilayers [66] is a memristor behavior (see Figs. 4e,f), reminiscent of the multi-level spin-orbit torque switching in bulk antiferromagnets (CuMnAs, Mn_2Au) discussed above. [2, 44, 47] This behavior is of great importance for neuromorphic computing where it can simulate synapses. It is attributed to a progressive current-induced switching of more magnetic domains in the ferromagnet, which are then kept fixed by the exchange coupling with the antiferromagnet (see Fig. 4d). A proof-of-concept artificial neural network based on the spin-orbit torque in a PtMn/CoNi structure has already been demonstrated. [73]

Outlook

The basic memory functionality, including electrical writing and readout has been demonstrated in antiferromagnets. Within a year of the initial demonstration of spin-orbit torque switching, the electrical pulse length has been reduced from milliseconds to picoseconds, opening a prospect of ultra-fast magnetic memories. The Heusler-compound related CuMnAs antiferromagnet used in the experiments can be grown epitaxially, and devices can be microfabricated on III-V or Si substrates, allowing for future integration in semiconductor circuits. Spin-orbit torque switching has also been demonstrated in Mn_2Au, which broadens the range of suitable materials to sputtered transition-metal films. Multilevel (memristor) switching is commonly observed in memories made of single-layer antiferromagnets or antiferromagnet/ferromagnet bilayers.

Momentum in the research area of antiferromagnetic spintronics is immense, yet much remains to be done. To fully utilize the potential of antiferromagnets, several key aspects must be better understood: The factors which contribute to the complex domain structures, and their relative importance, need to

be elucidated in order to design and engineer devices and material properties with the requisite domain patterns and stability for specific memory applications. The ultra-fast switching needs to be studied in detail. Promising steps have been made towards time-resolved optical detection [74], as discussed elsewhere in this focused issue in the article on opto-spintronics.

The electrical readout signals observed in antiferromagnets at room temperature have so far been relatively small. This could be sufficient for some applications, but larger readout signals would be desirable for high-density fast read-out memory application. Device and material optimization is necessary to extend the large readout signals observed at small temperatures to room temperature. The only electrical switching method that has been demonstrated so far is the bulk ISGE spin-orbit torque. Switching using spin-orbit torque due to the SHE could be more efficient and is expected to work in any antiferromagnet, whereas the ISGE spin-orbit torque requires antiferromagnets with specific symmetry. More material research is necessary to identify other antiferromagnets that could be switched via the ISGE spin-orbit torque. The spin-orbit torque generated by antiferromagnets on ferromagnets in the antiferromagnet/ferromagnet bilayers is promising, although its origin is not entirely understood. It is commonly attributed to the SHE, but this has not been proven and other effects likely contribute. Of particular interest is understanding how the spin-orbit torque and the SHE depend on the antiferromagnetic order.

Acknowledgements

Box 1 –Antiferromagnetic spin valves and tunneling junctions

Giant [75,76] and tunneling magnetoresistance [77,78] and spin-transfer torques [79, 80, 81] are among the key spintronics phenomena for applications in ferromagnetic memories. These effects occur in devices composed of two ferromagnetic layers separated by a thin metallic or insulating layer (see Fig. B1a). The metallic devices are called spin valves, while the tunneling ones are referred to as magnetic tunneling junctions. The giant and tunneling magnetoresistance are respectively the dependence of the ohmic or tunnel current on the relative magnetization-orientations of the two ferromagnetic layers. When an electrical current is flowing through the structure it transfers spin from one layer to the other, which generates a spin-transfer torque. For a sufficiently strong current, this torque enables switching between parallel and antiparallel configurations of the magnetic layers. The spin-transfer torque together with the tunneling magnetoresistance are used to create the basic building blocks of magnetic random access memories. [1]

Initial theoretical research in antiferromagnetic spintronics focused on antiferromagnetic analogues of spin valves and tunneling junctions (see Fig. 1a for illustration of two different states of such junctions). Núñez et al. [82] predicted that in an antiferromagnetic spin valve, a giant magnetoresistance as well as a spin-transfer torque will occur. They illustrated the existence of magnetoresistance and spin-transfer

torque with a 1D model (see Fig. B1b). Subsequent work found that these effects persist in more chemically realistic antiferromagnetic spin valve structures [83,84, 85] (see Fig B1c) and in tunneling junctions . [86,87] (See also reviews by MacDonald et al. [88] and Haney et al. [89] on the early calculations and comparison to ferromagnets.) Haney et al. [90] have shown that an antiferromagnet can also generate a torque on a ferromagnet. Similarly to ferromagnets, a spin-transfer torque is also predicted to occur for an antiferromagnetic domain wall [84, 91, 92]. All of these investigations, however, considered ballistic transport in perfectly epitaxial and commensurate heterostructures. A key issue is whether these effects will survive in realistic devices. Duine et al. [93] found that presence of inelastic scattering strongly reduces the giant magnetoresistance and the torque, in contrast to ferromagnetic spin valves. Nevertheless, it was argued that magnetoresistance and the torque should survive since the inelastic mean free path is typically relatively large and elastic scattering was assumed to not influence the magnetoresistance and the torque much. However, later studies [94,85, 95] found that the torque is very strongly suppressed even by elastic scattering (see Fig. B1d). Thus the torque (and likely also the magnetoresistance) in antiferromagnetic spin valves is probably limited to very clean samples and low temperatures. Recent calculations by Saidaoui et al. [96] suggest that the torque might be more robust against elastic scattering in tunneling junctions.

A very good epitaxy is expected to be necessary for the presence of magnetoresistance and torque in antiferromagnetic heterostructures. Therefore, while theoretical works have clearly demonstrated that giant and tunneling magnetoresistances and spin-transfer torques can in principle exist in purely antiferromagnetic structures, the observation of these effects would require clean and perfectly epitaxial devices. This is consistent with the fact that no torque, and only a tiny magnetoresistance [97,98, 99] have been observed in antiferromagnetic spin valves and tunneling junctions so far.

Finally we note that the research we have discussed so far focused mostly on collinear antiferromagnets. Recently Železný et al. [100] predicted that in non-collinear antiferromagnets, such as Mn_3Ir and Mn_3Sn, the electrical current is spin-polarized. Thus a robust torque and magnetoresistance could exist in spin valves or tunneling junctions based on these antiferromagnets.
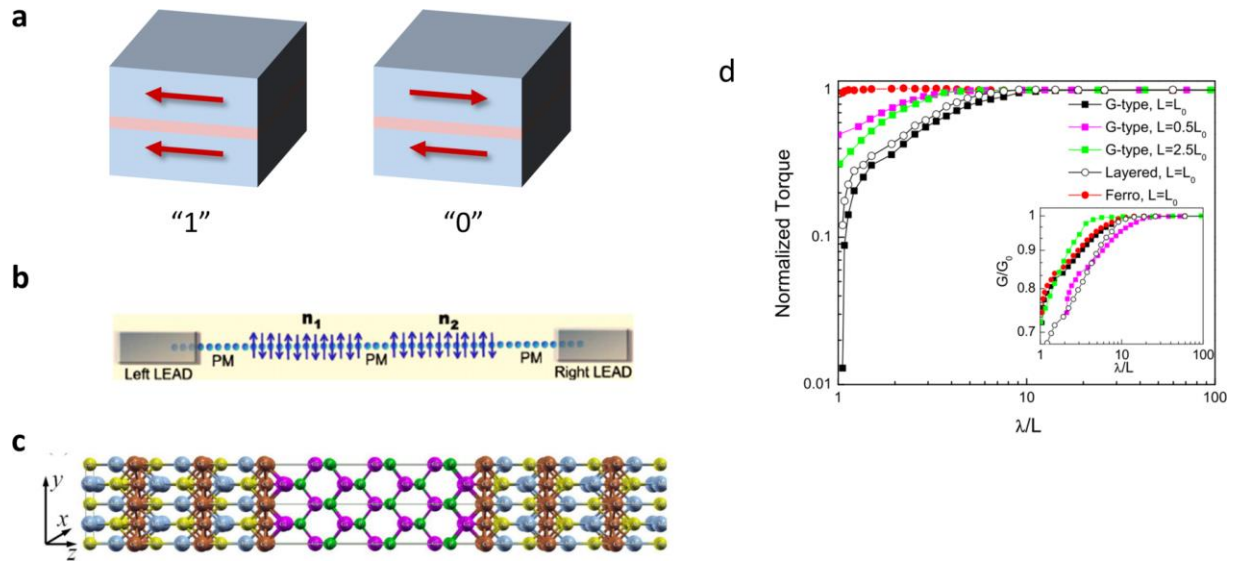
Figures

Fig B1. **a**, The two states of a ferromagnetic spin valve or tunneling junction. **b**, 1d tight-binding model used by Duine et al. [93] **c**, Chemically realistic antiferromagnetic tunneling junctions considered by Stamenova et al. [87] **d,** Calculations by Saidaoui et al. [94] for various spin valves, which show strong decrease of the torque in the presence of elastic scattering in the antiferromagnetic spin valves compared to a ferromagnetic one. Here, λ is the mean free path, L is the length of the spin valve, L_0 correspond to 20 atomic sites and the inset shows normalized conductivities. „G-type" and „layered" corresponds to different types of antiferromagnetic spin valves.
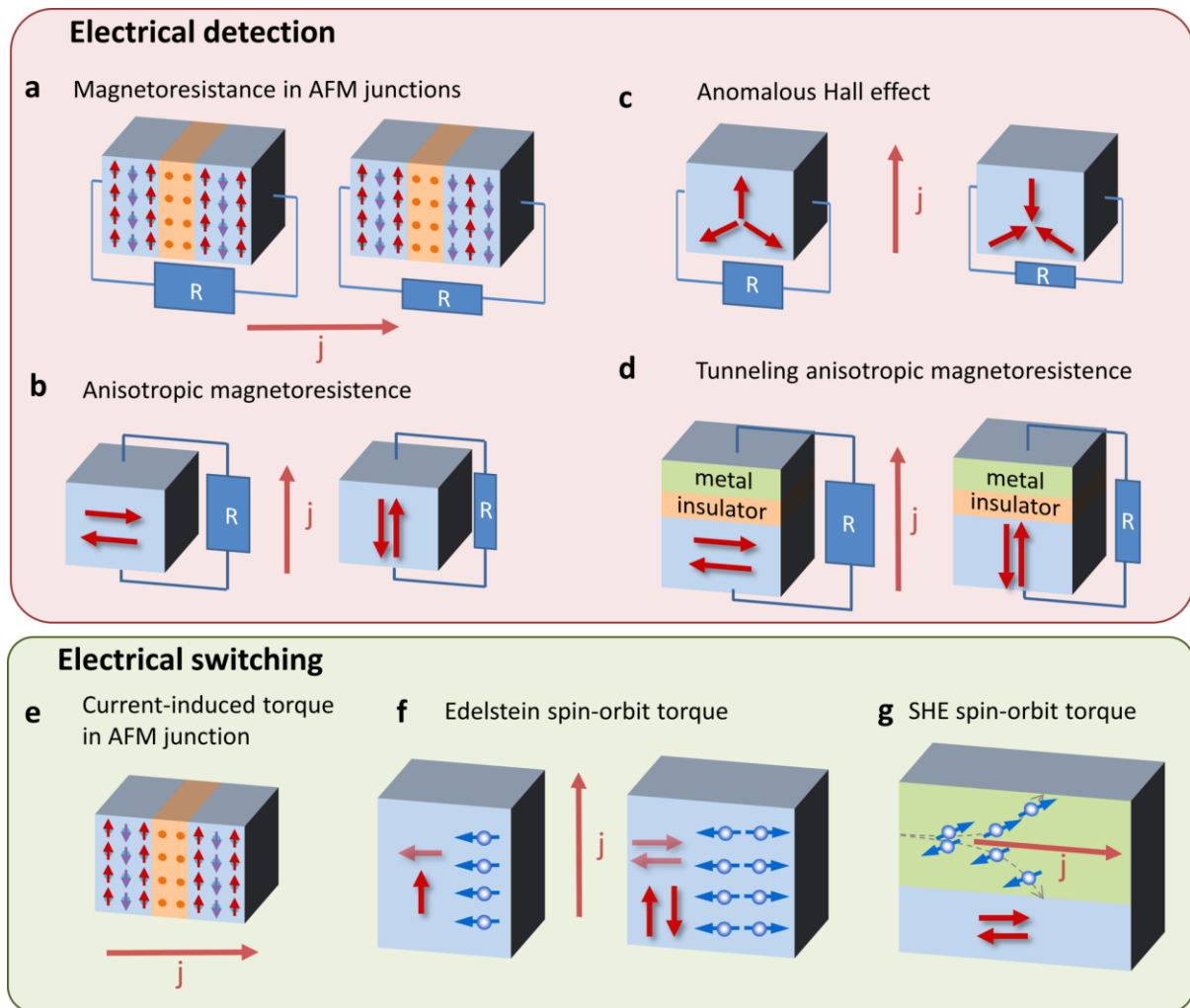
Figure 1. Illustration of the various concepts proposed for the electrical detection and manipulation of antiferromagnetic order. a, Magnetoresistance in antiferromagnetic spin valve or tunneling junction. It has been theoretically proposed, but so far has not been clearly detected experimentally. **b**, Anisotropic magnetoresistance. This methods has been demonstrated experimentally in several antiferromagnets. **c**, Anomalous Hall effect. This methods has been demonstrated experimentally in non-collinear antiferromagnets. **d**, Tunneling anisotropic magnetoresistance. A large readout signal has been experimentally demonstrated. **e**, Spin-transfer torque in an antiferromagnetic spin valve or tunneling junction. Such torques were theoretically proposed, but so far have not been demonstrated experimentally. **f**, ISGE spin-orbit torque (left) in a ferromagnet and (right) antiferromagnet. Switching using this torque has been demonstrated experimentally. **g**, SHE spin-orbit torque. The torque in such a device has been experimentally demonstrated, but switching has been recently observed with insulating antiferromagnets.
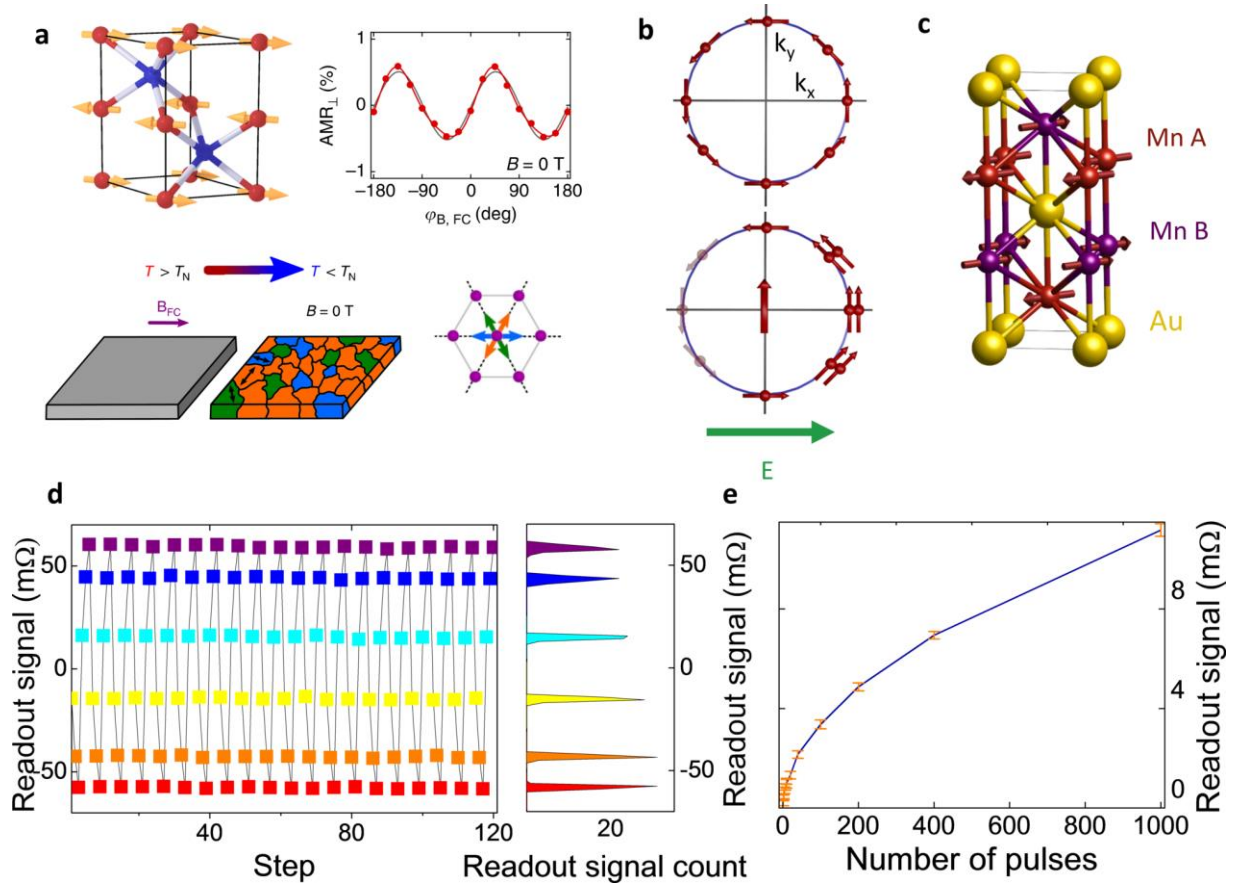
Figure 2 | AMR and ISGE spin-orbit torque in antiferromagnets. **a**, Measurement of AMR in MnTe. Top left: the crystal and magnetic structure of MnTe. Top right: The AMR signal obtained by field-cooling in magnetic fields with various directions. The measurement is done in zero magnetic field. Bottom: Illustration of the field-cooling procedure, which results in a distribution of magnetic domains between the 3 magnetic easy axis (bottom right). From Ref. [21]. **b**, Illustration of the ISGE effect. Top: Fermi surface of a system with spin-orbit coupling in equilibrium. Bottom: Applied electric field causes a redistribution of electrons which results in a non-equilibrium spin-polarization. Adapted from Ref. [4]. **c**, Crystal and magnetic structure of Mn$_2$Au. From Ref. [41]. **d**, Left: Electrical switching by the ISGE spin-orbit torque in CuMnAs demonstrating the multi-level stability and reproducibility of the results. For the measurement a series of three 100 μs long pulses was alternatively applied along perpendicular directions. Right:, Histogram of the six different states, obtained from 50 repetitions of the pulse sequence. All measurements were performed at room temperature. From ref. [47]. **e**, Electrical switching by the ISGE spin-orbit torque in CuMnAs using a series of 250 ps pulses as a function of the number of pulses. The error bars show a standard deviation of 15 repetitions. From ref. [47].
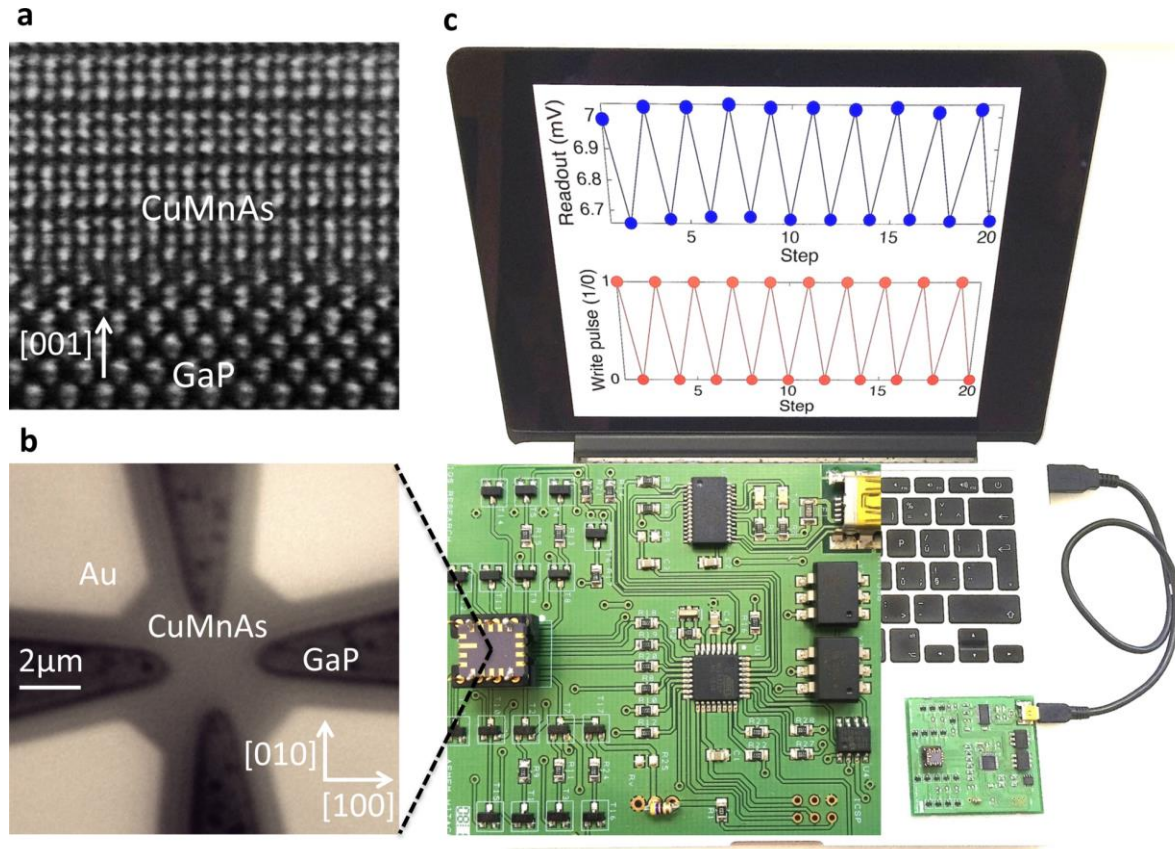
Figure 3 | Demonstration of microelectronic compatibility of the CuMnAs memory cell. **a**, Transmission electron miscroscope picture of the epitaxial growth of CuMnAs on GaP. From ref. [47]. **b**, The CuMnAs device used for electrical switching. From ref. [47]. **c**, The electrical switching of CuMnAs in a USB device. From ref. [47].
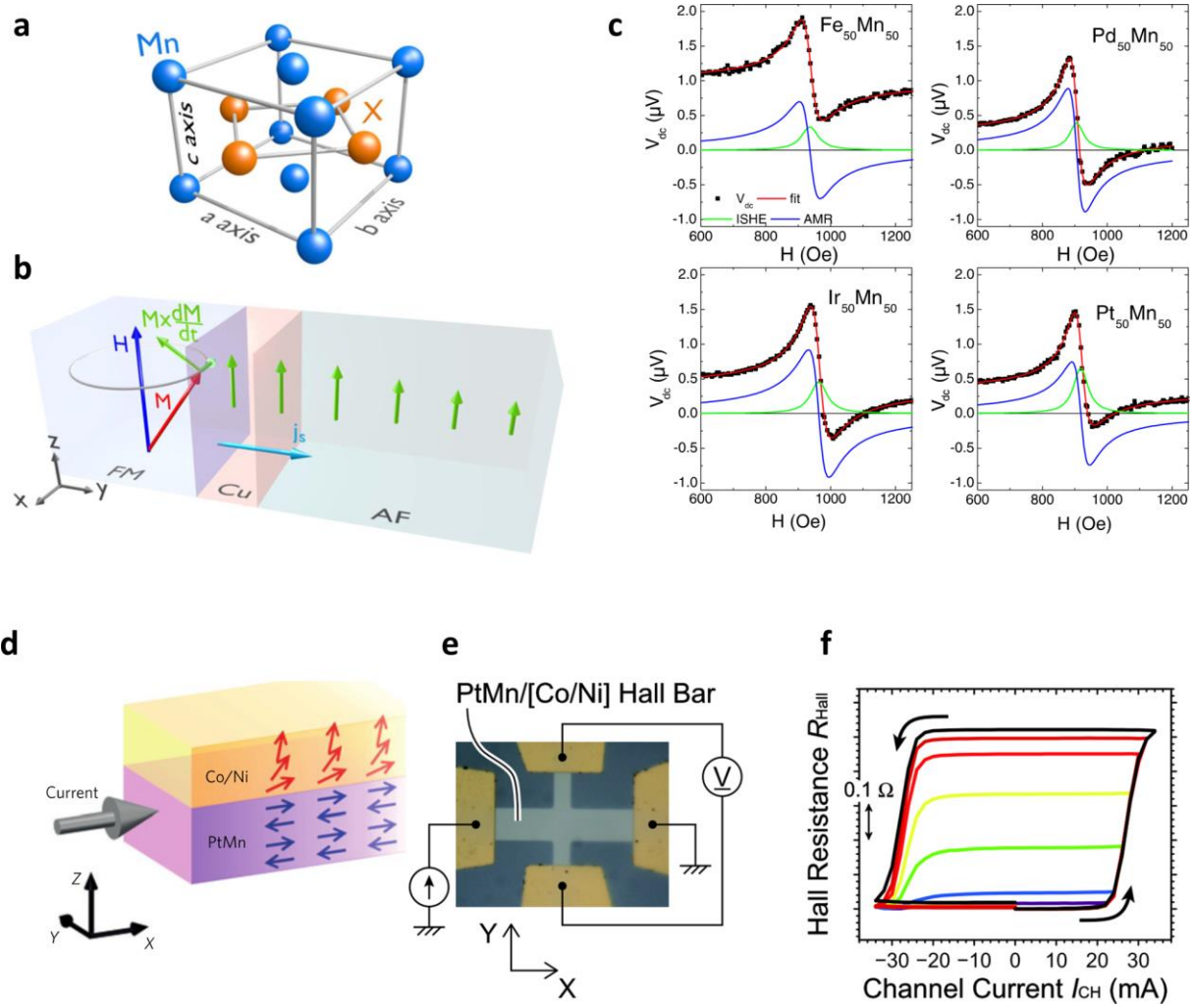
Figure 4 | SHE and SHE spin-orbit torque in antiferromagnets. a, Crystal structure of antiferromagnets MnX. From Ref. [60]. **b**, Schematic of the spin-pumping experiments. Combination of a DC and AC magnetic field induces a precession of the magnetization of the ferromagnetic layer, which causes a spin current flowing in the antiferromagnet. The spin current is then converted to voltage due to the inverse SHE. From Ref. [60]. **c**, Voltages detected in the spin-pumping experiment as a function of a DC magnetic field for several MnX antiferromagnets. The total signal contains a contribution from inverse SHE and AMR. From Ref. [60]. **d**, Illustration of the exchange bias in antiferromagnet/ferromagnet bilayers, which leads to a memristor like behaviour of the spin-orbit torque switching From Ref. [66]. **e**. The experimental setup used for the demonstration of the memristor behaviour. From Ref. [73]. **f**, Demonstration of the memristor-like behaviour in the PtMn/[Co/Ni] devices. 0.5 s long current pulses with magnitude varying between $-I_{max}$ and I_{max} were applied and the Hall resistance was measured after each pulse. Different values of I_{max} are denoted by different colours. From Ref. [73].

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