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Research articles

Antiferromagnets for spintronics

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ABSTRACT

Upon their original discovery, antiferromagnets were considered interesting magnetic materials, but without much practical relevance. This sentiment changed upon the development of spintronics, where the electrons' spin degree of freedom is utilized for new functionality in electronic devices. In this context antiferromagnets first found application as passive elements, where their insensitivity to applied magnetic fields allowed them to provide reference magnetic orientations via the exchange-bias effect. More recently it has been recognized that antiferromagnets can play a more active role in spintronics; namely they can generate, support, and manipulate spin currents. In fact, the magnetic structure of antiferromagnets may play a profound role in spin-transport phenomena, giving rise to new transport phenomena. We will briefly review both the passive and active roles that antiferromagnets may play for spintronics and provide a perspective for future opportunities.

1. Introduction

Magnetic materials and their intrinsic ability to generate noticeable forces over long distances, inspired human curiosity for at least two millennia. At the same time they found numerous applications; starting with the lodestone compass in ancient China to the pervasive availability of information in the modern society enabled by magnetic data storage, magnetic materials are used for many purposes ranging from energy technology to medicine [1]. The versatility of magnetic materials originates in the complexities of magnetic behavior that stems from competitions between magnetic interactions that span the length-scales from the atomic to the macroscopic world. Among the different known magnetic materials, one class of materials stands out: Antiferromagnets. In antiferromagnets, the exchange interaction between neighboring spins is negative, which means that spins on adjacent atomic positions orient antiparallel to each other with the consequence that there is no net magnetization for these materials. Since this magnetic order is not easily detected, it took after the initial theoretical prediction of antiferromagnets by Louis Néel in 1936 until the 1950's before antiferromagnetic order was experimentally verified through neutron diffraction. Even though initially antiferromagnets were considered of little practical use, they have become an integral component of many modern magnetic devices.

The insensitivity of the magnetic order in antiferromagnets to external magnetic fields makes them uniquely useful for defining magnetic reference directions. Namely, by combining antiferromagnets with ferromagnetic materials, the coupling between these two materials results in a phenomenon known as exchange bias [2], whereby the net magnetization of the ferromagnet couples preferentially to a subset of the magnetic moments in the antiferromagnet. Using a well defined magneto-thermal history results in magnetic hysteresis loops that have distinct asymmetric behavior with respect to externally applied magnetic fields. This in turn can be used to established a pinned ferromagnetic magnetization that can be used as reference for other magnetic components, *e.g.*, in magnetoelectric or so-called spintronics devices.

Besides this passive application of antiferromagnets that relies on a static magnetic structure, which is exchange coupled to a net ferromagnetic magnetization, antiferromagnets have gained recently interest as active components in spin-transport devices [3]. First, it was realized that insulating antiferromagnets can transmit spin currents much better than non-magnetic dielectric materials [4,5]. Soon thereafter, it was discovered that antiferromagnets can also be a good source for spin currents. For metallic antiferromagnets [6] spin–orbit coupling can convert a charge current into spin currents, an effect known as spin Hall effects [7]. Similarly, for insulating antiferromagnets thermal heat currents can have concomitant spin currents, which can be injected into adjacent materials; a phenomena known as spin Seebeck effect [8]. But the seminal contribution to antiferromagnetic spintronics was the realization that in special antiferromagnetic materials, where the antiferromagnetic moments reside on crystal lattice sites with opposite

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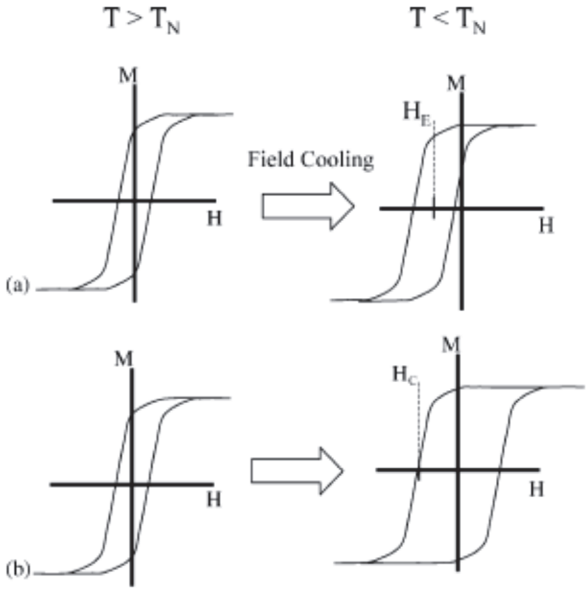

Fig. 1. Schematic of the exchange-bias effect. Upon cooling a ferromagnetic–antiferromagnetic coupled system through the Néel temperature T_N in the presence of an applied field, the magnetic hysteresis loop of the ferromagnetic component becomes (a) asymmetrically displaced from $H = 0$ and (b) generally also acquires an enhanced coercivity.

local inversion symmetry, then it is also possible to directly manipulate the antiferromagnetic order electrically [9]. This opened up the door to use antiferromagnetic materials also directly for information technologies, by encoding information in their antiferromagnetic structure, which ordinarily is not easily accessible or controllable. The advantages of using the "hidden" antiferromagnetic order for these applications is that there are little interactions, and therefore cross-talk, between closely packed devices (*e.g.*, for memories), and at the same time high insensitivity to external perturbations through external magnetic fields. But more importantly, since the dynamics of antiferromagnets is determined not only by crystal anisotropies, but also strong exchange interactions, the characteristic time-scales are much shorter than for ferromagnets, which may enable ultra-fast applications, where magnetic states can be modulated within ps.

The recent research on antiferromagnetic materials highlights two aspects that are germane to the investigations of magnetic materials in general, but also have been a mayor focus for the scientific work of Kannan M. Krishnan. One is that the microstructure can have a profound impact on the practical performance of magnetic applications [10]. The other one is that interactions across interfaces in magnetic heterostructures are a key ingredient for many novel magnetic phenomena, but also indispensable for the design of novel applications [11]. In this article, we will review selected examples that illustrate some of these developments.

2. Exchange bias

Exchange bias has been investigated for more than half a century and has been considered one of the most successful applications with respect to antiferromagnetic materials. From simple magnetometry, it manifests itself as a shift of the center of the magnetic hysteresis loop from $H = 0$, to $H_E \neq 0$ together with typically an enhancement of the coercivity, as is schematically shown in Fig. 1. This behavior is understood to arise from the interfacial coupling between ferromagnetic (FM) and antiferromagnetic (AFM) layers, upon field cooling the sample below the respective Curie, T_C, and Néel, T_N, temperatures. However, through continuous studies over the past decades, the scientific relevance of exchange bias has been recognized to reach far beyond just its relevance to static magnetization reversal. The study of exchange bias has inspired many important, subsequent discoveries in surface science, spin dynamics, spin electronics, and triggered many technological developments in advanced material characterizations. Furthermore, these studies also induced a general, increasing appreciation of antiferromagnets over the years, which prepared the knowledge foundation for antiferromagnetic spintronics, an emerging topic that has set a more ambitious goal to use antiferromagnets in a much more active fashion for future novel concepts in electronic computing and storage. [2]

2.1. Importance of microstructure

In contrast to ordered single-crystals, understanding the microstructures has always been a central issue for understanding both the fundamental physics and the applied impact for magnetic thin films. In exchange-biased heterolayers, the microstructure of thin films also connects to two other concepts that are important to thin-film antiferromagnets, *i.e.*, *defects* and *interfaces*. For magnetic systems in particular, both the chemical defects and interfaces as well as the magnetic ones have to be characterized and understood to identify unambiguously any solid structural-property relations for exchange bias. Such a goal demands advanced thin-film characterizations beyond conventional tabletop techniques such as X-ray diffraction or atomic-force microscopy [14]. Below, we discuss three examples of advanced characterization for studying the exchange-bias systems that can offer unique, important information about the microstructure, defects, and interfaces of thin films with antiferromagnets.

Transmission electron microscopy (TEM), being an "ultra-local" technique for both imaging and diffraction down to the atomic level, has found a great usage in characterizing the composition and microstructure of thin films. In particular, this enables to clarify their roles in determining the strength of the interfacial coupling [12]. As shown in the left panel of Fig. 2, the nature of the interface and the chemical integrity of the various layers in an exchange-bias Ni–Fe/Mn–Pt bilayer can be unambiguously studied, via an energy-filtered imaging and high-resolution phase contrast imaging of cross-section samples. It can be directly seen in Fig. 2(a), that the interfaces between the MgO, Ni–Fe, and Mn–Pt are chemically sharp and are devoid of any pinholes. However, the higher resolution image in Fig. 2(b) reveals that the interface between the Ni–Fe and Mn–Pt is structurally quite rough with significant strain. Any difference in the interfacial coupling caused by the crystallographic texture (through TEM diffraction), grain size and layer thickness (through high-resolution images), and chemical ordering or defects (through energy-filtered elemental images, shown in Fig. 2(c)) can be analyzed in conjugation with other magnetometry experiments.

As a powerful derivative of the TEM technique, electron holography offers even more 'magnetic' information via detecting the magnetic structure in the ferromagnetic components in exchange bias by analyzing the phase shift of electrons in a TEM experiment. For example, such electron holography technique has been applied to investigate the spin configurations at the AFM–FM interface in an epitaxial MnPd/Fe bilayer systems using similar cross-sectional specimens, see right panel of Fig. 2 [15]. For studying epitaxial exchange-bias samples, the specimens were usually prepared along both the hard and easy axes of the ferromagnetic layers, illustrated in Fig. 2(d), to accommodate the magnetocrystalline difference. After typical TEM images were recorded, see Fig. 2(e) and (f), for respective *c*- and *a*-oriented MnPd/Fe samples, one can reconstruct a phase image due to electron holography such as the one shown in Fig. 2(g). Clear contours can be identified to align parallel to the interface, representing the magnetization of the Fe layers. In addition, the directions of magnetization of the Fe layers, as estimated from a contrast gradient in the phase image, correspond well to the magnetization reversal as illustrated in Fig. 2(h).

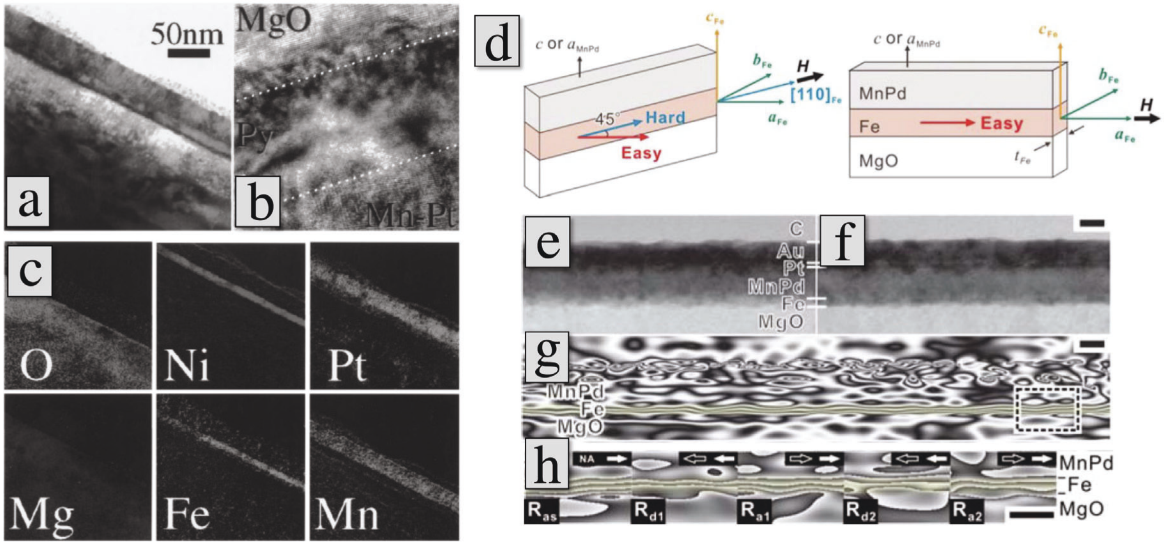

Fig. 2. Transmission electron microscopy (TEM) study of Ni–Fe/Mn–Pt bilayers. (a–b) Cross-sectional TEM images and (c) energy-filtered elemental images. Adapted from Ref. [12]. TEM hologram study of epitaxial MnPd/Fe bilayers. (d) Orientations in cross-sectional TEM specimens prepared along the hard and the easy axes of Fe layers. Applied field (H) direction for the magnetization-reversal process is presented. (e–f) Typical TEM images of c- and a-oriented samples, respectively. (g) Example of a reconstructed phase image for the c-axis sample along the hard axis. (g) reconstructed phase images showing directions of magnetization (solid arrow) and applied external magnetic field (open arrow) at the region indicated by the dotted rectangle in (g).
Source: Adapted from Ref. [13]

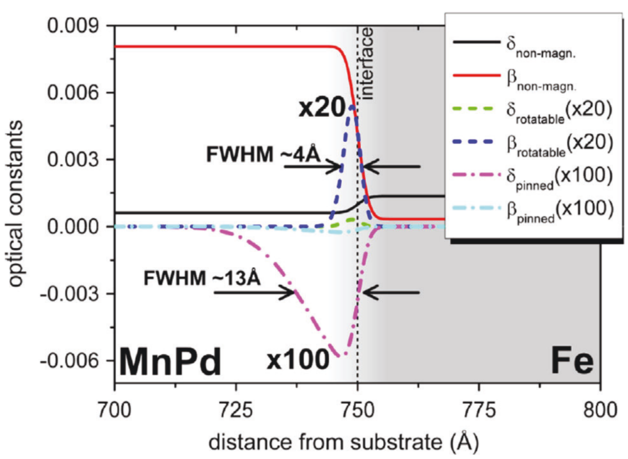

Fig. 3. X-ray optical and magneto-optic constants (absorptive part β and dispersive part δ) used for fitting resonant X-ray reflectivity measurements at the L_3 edge of Mn for a MnPd/Fe bilayer with magnetic fields applied parallel and anti-parallel to the exchange-bias direction. The difference between the two measurements enables to identify both rotatable and pinned uncompensated moments in the MnPd.
Source: Adapted from Ref. [15]

One of the most critical, long-standing questions in exchange bias is the atomic spin alignment at the interface, which is also one that is very challenging to answer experimentally. Additionally, many theoretical models also rely on the fundamental question of whether there are nontrivial uncompensated moments at the interfaces. Thanks to the modern development of synchrotron radiation and neutron sources, such a question has been explicitly addressed with respect to a variety of material systems. For example, for the Co/$LaFeO_3$ exchange-bias system, it was shown via polarized neutron reflectometry that there are net magnetizations at the interface that remain unchanged upon reversal of the magnetization of the Co layer [16]. Similarly, the element-specific magnetic structure of an epitaxial Mn–Pd/Fe bilayer was investigated with atomic-layer depth sensitivity at the FM/AFM interface by soft X-ray magnetic circular dichroism and magnetic reflectivity, see Fig. 3 [17,18]. The results reveal a complex magnetic interfacial configuration, consisting of a 2-monolayer-thick induced ferromagnetic region, and pinned uncompensated Mn moments that reach far deeper into the bulk antiferromagnet. These findings further allow the derivation of a precise picture of the interface with respect to the long-standing puzzle of interfacial spin-magnetic moments: (i) some Mn atoms which have Fe as neighbors couple to them strongly but align antiparallel to the Fe moments. (ii) Pinned Mn moments are found mostly below the rotatable ones, and they couple ferromagnetically to the Fe. In other words, they are aligned antiferromagnetically to the rotatable Mn, see Fig. 3. Those microscopic features down to the atomic spin level would otherwise be nearly impossible to resolve by other experimental means such as magnetometry and/or magneto-optics.

2.2. Role of anisotropies

The hallmark of exchange bias is the asymmetric shift of the hysteresis loop as shown in Fig. 1(a), which can be understood as an effective field acting on the ferromagnet due the coupling to a field-independent magnetic structure in the antiferromagnet. This can be described by a unidirectional anisotropy energy $-K_E\cos(\theta-\theta_E)$, where K_E describes the magnitude of the exchange bias, θ is the angle of the magnetization in the ferromagnet with respect to the applied magnetic field, and θ_E gives the direction of the unidirectional anisotropy typically established through specific thermomagnetic history. But in addition ferromagnetic materials have often many other magnetic anisotropies that determine their behavior, *i.e.*, due to their crystalline structure or due to the geometric shape of the ferromagnetic components. It turns out that the interplay between all these different anisotropies can result in very complex behaviors of exchange-bias systems.

A natural question is, whether the magnetization reversal on the two branches of the magnetic hysteresis loop are identical to each other. Since the Zeeman energy due to the interaction of the magnetization with an applied magnetic field is given by $-MH\cos\theta$ (with M being the magnetization of the ferromagnetic layer, and H being the applied magnetic field), it is apparent that any asymmetries will require the uniaxial anisotropy of the exchange bias to be in a different direction than the applied magnetic field. Under these circumstances there are readily pronounced asymmetries observed for the magnetization reversal [19,20]. As an example Fig. 4 shows different magnetic domain

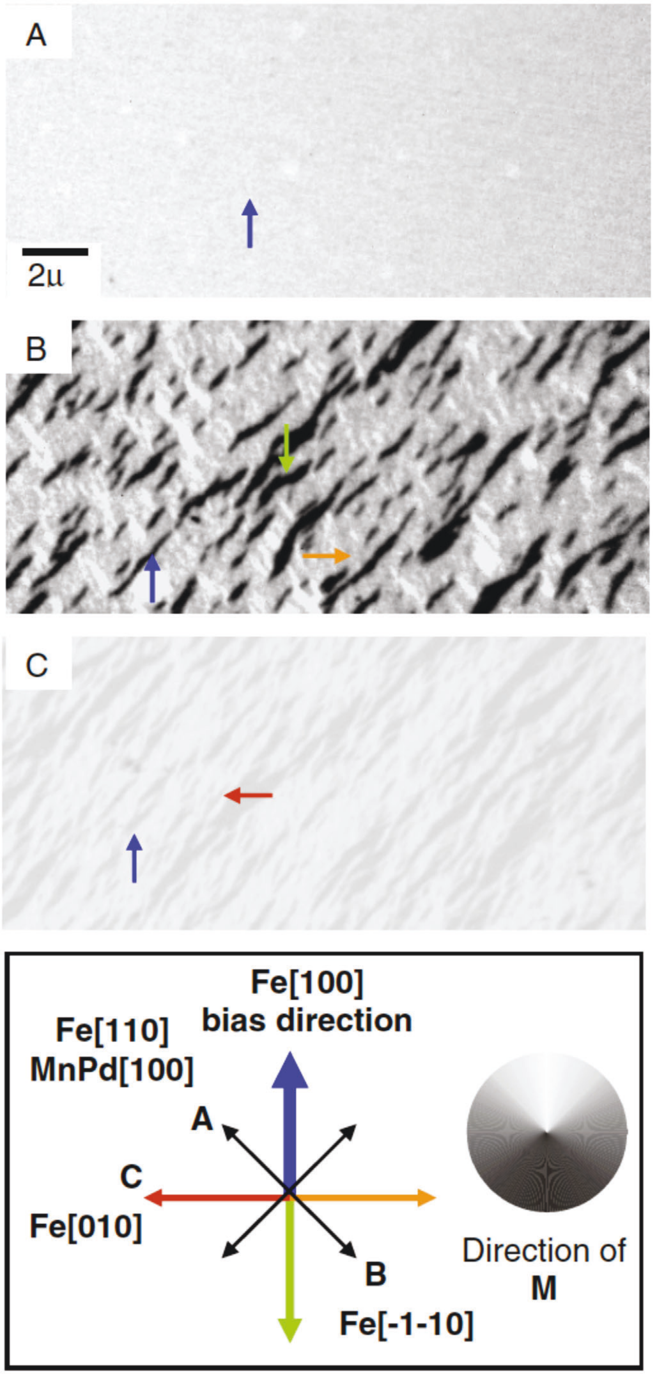

Fig. 4. Photoemission electron microscopy images with X-ray circular dichroism contrast of the magnetic domains in Fe/MnPd. The images were taken in remanence after saturating the sample along (a) Fe[110], (b) Fe[$\bar{1}\bar{1}$0], and (c) Fe[010]. The exchange-bias direction is along Fe[100].
Source: Adapted from Ref. [17]

images of a Fe/MnPd bilayer taken in remanence after saturating the magnetization in different directions. Depending on the initial direction of the applied magnetic field the magnetization reversal either proceeds via coherent magnetization rotation or via domain nucleation and growth.

The complex interplay between different magnetic anisotropy contributions can be systematically studied by using shape anisotropy, which can be modulated through the geometry of the ferromagnetic layer. For example, using patterned wires with different widths and orientations allows to continuously vary the relative strength of unidirectional anisotropy given by exchange bias and uniaxial anisotropy due to the shape anisotropy of the wire, as well as their relative orientation. The hysteresis loops can be readily modeled via the Stoner–Wohlfarth coherent rotation model [21,22], where the free energy of the magnetic system can be written as:

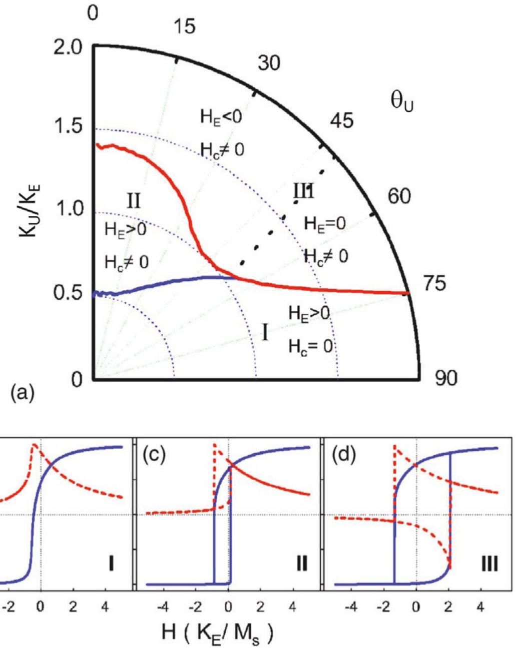

Fig. 5. (a) Phase diagram of different hysteretic behaviors for competing uniaxial K_U and unidirectional K_E magnetic anisotropies. Depending on the ratio K_U/K_E and the relative angle θ_U between their respective directions, three different types of magnetic hysteresis loops can be observed: (b) Reversible switching, (c) irreversible switching with negative hysteresis shift, and (c) irreversible switching with positive hysteresis shift.
Source: Adapted from Ref. [19]

$$E = -MH\cos\theta - K_E\cos(\theta-\theta_E) - K_U\cos^2(\theta-\theta_U), \qquad (1)$$

where K_U is the magnitude of the uniaxial anisotropy, and θ_U is its direction relative to the applied magnetic field H. Depending on the parameters, one can distinguish three distinct behaviors, as shown in Fig. 5; (I) completely reversible switching with negative loop shifts, (II) irreversible switching with negative loop shifts, and (III) irreversible switching with positive loop shifts. Note that the same direction of undirectional anisotropy may result in either positive or negative loop shifts, depending on the details of the additional uniaxial anisotropy, and that this behavior is well reproduced in experiments using Fe wires on top FeF_2 [21,22]. Similar complex behaviors have also been observed for lithography-patterned thin-film systems with competing shape, magnetocrystalline, and interfacial anisotropies [23–26] and in epitaxial Fe/IrMn with crystalline anisotropy [27–29].

Within the framework of the Stoner–Wohlfarth model, this behavior finds a simple interpretation via the Stoner–Wohlfarth switching steroid [30]. As is shown in Fig. 6(a) the unidirectional anisotropy results in an asymmetric shift of the astroid away from zero magnetic field, and for fields applied in directions different from this shift, the field lines will cross the astroid at inequivalent positions, indicating the asymmetry of the reversal. Similarly, the transition from irreversible to reversible switching can be easily recognized by the angle at which the field line does not intersect the astroid anymore. This later behavior has been explored for Co/IrMn bilayers, where the ratio of uniaxial to unidirectional anisotropy was varied through changing the Co thickness [30].

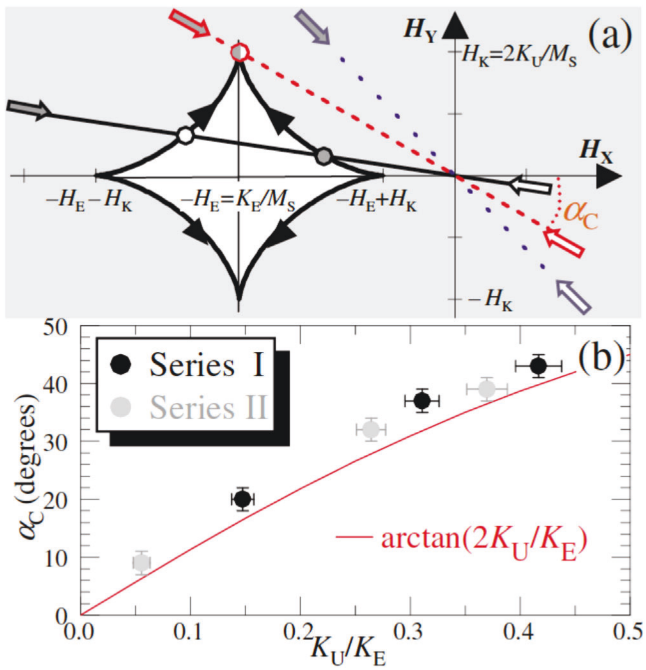

Fig. 6. (a) Asymmetries of the magnetization reversal can be readily understood within a Stoner–Wohlfarth coherent rotation model. A unidirectional anisotropy results in an asymmetric shift of the Stoner–Wohlfarth astroid, which provides a graphical solution for identifying irreversible switching events. Due to the shift the field-lines will cross the astroid at inequivalent locations, and therefore result in different switching behaviors with different amounts of magnetization rotation. (b) This representation also allows to easily identify a critical angle α_C, where the magnetization reversal becomes completely reversible.
Source: Adapted from Ref. [22]

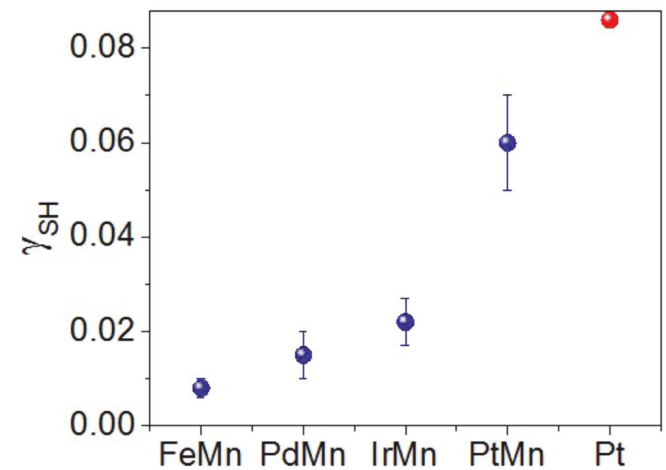

Fig. 7. Spin Hall angles γ_{SH} for different Mn-based metallic antiferromagnets. There is a systematic trend towards larger spin Hall angles for antiferromagnets containing heavier elements. Furthermore, for PtMn the spin Hall angle becomes comparable to Pt on its own.
Source: Adapted from Ref. [30]

So far the discussion focused on effects of the anisotropy in the ferromagnetic component of an exchange-bias system. But of course the anisotropy within the antiferromagnet is also important for understanding details of exchange bias. For example, this was studied for Fe/PdMn bilayers, where by growing the PdMn at different temperatures allowed to have either c-axis or a-axis oriented PdMn films [31]. While there were different magnitudes of exchange bias observed along with other crystal-dependent properties [32,33], it is however difficult to disentangle these changes from other effects, such as chemical ordering. However, the anisotropy in the antiferromagnet is important for understanding aspects, such as thermal stability, which influence the magnitude of the unidirectional anisotropy and coercivity enhancement in exchange-bias systems. Related to these are training effects, which are observed as a stepwise reduction of the exchange-bias hysteresis loop shift upon subsequent hysteresis loop. Using a similar coherent rotation model as discussed above, but now for understanding irreversibilities in the antiferromagnet, it was shown that the observation of these training effects may correlate with the symmetry of the anisotropies within the antiferromagnet. Namely, if the antiferromagnet has multiple easy anisotropy axis, then the field cooling procedure may generate a metastable, non-collinear spin structure that can relax during the magnetization reversal of the ferromagnet [34].

3. Spin transport

For the above discussed exchange bias, we mostly consider a static magnetic structure within the antiferromagnet, and how the interaction of this magnetic structure with other magnetic layers can be influenced by microstructure and interfacial properties. But more recently, dynamic magnetic excitations of antiferromagnets have become of increased interest. Even though antiferromagnetic materials have a vanishing net magnetization their atomic spin structure makes their response to spin excitations very different from truly non-magnetic material. For spin transport, we can generally distinguish two types of spin currents. One is due to spin-polarized charge carriers, which require conducting antiferromagnets, while the other on is due to magnetic excitations (magnons or spin waves), which are the fundamental quantum mechanical excitations of magnetically ordered systems. The latter can occur both in insulating and metallic antiferromagnets, and indeed in metallic systems both type of spin currents may coexist [35]. However, in the following we want to focus mainly on spin transport due to spin-polarized charge carriers.

3.1. Spin Hall effects

Generation of spin-polarized current is the key to nearly all spintronic applications, which is usually achieved by passing a charge current through a ferromagnetic polarizer. Recently, it has been shown that spin–orbit interaction can provide an alternative, yet more efficient pathway for the same purpose, even when using nonmagnetic conductors. Among the key phenomena arising from spin–orbit interactions is the spin Hall effect, which was theoretically predicted in 1971 [36]. Such effects convert an initially unpolarized charge current into a transverse spin current, resulting in spin accumulations at the boundaries of the conductor. A materials-specific spin Hall angle, given by the ratio of charge-to-spin current densities, has been used as a measure of the conversion efficiencies.

As one of the key topics in antiferromagnetic spintronics, the spin Hall effects of antiferromagnetic metals have been reported in the same materials that have been traditionally used for providing the exchange bias in the FM/AFM bilayers. For example, sizable spin Hall effects have been revealed in CuAu-I-type metallic antiferromagnets, FeMn, PdMn, IrMn, and PtMn [7,37]. Theoretical interpretations for the observed spin Hall effects in antiferromagnets have been largely centered on the important role of the heavy-metal element in these alloys, as well as the nontrivial modification of the bandstructure by the magnetic elements. As can be seen in Fig. 7 there is a systematic increase of the spin Hall angle as the atomic weight of the element alloyed with Mn increases and it becomes comparable to Pt, which often is used for electric manipulation of magnetizations.

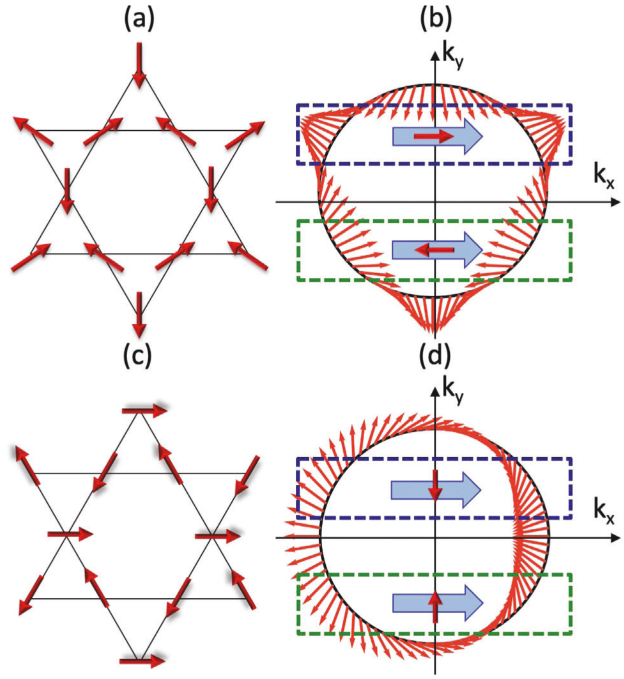

Fig. 8. Schematic illustrating the origin of magnetic spin Hall effects in metallic antiferromagnets with spins ordered on a kagome lattice. Depending on the orientation of the spins in real space (a) and (c) there is a corresponding spin texture in momentum space (b) and (d). A charge current in x-direction will then result in different net spin polarizations for states with $k_y > 0$ and $k_y < 0$. The resultant spin current can be polarized along x-direction (b) or the y-direction depending on the direction of the antiferromagnetic spins in real space. Also note that the spin polarization reverses, if the magnetic structure is reversed.

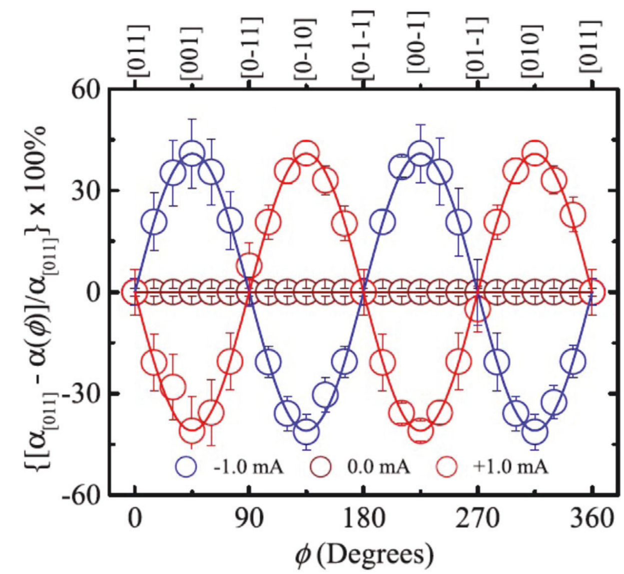

Fig. 9. Variation of the electric current depending Gilbert damping α in an $IrMn_3/Ni_{80}Fe_{20}$ bilayer. The angular dependence is even under magnetic field reversal, which indicates that the damping modulation originates from magnetic spin Hall effects. *Source:* Adapted from Ref. [41]

3.2. Magnetic spin Hall effects

Recently, it has also been found that the 'magnetic ordering' in antiferromagnets may even have a more direct impact to the generation of pure spin current with even nontraditional spin-polarization directions due to combined symmetry breaking, *i.e.*, resulting in a magnetic spin Hall effect [38,39]. Early hints of this were already given by the highly anisotropic nature of even conventional spin Hall effects, which were shown to depend strongly on the orientation of the antiferromagnetic moments [37]. This has been recently better understood, in terms of the spin structure of the antiferromagnetic order resulting also in a net spin polarization of the electron conduction; but unlike in a ferromagnet, this spin polarization becomes dependent on the direction of the electron propagation relative to the antiferromagnetic ordering vector as well as the orientation of the local magnetization [40,41]. This is shown schematically in Fig. 8, which depicts the spin polarization of the electronic states at the Fermi surface for two different spin configurations for non-collinear antiferromagnetic structures on a kagome lattice. Note that for these spin textures in momentum space a charge current in x-direction results in a pure spin current in y-direction, which can be spin polarized in either x- or y-direction depending on the orientation of the antiferromagnetic spins. Furthermore, a reversal of the antiferromagnetic spins, also results in a reversal of the spin polarization of the pure spin current.

Therefore, while ordinary spin Hall effects are just determined by the charge current and pure spin-current directions and associated torques are even under time reversal, magnetic spin Hall effects also depend on the relative orientation of electric current and applied magnetic field [42]. Therefore spin–orbit torques generated by magnetic spin Hall effects are odd under time-reversal. This can generate spin accumulations and spin torques with new symmetries that are otherwise not accessible with non-magnetic materials.

An example where the magnetic spin Hall effect is observed in experiments is shown in Fig. 9, which shows the angular dependence of the electric current induced changes of the magnetic damping α in an $IrMn_3/Ni_{80}Fe_{20}$ bilayer [39]. For these experiments, a 20-nm thick epitaxial film of $IrMn_3$ was grown on a (100)-oriented MgO substrate, and it was subsequently capped with 10-nm $Ni_{80}Fe_{20}$ and an additional 2-nm thick layer of Ti to prevent oxidation and an additional 200-nm thick SiO_2 to provide electrical insulation. X-ray diffraction confirms the (100)-growth of the $IrMn_3$ and therefore the kagome plane, which are in the 111 planes have a direction perpendicular to the interface with the $Ni_{80}Fe_{20}$ and therefore the antiferromagnetic order can generate pure spin currents with a spin polarization having a component perpendicular to that interface (see also Fig. 8). For the measurements the sample is flipped onto a coplanar waveguide and ferromagnetic resonance is measured using a vector network analyzer. The magnetic damping is determined by the frequency dependence of the resonance line-width. The damping is measured for different orientations of the externally magnetic field and different electric currents applied to the bilayer. Interestingly, there is a very large current-induced modulation of the damping of up to 40%, which indicates a magnetic spin Hall angle of $\gamma_{MSH} = 0.33 \pm 0.02$. The unusual aspect of the angular dependence is that the angular dependence is even in the magnetic field and therefore indicates the magnetic origin of the observed spin Hall effects. In general, it has recently been realized that the interplay between crystalline symmetries and spin-rotation symmetries can give rise to non-trivial spin transport [43], which await further experimental exploration.

4. Conclusion and outlook

In this article we provided a subjective selection of examples that demonstrate how microstructure and interfacial properties play an important role for utilizing antiferromagnetic materials for spintronic concepts. First we discussed exchange bias, which is used in spintronic devices for providing a reference magnetization direction. Here the microstructure influences sensitively the interfacial coupling and resultant magnetic anisotropies. This in turn can give rise to complex magnetic hysteresis effects, such as asymmetric switching pathways or metastable spin configurations, which result in training effects. Next we focused on spin-transport phenomena in metallic antiferromagnets. In particular the additional symmetry breaking due to the antiferromagnetic order results in non-trivial effects, such as electric current induced spin accumulations with novel symmetries. Both, exchange bias and spin-transport effects, show that antiferromagnets can give rise to a broad range of complex behavior, which also has direct relevance to technological applications. Thus they illuminate, why magnetism has remained such a vibrant research field up to the present day!

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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