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Nanoscale magnetic skyrmions in metallic films and multilayers: a new twist for spintronics — Source link

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Nano-scale magnetic skyrmions in metallic films and multilayers: a new twist for spintronics

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Abstract | Magnetic skyrmions are chiral quasiparticles that show promise for the transportation and storage of information. On a fundamental level, skyrmions are model systems for topologically protected spin textures and can be considered as the counterpart of topologically protected electronic states, emphasizing the role of topology in the classification of complex states of condensed matter. Recent impressive demonstrations of control of individual nanometer-scale skyrmions—including their creation, detection, manipulation and deletion—have raised expectations for their use in future spintronic devices, including magnetic memories and logic gates. From a materials perspective, it is remarkable that skyrmions can be stabilized in ultrathin transition metal films, such as Fe—one of the most abundant elements on earth—if these are in contact with materials that exhibit high spin-orbit coupling. At present, research in this field is focused on the development of transition-metal-based magnetic multilayer structures that support skyrmionic states at room temperature and allow for precise control of skyrmions by spin-polarized currents and external fields.

Introduction

Magnetic skyrmions (BOX 1) are knots in the magnetization distribution that have non-trivial topological properties, leading to an exceptional stability against transitions into trivial spin textures, such as the ferromagnetic state. The existence of magnetic skyrmions has been predicted quite a long time ago[1-3], but their observation is relatively recent: magnetic skyrmions have been detected in non-centrosymmetric complex crystals[4-11] and in ultrathin films of simple transition metals on substrates exhibiting high spin-orbit coupling[12-14]. In this last kind of systems, individual skyrmions with diameters on the single-digit nanometer scale, could be stabilized with the help of interfacial Dzyaloshinskii–Moriya (DM) interactions[15-23] (BOX 2). Their internal spin structure[24] was resolved by atomic-resolution spin-polarized scanning tunnelling microscopy (SP-STM)[25], and was found to be in excellent agreement with earlier theoretical predictions[1].
Using highly focussed spin-polarized electrons from a sharp SP-STM tip, it is possible to write, manipulate, and delete individual skyrmions[12]. This precise control at the single-skyrmion level in systems based on transition metal films, such as Fe, raises great hope for the application of skyrmions in spintronic devices, such as skyrmion-based race-track-type magnetic memories[26,27] or skyrmion-based logic devices[28]. As a result, a new research field has emerged, called skyrmionics. Skyrmionic devices would be based on a similar kind of magnetic multilayer technology as that developed over the past three decades for giant magnetoresistance (GMR) and tunnelling magnetoresistance (TMR) devices, but they would be made of ultrathin magnetic layers exhibiting non-collinear spin textures. Recently it has also been demonstrated, experimentally and theoretically, that non-collinear spin states lead to a novel type of magnetoresistance effect, which arises because of the non-

collinear nature of the spin texture[29,30]. Sensors based on this so-called non-collinear magnetoresistance (NCMR) can be used for an all-electrical detection of single skyrmions, instead of magnetic sensing elements[29,31]. To make skyrmionics a reality, current research is focussed on the observation and manipulation of small-sized skyrmions at room temperature[32] and on the study of their interaction with vertical and lateral spin currents[33] and with externally applied magnetic and electric fields[34].

Skyrmion lattices

Nanoskyrmion lattices in ultrathin transition metal films and multilayers. The magnetic states observed in ultrathin metallic films can differ substantially from those of the corresponding bulk materials. This difference can be due, for example, to the hybridization of electronic states at the interface between film and substrate, to strain effects resulting from heteroepitaxial thin film growth, or to lack of inversion symmetry at interfaces[35,36]. The lack of inversion symmetry at interfaces gives rise to interfacial DM interactions[15-23], which favour the formation of non-collinear spin textures with a unique rotational sense in ultrathin magnetic films that are in contact with materials that exhibit a large spin-orbit coupling (BOX 2). Examples of such interface-stabilized spin configurations include chiral magnetic domain walls[37-44], cycloidal[45-51] and conical spin spirals[52], and chiral skyrmion lattices[13,53-56].

These non-collinear spin states became accessible for atomic-scale studies thanks to the development of SP-STM[25,57]. Operating an SP-STM together with a 3D vector magnet[58] allows the direct real-space observation of complex non-collinear spin configurations in three dimensions, with atomic-scale spatial resolution. Moreover, the sense of rotation of chiral spin states can be unambiguously determined by 3D vector-resolved SP-STM measurements[48,13].

The discovery of skyrmion lattices in thin films. The first indications of an unconventional complex spin state in Fe monolayers on Ir(111) came from low-temperature SP-STM studies reported ten years ago[59-61]. In these measurements, a regular magnetic lattice with a periodicity of one nanometer and a square lattice symmetry was observed, in contrast with the hexagonal symmetry of the atomic Fe lattice and of the underlying Ir(111) substrate. Based on subsequent vector-resolved SP-STM measurements and on density functional theory (DFT) calculations, combined with simulations within an extended Heisenberg model, the observed complex spin state could be unambiguously attributed to an incommensurate 2D chiral nanoskyrmion lattice that formed spontaneously even in zero external magnetic field[13] (FIG. 1).

The period of the skyrmion lattice is determined by the competition between the magnetic exchange interaction and the DM interaction[45]. In ultrathin Fe films on Ir(111), the DM interaction is relatively strong, whereas the exchange interaction is significantly weakened at the Fe–Ir interface, which explains the amazingly small magnetic period of one nanometer. The DM interaction imposes the unique rotational sense of the observed nanoskyrmion lattice and, in combination with a sizable four-spin interaction for face-centred cubic (fcc)-grown Fe monolayers on Ir(111), it explains the stability of the observed nanoskyrmion lattice in the low-temperature limit, even in zero external magnetic field[13]. Raising the externally applied magnetic field to reach values of up to 9 T does not destroy the skyrmion lattice state[23], which means that no transition into a collinear ferromagnetic state occurs in magnetic fields with strengths up to this high value.

Interestingly, the symmetry of the skyrmion lattice can depend on the type of stacking of the epitaxially grown magnetic layer with respect to the underlying single crystal substrate. Indeed, whereas fcc-grown Fe monolayers on Ir(111) exhibit an incommensurate square skyrmion lattice, as mentioned above, hexagonal close-packed (hcp)-grown Fe monolayers on the same substrate reveal a commensurate hexagonal nanoskyrmion lattice[55]. Thus, the precise atomic configuration can have a significant influence on the exact spin structure of non-collinear magnetic states in ultrathin films, even for given material combinations. This can be understood considering the fact that atomic-scale DM interactions depend on the local atomic arrangement.

Thermal stability. The thermal stability of interface-stabilized skyrmionic lattices of fcc-grown Fe monolayers on Ir(111) has been investigated by variable-temperature SP-STM[54]. It was found that the skyrmionic lattice disappears at about 28 K, indicating a transition into a skyrmion liquid or into a paramagnetic state. Higher transition temperatures, up to room temperature and beyond—required for any type of future application— can be achieved by increasing the thickness of the transition metal film, making use of interlayer exchange coupling, or designing asymmetric multilayer structures. These routes will be discussed in the following sections.

Individual magnetic skyrmions

Skyrmions, in the original sense of the term, are particle-like solutions of non-linear field equations, and can be regarded as multidimensional, static, topological solitons[1,2,62] (BOX 1). Accordingly, magnetic skyrmions are localized non-collinear spin textures that should be observable individually, and not only in the form of skyrmionic condensates. Indeed, by tuning the relative strength of the competing magnetic interactions active at the interfaces of metallic multilayer systems, individual nanoscale skyrmions can be stabilized and observed with atomic-scale spatial resolution using a SP-STM[12,24,63] (FIG. 2). For example, a Pd-Fe bilayer grown epitaxially on Ir(111) is, at low temperature, in a mixed state, displaying both individual spin spirals and circular-shaped individual skyrmions, appearing at a typical external magnetic field strength of 1T (FIG. 2a). The ground state of this system in zero field is a cycloidal spin spiral state with a period of about 6-7 nm; the application of an external magnetic field initially leads to a transition into a skyrmionic state and then, in sufficiently strong external fields (~ 2T), into a fully polarized, ferromagnetic state[12].

Internal spin structure of magnetic skyrmions. A detailed knowledge of the internal spin structure of individual magnetic skyrmions is crucial for understanding the interactions between skyrmions, and the interactions of skyrmions with spin currents or magnons. SP-STM images show that a single skyrmion in a PdFe bilayer on Ir(111) has a diameter of about 3 nm. By using an out-of-plane sensitive spin-polarized tip, the axial symmetry of individual skyrmions in this bilayer system is clearly revealed (FIG. 2b). The additional use of in-plane sensitive SP-STM tips allows the verification of their unique rotational sense, confirming the chiral nature of individual skyrmions stabilized by interfacial DM interactions[12,24]. Line sections going through the centre of such chiral magnetic skyrmions in ultrathin films were found to be equivalent to profiles of 360° Néel-type magnetic domain walls[24]. Magnetic-field dependent experimental studies on the size and shape of individual skyrmions are in excellent agreement with the original theory describing chiral skyrmions[1,2]. These studies allowed the determination of the values of relevant material-dependent parameters, such as exchange stiffness, DM interaction constant, effective magnetic anisotropy constant, and saturation magnetization[24].

Room temperature stability. Whereas the individual nanoscale skyrmions in Pd/Fe bilayers on Ir(111) could be only observed at low temperature (typically 4 K) and high magnetic fields (typically 1.5 T), the design of more sophisticated metallic multilayer stacks can be employed to stabilize magnetic skyrmions at room temperature and in the absence of an external magnetic field. This has been nicely demonstrated using an Fe/Ni bilayer film exchange-coupled to a buried ferromagnetic Ni layer through a non-magnetic Cu spacer layer[64] (FIG. 3a). By an appropriate choice of the Cu layer thickness (~ 8.6 monolayers (ML)), the virtual magnetic field created by the interlayer exchange coupling of the 2 ML Fe / 2 ML Ni bilayer with the 15 ML-thick Ni layer underneath—which is magnetized out-of-plane and forms a single domain—has the right order of magnitude to stabilize an ensemble of roughly circular domains with a diameter of about 400 nm. By using spin-polarized low-energy electron microscopy[64], all three components of the magnetization vector of these objects could be imaged with a spatial resolution of about 20 nm, allowing their unambiguous identification as chiral Néel-type skyrmions[64] (FIG. 3b). This strategy for the stabilization of skyrmions at room temperature in zero external fields is highly promising for future skyrmion-based devices, though the size regime of the skyrmions (~ 400 nm in diameter) obtained in this particular multilayer stack[64] is too large for technological applications.

A route towards room-temperature skyrmions of smaller size has recently been proposed[32]. In metallic multilayers with Co layers sandwiched between two different heavy metal layers (for example Ir and Pt, FIG. 4a), additive interfacial DM interactions are realized, and they are sufficiently large to stabilize sub-100 nm skyrmions at room temperature in external fields of only a few tens of mT. It is believed that the same magnetic texture extends vertically throughout the multilayer structure, which has been imaged by scanning transmission X-ray microscopy (STXM), a technique sensitive to the out-of-plane component of the magnetization (FIG. 4b). Experimental X-ray magnetic circular dichroism signals have been compared with simulated profiles across individual skyrmions for various external magnetic field strengths (FIG. 4c). By studying the behaviour of the magnetic objects imaged by STXM as a function of the externally applied perpendicular magnetic field, it is possible to conclude that the nanoscale magnetic objects are skyrmions stabilized by large DM interactions[32]. Moreover, the evolution of the skyrmion size in patterned nanoscale disks and tracks was studied experimentally, and the results were compared with micromagnetic simulations[32]. This work on metallic multilayers demonstrated that the increase of the effective magnetic volume obtained by repeating the magnetic layer multiple times—in combination with an asymmetric sandwich structure that leads to additive and sizable DM interactions—can stabilize skyrmions at room temperature against thermal fluctuations, simultaneously resulting in skyrmion sizes on the order of a few tens of nanometers.

A summary of the ultrathin film, heterostructure, and multilayer systems in which magnetic skyrmions have successfully been observed, at different temperatures and external magnetic field strengths, can be found in Table 1.

Writing and deleting single skyrmions

Any application of skyrmions in future magnetic memory or logic devices will require the ability to create, observe, manipulate, and delete individual nanoscale skyrmions. One possible route to achieve these goals involves the use of spin-polarized electron injection; another approach makes use of an all-electrical writing, detecting, and deleting scheme. Here, we discuss both concepts and evaluate their strengths and weaknesses.

Control of skyrmions by currents. In the previous section, the real-space observation of individual nanoscale skyrmions by spin-polarized STM has been introduced. Low tunnelling currents, on the order of a few tenths of nA, and low bias voltages, on the order of a few tens of mV, are typically chosen for perturbation-free magnetic SP-STM imaging. It is possible to switch from this imaging mode to a local manipulation mode[12] by increasing the spin-polarized tunnelling current to several hundreds of nA and the applied bias voltage to several hundreds of mV. In this case, individual nanoscale skyrmions can be written and deleted in a reproducible fashion by locally injecting spin-polarized electrons, as was first demonstrated[12] in PdFe bilayers on Ir(111) (FIG. 5a). Whereas thermal noise and Joule heating effects were found to be negligible, the energy of the injected spin-polarized electrons plays a crucial role for the switching between the skyrmionic and the ferromagnetic state. Additionally, it was demonstrated that the spin transfer torque exerted by the locally injected spin-polarized tunnelling electrons[65,66] provides a means to control the directionality of the switching[12]. This first demonstration of controlled creation and annihilation of individual nanoscale skyrmions has revealed the great potential for the use of topological rather than electrical charges in future information storage concepts. The reason for the stability of the written skyrmionic bits has been analysed by atomistic Monte Carlo simulations[14]. It was found that a different magnetic field dependence of the activation energies for the skyrmionic and ferromagnetic states, combined with a lower attempt frequency for skyrmions, can explain the experimental observations[12,14] of individual skyrmion manipulation in PdFe bilayers on Ir(111).

Control of skyrmions by external fields. An alternative approach to the controlled writing and deleting of individual nanoscale skyrmions involves the use of local electric field effects combined with an electrical detection method. In this case, spin-polarized electrons are not required for the creation and annihilation of skyrmions, nor for imaging them in atomic-scale tunnelling magnetoresistance measurements.

An all-electrical scheme has first been demonstrated using a conventional STM with a non-magnetic tip. First, it has been shown that a novel type of magnetoresistance effect that occurs for non-collinear spin textures (so-called non-collinear magnetoresistance, NCMR) can be employed for detecting individual skyrmions, even with non-magnetic electrodes[29]. The NCMR effect arises from the mixing between the spin channels for non-collinear spin states, which alters their local electronic structure, allowing for a distinction between a skyrmion and a ferromagnetic state by an all-electrical detection scheme, as was theoretically explained using a simplified tight-binding model[29] and *ab initio* DFT calculations[30]. This all-electrical read-out scheme might be very promising for future skyrmion-based racetrack memories,[31] in which the tunnel junction for the detection of passing skyrmions does not necessarily have to include a magnetic counterelectrode (FIG. 5b). In contrast to more conventional types of read-out schemes based, for example, on the tunnelling magnetoresistance (TMR) effect, the anomalous Hall or the topological Hall effect, read-out methods based on the NCMR effect are particularly sensitive to non-collinear spin structures, such as skyrmions, and can easily discriminate between non-collinear spin states and conventional magnetic domains in ferromagnetic systems. Moreover, the NCMR effect can be employed to detect skyrmions efficiently and individually on a one-by-one basis, as required for most of the skyrmion-based device concepts that are currently being developed.

All-electrical schemes can also be used to write and delete individual skyrmions. It is known that electric fields can affect skyrmion lattices in insulating compounds[8] through magneto-electric coupling[67]. Recently, it has been demonstrated that individual skyrmions can be created and deleted by local electric fields even in ultrathin magnetic layers[34], thereby offering an interesting alternative to spin-transfer-torque-based switching by local spin-polarized current injection[12]. In the case of electric-field driven manipulation of skyrmions, the polarity of the applied bias voltage provides a means to control the directionality of the switching, that is, skyrmion writing or deleting processes. Importantly, electric-field-induced switching between skyrmionic and ferromagnetic states offers the advantage, compared to current-induced switching, of a dissipation-less and therefore inherently energy-efficient process. Combined with an electrical read-out of individual skyrmions based on the NCMR effect, it offers the possibility of realizing an all-electrical scheme for future skyrmion-based memory and logic devices.

Skyrmions on the track

Magnetic memory and logic devices based on skyrmions require the ability to align or move skyrmions along linear tracks[26,27,28,68-70]. Such tracks for skyrmions may be realized using lithographically fabricated stripes of magnetic layers in contact with materials with high spin-orbit couplings[32,33,71]. Alternatively, skyrmions may be aligned by spatially anisotropic or modulated strain fields, by spatially modulated magnetic anisotropies or by spatial modulations of the strength of the relevant magnetic interactions. For example, FIG. 6a shows four tracks for nanoscale skyrmions—similar to the tracks required for a skyrmion-based hard-disk memory—on an ultrathin three-layers-thick Fe film epitaxially grown on Ir(111)[34]. The individual skyrmion tracks are very narrow (about 3.5 nm in width), and the individual skyrmionic bits have a length of only 2.5 nm. The tiny dark spots correspond to individual atomic defects, further indicating the small size regime of the skyrmionic bit tracks. The individual skyrmions do not appear axisymmetric, in contrast to the nanoscale skyrmions observed in PdFe bilayers on Ir(111) discussed above. The strongly anisotropic, distorted shape of the skyrmions is due to spatially anisotropic and inhomogeneous strain fields, resulting from the heteroepitaxial growth of the ultrathin Fe film on the Ir(111) substrate. A large anisotropic deformation has been observed by Lorentz transmission electron microscopy already in skyrmionic crystals realized in strained non-centrosymmetric bulk materials[72]. In heteroepitaxial systems with a significant lattice mismatch between the substrate and the thin film grown on top, the strain can be huge. As a consequence, skyrmions can become mechanically deformed. Because the strain is partially released by introducing dislocation lines in the magnetic film (FIG. 6a), a spatially inhomogeneous distribution of magnetic anisotropies and magnetic interaction parameters strengths is generated, which eventually leads to a linear alignment of the individual skyrmions. Both these experimentally observed effects—the strong distortion of individual skyrmions due to spatially anisotropic strain fields and their linear alignment in the presence of spatially modulated magnetic anisotropies—can be reproduced by micromagnetic simulations[73] (FIGS 6b and c). These results were obtained for heteroepitaxial ultrathin film systems; it remains to be seen whether similar experimental approaches can be used for the alignment of skyrmions in textured thin films prepared by sputter deposition.

Towards skyrmion-based devices

The application of skyrmions in future magnetic memory and logic devices requires their stability at room temperature. Whereas magnetic skyrmion lattices have been observed well above room temperature in chiral bulk materials by Lorentz transmission electron microscopy[74], indications of individual skyrmions stabilized by interfacial DM interactions in ultrathin films and multilayer structures at room temperature or above were only recently obtained, based on both direct and indirect detection methods[71,32,33,64,75]. In order to stabilize skyrmions in ultrathin metallic films or multilayers at room temperature, the thickness of the magnetic layer has to be larger than one atomic layer. For the skyrmionic lattice obtained in a single Fe monolayer on Ir(111), a transition temperature of about 28 K was determined experimentally[54], whereas a transition temperature of around 100 K was theoretically predicted for a PdFe bilayer on Ir(111), based on spin dynamics calculations and Monte Carlo simulations that used *ab initio* derived parameters[76]. Interestingly, the top Pd layer appears to stabilize the skyrmions in the Fe monolayer. Moving from the Fe monolayer to an Fe double layer on Ir(111), the transition from an ordered non-collinear to a disordered state is found at a temperature of around 150 K, whereas the non-collinear spin states in three and four monolayers of Fe on Ir(111) exhibit transition temperatures above room temperature, as determined by variable-temperature SP-STM studies.
Besides employing sufficiently thick magnetic layers or increasing the effective magnetic material volume by using multilayer structures[32], the stability of skyrmions can be further enhanced by tailoring the interface structure and chemical composition of metallic multilayers, as has been shown by DFT calculations[77].

Given the existence of interface-stabilized skyrmions in ultrathin magnetic films and multilayers at room temperature—combined with the possibility to create, manipulate, and delete skyrmions by local spin current injection or even by local electric fields—a skyrmion-based device technology seems to be within reach. Numerous proposals for skyrmion-based memory and logic devices have been made in the past years [26,27,28]; they now seem to be close to experimental realization. Any application involving the movement of skyrmions, such as skyrmion-based racetrack memories, will profit from the fact that extremely low spin-polarized currents are sufficient to drive skyrmions, as shown by numerical simulations[26,78].
However, it remains to be further experimentally investigated which type of defects may pin skyrmions in ultrathin films and multilayers[79-82], leading to a modified behaviour compared to that predicted by theoretical models, which are usually based on ideal metal layer structures. In this respect, the comparison of experimental results obtained for epitaxially grown and sputter-deposited thin magnetic films and multilayer structures, as well as between polycrystalline and amorphous layers, can be very valuable—it can provide a deeper insight into the role of structural imperfections and spatial inhomogeneities of the relevant magnetic material parameters for the static properties and dynamic behaviour of nanoscale magnetic skyrmions. In a recent study[33], it has been demonstrated that short-length-scale variations in the local DM interaction strength, as those occurring in polycrystalline thin films, can lead to a

strong pinning of skyrmions, resulting in reduced skyrmion velocities and even in current-induced annihilation of pinned skyrmions. On the other hand, it was shown by a direct comparison between Pt/polycrystalline-Co/Ta and Pt/amorphous-CoFeB/MgO multilayer stacks that the use of amorphous CoFeB films sandwiched between a material generating strong interfacial DM interactions (Pt) and a material generating weak interfacial DM interactions (Ta or MgO) leads to a significantly reduced pinning as compared to polycrystalline Co films[33]. This is due to the absence of grain boundaries in amorphous films, which are believed to act as strong pinning sites for skyrmions. Remarkably, in these multilayer systems[33] not only individual skyrmions can be observed at room temperature, but it is also possible to drive trains of individual skyrmions, using short current pulses, along magnetic nanowire tracks at speeds exceeding 100 m/s (FIG. 7c). These results demonstrate the potential of current-driven skyrmions for future racetrack-type memory applications[83].

Conclusions

In a few years, amazing advances have been made in observing, writing, manipulating, and deleting individual skyrmions, making use of high-resolution spin-sensitive imaging techniques and local interactions with vertical and lateral spin-currents. Simultaneously, a large number of concepts for skyrmion-based spintronic devices has been developed, clearly highlighting the great potential of skyrmionics. Future research directions have to focus on identifying the most promising magnetic multilayer systems capable of hosting small-size skyrmions that are easily manipulated with currents and external fields at room temperature—this will pave the way for novel types of sensor, memory, and logic devices with improved performances. Ultimately, skyrmionic states might also become useful for the transmission of spin information in topology-based communication schemes[84,85].

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Competing financial interests

The author declares no competing financial interests.

References

1. Bogdanov, N. & Yablonskii, D. A. Thermodynamically stable “vortices” in magnetically ordered crystals: The mixed state of magnets. *Sov. Phys. JETP* **68**, 101-103 (1989).
2. Bogdanov, N. & Hubert, A. Thermodynamically stable magnetic vortex states in magnetic crystals. *J. Magn. Magn. Mater.* **138**, 255-269 (1994).
3. Rößler, U. K., Bogdanov, N. & Pfleiderer, C. Spontaneous skyrmion ground states in magnetic metals. *Nature* **442**, 797-801 (2006).
4. Mühlbauer, S. *et al.* Skyrmion lattice in a chiral magnet. *Science* **323**, 915-919 (2009).
5. Yu, X. Z. *et al.* Real space observation of a two-dimensional skyrmion crystal. *Nature* **465**, 901-904 (2010).
6. Yu X. Z. *et al.* Near room-temperature formation of a skyrmion crystal in thin-films of the helimagnet FeGe. *Nature Mater.* **10**, 106-109 (2011).
7. Yu X. Z. *et al.* Skyrmion flow near room-temperature in an ultralow current density. *Nature Commun.* **3**, 988 (2012).
8. Seki, S., Yu, X. Z., Ishiwata, S. & Tokura, Y. Observation of skyrmions in a multiferroic material. *Science* **336**, 198-201 (2012).
9. Nagaosa, N. & Tokura, Y. Topological properties and dynamics of magnetic skyrmions. *Nature Nanotechnol.* **8**, 899-911 (2013).
10. Milde, P. *et al.* Unwinding of a skyrmion lattice by magnetic monopoles. *Science* **340**, 1076-1080 (2013).
11. Park, H. S. *et al.* Observation of the magnetic flux and three-dimensional structure of skyrmion lattices by electron holography. *Nature Nanotechnol.* **9**, 337-342 (2014).
12. Romming, N. et al. Writing and deleting single magnetic skyrmions. Science **341**, 636-639 (2013).
    This has been the first report on the controlled creation, detection, and deletion of individual chiral skyrmions in a metallic bilayer system.
13. Heinze, S. et al. Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. Nature Physics **7**, 713-718 (2011).
    This has been the first report of a nanoscale skyrmionic lattice in an ultrathin magnetic film being stable in zero external magnetic field.
14. Hagemeister, J., Romming, N., von Bergmann, K., Vedmedenko, E. Y. & Wiesendanger, R. Stability of single skyrmionic bits. Nature Commun. **6**, 8455 (2015).
15. Dzyaloshinskii, I. A thermodynamic theory of „weak“ ferromagnetism of antiferromagnetics. *J. Phys. Chem. Solids* **4**, 241-255 (1958).
16. Moriya, T. New mechanism of anisotropic superexchange interaction. *Phys. Rev. Lett.* **4**, 228-230 (1960).
17. Moriya, T. Anisotropic superexchange interaction and weak ferromagnetism. *Phys. Rev.* **120**, 91-98 (1960).
18. Fert, A. & Levy, P. M. Role of anisotropic exchange interactions in determining the properties of spin glasses. *Phys. Rev. Lett.* **44**, 1538-1541 (1980).
19. Crépieux, A. & Lacroix, C. Dzyaloshinsky-Moriya interactions induced by symmetry breaking at a surface. J. Magn. Magn. Mater. 182, 341-349 (1988).
20. Fert, A. Magnetic and transport properties of metallic multilayers. *Materials Science Forum* **59-60**, 439-480 (1990).

21. Bogdanov, A. N. & Rößler, U. K. Chiral symmetry breaking in magnetic thin films and multilayers. *Phys. Rev. Lett.* **87**, 037203 (2001).
22. Vedmedenko, E. Y., Udvardi, L., Weinberger, P. & Wiesendanger, R. Chiral magnetic ordering in two-dimensional ferromagnets with competing Dzyaloshinsky-Moriya interactions. *Phys. Rev. B* **75**, 104431 (2007).
23. von Bergmann, K., Kubetzka, A., Pietzsch, O. & Wiesendanger, R. Interface-induced chiral domain walls, spin spirals and skyrmions revealed by spin-polarized scanning tunneling microscopy. *J. Phys.: Condens. Matter* **26**, 394002 (2014).
24. Romming, N., Kubetzka, A., Hanneken, C., von Bergmann, K. & Wiesendanger, R. Field-dependent size and shape of single magnetic skyrmions. Phys. Rev. Lett. **114**, 177203 (2015).
This has been the first report on the atomic-scale three-dimensional spin structure of individual chiral skyrmions.
25. Wiesendanger, R. Spin mapping at the nanoscale and atomic scale. *Rev. Mod. Phys.* **81**, 1495-1550 (2009).
26. Fert, A., Cros, V. & Sampaio, J. Skyrmions on the track. *Nature Nanotechnology* **8**, 152-156 (2013).
In this paper the potential of skyrmions for future magnetic memory and logic applications is highlighted.
27. Zhang, X. *et al.* Skyrmion-skyrmion and skyrmion-edge repulsions in skyrmion-based racetrack memory. *Sci. Rep.* **5**, 7643 (2015).
28. Zhang, X., Ezawa, M. & Zhou, Y. Magnetic skyrmion logic gates: conversion, duplication and merging of skyrmions. *Sci. Rep.* **5**, 9400 (2015).
29. Hanneken, C. *et al.* Electrical detection of magnetic skyrmions by tunneling non-collinear magnetoresistance. *Nature Nanotechnology* **10**, 1039-1043 (2015).
30. Crum, D. M. *et al.* Perpendicular reading of single confined magnetic skyrmions. *Nature Commun.* **6**, 8541 (2015).
31. Monchesky, T. L. Skyrmions: Detection with unpolarized currents. *Nature Nanotechnology* **10**, 1008-1009 (2015).
32. Moreau-Luchaire, C. *et al.* Additive interfacial chiral interaction in multilayers for stabilization of small individual skyrmions at room temperature. *Nature Nanotechnol.* DOI:10.1038/NNANO.2015.313 (2016).
33. Woo, S. *et al.* Observation of room temperature magnetic skyrmions and their current-driven dynamics in ultrathin films. *Nature Mater.* **15**, 501-506 (2016).
34. Hsu, P.-J. *et al.* Electric field switching of individual magnetic skyrmions. *Nature Nanotechnol.* DOI: 10.1038/NNANO.2016.234 (2016).
35. Pietzsch, O. & Wiesendanger, R. Non-collinear magnetic order in nanostructures investigated by spin-polarized scanning tunneling microscopy. *Pure and Applied Chemistry* **83**, 1981-1988 (2011).
36. Pietzsch, O. & Wiesendanger, R. in *Fundamentals of Picoscience* (ed. by Sattler, K. D.) 413-445 (CRC Press, Taylor & Francis 2013).
37. Pietzsch, O., Kubetzka, A., Bode, M. & Wiesendanger, R. Observation of magnetic hysteresis at the nanometer scale by spin-polarized scanning tunneling spectroscopy. *Science* **292**, 2053-2056 (2001).
38. Kubetzka, A., Bode, M., Pietzsch, O. & Wiesendanger, R. Spin-polarized scanning tunneling microscopy with antiferromagnetic probe tips. *Phys. Rev. Lett.* **88**, 057201 (2002).

39. Bode, M. *et al.* Magnetization-direction-dependent local electronic structure probed by scanning tunneling spectroscopy. *Phys. Rev. Lett.* **89**, 237205 (2002).
40. Kubetzka, A., Pietzsch, O., Bode, M. & Wiesendanger, R. Spin-polarized scanning tunneling microscopy study of 360 degrees walls in an external magnetic field. *Phys. Rev. B* **67**, 020401 (2003).
41. Heide, M., Bihlmayer, G. & Blügel, S. Dzyaloshinskii-Moriya interaction accounting for the orientation of magnetic domains in ultrathin films: Fe/W(110). *Phys. Rev. B* **78**, 140403 (2008).
42. Thiaville, A., Rohart, S., Jué, È., Cros, V. & Fert, A. Dynamics of Dzyaloshinskii domain walls in ultrathin magnetic films. *Europhys. Lett.* **100**, 57002 (2012).
43. Ryu, K.-S., Thomas, L., Yang, S.-H. & Parkin S. Chiral spin torque at magnetic domain walls. Nature Nanotechnol. 8, 527-533 (2013).
44. Torrejon, J. *et al.* Interface control of the magnetic chirality in CoFeB/MgO heterostructures with heavy-metal underlayers. *Nature Commun.* **5**, 4655 (2014).
45. Bode, M. *et al.* Chiral magnetic order at surfaces driven by inversion asymmetry. *Nature* **447**, 190-193 (2007).
46. Ferriani, P. *et al.* Atomic-scale non-collinear magnetic order in thin films induced by spin-orbit coupling. *Phys. Rev. Lett.* **101**, 027201 (2008).
47. Santos, B. *et al.* Structure and magnetism of ultra-thin chromium layers on W(110). *New J. of Phys.* **10**, 013005 (2008).
48. Meckler, S. *et al.* Real-space observation of a right-handed inhomogeneous cycloidal spin spiral by spin-polarized scanning tunneling microscopy in a triple axes vector magnet. *Phys. Rev. Lett.* **103**, 157201 (2009).
49. Meckler, S., Pietzsch, O., Mikuszeit, N. & Wiesendanger, R. Micromagnetic description of the spin spiral in Fe double-layer stripes on W(110). *Phys. Rev. B* **85**, 024420 (2012).
50. Menzel, M. Information transfer by vector spin chirality in finite magnetic chains. *Phys. Rev. Lett.* **108**, 197204 (2012).
51. Hsu, P.-J. *et al.* Guiding spin spirals by local uniaxial strain relief. *Phys. Rev. Lett.* **116**, 017201 (2016).
52. Yoshida, Y. *et al.* Conical spin-spiral state in an ultra-thin film driven by higher-order spin interactions. *Phys. Rev. Lett.* **108**, 087205 (2012).
53. Pfleiderer, C. Magnetic order: surfaces get hairy. *Nature Physics* **7**, 673-674 (2011).
54. Sonntag, A., Hermenau, J., Krause, S. & Wiesendanger, R. Thermal stability of an interface-stabilized skyrmion lattice. *Phys. Rev. Lett.* **113**, 077202 (2014).
55. von Bergmann, K., Menzel, M., Kubetzka, A. & Wiesendanger, R. Influence of the local atom configuration on a hexagonal skyrmion lattice. *Nano Lett.* **15**, 3280-3285 (2015).
56. Schlenhoff, A. *et al.* Magnetic nano-skyrmion lattice observed in a Si-wafer-based multilayer system. *ACS Nano* **9**, 5908-5912 (2015).
57. Wiesendanger, R., Güntherodt, H.-J., Güntherodt, G., Gambino, R. J. & Ruf, R. Observation of vacuum tunneling of spin-polarized electrons with the scanning tunneling microscope. *Phys. Rev. Lett.* **65**, 247-250 (1990).

58. Meckler, S., Gyamfi, M., Pietzsch, O. & Wiesendanger, R. A low-temperature spin-polarized scanning tunneling microscope operating in a fully rotatable magnetic field. *Rev. Sci. Instrum.* **80**, 023708 (2009).
59. von Bergmann, K. *et al.* Observation of a complex nanoscale magnetic structure in a hexagonal Fe monolayer. *Phys. Rev. Lett.* **96**, 167203 (2006).
60. von Bergmann, K. *et al.* Complex magnetism of the Fe monolayer on Ir (111). *New. J. of Phys.* **9**, 396 (2007).
61. von Bergmann, K. Complex magnetic order on the atomic scale revealed by spin-polarized scanning tunneling microscopy. *Phil. Mag.* **88**, 2627-2642 (2008).
62. Leonov, A. O. *et al.* The properties of isolated chiral skyrmions in thin magnetic films. *New. J. of Phys.* **18**, 065003 (2016).
63. Duine, R. Skyrmions singled out. *Nature Nanotechnology* **8**, 800-802 (2013).
64. Chen, G., Mascaraque, A., N'Diaye, A. T. & Schmid, A. K. Room temperature skyrmion ground state stabilized through interlayer exchange coupling. *Appl. Phys. Lett.* **106**, 242404 (2015).
65. Krause, S., Berbil-Bautista, L., Herzog, G., Bode, M. & Wiesendanger, R. Current-induced magnetization switching with a spin-polarized scanning tunneling microscope. *Science* **317**, 1537-1540 (2007).
66. Khajetoorians, A. A. Current-driven spin dynamics of artificially constructed quantum magnets. *Science* **339**, 55-59 (2013).
67. White, J. S. *et al.* Electric-field-induced skyrmion distortion and giant lattice rotation in the magnetoelectric insulator Cu_2OSeO_3. *Phys. Rev. Lett.* **113**, 107203 (2014).
68. Zhou, Y. & Ezawa, M. A reversible conversion between a skyrmion and a domain-wall pair in a junction geometry. *Nature Commun.* **5**, 4652 (2014).
69. Ma, F., Zhou, Y., Braun, H. B. & Lew, W. S. Skyrmion-based dynamic magnonic crystal. *Nano Lett.* **15**, 4029-4036 (2015).
70. Zhang X. *et al.* All-magnetic control of skyrmions in nanowires by a spin wave. *Nanotechnology* **26**, 225701 (2015).
71. Jiang, W. *et al.* Blowing magnetic skyrmion bubbles. *Science* **349**, 283-286 (2015).
72. Shibata, K. *et al.* Large anisotropic deformation of skyrmions in strained crystal. *Nature Nanotechnol.* **10**, 589-593 (2015).
73. Hagemeister, J., Vedmedenko, E. & Wiesendanger, R. Pattern formation in skyrmionic materials with anisotropic environments. arXiv:1603.01045.
74. Tokunaga Y. *et al.* A new class of chiral materials hosting magnetic skyrmions beyond room temperature. *Nature Commun.* **6**, 7638 (2015).
75. Boulle, O. et al. Room-temperature chiral magnetic skyrmions in ultrathin magnetic nanostructures. Nature Nanotechnol. DOI:10.1038/NNANO.2015.315 (2016).
76. Simon, E., Palotás, K., Rózsa, L., Udvardi, L. & Szunyogh, L. Formation of magnetic skyrmions with tunable properties in PdFe bilayer deposited on Ir(111). *Phys. Rev. B* **90**, 094410 (2014).
77. Dupé, B., Hoffmann, M., Paillard, C. & Heinze, S. Tailoring magnetic skyrmions in ultra-thin transition metal films. *Nature Commun.* **5**, 4030 (2014).
    This paper highlights the possibility to tune the properties of chiral skyrmions by interface engineering.

78. Sampaio, J., Cros, V., Rohart, S., Thiaville, A. & Fert, A. Nucleation, stability and current-induced motion of isolated magnetic skyrmions in nanostructures. *Nature Nanotechnology* **8**, 839-843 (2013).
79. Liu, Y.-H. & Li, Y.-Q. A mechanism to pin skyrmions in chiral magnets. *J. Phys.: Condens. Matter* **25**, 076005 (2013).
80. Silva, R. L., Secchin, L. D., Moura-Melo, W. A., Pereira, A. R. & Stamps, R. L. Emergence of skyrmion lattices and bimerons in chiral magnetic thin films with nonmagnetic impurities. *Phys. Rev B* **89**, 054434 (2014).
81. Müller, J. & Rosch, A. Capturing of a magnetic skyrmion with a hole. *Phys. Rev B* **91**, 054410 (2015).
82. Ding, J., Yang, X. & Zhu, T. Manipulating current induced motion of magnetic skyrmions in the magnetic nanotrack. *J. Phys.: Appl. Phys.* **48**, 115004 (2015).
83. Parkin, S. S. P., Hayashi, M. & Thomas, L. Magnetic domain-wall racetrack memory. *Science* **320**, 190-194 (2008).
84. Brede, J. *et al.* Long-range magnetic coupling between nanoscale organic-metal hybrids mediated by a nanoskyrmion lattice. *Nature Nanotechnol.* **9**, 1018-1023 (2014).
85. Cinchetti, M. Topology communicates. *Nature Nanotechnol.* **9**, 965-966 (2014).
86. Skyrme, T. H. A non-linear field theory. *Proc. R. Soc. London A* **260**, 127-138 (1961).
87. Skyrme, T. H. R. A unified field theory of mesons and baryons. *Nucl. Phys.* **31**, 556-569 (1962).
88. Wright, D. C. & Mermin, N. D. Crystalline liquids – the blue phases. *Rev. Mod. Phys.* **61**, 385-432 (1989).
89. Brey, L., Fertig, A. H., Côté, R. & MacDonald, A. H. Skyrme crystal in a two-dimensional electron gas. *Phys. Rev. Lett.* **75**, 2562-2565 (1995).
90. Al'Khawaja, U. & Stoof, H. T. C. Skyrmions in a ferromagnetic Bose-Einstein condensate. *Nature* **411**, 918-920 (2001).
91. Cross, M. C. & Hohenberg, P. C. Pattern formation outside of equilibrium. *Rev. Mod. Phys.* **65**, 851-1112 (1993).
92. Derrick, G. H. Comments on nonlinear wave equations as models for elementary particles. *J. Math. Phys.* **5**, 1252-1254 (1964).
93. Iwasaki, J., Mochizuki, M. & Nagaosa, N. Current-induced skyrmion dynamics in constricted geometries. *Nature Nanotechnology* **8**, 742-747 (2013).
94. Smith, D. A. New mechanisms for magnetic anisotropy in localised S-state moment materials. *J. Magn. Magn. Mater.* **1**, 214-225 (1976).
95. Zhou, L. *et al.* Strength and directionality of surface Ruderman-Kittel-Kasuya-Yosida interaction mapped on the atomic scale. *Nature Phys.* **6**, 187 (2010).
96. Khajetoorians, A. A. *et al.* Tailoring the chiral magnetic interaction between two individual atoms. *Nature Commun.* **7**, 10620 (2016).
This has been the first report on a direct real-space study of Dzyaloshinskii–Moriya interactions at the atomic-scale.

2.

Box 1| **Properties of magnetic skyrmions**

The name skyrmion derives from the British field theorist Tony Skyrme, who considered topologically protected defects (multidimensional solitons) in continuous non-linear field models as having properties of single particles[86]. Skyrmions are localized in space and have a non-singular internal structure and finite energy, exhibit mutual attractive or repulsive interactions, and can condense into ordered phases (skyrmion lattices). Skyrmions are characterized by a quantized topological charge, or topological skyrmion number, which is related to the topological properties of the field configuration.

Although the concept of skyrmions originated from elementary particle physics[87], it has found applications in various fields of physics, ranging from liquid crystals[88] to quantum Hall magnets[89] and Bose—Einstein condensates[90]. In most non-linear physical systems, however, multidimensional solitons can only exist as dynamic excitations[62,91], whereas the corresponding static solutions are unstable[92]. Stable skyrmionic solutions can arise in non-centrosymmetric condensed matter systems with broken inversion symmetry; examples of these systems include liquid crystals, chiral magnets, multiferroics, and ultrathin magnetic films and heterostructures. Recent advances in the detection[4] and real-space observation of skyrmion lattices[13,5-11] and isolated single skyrmions[12,24,29]—including the first demonstration of their individual creation, manipulation and deletion[12]—have renewed interest in skyrmions, and resulted in an explosion of theoretical and experimental studies on their stationary and dynamic properties.

The energetics of magnetic skyrmions, including their exceptional stability[14], is governed by the Dzyaloshinskii–Moriya (DM) interaction (BOX 2), which is relevant in material systems lacking inversion symmetry and exhibiting a large spin-orbit coupling. The chiral nature of the DM interaction causes a twist in the skyrmions' magnetization profile, resulting in non-trivial topological properties. The image shows a schematic picture of an individual Néel-type magnetic skyrmion, the type occurring in ultrathin magnetic films and multilayers because of interfacial DM interactions. The spin in the centre of the skyrmion and the spins in the ferromagnetic background point in opposite directions, as represented by the orientation of the cones. A line profile going through the centre of the skyrmion is equivalent to the line profile of a 360° Néel-type magnetic domain wall[24]. The smallest individual magnetic skyrmions observed so far have a diameter of only a few nanometres[12,24,34]—very small skyrmions are relevant for high-density magnetic memory and logic applications. In contrast to chiral magnetic skyrmions, magnetic bubbles are primarily stabilized by dipolar magnetic interactions (which are less strong than the DM interactions), and are therefore much larger in size. A small superimposed DM interaction may still lead to a unique sense of rotation of the magnetization profile of bubble domains, therefore such objects have been named 'skyrmion bubbles'[71].

Because of their non-collinear spin texture, magnetic skyrmions can interact very efficiently with (spin-polarized) electrons and magnons, thus they hold great potential for future spintronic devices. In current-driven devices, skyrmions exhibit a high mobility and can be driven by current densities several orders of magnitude smaller than those required for moving magnetic domain walls[26,78,93]. Therefore, magnetic skyrmions offer an interesting alternative to the use of domain walls in racetrack-type magnetic memories[83]. To produce systems fully compatible with the state-of-the-art technology, which has been developed for giant magnetoresistance and tunneling magnetoresistance devices, recent experimental research has focused on magnetic skyrmions in metallic multilayer systems, with the goal of stabilizing skyrmions of nanometer-scale size at room temperature[32,33,64,75].

Box 2| **The Dzyaloshinskii–Moriya interaction**

Magnetic skyrmions are stabilized by the so-called Dzyaloshinskii–Moriya (DM) interaction energy[15-17], which, at the atomic scale, is defined as $E_{DMI} = \mathbf{D} \cdot (\mathbf{S_1} \times \mathbf{S_2})$, where **D** is the DM vector and $\mathbf{S}_1$ and $\mathbf{S}_2$ are two coupled spins. This interaction favours a perpendicular orientation of the spins, in contrast to the Heisenberg (isotropic) exchange interaction, $E_{ex} = -J\, (\mathbf{S_1} \cdot \mathbf{S_2})$ (where J is the exchange constant), which favours collinear ferro- or antiferromagnetically coupled spins, at least for nearest-neighbour interactions. Whereas Moriya considered spin-orbit coupling within a superexchange model[17] to be the origin of this anisotropic magnetic exchange interaction, Smith[94] and Fert[18,26] showed that the DM interaction between two coupled spins can also result from an indirect exchange mechanism mediated by conduction electrons. In this case, the conduction electrons are exchange-coupled to the atomic spins, thus they become spin-polarized and can mediate a magnetic interaction. In this case, in addition to the ‘usual’ indirect Ruderman, Kittel, Kasuya, Yosida (RKKY) magnetic exchange interaction[95], the electrons can experience spin-orbit scattering at the non-magnetic host atoms of a heavy-element material.

The interaction between two magnetic atoms adsorbed on a non-magnetic substrate exhibiting large spin-orbit coupling is depicted in the image. The interaction between the two atoms (red and green) is mediated by conduction electrons that scatter at a substrate atom (grey), resulting in a Heisenberg-like exchange interaction (J) and in a DM interaction (**D**) between the two spins $\mathbf{S}_1$ and $\mathbf{S}_2$. The DM vector **D** is oriented perpendicular to the triangle defined by the two magnetic atoms and the substrate atom. The orientation of the spins of the two magnetic atoms is determined[96] by the overall isotropic (Heisenberg) and anisotropic (DM) exchange interaction contributions of all substrate atoms, by the on-site magnetic anisotropy of each magnetic atom (K_1 and K_2), and by the applied external magnetic field (B_z).

In a similar manner to the RKKY interaction[95], the DM interaction leads to a long-range coupling between the two spins $\mathbf{S}_1$ and $\mathbf{S}_2$. The coupling is characterized by the DM vector, which oscillates in amplitude and orientation as a function of the separation between $\mathbf{S}_1$ and $\mathbf{S}_2$: this oscillation has recently been visualized in real space in magnetic-field-dependent scanning tunneling spectroscopy measurements of Fe atoms on a Pt(111) substrate[96].

Remarkably, the atomic-scale DM interaction can be as strong as the RKKY interaction. Likewise, it was found that the DM interaction energy in one-dimensional spin spirals, which were realized using atomic Fe chains on Ir(001)[50], can be as large as the Heisenberg (isotropic) exchange interaction energy. This large DM interaction energy allowed the formation of the smallest possible spin spirals, with a period of three atomic unit cells. A sizable DM interaction energy—comparable to other relevant magnetic interaction energies—is also at the base of the small unit cell[13] (with a side length of only one nanometre) of the skyrmion lattice observed in monolayer Fe films on Ir(111). For Pd/Fe-bilayers on Ir(111), the strength of the DM interaction has been determined from the field-dependent size of individual skyrmions, as directly observed by SP-STM[24].

In summary, the DM interaction is responsible for the intriguing physics of skyrmions and for their exciting potential applications, compared to the physics and technological applications of magnetic bubble domains that were extensively studied some decades ago. A strong DM interaction is needed to support skyrmions with sizes small enough to make them viable for future skyrmion-based technologies. Moreover, because the DM interaction is chiral, it leads to magnetic skyrmions with a unique sense of rotation in their magnetization profile. This results in a uniquely defined direction of current-driven motion, which is another important ingredient for future magnetic memory and logic applications.

Figure Captions

Figure 1| **3D vectorial spin map of a periodic nanoskyrmion lattice in a monolayer Fe film**. Atomic-resolution spin-polarized scanning tunneling microscopy (SP-STM) images of an Fe monolayer grown epitaxially in face-centred cubic stacking on an Ir(111) substrate. The in-plane magnetization distribution is represented using a colour code (as shown by the colour wheel), whereas the out-of-plane magnetization distribution is represented by a grey scale. The square unit cell of the nanoskyrmion lattice has a side length of just 1 nm. The magnetization (indicated by the grey cones) points in the direction perpendicular to the plane at the corners of the magnetic unit cell, and becomes canted over atomic length scales towards the centre of the unit cell, where it is aligned in the direction opposite to that at the corners. The data was obtained in zero magnetic field at a temperature of T = 11 K. Adapted with permission from REF. 13, Nature Publishing Group.

Figure 2 **| Individual nanoscale skyrmions observed in Pd/Fe bilayer films. a|** Out-of-plane magnetization distribution of a PdFe bilayer film epitaxially grown on Ir(111). The system is in a mixed phase, showing an assembly of individual axisymmetric skyrmions with a diameter of about 3 nm together with some fragments of spin spirals. This spin-polarized scanning tunneling microscopy (SP-STM) data was obtained in an applied out-of-plane magnetic field of B = 1.5 T at a temperature of T = 2.2 K. The image size is 45 nm x 30 nm. **b|** Top view of the color-coded internal spin structure of an individual axisymmetric chiral skyrmion in a PdFe bilayer film on Ir(111). The SP-STM data, measured at B = 1.5 T and T = 2.2 K with out-of-plane (z-direction) spin sensitivity (left) is directly compared to the atomic-scale spin structure model of a single skyrmion (right). Panel a| has been adapted from REF. 12 with permission from AAAS. Panel b| has been adapted from REF. 24 with permission from AIP.

Figure 3| **Stabilization of skyrmions in Fe/Ni bilayer films by interlayer exchange coupling. a|** Sketch of an Fe/Ni bilayer exchange-coupled to a buried single-domain Ni layer through a Cu spacer layer, creating a virtual out-of-plane magnetic field H_{eff} that helps to stabilize skyrmions (sketched on top of the Fe layer). **b|** Spin-polarized low-energy electron microscopy image of room-temperature skyrmions in the topmost

Fe/Ni bilayer of the multilayer structure sketched in a|. The components of the skyrmions' magnetization vector are colour-coded according to the colour-wheel shown in the inset, whereas the black arrows highlight the skyrmion perimeter magnetization directions. The skyrmions in this system have a diameter of about 400 nm. Reprinted from REF. 64 with permission from AIP.

Figure 4| **Skyrmions in asymmetric magnetic multilayers. a|** Asymmetric metallic multilayer made of several repetitions of a trilayer composed of a ferromagnetic layer (FM, grey) sandwiched between two different heavy metals (A, blue, and B, green). **b|** Scanning transmission X-ray microscopy image of a $[Ir/Co/Pt]_{10}$ multilayer recorded at room temperature in applied out-of-plane magnetic fields of 68 mT (left) and 83 mT (right), showing the out-of-plane magnetization (m_z) maps. The size of the images is 1500 nm x 1500 nm. **c|** Experimental X-ray magnetic circular dichroism signal (black dots) measured across an individual skyrmion at B = 22 mT (left) and B = 58 mT (right). The dashed curves show the magnetization profile of an ideal skyrmion with a diameter of 60 nm (left) and 40 nm (right), the solid curves are fit to the experimental data points. The size of the images in the insets is 360 nm x 360 nm. Reprinted from REF. 32, Nature Publishing Group.

Figure 5| **Controlled creation, detection and deletion of individual nanoscale skyrmions. a|** Measured spin-polarized scanning tunneling microscopy (SP-STM) data showing several individual skyrmions of about 3 nm in diameter—together with their superimposed internal spin structure—after their sequential creation by local spin-polarized current injection from an atomically sharp SP-STM probe tip[12] (sketched) . The SP-STM map has been obtained in an applied magnetic field of B = 3.25 T at a temperature of T = 4.2 K. **b|** Conceptual illustration of a skyrmion-based racetrack memory. The individual current-driven skyrmions move along linear tracks and can be detected electrically by a nano-scale tunnel junction based on the non-collinear magnetoresistance effect[29,31].

Figure 6| **Nanoscale skyrmions on the track. a|** Spin-polarized scanning tunneling microscopy (SP-STM) image showing four tracks of distorted skyrmions in a three-atomic-layer-thick Fe film grown epitaxially on Ir(111). The distorted shape of the skyrmions originates from spatially anisotropic strain fields, which result from the lattice mismatch between the ultrathin Fe film and the Ir substrate, and leads to spatially anisotropic magnetic interactions. The dark spots are atomic defects, the dark lines are dislocations formed to release part of the strain. **b|** Micromagnetic simulations yield skyrmions of the same shape as those observed experimentally. The distorted skyrmions retain their chiral nature, as well as their topological charge, similar to their axisymmetric counterparts[73]. **c|** The alignment of the individual skyrmions along linear tracks originates from spatial modulations in the magnetic anisotropy, as verified by micromagnetic simulations as those shown in the image. These spatial modulations result from a spatially inhomogeneous strain release in the ultrathin Fe film by linear dislocation lines, which are visible in the SP-STM image in a|.

Figure 7| **Current-driven skyrmion motion along a magnetic nanowire track. a|** Sketch of a magnetic nanowire track with current contacts and skyrmions stabilized by an applied out-of-plane magnetic field. **b|** Sequential scanning transmission X-ray microscopy images revealing the displacement of skyrmions in a $[Pt/Co/Ta]_{15}$ multilayer after the injection of 20 unipolar current pulses along the track, with the indicated polarity. Individual skyrmions are outlined in coloured circles for clarity. **c|** Average skyrmion velocity along multilayer tracks made of $[Pt/Co/Ta]_{15}$ (closed symbols) and $[Pt/CoFeB/MgO]_{15}$ (open symbols) versus current density. Reprinted from REF. 33, Nature Publishing Group.

Table 1| **Overview of ultrathin film and multilayer systems exhibiting magnetic skyrmions**

Systems	Temperature	Magnetic field	Skyrmion size	Refs
a) Ultrathin epitaxial films and multilayers				
1 ML Fe / Ir(111)	11 K	0 T	1 nm	13
1 ML Fe / Ir(111) / YSZ / Si(111)	26.4 K	0 T	1 nm	56
1 ML Pd / 1 ML Fe / Ir(111)	2.2 K	1.5 T	3 nm	12
3 ML Fe / Ir(111)	7.8 K	2.5 T	~ 3 nm	34
2-3 ML Fe/2 ML Ni/ 5-15 ML Cu/15 ML Ni/Cu(001)	300 K	0 T	~ 400 nm	64
b) Sputtered multilayers				
[Ta(5)/CoFeB(1.1) /TaO_x(3)]	300 K	0.5 mT	700-2000 nm	71
$[Pt(3)/Co(0.9)/Ta(4)]_{15}$	300 K	0-2 mT	400-500 nm	33
$[Pt(4.5)/CoFeB(0.7)/MgO(1.4)]_{15}$	300 K	0-2 mT	400-500 nm	33
$[Ir(1)/Co(0.6)/Pt(1)]_{10}$	300 K	0-80 mT	40-90 nm	32
c) Nanostructured sputtered multilayers				
$[Pt(3)/Co(0.9)/Ta(4)]_{15}$	300 K	0-2 mT	400-500 nm	33
$[Ir(1)/Co(0.6)/Pt(1)]_{10}$	300 K	8 mT	50-90 nm	32
Ta(3)/Pt(3)/Co(0.5-1)/MgO_x/Ta(1)	300 K	0-4 mT	70-190 nm	75

In a) ML: monolayer, YSZ: Yttria-stabilized zirconia; in b) and c) the layer thickness is given in nm.