Published in final edited form as:
Nat Phys. 2018 March ; 14(3): 217–219. doi:10.1038/s41567-018-0050-y.

Synthetic Antiferromagnetic Spintronics

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Abstract

Spintronic and nanomagnetic devices often derive their functionality from layers of different materials and the interfaces between them. This is especially true for synthetic antiferromagnets — two or more ferromagnetic layers that are separated by metallic spacers or tunnel barriers and which have antiparallel magnetizations. Here, we discuss the new opportunities that arise from synthetic antiferromagnets, as compared to crystal antiferromagnets or ferromagnets.

Introduction

Advances in nanofabrication techniques for magnetic materials — such as Fe, Ni, Co, Cr and their alloys — have, since the late 1980's, enabled researchers to engineer stacks of thin (nanometers) layers of magnetic and nonmagnetic material. The study of such magnetic multilayers and superlattices – i.e., periodic multilayers – has led to many discoveries and potential applications. The first among these is the existence of a coupling between two magnetic layers adjacent to the same non-magnetic spacer.[1–3] This interlayer exchange coupling is essentially a Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling that is rooted in spin - dependent Friedel-like spatial oscillations in the spin density of the non-magnetic spacer that are caused by the adjacent ferromagnets. The oscillating spin density in turn leads to an interlayer exchange coupling that oscillates with the distance between the ferromagnetic layers.[4–7] By changing the thickness of non-magnetic material between two magnetic layers one can therefore tune the interaction from ferromagnetic — preferring parallel alignment — to antiferromagnetic, preferring antiparallel alignment, whereas for thick spacers the interlayer exchange coupling is suppressed. Trilayers, multilayers or superlattices, in which the interaction between magnetic layers is antiferromagnetic are now commonly referred to as synthetic antiferromagnets (see Fig. 1). The antiferromagnetic coupling was crucial for the discovery that the resistance of metallic magnetic multilayers depends on the relative orientation of the magnetization in adjacent layers.[8,9] This finding —

called giant magnetoresistance (GMR) or, in the case of a tunneling barrier, tunneling magnetoresistance (TMR) — kickstarted the field of nanomagnetism and spintronics.

Let us first compare synthetic with crystal antiferromagnets, i.e., the antiferromagnets found in nature as bulk single crystals. An important difference is that the interlayer exchange coupling in synthetic antiferromagnets is much weaker than the direct exchange or superexchange coupling in crystal antiferromagnets. This difference allows for manipulation of the antiferromagnetic order more easily in synthetic antiferromagnets than in crystal antiferromagnets. Moreover, the magnetic state or texture in synthetic antiferromagnets is easily detectable by the magneto-optical Kerr effect or the anomalous Hall effect (when making thicknesses of two ferromagnetic layers slightly different). As a result, antiferromagnetic magnetization dynamics in synthetic antiferromagnets can be studied using conventional techniques employed for ferromagnets as e.g. shown in Ref. 10, an approach that is challenging for crystal antiferromagnets.

Another difference is that the repeat distance of the antiferromagnetic order in synthetic antiferromagnets is larger than in crystal antiferromagnets. While in the latter, the magnetic order alternates on atomic length scales, the layer thickness in magnetic multilayers is typically several nanometers. For most situations, electron transport within one magnetic layer is therefore appropriately described by a spin-dependent semi-classical model.[11] GMR, for instance, is typically modelled by taking into account electron diffusion within the magnetic layers supplemented with spin-dependent resistances of the various layers and interfaces between them, as well as spin relaxation. For crystal antiferromagnets this picture breaks down as the electrons are in that case phase coherent over a region that is larger than the length scale of the antiferromagnetic order.

Because of the above-mentioned energy and spatial scales, synthetic antiferromagnets are largely tunable via layer thickness and material composition. In the remainder of this commentary we review some features of synthetic antiferromagnets and discuss possible new directions that derive from this tunability.

Statics and dynamics

The tunability of synthetic antiferromagnets, and magnetic multilayers in general, allows for optimization of properties that are desirable for applications including magnetic-field sensing and magnetic random access memory (MRAM).[12–17] In these examples, the important physics is the tuning of stray fields to manipulate stability and sensitivity, and the extra degrees of freedom provided by the layers and coupling between them. The latter leads to additional – with respect to a single magnetic layer – dynamical modes that alter the dynamics and may decrease the switching time of the memory cells. These are also relevant for the development of spin-torque oscillators based on synthetic antiferromagnets[18] with increased tunable frequency range and reduced linewidth, which is an active and ongoing research topic. The dynamics of synthetic antiferromagnets is also relevant for switching by spin-orbit torques that has recently been demonstrated in devices containing synthetic antiferromagnetic layers.[19,20].

An attractive research direction that brings the tunability to the next level is to alter the magnetic properties of the synthetic antiferromagnets *in-situ* by electric fields, rather than by engineering different systems with different properties. For example, it was theoretically proposed in Ref.[21] that the interlayer exchange coupling can be switched from ferromagnetic to antiferromagnetic either by an electric field – as demonstrated experimentally very recently[22] - or by making use of a ferroelectric layer.

While the magnetic layers in synthetic antiferromagnets are presently almost always metallic, an interesting possibility is to consider insulators. Structures based on insulators have, for example, been predicted to exhibit thermal spin torques leading, e.g., to dynamical instabilities such as switching and auto-oscillations[23]. Moreover, the tunability and rich dynamics of magnetic multilayers could be put to use to enhance and manipulate effects, such as the spin Seebeck and the spin Peltier effects[24], that have been recently discovered in insulator spintronics. One of the most interesting prospects of this field is that of room-temperature spin superfluidity[25]. Here, the partial cancellation of dipolar fields in a synthetic antiferromagnetic insulator would lead to the desired reduction of the critical current below which the spin superflow is prohibited. The workhorse of insulator spintronics is the magnetic insulator Yttrium Iron Garnet (YIG) of which it is very hard to make arbitrary heterostructures. Nonetheless, some progress has been made, for example in experiments on heterostructures of YIG and the antiferromagnetic insulator NiO that demonstrate spin transport through the NiO[26]. More developments in this direction are expected in the near future.

Domain walls and solitons

The motion of domain walls and solitons in synthetic antiferromagnets has been studied both theoretically and experimentally.[27–31] Most of the ongoing research on current-driven domain wall motion focuses on multilayers that involve heavy elements with strong spin-orbit coupling, such as Pt or Ta, as the nonmagnetic layers. This spin-orbit coupling has several new physical consequences. First of all, the boundary between heavy nonmagnetic and magnetic metal leads to interface-induced Dzyaloshinskii-Moriya (DM) interactions[32, 33] (see box). These interactions lead to chiral domain walls — domain walls in which the spins have a preferred sense of rotation. In particular, the interfacial DM interactions stabilize Ńeel domain walls that are efficiently driven by spin-orbit torques. These spin-orbit torques are also induced by the spin-orbit coupling in the heavy metallic layer. As shown in Ref. 10, the interlayer exchange coupling in synthetic antiferromagnets stabilizes the Ńeel structure of the walls such that they can be driven more efficiently by spin-orbit torques. On top of this, the interlayer exchange coupling leads to additional torques that efficiently drive the domain walls in both ferromagnetic layers in the same direction. It was experimentally shown in Ref. 10 that large domain wall velocities (of up to 750 m/s) are obtained for domain walls in synthetic antiferromagnets of Co/Ni magnetic layers, separated by thin layers of Ru. This large velocity is basically due to the interlayer-exchange-enhanced dynamics that we discussed previously in the context of magnetic memories and spin-torque oscillators.

Control of the motion of a completely different type of domain walls was demonstrated by Lavrijsen *et al.*[31]. The domain walls considered in this work are kink defects in the antiferromagnetic order of the synthetic antiferromagnet such that two adjacent magnetic layers have magnetizations that are parallel, rather than antiparallel. In a superlattice designed with different interlayer exchange coupling and different magnetic layer thicknesses, these authors were able to demonstrate injection and propagation of kinks by external field pulses. This latter work is an attractive example of how the large tunability of synthetic antiferromagnets, and magnetic multilayers in general, can be put to use to enable new functionalities.

Textures and spin waves

Most experimental research in magnetic multilayers has so far focused on magnetic states where the magnetization within one layer is approximately homogeneous. As the examples of spin superfluidity and domain walls show, it is interesting to move away from this paradigm and to consider inhomogeneity and/or propagation in the lateral direction. It has been known that the interplay between inter and intralayer exchange and magnetostatic effects may lead to interesting textured ground states. (See for example Ref. 34.) The interest in such textures has been revived in the context of magnetic skyrmions that are stabilized by DM interactions. In these developments, magnetic multilayers are playing an important role. The dynamics of skyrmions in synthetic antiferromagnets is particularly interesting. While there has not been much work yet in this direction, Ref. 35 pointed out that the Magnus force that acts on a skyrmion — or more generally on two-dimensional magnetic structures that have a nonzero winding number — and pushes them sideways is counteracted and cancelled by the interlayer exchange coupling in synthetic antiferromagnets. This is beneficial for applications in which skyrmions are driven along narrow wires, as the sideways motion may cause the skyrmions to interact with the edges of the wire and disappear.

Another active direction of current research is magnonics, which aims to exploit spin waves in building beyond-Moore devices. While this field has seen substantial experimental progress recently[36], it is mostly restricted to YIG because of its low spin-wave damping. Connecting to our earlier remarks about insulators, it would be interesting to put synthetic antiferromagnets to use for manipulating spin waves. Tuning their magnetic properties or spin textures would directly translate to tuning the properties, such as velocity and gap, of the spin waves. An example towards this direction is that in the presence of Dzyaloshinskii-Moriya interaction, a magnetic domain wall in a synthetic antiferromagnet serves as spin wave polarizer and retarder.[37] In general, spin waves have elliptical precession but with a well-defined rotational sense. In ferromagnets, they have only one sense, typically right-handed, but in antiferromagnets, they have both, allowing antiferromagnetic magnonics to mimic various functionalities of optics. Another example is that of Ref. 37 which shows that the spin-wave non-reciprocity can be tuned by the interlayer exchange coupling.

So far we have discussed synthetic antiferromagnets with a layered structure, so that the superlattice is one dimensional. A very different example is that of artificial spin ice[39]. This is a synthetic antiferromagnet with a two-dimensional frustrated superlattice. While most of the interest in such systems is motivated by simulating and understanding equilibrium properties of frustrated magnets, artificial spin ice has recently also been exploited for manipulating spin waves.[40] More generally, going from one to two dimensions and using the superlattice geometry adds an interesting new degree of tunability that seems little explored in the context of spintronic functionalities, such as the interplay between magnetic order and spin and charge transport.

In conclusion, the examples we have discussed ultimately show that synthetic antiferromagnets should be thought of as materials with properties in between those of ferromagnets and antiferromagnets. Some of their properties derive from the ferromagnetic layers that constitute them, whereas other properties derive from the coupling between these layers. Engineering and exploiting their tunability will surely lead to new physics and applications for the years to come.

Acknowledgments

RD is supported by the Stichting voor Fundamenteel Onderzoek der Materie (FOM), the European Research Council (ERC), and is part of the D-ITP consortium, a program of the Netherlands Organization for Scientific Research (NWO) that is funded by the Dutch Ministry of Education, Culture and Science. K.-J.L. was supported by the National Research Foundation of Korea (NRF) (NRF-2015M3D1A1070465, NRF-2017R1A2B2006119). This work was in part supported by EU FET Open RIA Grant no. 766566.

References

1. Grünberg P, Schreiber R, Pang Y, Brodsky MB, Sowers H. Layered magnetic structures: Evidence for antiferromagnetic coupling of Fe layers across Cr interlayers. Phys Rev Lett. 1986; 57:2442–2445. [PubMed: 10033726]
2. Majkrzak CF, Cable JW, Kwo J, Hong M, McWhan DB, Yafet Y, Waszczak JV, Vettier C. Observation of a Magnetic Antiphase Domain Structure with Long-Range Order in a Synthetic Gd-Y Superlattice. Phys Rev Lett. 1986; 56:2700–2703. [PubMed: 10033068]
3. Salamon MB, Sinha S, Rhyne JJ, Cunningham JE, Erwin RW, Borchers J, Flynn CP. Long-range incommensurate magnetic order in a Dy-Y multilayer. Phys Rev Lett. 1986; 56:259–262. [PubMed: 10033138]
4. Slonczewski JC. Conductance and exchange coupling of two ferromagnets separated by a tunneling barrier. Phys Rev B. 1989; 39:6995–7002.
5. Parkin S, More N, Roche KP. Oscillations in Exchange Coupling and Magnetoresistance in Metallic Superlattice Structures: Co/Ru, Co/Cr, and Fe/Cr. Phys Rev Lett. 1990; 23:130.
6. Edwards DM, Mathon J, Muniz RB, Phan MS. Oscillations of the exchange in magnetic multilayers as an analog of de Haas - van Alphen effect. Phys Rev Lett. 1991; 67:493–496. [PubMed: 10044908]
7. Bruno P. Theory of interlayer magnetic coupling. Phys Rev B. 1995; 52:411.
8. Baibich MN, Broto JM, Fert A, Nguyen Van Dau F, Petroff F, Eitenne P, Creuzet G, Friederich A, Chazelas J. Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices. Phys Rev Lett. 1988; 61:2472–2475. [PubMed: 10039127]
9. Binasch G, Grunberg P, Saurenbach F, Zinn W. Enhanced magnetoresistance in layered magnetic structures. Phys Rev B. 1989; 39:4828–4830.
10. Yang SH, Ryu KS, Parkin S. Domain-wall velocities of up to 750 m/s driven by exchange-coupling torque in synthetic antiferromagnets. Nat Nanotechnol. 2015; 10:221–226. [PubMed: 25705867]
11. Valet T, Fert A. Theory of the perpendicular magnetoresistance in magnetic multilayers. Phys Rev B. 1993; 48:7099–7113.
12. Parkin S, Jiang X, Kaiser C, Panchula A, Roche K, Samant M. Magnetically engineered spintronic sensors and memory. Proc IEEE. 2003; 91:661–679.

13. Bandiera S, Sousa RC, Dahmane Y, Ducruet C, Portemont C, Baltz V, Auffret S, Prejbeanu IL, Dieny B. Comparison of synthetic antiferromagnets and hard ferromagnets as reference layer in magnetic tunnel junctions with perpendicular magnetic anisotropy. IEEE Magn Lett. 2010; 1:3000204.
14. Smith, NeilMaat, StefanCarey Matthew, J., et al.Coresonant Enhancement of Spin-Torque Critical Currents in Spin Valves with a Synthetic-Ferrimagnet Free Layer. Phys Rev Lett. 2008; 101:247205. [PubMed: 19113662]
15. Lee SW, Lee KJ. Current-induced magnetization switching of synthetic antiferromagnetic free layer in magnetic tunnel junctions. J Appl Phys. 2011; 109:07C904.
16. Hayakawa J, Ikeda S, Lee YM, Sasaki R, Meguro T, Matsukura F, Takahashi H, Ohno H. Current-induced magnetization switching in MgO barrier based magnetic tunnel junctions with CoFeB/Ru/CoFeB synthetic ferrimagnetic free layer. Jpn J Appl Phys. 2006; 45:L1057–L1060.
17. Bergman A, Skubic B, Hellsvik J, Nordstrom L, Delin A, Eriksson O. Ultrafast switching in a synthetic antiferromagnetic magnetic random-access memory device. Phys Rev B. 2011; 83:224429.
18. Houssameddine D, Sierra JF, Gusakova D, Delaet B, Ebels U, Buda-Prejbeanu LD, Cyrille MC, Dieny B, Ocker B, Langer J, Maas W. Spin torque driven excitations in a synthetic antiferromagnet. Appl Phys Lett. 2010; 96:072511.
19. Lau YC, Betto D, Rode K, Coey JMD, Stamenov P. Spinorbit torque switching without an external field using interlayer exchange coupling. Nat Nanotechnol. 2016; 11:758. [PubMed: 27240416]
20. Bi C, Almasi H, Price K, Newhouse-illige T, Xu M, Allen SR, Fan X, Wang W. Spin-orbit torque switching of synthetic antiferromagnets. Phys Rev B. 2017; 95:104434.
21. Fechner M, Zahn P, Ostanin S, Bibes M, Mertig I. Switching magnetization by 180 degrees with an electric field. Phys Rev Lett. 2012; 108:197206. [PubMed: 23003084]
22. Newhouse-Illige T, Liu Y, Xu M, Reifsnyder Hickey D, Kundu A, Almasi H, Bi C, Wang X, Freeland JW, Keavney DJ, Sun CJ, Xu YH, Rosales M, Cheng XM, Zhang S, Mkhoyan KA, Wang WG. Voltage-controlled interlayer coupling in perpendicularly magnetized magnetic tunnel junctions. Nature Communications. 2017; 8:15232.
23. Bender SA, Tserkovnyak Y. Thermally driven spin torques in layered magnetic insulators. Phys Rev B. 2016; 93:064418.
24. Bauer GEW, Saitoh E, Van Wees BJ. Spin Caloritronics Nature Materials. 2012; 11:391. [PubMed: 22522639]
25. Takei S, Tserkovnyak Y. Superfluid Spin Transport Through Easy-Plane Ferromagnetic Insulators. Phys Rev Lett. 2014; 112:227201. [PubMed: 24949786]
26. Hahn C, de Loubens G, Naletov VV, Ben Youssef J, Klein O, Viret M. Europhys Lett. 2014; 108:57005.
27. Herranz D, Guerrero R, Villar R, Aliev FG, Swaving AC, Duine RA, van Haesendonck C, Vavra I. Anomalous low-frequency noise in synthetic antiferromagnets: Possible evidence of current-induced domain-wall motion. Phys Rev B. 2009; 79:134423.
28. Saarikoski H, Kohno H, Marrows CH, Tatara G. Current-driven dynamics of coupled domain walls in a synthetic antiferromagnet. Phys Rev B. 2014; 90:094411.
29. Shiino T, Oh SH, Haney PM, Lee SW, Go G, Park BG, Lee KJ. Antiferromagnetic Domain Wall Motion Driven by Spin-Orbit Torques. Phys Rev Lett. 2016; 117:087203. [PubMed: 27588878]
30. Komine T, Aono T. Micromagnetic analysis of current-induced domain wall motion in a bilayer nanowire with synthetic antiferromagnetic coupling. AIP Adv. 2016; 6:056409.
31. Lavrijsen R, Lee J-H, Fernández-Pacheco A, Petit DCMC, Mansell R, Cowburn RP. Magnetic ratchet for three-dimensional spintronic memory and logic. Nature. 2013; 493:647–50. [PubMed: 23364743]
32. Dzyaloshinskii I. A thermodynamic theory of “weak” ferromagnetism of antiferromagnetics. J Phys Chem Solids. 1958; 4:241–255.
33. Moriya T. Anisotropic superexchange interaction and weak ferromagnetism. Phys Rev. 1960; 120:91–98.
34. Roessler UK, Bogdanov AN. Magnetic states reorientation transitions in antiferromagnetic superlattices. Phys Rev B. 2004; 69:094405.

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35. Zhang X, Zhou Y, Ezawa M. Magnetic bilayer-skyrmions without skyrmion Hall effect. Nat Commun. 2015; 7:10293.

36. Chumak AV, Vasyuchka VI, Serga AA, Hillebrands B. Magnon Spintronics. Nature Physics. 2015; 11:453.

37. Lan J, Yu W, Xiao J. Antiferromagnetic domain wall as spin wave polarizer and retarder. Nat Commun. 2017; 8:178. [PubMed: 28769036]

38. Di K, Feng SX, Piramanayagam SN, Zhang VL, Lim HS, Ng SC, Kuok MH. Enhancement of spin-wave nonreciprocity in magnonic crystals via synthetic antiferromagnetic coupling. Scientific Reports. 2015; 5:10153. [PubMed: 25950082]

39. Marrows C. Experimental Studies of Artificial Spin Ice. ArXiv. 2016; 1611:00744.

40. Bhat VS, Heimbach F, Stasinopoulos I, Grundler D. Magnetization dynamics of topological defects and the spin solid in a kagome artificial spin ice. Phys Rev B. 2016; 93:140401(R).

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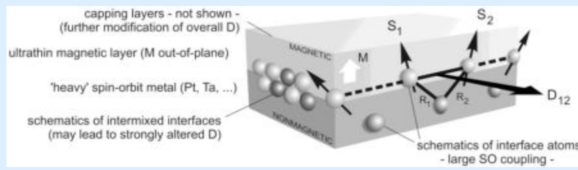
BOX

DZYALOSHINSKII-MORIYA (DM) EXCHANGE INTERACTIONS

Apart from the well-known Heisenberg-type exchange interactions between spins in ferromagnetic materials, there can exist so-called Dzyaloshinskii-Moriya (DM) interactions in magnetic systems that lack a center of inversion and exhibit spin-orbit coupling. In the situation of two magnetic atoms (spin $\mathbf{S_1}$ and $\mathbf{S_2}$) in presence of a third non-magnetic atoms with spin-orbit coupling (see figure) this interaction has the form $\sim\mathbf{D}\cdot\mathbf{S_1}\times\mathbf{S_2}$, with **D** the Dzyaloshinskii vector and $\mathbf{R_1}$ and $\mathbf{R_2}$ the respective positions of the magnetic atoms with respect to the non-magnetic one.



This interaction clearly favors a certain misaligned and turning sense (chirality) of the magnetic moments. Most important for magnetic multilayers are the DM interactions induced by interfaces between magnetic metals and metals with strong spin-orbit coupling. Figure adapted from Nature Nanotech. 8, 152 (2013).

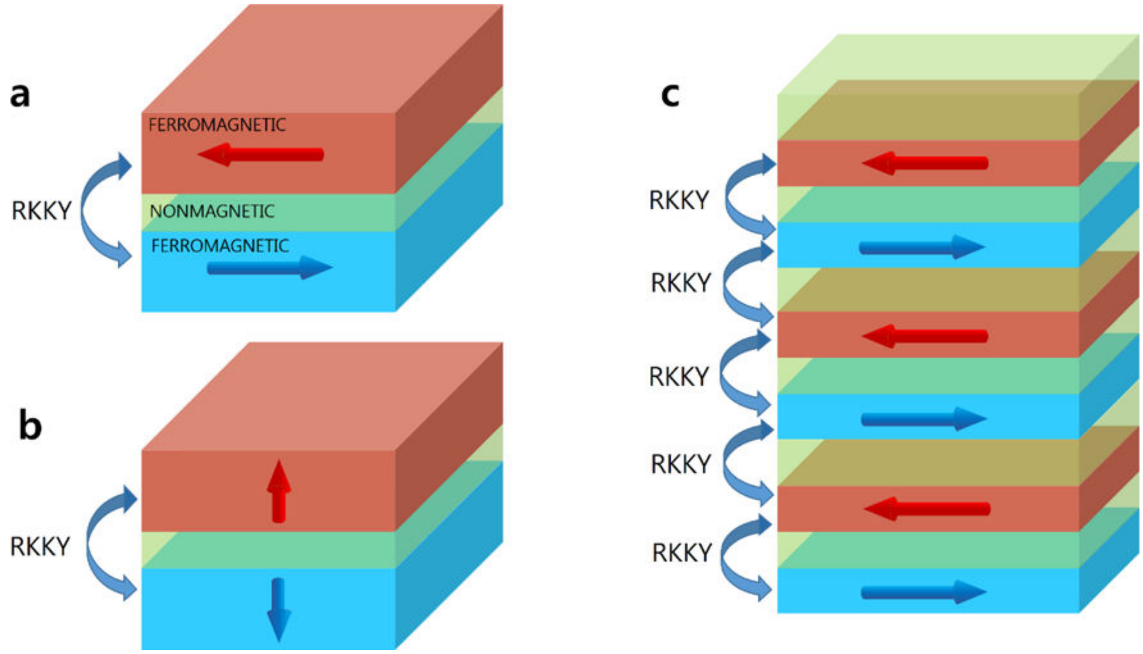


Figure 1.

Schematic of synthetic antiferromagnets. a, bilayers with in-plane magnetization. b, bilayers with out-of-plane magnetizations. c, multilayers. The arrows within each ferromagnetic layer indicate the direction of magnetization. Depending on the magnetic configurations the RKKY coupling and dipolar fields add (a) or subtract (b) leading in part to the large degree of tunability of multilayers.