Journal of Applied Physics

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Cite as: J. Appl. Phys. **128**, 070401 (2020); https://doi.org/10.1063/5.0023614
Submitted: 31 July 2020 . Accepted: 03 August 2020 . Published Online: 19 August 2020

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Published Online: 19 August 2020

View Online Export Citation CrossMark

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Note: This paper is part of the special topic on Antiferromagnetic Spintronics.

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Antiferromagnetism was discovered in the 1930s by Louis Néel as the second type of magnetic order following ferromagnetism. For this achievement he was awarded the Nobel Prize in Physics in 1970. In his Nobel lecture, he noted that antiferromagnetic substances "*are extremely interesting from the theoretical standpoint but do not appear to have any practical applications.*"[1] For about half a century, this was true and antiferromagnets were utilized only for limited purposes, e.g., as sources of exchange bias[2] in spin valves. Recently, however, the situation has gradually changed in the field of spintronics and a new paradigm—antiferromagnetic spintronics—has been established.[3–5]

Recent studies have demonstrated various intriguing phenomena in antiferromagnets similar or superior to their ferromagnetic counterparts. These phenomena include characteristic spin transport such as anisotropic magnetoresistance,[6] the spin Hall effect giving rise to spin-orbit torque,[7,8] the anomalous Hall effect,[9] electrical[10,11]/optical[12] manipulation of the Néel vector, long-distance spin-wave propagation,[13] the anomalous Nernst effect,[14] and so on. At the same time, synthetic antiferromagnets with interlayer exchange coupling[15] have also attracted increasing attention as they can also enjoy the benefits of bulk antiferromagnets, such as fast magnetic domain wall[16] and skyrmion[17] motion. These findings have changed our perception of antiferromagnetic substances from materials lacking practical application to promising candidates for active elements of electronics.

From the theoretical point of view, the newly found phenomena are related to the complicated structure of antiferromagnets compared to their ferromagnetic counterparts. First, strong exchange coupling between the antiferromagnetically coupled sublattices is involved in the magnetic dynamics, which results in the enhancement of the effective fields and characteristic frequencies and makes antiferromagnets fast and robust with respect to external magnetic fields.[18] Second, while in some materials the antiferromagnetic ordering breaks time- and space-inversion symmetry separately, the system nevertheless remains invariant with respect to a combination of both operations.[19] This combined symmetry enables a pronounced anisotropic magnetoresistance effect which appears due to dependence of the topological properties of the Dirac points on the orientation of the staggered magnetization of an antiferromagnet. This opens a way to the effective electrical reading of the antiferromagnetic state via anisotropic magnetoresistance and manipulation of electronic properties by rotation of the magnetic moments. Another effect enabled by the combined time- and space-inversion symmetry is related to the electrical manipulation of the antiferromagnetic state. An electrical current flowing through an antiferromagnet with the combined symmetry can induce a staggered non-equilibrium spin polarization that is commensurate with the staggered equilibrium Néel order.[3] Third, antiferromagnetically ordered materials frequently show strong spin-orbit coupling, which in combination with the special symmetry properties and non-trivial magnetic structure creates a class of so-called topological antiferromagnets.[20] These materials show a bunch of transport phenomena such as the anomalous Hall effect,[21,22] spin Hall effect,[23] crystal Hall effect,[24,25] etc., some of which have no counterpart in paramagnetic and ferromagnetic compounds.

The discoveries of unconventional physical properties have turned the disadvantages of antiferromagnets into advantages. Because antiferromagnets inherently have no or negligible net magnetization, which has so far limited practical usage of antiferromagnets, they are expected to be favorable for dense packing and also stable against external fields. In addition, the typical characteristic frequency of antiferromagnets is close to THz due to the effect of exchange enhancement, in contrast to ferromagnets, whose ∼GHz frequencies are governed by the magnetic anisotropy only. These features show promise for boosting spintronics technology to a realm inaccessible by conventional ferromagnets. In addition, many studies on current-induced control of antiferromagnets[10] or antiferromagnet/ferromagnet heterostructures[8] reveal analog-like behavior, unlike ferromagnetic systems. Such properties may be useful for unconventional devices and circuits for information processing.[26] Proof-of-concept neuromorphic computing[27] and pulse-counter devices[28] have been demonstrated. Not being limited to these examples, antiferromagnetic spintronics provides a variety of opportunities in applications that Louis Néel never envisioned.

This "Antiferromagnetic Spintronics" Special Topic in the *Journal of Applied Physics* offers an overview of the most active research areas currently under investigation in the broad field of antiferromagnetic spintronics. In particular, featured topics include fundamental magnetic properties, spin transport, switching, and domain wall or skyrmion motion of collinear and non-collinear antiferromagnets, as well as growth and characterization techniques.

A variety of theoretical and experimental works on fundamental magnetic properties of various antiferromagnetic materials are reported. Special attention is given to investigation of the magnetic anisotropy profiles, the detailed structure of which are extremely important for the effective control of antiferromagnetic states. In the papers of O'Grady *et al.*[29] Nozaki *et al.*[30] Feldl *et al.*[31] and Surýnek *et al.*[32] readers can learn about different experimental techniques used to measure magnetic anisotropies of antiferromagnets. Wu *et al.* present the study of the magnetic and transport properties in antiferromagnetic-ferromagnetic multilayers depending on microstructure and field-cooling conditions.[33] The theoretical first-principles research of Thöle *et al.* focuses on (spin) transport and magnetoelectrical properties of antiferromagnets based on the concept of magnetoelectrical multipoles and demonstrates the importance of previously neglected toroidal moments.[34] The issue also includes first-principles studies of antiferromagnets that predict antiferromagnetic phases in Heusler alloys[35] and tuning of the Néel temperature by doping of the spinel $Mg_3Si_6As_8$.[36]

A number of articles present growth and characterization techniques for high-quality antiferromagnetic thin films optimized for spintronics applications. Bommanaboyena *et al.* prepare Mn_2Au (001) thin films by molecular beam epitaxy as an alternative deposition technique to sputtering, demonstrating improved crystallinity and morphology for antiferromagnetic spintronics.[37] Kurdi *et al.* demonstrate high-quality single-crystal Ru (0001) epitaxial films on c-Al_20_3 substrates using radio frequency-magnetron sputtering, which serve as buffer layers for the deposition of highly epitaxial and single phase non-collinear antiferromagnetic Mn_3X films.[38] Miki *et al.* grow antiperovskite nitride noncollinear antiferromagnetic $Mn_3Ni_{0.35}Cu_{0.65}N$ films and observe an orientation-dependent anomalous Hall effect of (001) and (111) films due to the nonzero Berry curvature, highlighting the importance of post-annealing conditions to film quality and the strength of the anomalous Hall effect signal.[39]

Articles in the area of transport and switching in antiferromagnets report progress in the electrical manipulation and readout of antiferromagnetic order, which form the foundation of antiferromagnetic spintronics. Siddiqui *et al.*[40] provide a review of phenomena specific to metallic antiferromagnets that enable the complex interplay between electronic degrees of freedom, optical excitation, and magnetic order dynamics. Omari *et al.*[41] demonstrate electrical-induced switching of CuMnAs/GaP using nanosecond current pulses with reproducible behavior. Anomalous Hall effect measurements are used in the works by Asa *et al.*[42] to detect the state of IrMn using Ta/IrMn heterostructures, and by Chongthanaphisut *et al.*[43] to observe a temperature-induced transition between ferromagnetic and antiferromagnetic interlayer exchange coupling in trilayer structures of (Ga,Mn)(As,P) with a GaAs:Be spacer. Geprägs *et al.*[44] show that spin Hall magnetoresistance is a useful tool to probe spin configuration and investigate magnetoelastic effects in antiferromagnetic multidomain materials; Miura *et al.*[45] also show the spin Hall magnetoresistance is capable of probing antiferromagnetic order in $MnTiO_3$ thin films. Samanta *et al.*[46] use spin density functional theory to investigate the magnetic ground state and anomalous Hall response of $SrRuO_3$ ultra-thin films.

Several articles focus on magnetic domains, domain walls and skyrmions in antiferromagnets. Analytical and numerical work on the static and dynamic properties of domain walls in antiferromagnets are presented by Shen *et al.*[47] and Conzelmann *et al.*[48] The former studies interaction with magnons, whereas the latter studies the effect of Dzyaloshinskii-Moriya interactions on antiferromagnetic domain walls. Antiferromagnetic skyrmions are also studied by Tascano *et al.*[49] and Potkina *et al.*[50] Effects of pinning[49] and thermal stability against collapse and escape[50] are discussed. An experimental study on domain patterns in antiferromagnetic $La_{0.7}Sr_{0.3}FeO_3$ is reported by Lee *et al.*[51] They use x-ray photoemission electron microscopy and elucidate several factors determining the antiferromagnetic domain structure.

A review paper by Kurenkov *et al.*[52] provides an overview on neuromorphic computing with antiferromagnetic spintronics, introduces the main concepts and building blocks, and demonstrates artificial neural networks based on antiferromagnets. Future prospects and challenges of antiferromagnetic spintronics for neuromorphic computing are discussed.

In summary, recent advances in unravelling and utilizing unexplored functionalities of antiferromagnets have opened a new paradigm, antiferromagnetic spintronics, where one aims to understand and control the dynamics of antiferromagnetic moments or spin transport for use in new-concept devices and circuits. As research in this field expands rapidly in depth and breadth, it becomes increasingly important for the community to consolidate and share its knowledge. This Special Topic on antiferromagnetic spintronics provides a timely forum for investigators to share their new results, methods, and perspectives in a format that allows for in-depth analysis and discussion. We hope that this "Antiferromagnetic Spintronics" Special Topic will inspire many scientists and engineers, and accelerate the development of spintronics.

The guest editors sincerely thank the staff and editors of the *Journal of Applied Physics* for putting this Special Topic together and all the authors and reviewers for their contributions. S.F. acknowledges financial support from JST-CREST JPMJCR19K3 and JSPS Kakenhi 19H05622. V.O.L. acknowledges support by the NSF through the University of Illinois at Urbana-Champaign Materials Research Science and Engineering Center DMR-1720633. O.G. acknowledges EU FET Open RIA Grant No. 766566 and funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - TRR 173–268565370 (project B12).

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