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Preview

Uncompensated antiferromagnetic interfaces unlock new possibilities in van der Waals junctions

Jose L. Lado[1,*] and Saroj P. Dash[2,*]
[1]Department of Applied Physics, Aalto University, 00076 Espoo, Finland
[2]Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-41296 Göteborg, Sweden
*Correspondence: jose.lado@aalto.fi (J.L.L.), saroj.dash@chalmers.se (S.P.D.)
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Unlike conventional ferromagnetic systems, antiferromagnets offer benefits such as zero stray fields and ultrafast dynamics. Using first-principles calculations, Yang et al. further discover that the uncompensated interface magnetization of antiferromagnetic electrodes leads to a significant tunneling magnetoresistance, offering new design principles for spintronic technologies.

Hybrid materials based on magnetic systems offer highly versatile platforms for controlling electric currents. A paradigmatic example is tunneling magnetoresistance (TMR), where the magnetic alignment between electrodes enables a significant change in the electrical resistance of a junction. These devices have been instrumental in electronic technology and continue to serve as a cornerstone for future spintronic applications.

Van der Waals materials provide an alternative platform to bulk compounds for creating electronic devices with novel functionalities. Their two-dimensional nature facilitates the easy formation of interfaces between materials, owing to the weak van der Waals forces. Interestingly, these weak forces also enable precise control over the twist angle between materials, allowing for the tuning of interface properties and the emergence of new correlated phases. While the critical temperatures of magnetic order of van der Waals materials are often lower than those in bulk counterparts, spintronic devices based on van der Waals materials can play a crucial role in low-temperature control electronics, which are essential for future cryogenic spin and quantum technologies. Ultimately, the development of van der Waals ferromagnetic and antiferromagnetic materials with critical temperatures above room temperature would expand their applications in ambient temperatures.

Van der Waals materials exhibiting magnetic order have been successfully isolated in the monolayer limit. The first examples include monolayers of Fe_2GeTe_3,[1] $CrBr_3$,[2] and CrI_3,[3] which develop out-of-plane ferromagnetic order due to uniaxial anisotropy, while $CrCl_3$[4] exhibits in-plane ferromagnetism. While these ferromagnets have relatively low critical temperatures, compounds such as Fe_xGeTe_2 and Fe_xGaTe_2 have recently emerged as promising candidates for higher-temperature magnetism, potentially beyond room temperature. These materials serve as a promising starting point for engineering other higher-temperature phases through alloying with different elements, enabling the creation of both ferromagnetic and antiferromagnetic van der Waals compounds.[5]

A study in *Newton* conducted by an international collaboration led by Ding-Fu Shao from the Chinese Academy of Sciences introduces a prototype of antiferromagnetic tunnel junctions based on interface effects.[6] Unlike conventional magnetic tunnel junctions (MTJs), which rely on ferromagnets, their proposal focuses on utilizing antiferromagnets. The use of antiferromagnets in MTJs offers several promising advantages over ferromagnets, including zero stray fields due to compensated magnetic moments and ultrafast THz-regime magnetization dynamics.

Antiferromagnets have been employed in spintronics through various strategies, two of which are particularly relevant here. The first involves using antiferromagnetic insulators as spin filters, where magnetic switching is leveraged to achieve TMR. The second relies on exploiting spin-dependent bulk electronic properties in metallic antiferromagnets for TMR. The researchers propose an alternative strategy that uses a specific type of antiferromagnetic stacking. This approach creates magnetically uncompensated interfaces that generate spin-polarized tunneling currents, even as the bulk remains compensated.

The researchers based their analysis on first-principle and quantum-transport calculations, focusing on heterostructures built from Fe_4GeTe_2. While pristine Fe_4GeTe_2 is ferromagnetic, it can be switched to an A-type antiferromagnetic state through co-doping. The study specifically examined interfaces with hBN, where their calculations revealed the emergence of significant spin polarization (Figure 1).[6] This interfacial polarization leads to sizable magnetoresistance. The researchers also propose applications in antiferromagnetic memories, where data are written using spin torques and read via TMR devices: MTJs. Specifically, such magnetic junctions can be useful for readout in spin-orbit torque-based magnetic memory devices employing van der Waals heterostructures.[7]

While their work is purely computational, the current proposal can motivate further experimental efforts in creating these types of van der Waals interfaces. Beyond the specific proposal presented, the use of antiferromagnetic van der Waals materials is likely to have a broad and far-reaching impact in the field of antiferromagnetic spintronics.

Beyond antiferromagnets, the use of compensated magnets, including spin spirals, can offer similar advantages of vanishing stray fields with antiferromagnets.

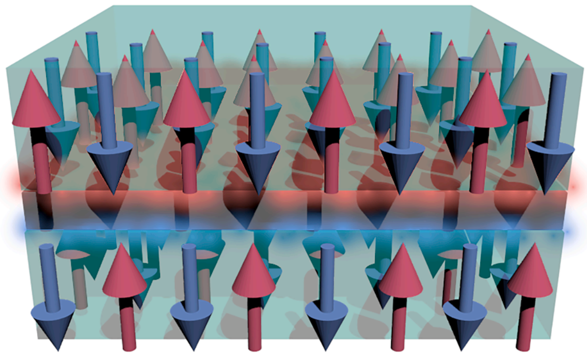

Figure 1. Schematic of an antiferromagnetic MTJ
Antiferromagnetically coupled magnetic moments, represented by blue and red arrows, induce uncompensated exchange fields at the junction interface, resulting in a large magnetoresistance.

Of particular interest is NiI_2,[8] a recent spin-spiral monolayer material, which, beyond its magnetic order, exhibits ferroelectric polarization, resulting in multiferroic behavior. Other compensated spiral magnets may also emerge in van der Waals materials, such as 1T-TaS_2 and 1T-$TaSe_2$, due to the inherent frustration within their lattice structures.

Beyond the realm of spintronics, antiferromagnets and compensated magnets can significantly impact the field of superconducting electronics. This is due to their absence of net exchange fields when combined appropriately with superconductors. Specifically, antiferromagnets could be further used to create Josephson diodes[9] and topological superconductors.[10] When integrated with the heterostructures proposed by the researchers, these devices could further extend the influence and applicability of van der Waals antiferromagnets into the domain of superconducting quantum technologies.

Overall, the use of van der Waals magnets in spintronics represents a promising direction in materials research, offering the potential to leverage stacking flexibility for engineering devices that are challenging to realize with bulk compounds. Further experimental implementation of the proposed van der Waals magnetic junctions could significantly advance information and communication technologies, given their tunability and broad applicability across various materials and heterostructures. They provide a new approach to integrating memory and logic into antiferromagnetic systems and are poised to become central components in future high-speed, high-efficiency spintronic and quantum technologies.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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