Challenges and opportunities in orbitronics

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The ability to control electron's spin degrees of freedom has enabled the development of spintronics—devices that use spin, rather than just electric charge, to store and process information. The concepts of spintronics are now applied in technologies, such as magnetic sensors and nonvolatile memory devices. In addition to spin, electrons can carry orbital angular momentum. However, research into the use of orbital angular momentum is still in its early stages. Recent discoveries of phenomena mediated by orbital angular momentum have led to a new branch of physics called orbitronics. This perspective explores how orbitronics may represent the next phase in the evolution of spintronics by reviewing the current theoretical understanding, challenges, and experimental results related to orbital effects. It also outlines key open questions and discusses potential applications, with a focus on non-volatile memory technologies.

Spintronics has advanced information and communications technology by integrating the electron's spin degree of freedom into conventional electronics, enabling the electrical detection and manipulation of magnetization. Examples of spintronic effects include giant magnetoresistance, tunnelling magnetoresistance[1] and spin-transfer torque[2]. Discovery of these effects has led to practical applications such as magnetic sensors and magnetoresistive random access memories (MRAMs). In particular, MRAM using spin-transfer torque-induced magnetization switching for the write operation has been commercialized. It holds great potential to make large-scale integrated circuits more energy-efficient.

Spin-orbitronics emerged as the next step beyond spintronics by incorporating the orbital degree of freedom to control electron's spin angular momentum through spin−orbit coupling. Traditional spintronic devices rely on magnetic materials to produce spin-polarized electrons. However, spin−orbit coupling can generate spin currents even in nonmagnetic materials, as represented by the spin Hall effect [Fig. 1(a)], where electrical currents (gray arrow) can generate transverse spin currents (green and orange arrows). Similarly, in the Rashba-Edelstein effect [Fig. 1 (b)], non-equilibrium spin accumulations (green arrows) occur at the interfaces between typically a magnetic and a non-magnetic layer due to the spin−orbit coupling. As a consequence, in stacks having magnetic and non-magnetic layers with broken spatial inversion symmetry, a magnetic torque, termed spin−orbit torque, arises when an electric current is applied. This provide an alternative to electrically manipulate magnetization[3,4], distinct from the spin-transfer torque that is generated by magnetic materials. With the spin−orbit torque, controlling the Néel vector, the order parameter to represent the orientation of magnetic moments in antiferromagnets, is also made possible, allowing one to encode and manipulate information in antiferromagnetic spintronic devices. This is crucial as the antiferromagnetic devices possess several unique attributes that the ferromagnetic counterparts do not, forming the basis of antiferromagnetic spintronics[5]. In terms of applications, MRAMs based on spin−orbit torque have been developed to achieve high-speed memories in integrated circuits[6,7] with better performance levels in some aspects, compared to the conventional spin-transfer torque MRAMs.

Spin-related phenomena have long dominated the focus of condensed matter and spintronics research. However, recent theoretical and experimental advances have begun to highlight the unique physical effects governed by the orbital degrees of freedom, where the electron's orbital angular momentum plays pivotal roles instead of the spin angular momentum[8,9]. This has sparked a growing interest in leveraging orbital angular momentum to develop device functionalities that go beyond conventional mechanisms such as spin-transfer torque and spin–orbit torque. Additionally, theoretical work has expanded the understanding of orbital angular momentum transport under nonequilibrium conditions, uncovering phenomena such as the orbital Hall effect and the orbital Rashba–Edelstein effect, which mirror their spin-based counterparts and may prove at least equally significant[10]. The development of spin–orbit torque MRAM has further underscored the need to enhance torque generation efficiency, driving efforts to identify new mechanisms that can amplify these effects. As a result, controlling the orbital degrees of freedom of electrons is emerging as a promising and active field of research referred to as orbitronics[11,12].

In this perspective, we provide an overview of orbitronics, highlighting opportunities and challenges in this field. We review some key experimental and theoretical results that go beyond the conventional spintronic and spin-orbitronic effects and discuss some open questions. Finally, we focus on how orbitronics could enhance the efficiency of state-of-the-art spin–orbit torque MRAM.

Experimental progress in orbitronics characterization

When currents are injected in a material, a wavevector-dependent orbital angular momentum of electrons can occur as we will discuss later. A large number of predictions deal with the importance of orbital angular momentum and torques, including predictions of the orbital Hall effect[9,10] and the orbital Rashba-Edelstein effect[11-13]. Their mechanisms are shown schematically in Fig. 1(c),(d), where the orbital Hall effect interconverts a charge current and an orbital angular momentum current in the bulk of the material, while the orbital Rashba-Edelstein effect interconverts a charge current and a non-equilibrium orbital angular momentum density at the interface.

There are different experimental approaches to study and understand orbitronic effects. A commonly used method is to study the torque due to the orbital effects with the spin-torque ferromagnetic resonance or second harmonic analysis[3]. These measurements are typically performed in layered magnetic heterostructures, as illustrated in Fig. 2. Conventional spin currents are fully absorbed by ferromagnets within a few nanometers leading to the same behaviour for all ferromagnets. Therefore, the strong dependence of the torques on the ferromagnetic material can be used as an experimental fingerprint to identify orbital effects. However, simply generating orbital angular momentum currents or accumulation is insufficient to influence the magnetization directly, because it arises from spin in most conventional magnets. Therefore, to make orbital torque effective and efficient, the orbital angular momentum must first be converted into spin angular momentum through spin–orbit coupling. As shown in Fig. 2(a), this can occur in the ferromagnet itself. However, not all ferromagnets are efficient at this conversion. For example, it was reported[14-16] that this process is more efficient in permalloy (Ni−Fe) and Ni than in CoFeB. To increase the efficiency, one can introduce an additional conversion layer that converts orbital to spin angular momentum [Fig. 2(b)]. Pt[14,17] or 4*f* transition metals[15] have been previously used as such a conversion layer. Furthermore, one can also alloy these with the magnetic material.

There are a range of different techniques to explore orbitronics, which we briefly list here. Later we highlight some of the seminal experimental findings using the techniques. Many experiments on orbitronics have used torque measurement techniques, however a quantitative analysis is still challenging because of the number of effects involved. The generation of orbital angular momentum, the transport of orbital angular momentum (in particular across interfaces, which is still not very clear[18]), the conversion to spin, the spin transport and the transfer to the magnetic moment exerting a torque can contribute and these effects cannot be easily disentangled.

Apart from measuring torques, magnetoresistance effects in these multilayers can also be used as an alternative approach to explore orbitronics[19]. The inverse effect of the torques—namely the pumping of orbital angular momentum that is converted into charge currents and utilized for terahertz emission — offers a complementary experimental probe[20,21]. A more direct technique is to image the orbital angular momentum accumulation based on circular dichroism as recently demonstrated by magneto-optical[22,23] and electron microscopy or energy-loss spectroscopy[16] methods. Last but not least, one can also employ orbital Hanle magnetoresistance[24], which, however, needs to be carefully delineated from ordinary magnetoresistance.

Although these different techniques and approaches have been employed in the past, substantial further research is required for an unambiguous quantitative understanding of orbitronic effects.

Using some of the techniques mentioned, early experiments showed that oxide layers, such as CuO_x can enhance orbital torque effects. Although these results were not initially linked to orbital phenomena, later studies identified CuO_x, as a strong source of orbital angular momentum[19,25,26]. In particular, considerable enhancement of spin torques observed in Thulium Iron Garnet (TmIG)/Pt/CuO_x heterostructures, was attributed to the orbital currents generated by the orbital Hall or orbital Rashba Edelstein effect in CuO_x. These currents are efficiently converted to spin currents in Pt, leading to a sixteen-fold increase in the resulting torques acting on the magnetic layer[25]. This key observation was complemented by the identification of the orbital Rashba-Edelstein effect in Ni–Fe/CuO_x heterostructures where strong non-equilibrium orbital accumulation was converted in the Ni–Fe layer to a spin current that leads to strong torques[19,22]. Beyond CuO_x based complex heterostructures that are often difficult to control, a large orbital Hall effect has also been predicted in transition metals such as Nb, Ta and Ru[27].

By studying the layer thickness, it was observed that orbital currents can travel through ferromagnets over much longer distances than spin currents, which typically decay very quickly[14,15,21,22,28]. The sign of the observed torques enabled identification of the dominating mechanism (spin or orbital)[14]. As the next step, the orbital angular momentum needs to be converted to spin and this conversion was systematically studied[15] and more recently rare earth materials were identified to be efficient in this conversion[29].

Torque efficiency also can be enhanced by tuning the crystal symmetry of the ferromagnet[30,31]. For example, in FeMn/CoPt bilayers, the torque efficiency varies with ferromagnet thickness depending on crystal symmetry of the CoPt layer, which is attributed to orbital-dependent energy splittings and hybridizations[31]. Furthermore, recent studies have extended the number of magnetic materials in which the orbital torque is observed in antiferromagnets[32] or two-dimensional[33] and perpendicular[34] ferromagnets.

The reciprocal effect to the conversion from charge to orbital angular momentum leading to orbital torques is the conversion from orbital angular momentum to charge as measured by orbital pumping. This reciprocal orbital pumping was reported, corroborating the long transport length scales and the strong dependence on the ferromagnet[20]. Although one might expect full reciprocity between orbital-to-charge and charge-to-orbital effects on a fundamental level, this is still not fully understood. Some studies on local and non-local transport show reciprocal behaviour[35], whereas others do not[36,37], opening up directions for further research.

Beyond measuring torques, magnetoresistance and pumping effects, a more direct way to quantify the orbital currents is to image the orbital accumulation. This has been demonstrated in thin films using measurements of the magneto-optical Kerr effect[22,23], which is sensitive to both orbital and spin angular momentum. However, an even more direct way to identify the orbital contribution is electron magnetic linear dichroism[16]. These measurements also enable the analysis of the orbital angular momentum diffusion length.

Apart from conventional multilayer heterostructures, two-dimensional van der Waals systems have recently been explored in the context of orbitronics. The orbital Hall effect in transition metal dichalcogenides was theoretically studied[38-40]. In particular, the transport of orbital angular momentum was first interpreted in terms of the valley Hall effect and only later, it was realized that the orbital Hall effect might play a key role. The transport of orbital angular momentum in terms of a valley Hall effect entails also transport of magnetic moments[41]. However, the calculations based on the valley Hall effect have encountered conceptual difficulties namely the artificial separation of the Brillouin zone. More recent analysis has revealed that the orbital Hall effect is a more appropriate description of the transport of orbital angular momentum in bilayer transition metal dichalcogenides. Recently, the orbital Hall effect and valley Hall effect were disentangled theoretically[42]. It was also predicted that the orbital Hall effect in the insulating gap can even attribute a Chern number confirming a possible topological nature of orbital Hall insulators[38,39] that were observed in rare-earth dichalcogenides[40]. Finally, it is worth pointing out that orbital torque intrinsic to single materials can also be present in two-dimensional layered compounds[43].

Theoretical understanding of orbitronics and open questions

The basic principle of the orbital Hall effect, which occurs in all conducting solids, is described in Box 1. In addition to the bulk orbital Hall effect, the interfacial orbital Rashba-Edelstein effect also generates orbital angular momentum. Similar to the orbital Hall effect, the orbital Rashba-Edelstein effect exists in general even in the absence of spin–orbit coupling, because it arises from orbital Rashba coupling[11]. When an orbital angular momentum, produced by either effect, is injected into a ferromagnet, it exerts an orbital angular momentum torque, or orbital torque[44].

The usefulness of orbital degrees of freedom in spintronics depends on two closely related factors: the magnitude of orbital angular momentum torque and the relaxation process of orbital angular momentum current. Currently, the theoretical understanding of these factors is far from complete, but they represent important research topics to deepen our understanding on orbital transport in solids.

The magnitude of orbital angular momentum torque is determined by the orbital angular momentum accumulation at the ferromagnet/normal metal interface or within the ferromagnet, in a way similar to how the spin torque magnitude is determined. Consequently, the orbital angular momentum torque depends not only on the orbital angular momentum Hall conductivity and the orbital Rashba-Edelstein effect, but also on the orbital angular momentum relaxation processes. Theoretical calculations predict large orbital angular momentum Hall conductivities in various materials[27,45], driven by the orbital–lattice coupling (see Box 1). This coupling, mediated by crystal fields with energy scales around 1 eV, is exceptionally strong. Given that this coupling facilitates the generation of orbital angular momentum currents, it must also be equally effective at dissipating them efficiently. Importantly the coupling itself cannot create orbital angular momentum — it only enables its exchange between orbital and lattice. The strong dissipation of orbital angular momentum is consistent with the well-known phenomenon of quenching of orbital angular momentum in solids. As a result, substantial non-conservation of orbital angular momentum currents is expected in solids.

Several experiments have reported a long orbital relaxation length[14,15,21,22,28], much longer than the spin relaxation length, which is challenging to reconcile theoretically. As mentioned above, the crystal field coupling (~ 1 eV), which governs orbital relaxation, is much stronger than the spin–orbit coupling (10 ~ 100 meV) responsible for spin relaxation. In this context, the experimental observations of long-range orbital transport call for further theoretical development. Two conflicting theories have emerged related to this issue. First-principles calculation proposes long-range orbital torques in ferromagnets, attributing it to the physics of hotspots—specific locations in momentum space in the band structure where nearly degenerate orbital bands exist[46]. In contrast, another first-principles calculation predicts an extremely short orbital diffusion length in normal metals[18]. Because there is no clear reason why orbital relaxation should differ substantially between ferromagnets and normal metals, this discrepancy leaves the orbital relaxation process an unresolved issue. From a practical perspective a shorter orbital relaxation length is preferable, as torque efficiency is proportional to $[1 - \exp(-d/\lambda)]$, where d and λ are the thickness and the orbital diffusion length of normal metal, respectively.

Understanding the mechanisms behind orbital relaxation is crucial for advancing our knowledge of orbital transport in the presence of strong crystal field coupling.

Opportunities and challenges for applications

Similar to the spin–orbit torque, the orbital torque has several potential applications, including MRAM, oscillators, random number generators, logic devices, and terahertz emitters. We focus primarily on the application to MRAM devices and discuss the issues faced by conventional spin–orbit torque, the advantages the orbital torque could provide, and the challenges the orbital torque should overcome.

Box 2 illustrates the key requirements for MRAM applications, along with a schematic of a three-terminal magnetic tunnel junction device array, where both spin–orbit torques and orbital torques can be used for writing operation. The W/CoFeB/MgO system, exhibiting a large current-induced torque due to the substantial spin Hall effect of W[47], reasonably meets the requirements, being employed in the prototypes of spin–orbit torque MRAM[6,7]. This type of material system, which typically has relatively high resistivity, however, presents an inherent trade-off between achieving low write current and maintaining low channel resistance. This challenge has motivated the development of other material systems as well as the exploration of alternative driving mechanisms that can deliver higher torque generation efficiency with lower resistance. Various unconventional physical mechanisms for current-induced torque generation, *e.g.*, spin–momentum locking at the surface or bulk of topological insulators or Weyl semimetals, anomalous Hall effect-induced spin current, spin-splitter torque of altermagnets, and magnon-mediated spin–orbit torque, have been extensively studied in material systems beyond the spin Hall effect in 5d heavy metals such as W. However, it remains challenging to satisfy all the requirements shown in Box 2 simultaneously.

Given these circumstances, orbital torque could emerge as a potential alternative driving mechanism due to several favourable characteristics. For example, unlike spin-based mechanisms, the generation and accumulation of orbital angular momentum do not rely on the spin–orbit coupling. This allows for the use of light metals such as Ti, V, and Cr, which typically exhibit much smaller resistivity than W. Additionally, these materials are generally compatible with standard integration process, potentially fulfilling the requirements.

However, the use of orbital torque also presents some specific challenges. The first issue is to increase the magnitude of generated torque relative to the current density, often quantified by a dimensionless parameter $\xi = 2eH_{\mathrm{eff}}M_{\mathrm{S}}t/\hbar J$ (where e is the elementary charge, H_{eff} represents effective field of anti-damping torque, M_{S} is the saturation magnetization, t is the thickness of ferromagnetic layer, $\hbar$ *is* Dirac constant and J is the current density), which corresponds to the effective spin Hall angle when the torque originates from the spin Hall effect. To date, the reported ξ of the orbital torque is up to around 0.4[48]. However, values at least a factor 2 larger are required to achieve satisfactorily low write current and high endurance. The second challenge is the generation of a substantial orbital torque in systems that are compatible with high tunnelling magnetoresistance. Although considerable orbital torques have been observed with ferromagnetic materials with large spin–orbit coupling, such as Ni and Ni–Fe[14,49] or in stacks including high spin–orbit coupling nonmagnetic layers such as Pt[14,17] and Tb[15], these systems are generally incompatible with high tunnelling magnetoresistance. Achieving substantial orbital torque in body centred cubic ferromagnets such as CoFeB is desirable so that coherent tunnelling of MgO barrier is harnessed. Ferromagnets with large spin–orbit coupling generally have a large damping constant and often require special seed layer, posing a challenge for applications. Third challenge is that although experimental studies have reported considerably large thicknesses for both the nonmagnetic and ferromagnetic layers where strong orbital torque emerges, these thicknesses need to be reduced for applications. This can be achieved by shortening the orbital angular momentum diffusion length to meet the low write-current requirement. Addressing these challenges through material engineering will be essential for the successful implementation of MRAMs based on orbital torque.

As an effort towards MRAM applications, several studies have been carried out. For example, orbital torque-induced switching was investigated in devices featuring a 100-nm ferromagnetic dot with a perpendicular easy axis, showing 50% reduction of switching power compared to spin–orbit torque devices using Pt[48]. A comparison between representative spin–orbit torque and orbital torque-dominant systems —W/CoFeB/MgO and Cr/CoFeB/MgO, respectively—has been performed, quantitatively revealing both the aforementioned opportunities and challenges of devices leveraging the orbital torque[50]. Beyond memory applications, the ability to generate large angular momentum has been utilized for terahertz emission[21,51] . Orbitronics also shows promise for unconventional computing[34] underscoring the broad impact of this field.

Outlook

Orbitronics is particularly attractive because orbital texture exists even in the absence of spin–orbit coupling. This allows for the use of light, abundant, inexpensive and environmentally non-hazardous materials for applications. Although solid evidence for the importance of orbital effects has been established both experimentally and theoretically, the specific processes involved in their generation are not well understood. This includes strong material dependence of orbital angular momentum generation, its long-distance transport through and across interfaces between different materials, the conversion of orbital angular momentum to spin angular momentum and enhancement of torques and other orbitronic effects in two-dimensional materials. In addition, the sensitivity of orbital angular momentum to chemical and crystal environments suggests that many kinds of orbitronics effects can be tuned by a variety of means such as crystal structure and interface engineering. Also, the orbital angular momentum is not dissipated by Gilbert damping in the same manner as spin and is expected to be much less sensitive to magnetic perturbations, making it potentially more robust. Finally, orbital angular momentum of electrons can be potentially coupled with and transduced into that of various quasiparticles such as photons and phonons, offering promises to explore new directions in condensed-matter physics through integration with photonics, phononics and others.

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Competing Interests

The authors declare no competing interests.

BOX 1 Orbital angular momentum generation from momentum-space orbital texture

The orbital Hall effect arises from momentum-space orbital texture (in short, orbital texture)[8,10], where the orbital refers to a linear combination of real orbitals, which do not carry orbital angular momentum. These real orbitals are described by operators of even-order symmetrized products of the orbital angular momentum operator L[8,52]. For *p*-orbitals, for example, the operators are described by $\{L_i, L_j\}$, the anticommutation of L_i and L_j.

Importantly, orbital textures exist even in systems that preserve both time-reversal and inversion symmetries, making its presence general. For such systems, the Hamiltonian for *p*-orbitals is[8]:

$$\mathcal{H} = Ak^2 + \sum_{i,j=x,y,z} B_{ij}\{k_i, k_j\}\{L_i, L_j\}, \tag{1}$$

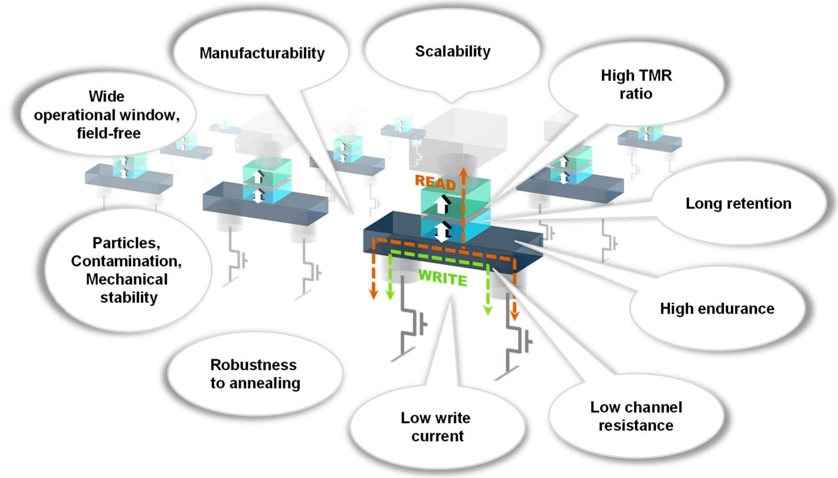
where A, B_{ij} are material constants and k is the crystal momentum. Assuming $B_{ij} = B$, which is a reasonable approximation near the Γ point, the second term of Eq. (1) simplifies to $B(\mathbf{L}\cdot\mathbf{k})^2$ [Ref. [8]], clearly illustrating the momentum-dependent texture of $\mathbf{L}^2$, meaning the orbital texture.

When an electric field is applied, it induces the dynamics of $\{L_i, L_j\}$ [Ref. [52]]:

$$\frac{d\{L_i, L_j\}}{dt} = \frac{[\{L_i, L_j\},\ \mathcal{H}]}{i\hbar} = \sum_l c_{ijl} L_l, \tag{2}$$

where $(i, j, l) = (x, y, z)$ and c_{ijl} is a material-dependent coefficient. This $\{L_i, L_j\}$ dynamics creats L_l (orbital angular momentum), which is the underlying origin of the orbital Hall effect.

BOX 2 Requirements on three-terminal magnetic tunnel junction devices for non-volatile memory applications.



The three-terminal magnetic tunnel junction devices illustrated here have separated write and read current paths (shown by the dashed green and orange lines respectively), allowing for higher speed operation than the two-terminal counterpart used in spin-transfer torque-MRAMs. Several requirements that will need to be satisfied simultaneously for practical applications are indicated in the schematic.

High tunneling magnetoresistance (TMR) ratio is necessary for stable read operation and requires a material system compatible with coherent tunnelling such as CoFeB/MgO. A long retention for stable data storage requires sufficiently high magnetic anisotropy energy of the free layer. Materials with long retention capability are also beneficial for the write operation with low error rate. High endurance of the write current path is necessary to replace semiconductor working memories. This requires the channel material generating torque upon a write current application to have sufficient durability against electromigration, an effect to degrade the quality of electrodes due to the momentum transfer of conduction electrons. Low channel resistance is necessary for low-voltage operations, ideally lower than about 0.1 V. A low write current, roughly lower than 100 μA allows for low-power operation and small cell (transistor) size, which requires a material system generating large torque with respect to the applied current. Robustness to annealing is necessary for the formation of interconnects and process of packaging, where high-temperature annealing typically at 400ºC is conducted. Negligible contaminant particles and atoms, as well as high mechanical stability, are a general requirement for the integration process. A wide operational window ensuring device functionality over a wide range is required in terms of temperature, magnetic field and other environmental factors. Magnetic field-free operation is of course necessary. The manufacturability represents that the stack can be formed on amorphous substrates such as Si-O and Si-N, stack can be easily etched with sufficient process margin, and the properties should not essentially change with patterning and encapsulation processes. The device needs to be scalable, meaning that the favourable properties are maintained or improved with the miniaturization of devices in order to be integrated into cutting-edge semiconductor integrated-circuits.

References

1 Hirohata, A. *et al.* Review on spintronics: Principles and device applications. *Journal of Magnetism and Magnetic Materials* **509**, 166711 (2020). https://doi.org/https://doi.org/10.1016/j.jmmm.2020.166711

2 Brataas, A., Kent, A. D. & Ohno, H. Current-induced torques in magnetic materials. *Nat. Mater.* **11**, 372–381 (2012). https://doi.org/10.1038/nmat3311

3 Manchon, A. *et al.* Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems. *Rev. Mod. Phys.* **91** (2019). https://doi.org/10.1103/RevModPhys.91.035004

4 Shao, Q. *et al.* Roadmap of Spin–Orbit Torques. *IEEE Trans. Magn.* **57**, 1–39 (2021). https://doi.org/10.1109/tmag.2021.3078583

5 Jungwirth, T., Marti, X., Wadley, P. & Wunderlich, J. Antiferromagnetic spintronics. *Nat. Nanotechnol.* **11**, 231–241 (2016). https://doi.org/10.1038/nnano.2016.18

6 Natsui, M. *et al.* Dual-Port SOT-MRAM Achieving 90-MHz Read and 60-MHz Write Operations Under Field-Assistance-Free Condition. *IEEE J. Sol.-Sta. Cir.* **56**, 1116–1128 (2021). https://doi.org/10.1109/jssc.2020.3039800

7 Song, M. Y. *et al.* in *2022 IEEE Symposium on VLSI Technology and Circuits (VLSI Technology and Circuits).* 377–378.

8 Bernevig, B. A., Hughes, T. L. & Zhang, S.-C. Orbitronics: The Intrinsic Orbital Current in p-Doped Silicon. *Phys. Rev. Lett.* **95**, 066601 (2005). https://doi.org/10.1103/PhysRevLett.95.066601

9 Kontani, H., Tanaka, T., Hirashima, D. S., Yamada, K. & Inoue, J. Giant Orbital Hall Effect in Transition Metals: Origin of Large Spin and Anomalous Hall Effects. *Phys. Rev. Lett.* **102**, 016601 (2009). https://doi.org/10.1103/PhysRevLett.102.016601

10 Go, D., Jo, D., Kim, C. & Lee, H.-W. Intrinsic Spin and Orbital Hall Effects from Orbital Texture. *Phys. Rev. Lett.* **121**, 086602 (2018). https://doi.org/10.1103/PhysRevLett.121.086602

11 Park, S. R., Kim, C. H., Yu, J., Han, J. H. & Kim, C. Orbital-Angular-Momentum Based Origin of Rashba-Type Surface Band Splitting. *Phys. Rev. Lett.* **107**, 156803 (2011). https://doi.org/10.1103/PhysRevLett.107.156803

12 Salemi, L., Berritta, M., Nandy, A. K. & Oppeneer, P. M. Orbitally dominated Rashba-Edelstein effect in noncentrosymmetric antiferromagnets. *Nat. Commun.* **10**, 5381 (2019). https://doi.org/10.1038/s41467-019-13367-z

13 Kim, J. *et al.* Nontrivial torque generation by orbital angular momentum injection in ferromagnetic-metal/$¥mathrm{Cu}/{¥mathrm{Al}}_{2}{¥mathrm{O}}_{3}$ trilayers. *Physical Review B* **103**, L020407 (2021). https://doi.org/10.1103/PhysRevB.103.L020407

14 Bose, A. *et al.* Detection of long-range orbital-Hall torques. *Physical Review B* **107**, 134423 (2023). https://doi.org/10.1103/PhysRevB.107.134423

15 Sala, G. & Gambardella, P. Giant orbital Hall effect and orbital-to-spin conversion in $3d$, $5d$, and $4f$ metallic heterostructures. *Phys. Rev. Res.* **4**, 033037 (2022). https://doi.org/10.1103/PhysRevResearch.4.033037

16 Idrobo, J. C. *et al.* Direct observation of nanometer-scale orbital angular momentum accumulation. arXiv:2403.09269 (2024). <https://arxiv.org/abs/2403.09269>.

17 Lee, S. *et al.* Efficient conversion of orbital Hall current to spin current for spin-orbit torque switching. *Commun. Phys.* **4**, 234 (2021). https://doi.org/10.1038/s42005-021-00737-7

18 Rang, M. & Kelly, P. J. Orbital relaxation length from first-principles scattering calculations. *Physical Review B* **109**, 214427 (2024). https://doi.org/10.1103/PhysRevB.109.214427

19 Ding, S. *et al.* Observation of the Orbital Rashba-Edelstein Magnetoresistance. *Phys. Rev. Lett.* **128**, 067201 (2022). https://doi.org/10.1103/PhysRevLett.128.067201

20 Hayashi, H., Go, D., Haku, S., Mokrousov, Y. & Ando, K. Observation of orbital pumping. *Nature Electronics* **7**, 646–652 (2024). https://doi.org/10.1038/s41928-024-01193-1

21 Seifert, T. S. *et al.* Time-domain observation of ballistic orbital-angular-momentum currents with giant relaxation length in tungsten. *Nat. Nanotechnol.* **18**, 1132–1138 (2023). https://doi.org/10.1038/s41565-023-01470-8

22 Choi, Y.-G. *et al.* Observation of the orbital Hall effect in a light metal Ti. *Nature* **619**, 52–56 (2023). https://doi.org/10.1038/s41586-023-06101-9

23 Lyalin, I., Alikhah, S., Berritta, M., Oppeneer, P. M. & Kawakami, R. K. Magneto-Optical Detection of the Orbital Hall Effect in Chromium. *Phys. Rev. Lett.* **131**, 156702 (2023). https://doi.org/10.1103/PhysRevLett.131.156702

24 Sala, G., Wang, H., Legrand, W. & Gambardella, P. Orbital Hanle Magnetoresistance in a $3d$ Transition Metal. *Phys. Rev. Lett.* **131**, 156703 (2023). https://doi.org/10.1103/PhysRevLett.131.156703

25 Ding, S. *et al.* Harnessing Orbital-to-Spin Conversion of Interfacial Orbital Currents for Efficient Spin-Orbit Torques. *Phys. Rev. Lett.* **125**, 177201 (2020). https://doi.org/10.1103/PhysRevLett.125.177201

26 Kim, J. *et al.* Oxide layer dependent orbital torque efficiency in ferromagnet/Cu/oxide heterostructures. *Physical Review Materials* **7**, L111401 (2023). https://doi.org/10.1103/PhysRevMaterials.7.L111401

27 Salemi, L. & Oppeneer, P. M. First-principles theory of intrinsic spin and orbital Hall and Nernst effects in metallic monoatomic crystals. *Physical Review Materials* **6**, 095001 (2022). https://doi.org/10.1103/PhysRevMaterials.6.095001

28 Hayashi, H. *et al.* Observation of long-range orbital transport and giant orbital torque. *Commun. Phys.* **6**, 32 (2023). https://doi.org/10.1038/s42005-023-01139-7

29 Ding, S., Kang, M.-G., Legrand, W. & Gambardella, P. Orbital Torque in Rare-Earth Transition-Metal Ferrimagnets. *Phys. Rev. Lett.* **132**, 236702 (2024). https://doi.org/10.1103/PhysRevLett.132.236702

30 Fukunaga, R., Haku, S., Gao, T., Hayashi, H. & Ando, K. Impact of crystallinity on orbital torque generation in ferromagnets. *Physical Review B* **109**, 144412 (2024). https://doi.org/10.1103/PhysRevB.109.144412

31 Gao, T. *et al.* Control of dynamic orbital response in ferromagnets via crystal symmetry. *Nature Physics* **20**, 1896–1903 (2024). https://doi.org/10.1038/s41567-024-02648-0

32 Zheng, Z. *et al.* Effective electrical manipulation of a topological antiferromagnet by orbital torques. *Nat. Commun.* **15**, 745 (2024). https://doi.org/10.1038/s41467-024-45109-1

33 Li, D. *et al.* Room-temperature van der Waals magnetoresistive memories with data writing by orbital current in the Weyl semimetal $¥mathrm{TaIrT}{¥mathrm{e}}_{4}$. *Physical Review B* **110**, 035423 (2024). https://doi.org/10.1103/PhysRevB.110.035423

34 Zhao, Q. *et al.* Efficient Charge-to-Orbit Current Conversion for Orbital Torque Based Artificial Neurons and Synapses. *Advanced Electronic Materials* **11**, 2400721 https://doi.org/https://doi.org/10.1002/aelm.202400721

35 Gao, W. *et al*. Nonlocal electrical detection of reciprocal orbital Edelstein effect. *Nat. Commun.* **16**, 6380 (2025). https://doi.org/10.1038/s41467-025-61602-7

36 Mendoza-Rodarte, J. A., Cosset-Chéneau, M., van Wees, B. J. & Guimarães, M. H. D. Efficient Magnon Injection and Detection via the Orbital Rashba-Edelstein Effect. *Phys. Rev. Lett.* **132**, 226704 (2024). https://doi.org/10.1103/PhysRevLett.132.226704

37 Ledesma-Martin, J. O. *et al.* Nonreciprocity in Magnon Mediated Charge-Spin-Orbital Current Interconversion. *Nano Letters* **25**, 3247–3252 (2025). https://doi.org/10.1021/acs.nanolett.4c06056

38 Costa, M. *et al.* Connecting Higher-Order Topology with the Orbital Hall Effect in Monolayers of Transition Metal Dichalcogenides. *Phys. Rev. Lett.* **130**, 116204 (2023). https://doi.org/10.1103/PhysRevLett.130.116204

39 Ji, S., Quan, C., Yao, R., Yang, J. & Li, X. a. Reversal of orbital Hall conductivity and emergence of tunable topological quantum states in orbital Hall insulators. *Physical Review B* **109**, 155407 (2024). https://doi.org/10.1103/PhysRevB.109.155407

40 Zeer, M. *et al.* Spin and orbital transport in rare-earth dichalcogenides: The case of ${¥mathrm{EuS}}_{2}$. *Physical Review Materials* **6**, 074004 (2022). https://doi.org/10.1103/PhysRevMaterials.6.074004

41 Xiao, D., Liu, G.-B., Feng, W., Xu, X. & Yao, W. Coupled

Spin and Valley Physics in Monolayers of ${¥mathrm{MoS}}_{2}$ and Other Group-VI Dichalcogenides. *Phys. Rev. Lett.* **108**, 196802 (2012). https://doi.org/10.1103/PhysRevLett.108.196802

42 Cysne, T. P. *et al.* Disentangling Orbital and Valley Hall Effects in Bilayers of Transition Metal Dichalcogenides. *Phys. Rev. Lett.* **126**, 056601 (2021). https://doi.org/10.1103/PhysRevLett.126.056601

43 Saunderson, T. G., Go, D., Blügel, S., Kläui, M. & Mokrousov, Y. Hidden interplay of current-induced spin and orbital torques in bulk ${¥mathrm{Fe}}_{3}{¥mathrm{GeTe}}_{2}$. *Phys. Rev. Res.* **4**, L042022 (2022). https://doi.org/10.1103/PhysRevResearch.4.L042022

44 Go, D. & Lee, H.-W. Orbital torque: Torque generation by orbital current injection. *Phys. Rev. Res.* **2**, 013177 (2020). https://doi.org/10.1103/PhysRevResearch.2.013177

45 Jo, D., Go, D. & Lee, H.-W. Gigantic intrinsic orbital Hall effects in weakly spin-orbit coupled metals. *Physical Review B* **98**, 214405 (2018). https://doi.org/10.1103/PhysRevB.98.214405

46 Go, D. *et al.* Long-Range Orbital Torque by Momentum-Space Hotspots. *Phys. Rev. Lett.* **130**, 246701 (2023). https://doi.org/10.1103/PhysRevLett.130.246701

47 Pai, C.-F. *et al.* Spin transfer torque devices utilizing the giant spin Hall effect of tungsten. *Appl. Phys. Lett.* **101**, 122404 (2012). https://doi.org/10.1063/1.4753947

48 Gupta, R. *et al.* Harnessing orbital Hall effect in spin-orbit torque MRAM. *Nat. Commun.* **16**, 130 (2025). https://doi.org/10.1038/s41467-024-55437-x

49 Lee, D. *et al.* Orbital torque in magnetic bilayers. *Nat. Commun.* **12**, 6710 (2021). https://doi.org/10.1038/s41467-021-26650-9

50 Chiba, S., Marui, Y., Ohno, H. & Fukami, S. Comparative Study of Current-Induced Torque in Cr/CoFeB/MgO and W/CoFeB/MgO. *Nano Letters* **24**, 14028–14033 (2024). https://doi.org/10.1021/acs.nanolett.4c03809

51 Liu, Y. *et al.* Efficient Orbitronic Terahertz Emission Based on CoPt Alloy. *Advanced Materials* **36**, 2404174 (2024). https://doi.org/https://doi.org/10.1002/adma.202404174

52 Han, S., Lee, H.-W. & Kim, K.-W. Orbital Dynamics in Centrosymmetric Systems. *Phys. Rev. Lett.* **128**, 176601 (2022). https://doi.org/10.1103/PhysRevLett.128.176601

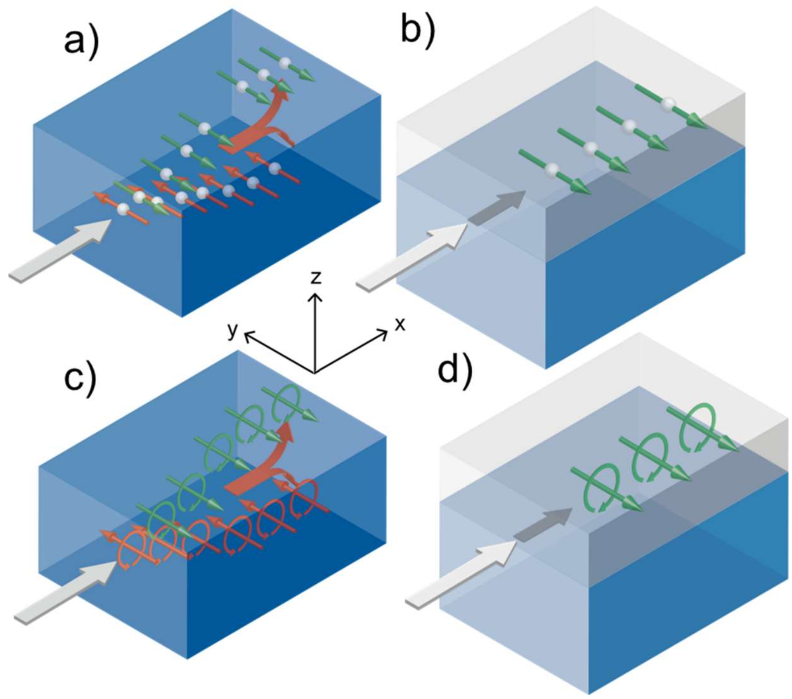


Figure 1: Schematic depictions of the spin-orbit torque and orbital torque mechanisms. (a) The spin Hall effect converts a charge current (grey arrow) into a transverse spin current and (c) the equivalent process of the orbital Hall effect generates a transverse orbital angular momentum current. The corresponding mechanism to (b) the Rashba-Edelstein effect that converts a charge current into a non-equilibrium spin density is (d) the orbital Rashba-Edelstein effect where a non-equilibrium orbital angular momentum density is generated at the interface between a non-magnetic material (blue) and for example, a ferromagnet (grey)

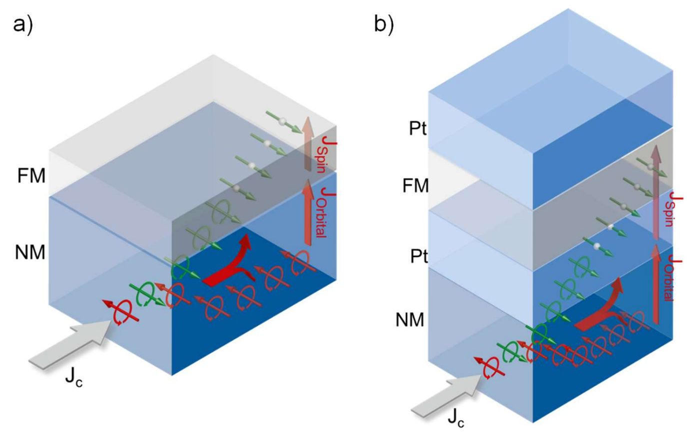


Figure 2: Schematic of the concept of orbital torques in a multilayer. a) In a heterostructure made of a non-magnetic (NM) and a ferromagnetic (FM) materials, a charge current J_c is converted into an orbital current. The transverse orbital current $J_{Orbital}$ diffuses into the ferromagnet and is converted to a spin current J_{Spin} that acts as a torque on the magnetization in the ferromagnet. The material-dependent efficiency of the $J_{Orbital} \rightarrow J_{Spin}$ conversion underlies the strong dependence of the torques on the ferromagnetic material, which is a signature of orbital torques. (b) To enhance the efficiency of the orbital to spin current conversion, an additional strong spin-orbit coupling material, such as Pt can be inserted as a conversion layer between the non-magnetic material (NM) and the ferromagnet (FM). This enables the efficient conversion $J_{Orbital} \rightarrow J_{Spin}$. A second Pt layer can be added on top to compensate for spin current generated by the spin Hall effect in the Pt layer allowing for an easier identification of orbitronic effects.