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This Special Topic collection is focused on the fast-growing field of electronic materials and structures in which spin and charge can be converted from one to the other through microscopic physical mechanisms intrinsic to these materials. Spin-charge interconversion is of great interest for spintronics¹—the emerging field of research which exploits the electron's spin degree of freedom apart from its charge for information processing, storage, and sensing, with potential to outperform semiconductor devices for some tasks and enable post-Moore's law technology.² The operation principle of spintronics is based on the efficient control of magnetization in nanomagnets by spin currents representing the flow of a spin angular momentum. In a spin-valve configuration (i.e., ferromagnetic layer/nonmagnetic spacer layer/ferromagnetic layer structures), the spin-polarized charge current injected from one ferromagnetic layer and flowing perpendicular to its plane passes to the other ferromagnetic layer, exerting a spin transfer torque (STT) on its magnetization and eventually resulting in magnetization switching. This mechanism is currently in use for the STT magnetic random access memory (STT-MRAM), which has been successfully manufactured and commercialized by the major semiconductor foundries.³

As an alternative, spin-orbit coupling can generate a pure spin current based on charge-to-spin conversion mechanisms, such as spin-Hall and Rashba-Edelstein effects, a research topic that has become the primary focus of the field of spintronics.⁴ These

mechanisms take place when a current is injected in the plane of magnetic multilayers containing heavy-metal layers with strong spin-orbit coupling or other spin-source materials, leading to the generation of a vertically flowing spin current or a local interfacial spin density that can exert a spin-orbit torque (SOT) on an adjacent free magnetic layer. Compared to the spin-polarized current obtained in spin valves, the pure spin current induced by spin-orbit coupling enables magnetization manipulation in a broader range of magnetically ordered materials, including ferrimagnetic insulators and antiferromagnets. From the device point of view, SOT-based MRAM has the potential for higher efficiency compared to STT-MRAM because in SOT-MRAM, each electron can transfer angular momentum to the magnet many times, rather than just once. In addition, the writing and reading paths are decoupled in SOT-MRAM due to the separation of spin and charge current channels, which gives better device endurance and faster switching speed than STT-MRAM. For the future development of SOT-MRAM with reduced power dissipation, low write latency, and field-free operation, the efficiency of charge-to-spin conversion becomes the key factor.

Among the promising material candidates for efficient spin-charge interconversion, elemental 5d metals such as platinum and tungsten are the current benchmark systems because they exhibit relatively large spin-charge interconversion and are easy to

integrate within CMOS-compatible processes. Meanwhile, the discovery of giant spin–charge interconversion in topological insulators due to the spin–momentum locking effect opens up new avenues for searching for material systems with highly efficient spin–charge interconversion beyond conventional heavy metals. With the intensive investigation of a growing family of different materials systems, substantial spin–charge interconversion has been reported in topological insulators, topological semimetals, Rashba interfaces, transition metal oxides, 2D materials, and noncollinear antiferromagnets, often with unique spin-dependent and symmetry-dependent properties. These emergent materials give rise to new phenomena, such as the voltage-tunable spin–charge interconversion and unconventional spin polarizations, which may eventually lead to new device functionalities with high efficiency.

In this Special Topic, we compile a series of papers to give an overview, highlight recent advances, and indicate new directions in the development of emerging materials for spin–charge interconversion, including discussions of materials synthesis and characterization and predictions of spin-dependent properties.

To study spin–charge interconversion in different material systems, accurate characterization techniques of SOT are important. In the Perspective by Nguyen and Pai,⁵ the authors provide an overview of SOT characterization techniques, and for each technique, they summarize the operation principles, advantages, and shortcomings. They list the challenges to quantify spin–charge interconversion in emerging materials (i.e., topological insulators) due to their imbalanced current distribution at the interface and large thermoelectric effects. The influence of thermoelectric effects on spin–charge conversion measurements is also covered by Yue *et al.*⁶ The authors review recent spin pumping experiments in Bi films and Bi/Ag Rashba interfaces and show that the spin–charge conversion in such systems is negligibly small. Besides quasistatic and microwave measurements, terahertz emission spectroscopy can be another powerful tool to study spin–charge interconversion with high time resolution. Cheng *et al.*⁷ review terahertz emission experiments in an extensive variety of materials and heterostructures. The advantages and future perspectives of spintronic terahertz emitters are also discussed.

Another Research Update in the area of spin–charge interconversion characterization by Dey *et al.*⁸ focuses on ferromagnetic resonance techniques, especially spin–torque ferromagnetic resonance and spin pumping measurements for spin–charge interconversion in topological insulators interfaced with metallic or insulating ferromagnets. By using spin pumping, He *et al.*⁹ report how different metal insertion layers affect spin–charge conversion by topological insulators, with an enhancement of spin–charge conversion by over 60% with a Ru insertion.

In the Perspective by Han and Liu,¹⁰ experiments on SOT switching of magnetization by topological insulators are extensively reviewed. The authors summarize the spin–charge interconversion efficiency, the critical switching current, and the power consumption in various topological insulator/ferromagnet heterostructures. The prospects for further improvement of the switching efficiency are discussed. In particular, it is proposed to generate an out-of-plane spin polarization using topological insulators with lower symmetry, which can enable a field-free switching of magnets with perpendicular magnetic anisotropy. On this topic, Xie *et al.*¹¹ report the field-free switching of perpendicularly magnetized SrRuO₃

by the out-of-plane spin polarization originated from WTe₂, a transition metal dichalcogenide with the reduced crystal symmetry. Li *et al.*¹² pursue another strategy for broken symmetry by using a wedged structure and demonstrate the field-free switching of perpendicularly magnetized samples.

Spin–charge interconversion in van der Waals materials is reviewed by Galceran *et al.*¹³ with highlights on 2D material synthesis, 2D material-based SOT device fabrication, and the resulting physics. This Special Topic provides a summary of spin–charge interconversion parameters in a vast variety of van der Waals heterostructures, including transition metal dichalcogenides and 2D ferromagnets. The challenges of using van der Waals heterostructures for SOT devices are described. Anadón *et al.*¹⁴ report the effect of a graphene monolayer insertion within a heavy-metal/ferromagnet bilayer on the spin transport and spin–charge interconversion.

In the material system of oxides, Chen and Yi¹⁵ review recent theoretical and experimental efforts on 4d/5d transition metal oxides with large spin–orbit coupling for spin–charge interconversion. The progress in using three representative materials, IrO₂, SrIrO₃, and SrRuO₃, with large spin–Hall angles is summarized. Other possible candidate 4d/5d transition metal oxides with exotic electronic properties are also surveyed. In a different aspect, ferroelectricity in oxides can be used to control the spin-dependent transport. This topic is reviewed by Fang *et al.*¹⁶ with their emphasis on ferroelectric control of spin–charge interconversion and magnetoelectric spin–orbit devices.

Two papers explore the potential of using the non-collinear antiferromagnetic material Mn₃Sn for spin–charge interconversion. Yu *et al.*¹⁷ report the spin–charge interconversion efficiency of Mn₃Sn to be two times of that of the heavy-metal Ta in YIG/Mn₃Sn heterostructures. Cheng *et al.*¹⁸ show that in Mn₃Sn/Pt bilayers, the spin–orbit coupling in Pt and the Dzyaloshinskii–Moriya interaction at the interface help improve the onset temperature of the topological Hall effect in Mn₃Sn.

Several papers deal with the challenge of enhancing the spin–charge interconversion and reducing the switching current in the heavy-metal system. Shi *et al.*¹⁹ investigate spin–charge interconversion in PtRh as a function of Rh fraction and find an optimized PtRh composition for the enhanced spin–Hall conductivity. Chi *et al.*²⁰ focus on another alloy system, PtBi, and study the dependence on the PtBi composition of the spin–Hall conductivity and the magnetic anisotropy of the Co overlayer. Lau *et al.*²¹ report a strong crystallinity dependence of spin–charge interconversion in PtAl alloys, in which the switching power consumption of the textured film can be significantly reduced compared to that of the polycrystalline film. Xue *et al.*²² show a large enhancement of the SOT efficiency by the insertion of a thin layer of Co with perpendicular anisotropy in a heavy-metal/ferromagnet heterostructure. The temperature dependence of the current induced SOT switching in heavy-metal/ferrimagnetic insulator heterostructures is studied by Ren *et al.*²³ The authors report the role of current induced Joule heating on the switching behavior of SOT devices.

In the field of superconducting spintronics, Yang *et al.*²⁴ review recent progress in the study of spin transport and spin supercurrents in superconductor/ferromagnet hybrid systems. The potential of superconducting spin currents and the fundamental challenges for both experiments and theory are discussed.

Finally, besides the conventional inverse spin-Hall effect configuration, the theory of generating a charge current vortex by localized spin current injection at a point contact is proposed by Fujimoto *et al.*²⁵ The authors analyze the spatial profile of the current that can act as a probe for the electronic structure of spin-orbit coupled systems.

Overall, this Special Topic reviews recent progress in the field of spin-charge interconversion, highlighting advances in emergent materials, material-based solutions, and challenges in the realization of SOT devices. We hope this Special Topic will inspire readers who are interested in this fast-growing field, stimulate new materials discovery with potential for spin-charge interconversion, and facilitate new developments to utilize spin-charge interconversion in spintronics.

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