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Spintronic devices for energy-efficient data storage and energy harvesting

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The current data revolution has, in part, been enabled by decades of research into magnetism and spin phenomena. For example, milestones such as the observation of giant magnetoresistance, and the resulting development of the spin-valve read head, continue to motivate device research. However, the ever-growing need for higher data processing speeds and larger data storage capabilities has caused a significant increase in energy consumption and environmental concerns. Ongoing research and development in spintronics should therefore reduce energy consumption while increasing information processing capabilities. Here, we provide an overview of the current status of research and technology developments in data storage and spin-mediated energy harvesting in relation to energy-efficient technologies. We give our perspective on the advantages and outstanding issues for various data-storage concepts, and energy conversion mechanisms enabled by spin.

Data storage capacity in our society has drastically increased so to keep up with ever-increasing data generation. Simultaneously, memory devices have reduced in size. This increase in data storage capacity at reduced dimensions in part facilitates the carrying of information such as images and music in mobile phones, and allows exchanging them online. Part of this technological advancement has been enabled by manipulating the spin degree of freedom of electrons in electronics, and this field of research and technology is therefore often called spintronics. A crucial milestone in the development of sprintronics was the discovery of giant magnetoresistance[1,2]. The giant magnetoresistance mechanism enabled replacing the core operation concept of memory devices, the collective magnetisation of localized spins in ferromagnetic layers, with electronic conduction depending on the electron spin state. Digital information is recorded following a binary state of 0 and 1 formed by two different spin configurations.

However, this increase in data storage capacity has come with a significant increase in energy consumption. Cloud data storage and sharing information online are powered by big data centres, which in 2010 were estimated to consume 1–1.5% of the global electricity usage[3,4], with predictions of increment from 3 to 13% consumption by 2030, depending on the measures taken

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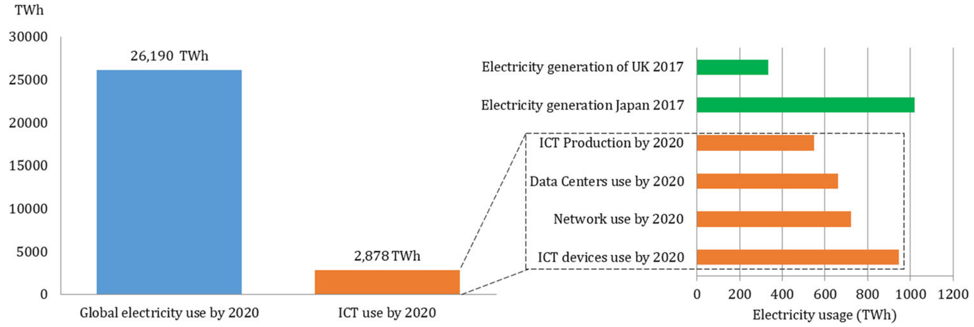

Fig. 1 Electricity consumption of the information and communication technology (ICT) sector. Expected consumption of electricity by 2020 of the ICT sector accounts for 11% of the Global use of electricity (data from ref. [5]). For comparison, the electricity usage of Data Centres and Network exceeds the electricity generation of United Kingdom in 2017, and the ICT device usage is comparable to the electricity generation of Japan in 2017 (data from ref. [6]).

to reduce electricity expenditure[5]. For example, electricity consumption associated with the information and communication sector is predicted to represent 11% of the global electricity consumption in 2020 (see Fig. 1)[5]. Electrical usage by data centres globally in 2020 might also be larger than electricity generated in the United Kingdom in 2017, and the global use of electricity by ICT devices in 2020 (such as mobile phones, computers and smart televisions) may be comparable to electricity generated by Japan in 2017[6]. Although ICT can help to reduce the global consumption of energy by aiding the development of more efficient industrial processes, the undeniable increasing demand for ICTs must be dealt with carefully. In a typical data centre, cooling infrastructure accounts for about (50%) of energy consumption, while servers and storage require about (26%) combined[7]. Beyond the challenge of energy supply for the ICT sector, there are also increasing concerns regarding the predicted environmental impact, such as the greenhouse gas emissions[8]. In this Review we discuss on-going efforts towards energy-efficient spintronic devices related to ICTs, incoming technologies, and open questions. We start our discussion with a summary of progress in non-volatile memory devices and logic operational mechanisms that aim to mimicking brain-like operations. Then, we describe efforts towards spin-mediated energy interconversion between electricity, heat, sound, vibration and light. We conclude with a discussion of the outstanding challenges for spintronics-based devices for energy-efficient data storage and energy harvesting.

Data storage from memory to logic devices

Magnetic random-access memory to racetrack memory. Arguably, nowadays, storage of digital information is mostly accomplished by flash memories, dynamic random-access memory (DRAM), and hard disk drives (HDD). Regarding HDD, the most critical issue is its operation dependence on the mechanical movement of its two main components, a storage disk, and a read/write head. The mechanical movement reduces reliability, slows down operation and increases power consumption. In contrast, the DRAM consists of non-moving parts, allowing for faster sequential read/write operations (HDD ~ 100 MB/s, DRAM ~ 500 MB/s) for moving large files, and larger input/output operations per second (HDD ~ 100, DRAM ~ 100,000) for better multitasking performance at lower power consumption.

However, in spite of its virtue, technologists are attempting to find a substitute for the DRAM due to its volatile nature, meaning that when the devices are powered off the capacitor leaks the electrical charge information. Flash memory does not contain capacitors, giving it a non-volatile nature, however, with the caveat of limited endurance. Hence, we look towards spintronic concepts and devices as promising alternatives since they solely show a non-volatile characteristics with an infinite endurance[9].

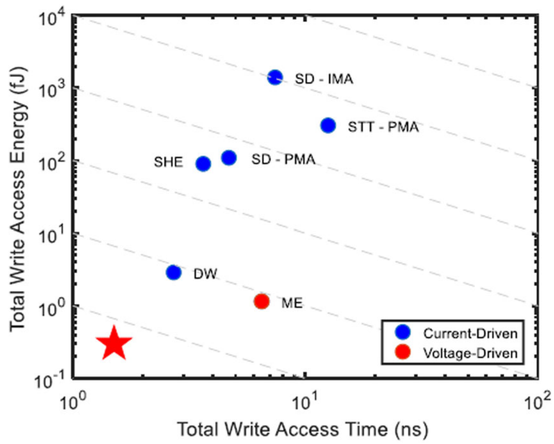

Fig. 2 Performance estimates, writing energy vs time, for various spintronic memory cells. SD: spin diffusion, STT: spin-transfer torque, SHE: spin Hall effect, DW: domain wall motion, ME: magnetoelectric switching, IMA: in-plane magnetic anisotropy, PMA: perpendicular magnetic anisotropy. A red star designates the preferred corner (2017 IEEE, reprinted, with permission from ref. [10]).

Benchmarks of performance of spin-based/magnetic memories (non-volatile) with high endurance[10] capture the most salient trends relating to the write energy and time costs on the underlying physical phenomena (Fig. 2). In-plane magnetic anisotropy devices are both slower and less energy efficient than perpendicular magnetic anisotropy. Spin-diffusion writing and spin Hall effect (SHE) memory are more energy efficient because they require a smaller voltage due to a lower resistance writing path. Also they are faster, because it is easier to create overdrive relative to the critical current. The SHE label here is not limited to the bulk spin–orbit effects, but rather encompasses all sorts of spin–orbit torque. Domain wall (DW) memories are expected to switch at an even smaller driving current and are thus estimated to operate with quite low energy. Bear in mind that the domain wall devices considered here incorporate a domain wall motion within a single cell of the random-access memory (RAM). Racetrack memory, in which a domain wall moves over multiple positions of bits, is not RAM, but rather a sequential storage device.

Magnetoelectric (ME) memories have the lowest energy cost of the considered types, since they are relying on charging a capacitor rather than current-generated torque. The value of the ME field may result in somewhat slower switching speed. The caveat here is that only spin-transfer torque (STT) memories have been commercialised. The rest are at various stages of research and development, with ME memories being the least mature.

Interestingly, most of the research and developments towards new memories are based on magnetic tunnel junction (MTJ) structures. It is illustrative to recall its properties, recent research advancements and its open challenges. In the MTJ structure, an oxide tunnelling barrier is sandwiched by two ferromagnetic layers named a free layer and a pinned layer. Here only the free layer is allowed to switch its magnetisation direction. The data reading is accomplished by tunneling magnetoresistance (TMR), which depends on the magnetisation configuration of the two layers; low (high) resistance when the parallel (anti-parallel) magnetisation state is prepared[11–13]. Particularly, the TMR is remarkably enhanced after employing the MgO as a tunneling barrier[14,15].

For data writing, the magnetisation switching is achieved via spin-transfer torque, where a spin-polarised current from the pinned layer is injected into the free layer[16–18]. In 2010, a MTJ constituted by perpendicularly aligned ferromagnetic layers was successfully achieved[19]. This result allowed enhancements of spatial scalability and thermal stability for the MTJ structures. However, despite the remarkable enhancement of performance, the MTJ structure has an inherent drawback on the writing process. The MTJ needs an incubation time during the writing process to create a magnetic configuration for the spin-transfer torque action. Since the thermal agitation determines the incubation, it encounters difficulty for lowering the writing time below ten nanoseconds (ns). The relatively slow writing time eventually creates an obstacle to achieve low operating power. This issue can be overcome by reconsidering the design from perpendicularly arranged magnetisation[20]. However, the development of STT-MRAM for ultrafast applications remains problematic. Fast switching requires large current through the thin oxide barrier of a MTJ, which leads to reliability issues and accelerated aging of the barrier. An alternative solution to these issues may be found using spin–orbit torque (SOT) switching mechanism via spin conversion[21].

A conversion between spin and charge (spin conversion) induced by spin–orbit coupling (SOC) provides a cornerstone for a novel type of Spintronic devices, so-called Spin-orbitronics[22]. In early days, the spin Hall effect, which initiates an opposite spin-dependent trajectory for opposite spin states, was suggested for bulk systems[23]. Pioneering experimental works succeeded to observe the spin conversion by spin Hall effect in GaAs[24] or Pt[25]. The utility of the spin Hall effect for spin manipulation was verified in magnetic heterostructures induced by efficient STT from heavy materials such as Pt, W or Ta[26,27]. Alternatively, interfaces with spin textures offer an additional spin conversion system. The interfaces such as topological insulators[28,29] and Rashba interfaces[30] show equal or better spin conversion efficiency than the SHE in bulk systems. Spin conversion enabled a significant advancement in the design and operation mechanism of MTJ structures. In MTJ structures under spin conversion, the charge current does not need to penetrate a high-resistive tunneling barrier, in contrast to the conventional MTJ devices. Therefore, magnetisation switching can take place in sub-ns, allowing ultrafast writing under low incident power[21].

Despite the advantage of the spin conversion MTJ, we still encounter challenging issues: assistant field for the magnetisation switching and the relatively large size of devices. Remarkably, recent studies suggest alternatives without the need for the assistant field by utilising the spin-polarised current generated from two dimensional systems[31] or two-terminal spin–orbit torque memory configurations[32]. In addition, lowering the switching energy is actively pursued by spin conversion. A recent report showed that hybridizing voltage-controlled magnetisation anisotropy is a powerful method for reducing the switching power[33]. Efficient spin conversion in a highly conductive material[34–36] and enhanced spin torque efficiency using ferrimagnets[37] also provides intriguing new directions for spin manipulation at low power consumption.

An alternative proposal to push further the data density while preserving thermal stability, it is to look at domain walls (DW) in nanowires arranged in 3-dimensions, instead of the 2-dimensional operation in current MRAM technology. This novel concept is known as racetrack memory[38]. In racetrack memory, the current-induced domain wall motion records a memory bit that corresponds to a magnetic domain. To achieve an efficient racetrack memory, the domain wall should move fast with a small incident current. A recent report shows that merging the DMI (Dzyaloshinskii–Moriya interaction) mechanism with an anti-ferromagnetic configuration enhances the velocity of domain wall motion tremendously[39]. Despite these encouraging advancements, the stochastic nature[40] of the perpendicularly aligned magnetic layers under a low driving force due to the creep motion[41] is an inherent obstacle to realise the racetrack memory. An alternative may be found via the recent reported fast domain wall motion in ferrimagnets[42]. In addition, with a similar operating mechanism, magnetic Skyrmions formed by DMI is arising as a very attractive direction due to the less demanding critical energy for motion and other intriguing functionalities such as spin Hall-like driving dynamics[43].

Spin logic device to neuromorphic computation

The performance of logic circuits encompasses the same trends as memories plus some additional considerations (see Fig. 3). Field-effect transistors (FET) are in general faster than spintronic logic, because charging the capacitors in the gate is faster than the

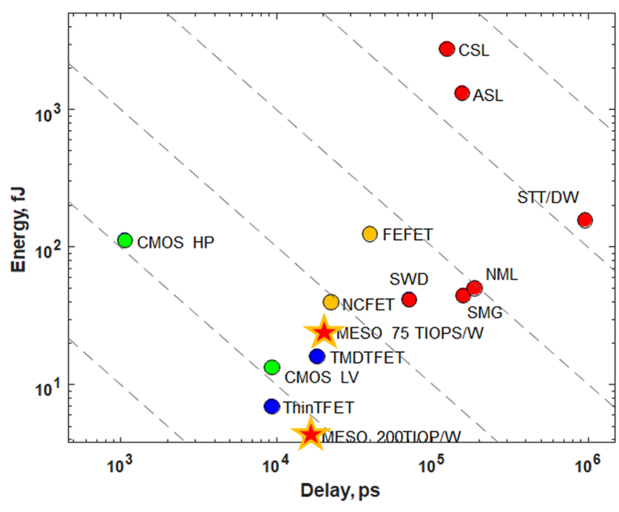

Fig. 3 Benchmarks of performance, switching energy vs. delay in one clock cycle of a 32-bit arithmetic logic unit (ALU). CMOS HP: high-performance transistors from the 2018 process generation (0.73 V supply), CMOS LV: low voltage (0.3 V) transistors, FEFET: ferroelectric field-effect transistors, NCFET: negative capacitance FET, STT/DW: spin-transfer-torque domain-wall device, ASL: all-spin logic, CSL: charge-spin logic, NML: nanomagnetic logic, SMG: spin majority gate, magnetoelectric, SWD: spin wave device, with magnetoelectric transduction, ThinTFET: 2D-material vertical tunnel FET, TMDTFET: transition-metal dichalcogenide tunnel FET, MESO: magneto-electric spin–orbit logic, two versions with different material parameters resulting in different computing throughput per dissipated power. Adapted from ref. 74 by permission from Springer Nature, ©2019.

precession of magnetisation. However, spintronic logic is non-volatile, in essence combining logic with embedded memory, while most of FET are volatile. Ferroelectric FET is a special case: it is non-volatile, but limited by the intrinsic time of ferroelectric switching. Magnetoelectric logic, and especially MESO (magneto-electric spin–orbit logic), is predicted to reach extremely low operation energies.

The energy and delay of operation are the linked quantities relevant to a user: dissipated power and computing throughput, i.e., the number of operations performed on a chip. In previous decades, computing performance was limited by a single-core and was synonymous with the speed of operation. In the last decade, computing is limited by the dissipated power, in three aspects: (1) the ability to remove dissipated heat from a chip; (2) the amount of energy supplied by a battery, especially in mobile devices; (3) the power available to a system with multiple multi-core chips mostly doing parallel processing. The last consideration is especially applicable to the usage case of a data centre (a server farm). To quantify the above considerations, a limit of power density, aka cap is applied to estimate the circuit performance (Fig. 4). The above obstacles are tackled by embracing green, i.e., energy-efficient computing. In that thrust, only the energy, not the speed of operation is the most valued figure of merit.

Following this bench-marking, we overview the developments since 2010. A report in 2010 by Behin-Aein et al.[44] proposed the development of an all-spin logic device based on a non-local spin valve, where two nanomagnets are interconnected by a nano-channel with a distance shorter than its spin-diffusion length. A non-local spin valve generates pure spin current without electrical charge flowing in the nano-channel, the spin current contains information of the magnetisation of the input nanomagnet and transfers the information to the output nanomagnet via spin-transfer torque. The functionality of non-local spin-valve structures has been widely applied for research of spin properties of diverse materials[45]; however, it does not fulfil the essential characteristics of a logic device: nonlinearity, concatenability, feedback suppression, gain and Boolean operations. The nonlinearity and concatenability are achieved by making identical input and output, which facilitates connectivity, scalability and induces bistability. Feedback suppression means a diode-like behaviour, where the input modifies the output but not vice versa. If input and output are similar, the feedback suppression can be controlled by the interfaces; each nanomagnet has two interfaces, one input with a tunneling barrier to facilitate spin injection and one output with low resistance to suppress reflection. Ensuring gain implies that the energy use in the output operation should not exclusively come from the input. The output operation requires energy equal or larger than its energy barrier. This energy can be supplied by an external voltage to place the output nanomagnet in a neutral position; then, the input information locates the nanomagnet in either of its two lower states of minimal energy. Binary operation can be achieved by superposition of spin currents from two inputs with opposite magnetisation, the polarity of the gate voltage in the inputs dictates the construction of a AND/OR operation or NAND/NOR, and extra fix input nanomagnet can flip the order of the inputs from AND/OR to OR/AND.

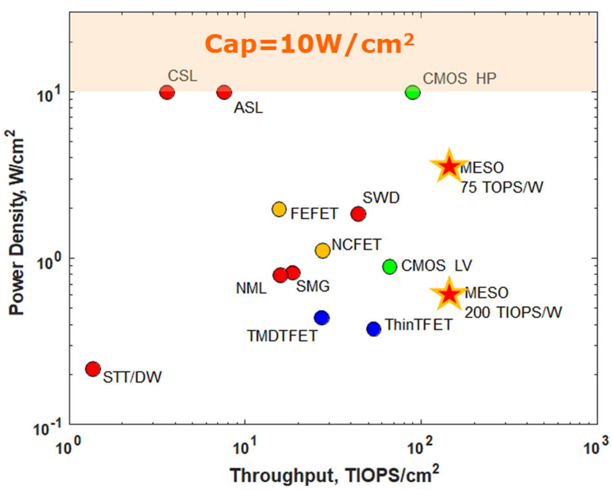

Fig. 4 Dissipated power density vs. computing throughput (in tera-integer-operations per second). The device labels are as in Fig. 3. The power density is capped at 10 W/cm^2. If the estimated power density exceeds it, the passive area is inserted, and throughput is reduced. Adapted from ref. [74] by permission from Springer Nature, ©2019.

The proposal of an all-spin logic device based on the spin-transfer torque mechanism was indeed catalytic; nevertheless, its application is strongly withheld by its gain dependence to applied external voltage and bias magnetic field. An alternative came with the so-called spin torque nano-oscillators (STNOs)[46]. The STNO structure consists of an asymmetric MTJ; with a ferromagnetic layer exchange coupled with antiferromagnetic pinning layer with in-plane easy axis, and a ferromagnetic free layer with interfacial perpendicular anisotropy. A d.c. current flowing from the pinned layer to free layer drives coherent precession of the free layer magnetisation. The STNO can be driven with low charge currents (10^8 A/m^2) without bias magnetic field or voltage, with output powers of tens of nW in MHz to GHz frequencies, suitable for high-speed digital systems[47]. These characteristics allow reducing the size of the devices down to tens of nanometres.

Moreover, in a network of compact arrays of STNOs, the STNOs are very sensitive to the dynamics of neighbouring oscillators, in close analogy to the coupling mechanism in neuron networks[48]. Interestingly, a recent report demonstrated the feasibility of vowel recognition by synchronizing only four STNOs[49]. Neuromorphic computing based on STNOs offers a platform with a similar geometry to the already developed STT-MRAM integrated with CMOS technology, with great potential for fabrication of high-density networks of STNOs. However, in spite of being a very promising route, the demonstrated energy consumption is limited to pico-Joules and optimisation has to be done to reach the atto-Joule operation of brain-like activity. Also, so far, the neuromorphic computing based on STNOs require a training process via an online learning algorithm, which has to be optimised and perhaps in the future substituted by an offline self-learning mechanism.

Neuromorphic circuits[50] are drastically different than the typical Boolean circuits. For one, they are much tightly integrated with the memory. As such, the speed of their operation is not limited by the von Neumann bottleneck: transfer of data between the memory and the arithmetic processor. Both the device type and the type of neural network architecture determine the performance (see Fig. 5). The magnetoelectric devices still result in the lowest energy among neural networks of the same type. The analogue ferroelectric device proves to be the fastest. Other types of spin devices have higher energy or longer time of operation. The digital CMOS implementation losses out on both time and energy, because non-linear functions of neurons multiplied by the number of bits require multiple transistors.

For a time-perspective, we present a synthesis of major achievements towards non-volatile storage devices and promising candidates for near-future developments in Fig. 6.

Spin-dependent energy harvesting

Although, spin-mediated energy harvesting by itself is far from the state of the art efficiencies of energy harvesting without involvement of spin, it is certainly intriguing to explore the fundamentals and prospects of application of the energy harvesting with participation of the spin degree of freedom. Various efforts in this direction have already achieved fascinating results of spin conversion among diverse energy types we experience every day, such as heat, light, vibrations, sound and electricity[22]. Schematic in Fig. 7 shows spin conversion energy powering servers in data centres. In the following we describe the main advancements in these topics and their limitations.

Spin thermoelectric generation

The TE (thermoelectric) physics is based on the unbalance of electron and holes at the Fermi energy in metals. A temperature difference in the metal creates a heat current carried by both hot electrons and holes. When the electron current is larger than the hole current, it results in a net charge current in opposite direction to the heat flow. Interestingly, the thermal energy in the form of heat gradients can also couple to gradients of angular momentum or spin currents. Research on this coupling has already demonstrated the spin Seebeck/Peltier effect, anomalous Nernst effect, TE Hall conversions and spin-transfer torque mediated by thermal conductance. For deeper insight of the Physics behind these spin TE phenomena we refer the reader to a specialised review in the topic in ref. [51]. Although, there are indeed important applications for domain wall motion and spin-transfer torque by heat currents[52], we focus our discussion in the TE power conversion efficiency based on spin phenomena.

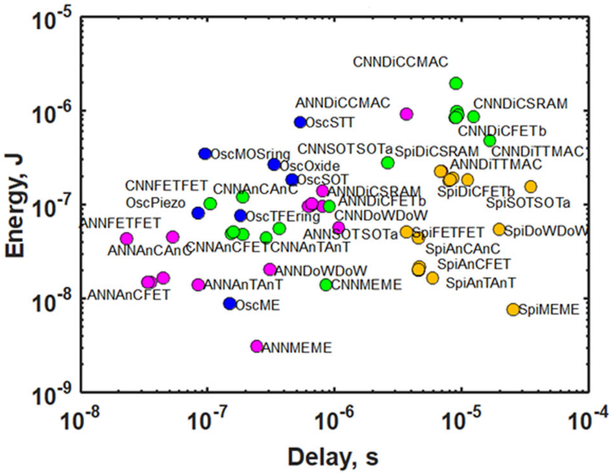

Fig. 5 Energy vs. delay for one inference in a circuit implementing the LeNet convolutional neural network. Artificial neural networks (ANN, magenta dots), cellular neural networks (CNN, green dots), spiking neural networks (SNN, Spi (gold dots)), oscillator neural networks (ONN, Osc (blue dots)). Labels for device-architecture combinations include DiC: digital CMOS, AnC: analogue CMOS, FET: ferroelectric transistor, STT: spin-transfer torque, SOT: spin-orbit torque, DoW: domain wall motion, ME: magnetoelectric switching. Reproduced from ref. [50].

The figure of merit of a TE power device is given by the dimensionless factor $ZT = \frac{\sigma S^2 T}{\kappa}$, where electrical conductivity is σ, Seebeck coefficient S, thermal conductivity κ and temperature T. We first focus on the spin TE conversion at magnetic insulator/nonmagnetic metal bilayers via longitudinal spin Seebeck effect (SSE) and spin–orbit coupling (SOC). This device structure has the advantage of a simplified fabrication and TE conversion directly proportional to the device area, suitable for large TE power generators[53]. In contrast, enhancements in charge based TEs are bound to parallel arrangements of individual modules, as schematically shown in Fig. 8a, adapted from ref. [54]. Moreover, utilising a magnetic insulator allows to separate the contributions of the thermal conductivity of the magnetic material κ and the electrical conductivity of the metal layer for spin to charge conversion mechanism σ. Tuning these two parameters independently facilitates the design for maximum TE power conversion by careful selection of materials. Although, the ZT factors of spin-based TEs ($ZT \sim 0$–0.1) are still below to the state-of-the-art values for charge based TEs ($ZT \sim 1$–3), these encouraging features of spin TEs allow for new device architectures and larger collective efficiencies.

Another intriguing option for spin thermoelectric generation is the Anomalous Nernst effect (ANE). A crucial difference between SSE and the anomalous Nernst effect (ANE) is the direction of the output current generated. As schematically shown in Fig. 8b, the ANE output is perpendicular to the temperature gradient, while the SSE output is parallel (longitudinal) to the temperature gradient. Since the generated output current creates additional thermal instabilities, it ultimately sets a lower limit of conversion for the SSE when compare with ANE (see Fig. 8c)[55]. Additional to this, while the Peltier heat current in a SSE device carries heat from the hot to the cold side of the device, decreasing the overall efficiency. On the other hand, in a ANE the Ettingshausen heat current carries heat from cold to hot side, increasing the overall efficiency. In ferromagnets, the level of ANE signal conversion is directly proportional to the applied external magnetic field. Interestingly, recently it was observed that ANE signals obtained in antiferromagnets (AF) are within the level of the best reported values for ferromagnets but under lower applied magnetic fields, see Fig. 8d adapted from ref. [56].

Spin thermoelectric effects can be also benefited by the redustribution of density states and lowering of Fermi energy as consequence of the Rashba[57]. Engineering of this side effect has not been explored and is poorly understood.

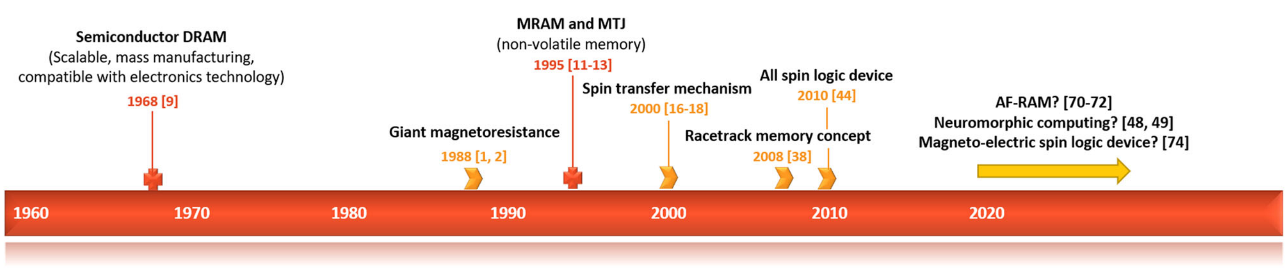

Fig. 6 Timeline of major research and technology milestones in data storage devices. We present a synthesis of major achievements towards non-volatile energy-efficient storage devices. Cross symbols indicate a commercialise technology and chevron arrows indicate a research concept.

Spin photovoltaics

The perspectives for developments of a commercial spin-polarised photovoltaic cell are still limited at this time. The major limitations are the necessity of circular polarisation of light and the specific range of semiconductor materials for absorption of light at energies with relevance for solar cell developments. One alternative is the fabrication of a p-n semiconductor junction where one of the layers is a ferromagnet[58]. Under non-polarised illumination internal build-up electric field separates the holes and electrons creating a non-polarised photocurrent, however, in the presence of a ferromagnetic layer a preferential spin tunneling takes place and as a result preferential spin-polarised electrons are extracted with no need for circular polarisation. Also, broadband light excitation in the solar cell spectrum at room temperature has been recently reported, where the spin current is generated in a magnetic insulator/nonmagnetic metal bilayer, and then the spin to charge current conversion is done by inverse spin Hall effect[59]. Although, these results represent important advancement of Spintronic research in photovoltaics, the projected efficiencies are still far from the state-of-art efficiencies of solar cell modules, with reported efficiencies around 30% for GaAs and Si-based cells[60].

Perhaps more intriguing, it is the advent of a new family of materials, perovskites; the outstanding improvements of the conversion efficiencies in structures based on perovskites such as $FAPbI_3$ ($FA{=}CH(NH_2)_2^{+}$), MAPbI ($MA{=}CH_3NH_3^{+}$) and PbI_2, already place them in close proximity to those efficiencies achieved by GaAs and Si, see Fig. 9 adapted from data in ref. [60]. These lead-based organometal halide perovskites posses very strong spin–orbit coupling (SOC). It has been already demonstrated that SOC in these compounds induces strong modifications in the electronic structure, band-gap tuning and carrier

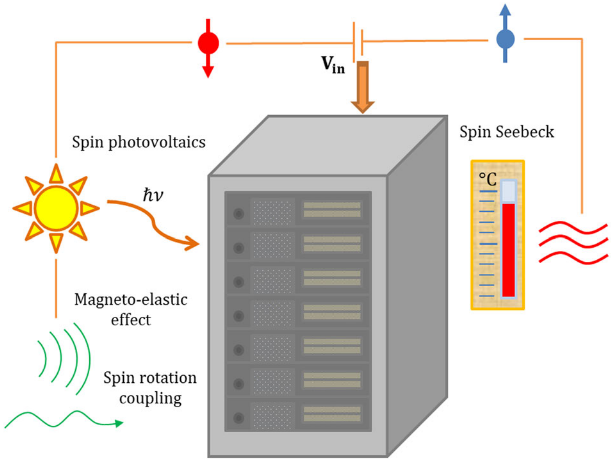

Fig. 7 Energy interconversion rectified by the electron spin. Diverse spin phenomena can act as energy interconversion rectifiers among energy sources such as heat (spin Seebeck effect), light (spin photovoltaics), sounds and vibrations (magnetoelastic effect and spin–rotation coupling). The collected energy can feedback power to servers in data centres.

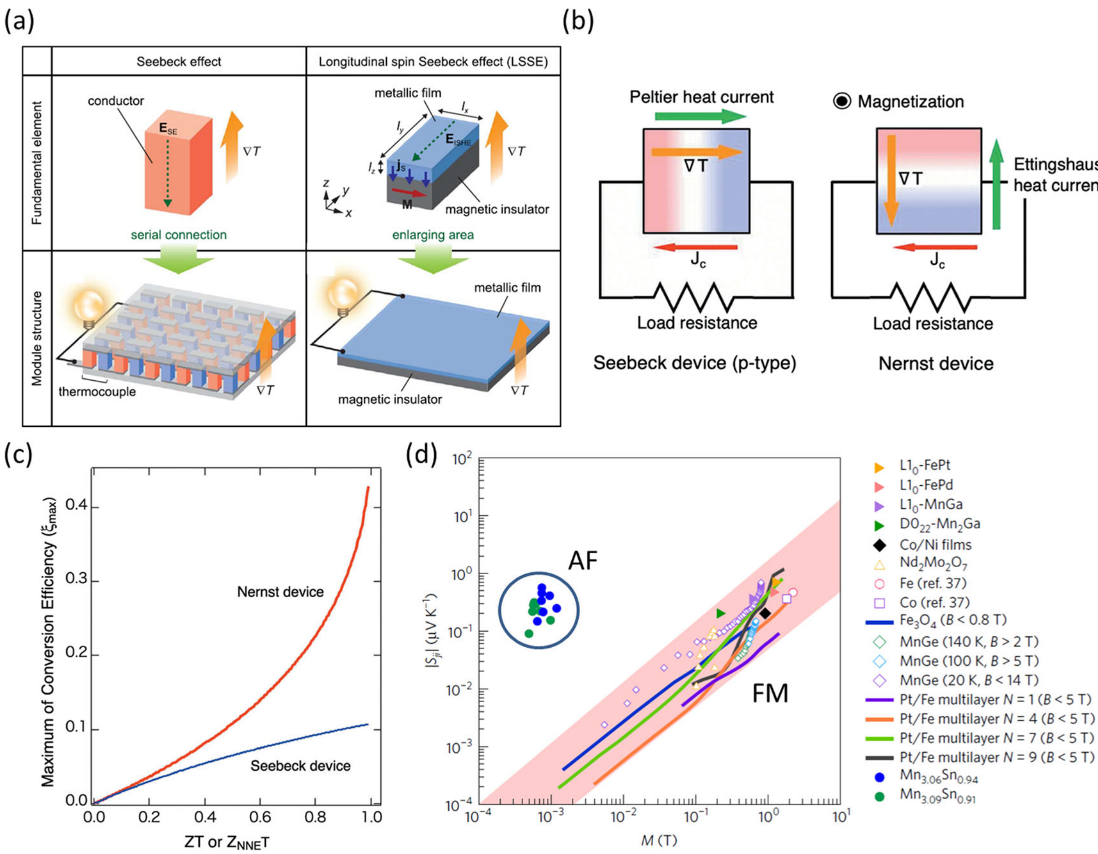

Fig. 8 Spin thermoelectric generation mechanism. a Comparison between fundamental element of a Seebeck effect device and longitudinal spin Seebeck effect device, and their corresponding module architectures (2016 IEEE, reprinted, with permission from ref. [54]). **b**, **c** Show the schematics of the thermoelectric conversion mechanism for a Seebeck device and a Nernst effect device, and comparison of the maximum conversion efficiencies ζ_{max} under a temperature gradient $\Delta T = 300$ K (figures reproduced from ref. [55]). **d** Comparison of Nersnt signals S_{ji} for ferromagnets (FM) and the non-collinear antiferromagnet (AF) Mn_3Sn. Adapted from ref. [56] by permission from Springer Nature, ©2017.

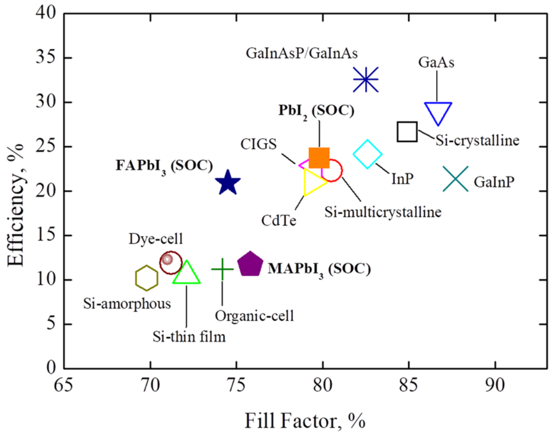

Fig. 9 Efficiencies of solar cells tested under one sun terrestial irradiance AM1.5 spectrum (1000 W/m^2) at 25°. We summarise the relation of best reported efficiencies (*y*-axis) vs fill factor (*x*-axis) which gives a relation of the maximum power achived by the cell. Solid symbols show the lead-based organometal halide perovskites which posses strong spin–orbit coupling (SOC). The plotted data are based on tables reported in ref. [60].

lifetime enhacements[61–63]. However, there is a crucial limitation, the stability of perovskites in ambient conditions. Recent reports demonstrated that hybrid organic/inorganic perovskite structures are a promising route to overcome the stability issues[64]. Interestingly, these hybrid structures also possess relatively large Rashba spin splitting allowing for Spintronic applications[65]. Further understanding of the role played by the SOC in perovskites may help to improve their optical absorption and stability, opening opportunities for spin photovoltaic applications[66].

Spin mechanics

Phonons, the quantum description of lattice vibrations, can be coupled to the electron spin and magnons, allowing the generation of spin current from energy taken from mechanical vibrations and sound. Although, the fundamental relation of magnetic and elastic energies, the magnetoelastic effect is a well-known concept, the generation of spin current by magnetoelastic coupling has not been reported until recently. Ferromagnetic resonance is induced by microwave surface acoustic waves injecting spin current into a nonmagnetic layer to finally convert the spin current into charge current via inverse spin Hall effect or inverse Edelstein effect[67,68]. Perhaps even more intriguing, it is the proposal for generation of spin currents in the absence of magnetic materials or external magnetic fields. This novel proposal relies on the spin–rotation coupling based on the direct transfer of angular momentum from mechanical energy and the electron spins bound to the atomic lattice[69].

In terms of applications, at the moment it is difficult to estimate the impact of the generation of spin currents via mechanical energy, however, one may think of energy-efficient sensors based on surface acoustic waves, a well-developed sensing technology, where collection of otherwise wasted energy could be converted to charge current by magnetoelastic coupling and SOC. Moreover, the spin–rotation coupling does not require SOC or magnetic fields to generate spin currents, opening a new sub-field of Spintronics research and route for developments of novel devices.

Outlook

Great advancement has been achieved in the last 10 years or so, towards energy-efficient storage devices and energy harvesting with spin information. However, many interesting challenges remain open. In terms of storage information the challenge of increasing data density and speed operation is pursued by domain wall motion in ferromagnetic nanostructures. However, there are two important limits to overcome; first the stray fields can act as disturbance noise for densely packed devices, and second, the so-called Walker-breakdown: a threshold driving force at which the internal magnetisation of the domain wall starts to precess, reaching a limit of the velocity of domain walls.

Different from ferromagnets, the exchange interaction in antiferromagnets protects the domain walls, increasing the Walker-breakdown field to values out of the disturbance zone for applications[70]; therefore, the speed operation limit is set by the magnon velocity (spin wave propagation velocity) itself which reaches values of THz frequencies. Three orders of magnitude larger than ferromagnets. The antiferromagnetic ordering itself also nullifies the stray fields allowing for increase in data density, making antiferromagnets a very attractive platform for device developments[71]. Furthermore, antiferromagnets manifest intriguing spin–orbit phenomena, such as the recently reported magnetic control of spin Hall effect[72], which may facilitate control operations.

The demonstration of neuromorphic computing by coupling of few oscillators opened a new route towards the ultimate limit of energy-efficient data processing in the form of brain-like operation. New challenges may appear as the number of oscillators scale-up, and interactions create complex networks. Few proposals using deep learning in neural networks may be interesting to apply in neuromorphic computing devices[73].

In the full integration for novel CMOS architectures, the combination of magneto-electric control and SOC in topological state of matter may permit to realise the recent Intel proposal of a magneto-electric spin logic device[74].

In terms of energy harvesting with spin information, perhaps the most revolutionary concept in the last years has been the advent of the spin Seebeck effect and anomalous Nernst effect with already on-going commercial thermoelectric device developments. The conversion magnitude of these thermoelectric devices is proportional to the magnetisation in ferromagnets, which may set a limit in device performance. An alternative may be in topological antiferromagnets, although, the magnetisation in antiferromagnets is weak, a recent report showed anomalous Nernst effect three orders of magnitude larger than expected. This unexpected finding has been explained in terms of enhancement of Berry curvature: in electrodynamics, the phase acquired by a vector potential in an adiabatic process. Such enhancement can be realised with the associated chirality of a Weyl point at the Fermi level[56]. Further studies are necessary for better understanding of the thermoelectric effects in topological antiferromagnets and their potential applications.

In photovoltaics, the absence of spatial inversion symmetry inducing spin–orbit coupling and Berry curvature may help to overcome the long-standing ShockleyQueisser limit of conversion: the maximum theoretical photovoltaic conversion efficiency set by radiative recombination. Recent reports showed evidence of this phenomenon by the steady-state photocurrent generation in ferroelectrics and metal halide perovskites[75,76]. As previously exhibited, another consequence of the absence of spatial inversion symmetry is the splitting of spin sub-bands, opening venues for spin photovoltaic conversion mechanisms. Moreover, very recently it has been reported initial evidence of the spin-dependent photovoltaic conversion in metallic interfaces and metallic/oxide interfaces at photon energies where optical absorption is expected to be low[77,78]. The explanation at the moment relies on modifications of the electronic structure due to spin–orbit interaction. More studies towards this direction are needed in novel heterostructures.

The spin conversion of energy from mechanical displacement is a relatively new subject; nonetheless, recent encouraging reports showed the spin hydrodynamic generation by the vorticity in liquid Hg and initial evidence of the spin–rotation coupling in solid nonmagnetic metal/ferromagnetic metal bilayer[79,80]. As next step, it would be desirable to show similar demonstration in non-toxic elements and spin–rotation coupling without magnetic materials to push forward the broad potential for applications.

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Author contributions

Y.O. proposed the content of the paper, contributed to the discussion of all topics and the writing of the paper. K.K. contributed to the research and discussion of all topics in the present review. J.K. contributed to the research and discussion of all topics in the present review. J.P. proposed the content of the paper, contributed to the research and discussion of all topics in the present review and writing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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