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Bridging Performance Gaps: Exploring New Classes of Materials for Future Spintronics Technological Challenges

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Technological challenges, such as insufficient computation power, inefficient data storage, and unsafe communication, may not be tackled by currently utilized semiconductors or superconductors, which are still far from meeting the requirements of quantum-age applications. Spintronics, focused on electron transport phenomena dependent on spin, holds promise as an advanced technology. Nevertheless, most recent quantum technologies adopted by leading businesses and start-ups rely heavily on others, and there is a race to increase the number of qubits to gain a computational advantage. Therefore, it is crucial to consider new classes of materials instead of the conventional ones. Developing high-performance organic spintronics based on new classes of materials, namely, ionic liquids (ILs), liquid and soft crystals, and macroradicals, can support high-speed and low-power computing applications, offering higher spin-relaxation times in the order of microsecond at room temperature. This perspective discusses the key challenges of the currently utilized inorganic semiconductors, small molecules, and π-conjugated polymers. It also discusses how the new classes of organic spintronics can bridge these performance gaps.

1. Introduction

Different materials have been utilized as Quantum bits (Qubits), including defects and impurities in solids, photons, superconducting systems, trapped ions, and spintronics using single-molecule, as well as quantum dots.[1] However, the significance of spintronic materials and devices has grown rapidly over the past decade as they exhibit various spin phenomena, such as spin injection and transport, switching, spin filtering, spin rectification, spin valves, and spin currents.[2] Since the first experimental evidence of room temperature direct spin-polarized injection, spintronics has emerged as a field with the potential to produce the next generation of nanoelectronic devices, which can reduce power consumption and enhance memory and processing capabilities.[3] With their high-performance computation and data storage power, spintronics can help, for instance, gain new insights from massive datasets and safeguard organizations and society. Modern semiconductors do not fulfill the requirements for spintronic technology, including high-speed, high-density, and low-power, since inorganic semiconductors' electron spin relaxation times are in the nanosecond range.[4] The performance of such spintronics highly depends on efficient spin injection, transport, and detection that requires integrating ferromagnetic materials with semiconductors, which is sometimes challenging due to the compatibility between different types of materials.[4a,5]

Inorganic spintronics loses spin information over time due to environmental interactions.[6] In contrast, organic semiconductors offer higher spin-relaxation times, reaching hundreds of microseconds at low temperatures and microseconds at room temperature.[7] Unlike inorganic spintronics, which typically consist of heavy atoms, organic spintronics primarily comprise lighter atoms, such as hydrogen, carbon, nitrogen, and oxygen. Since spin-orbital coupling plays a crucial role in spin relaxation, where its intensity is directly related to the fourth power of the atomic number, organic semiconductors generally exhibit considerably longer spin lifetimes than inorganics.[1h,7,8] Spintronics based on inorganic materials strongly depend on temperature, which can limit its usefulness in practical applications.[9] Due to their composition predominantly involving lighter atoms, organic spintronics show a weakened spin-orbital coupling and a more extended spin lifetime compared to others, rendering them highly appropriate for spintronic applications at room temperature.[10] Small molecules and π-conjugated polymers have not performed well in organic spintronics compared to

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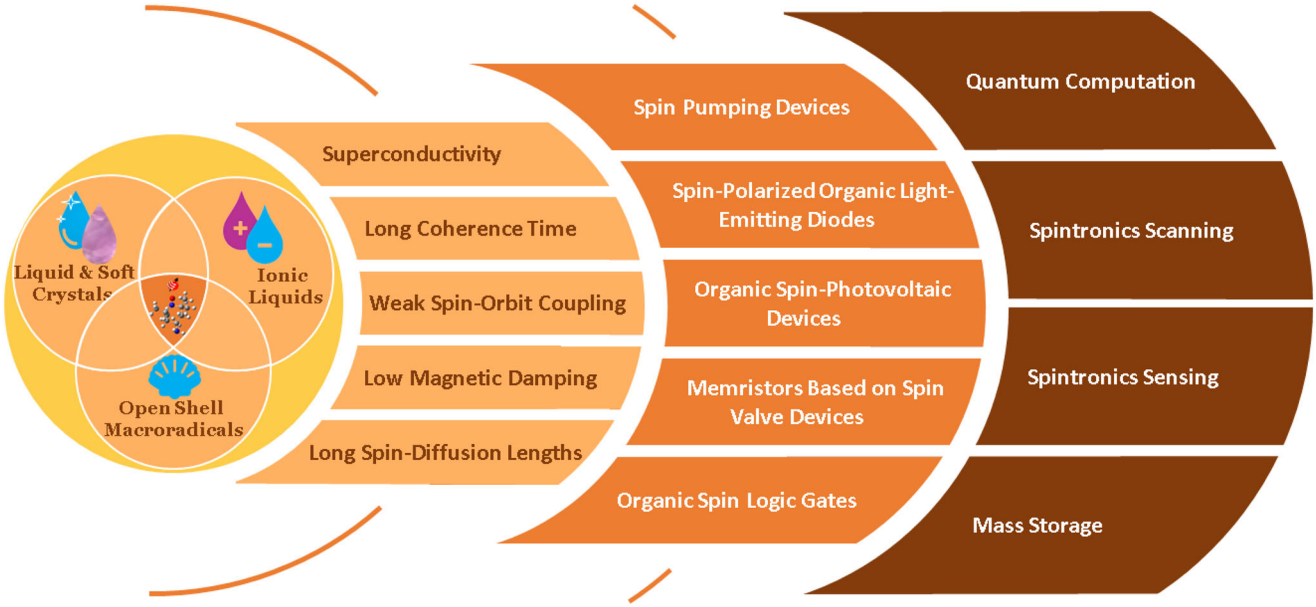

Figure 1. Summary of properties, devices, and applications of organic spintronics based on open-shell macroradical, liquid and soft crystals, and ionic liquids.

organic electronics due to the challenge of achieving a pure spin current.[11] Also, the device-related artifacts can affect their measurement values.[12] Inorganic spintronics requires advanced manufacturing processes to ensure accurate device geometries without impacting material properties, leading to complicated and expensive fabrication techniques.[13] Defects and impurities resulting from fabrication techniques can impact the spin properties of the inorganic spintronics.[14] For instance, recent research showed that epitaxial growth techniques, as an advanced manufacturing process, including molecular beam epitaxy and atomic layer deposition, can create high-quality thin films; still, they need to be further developed to meet the required atomic precision necessary to achieve high-performing spintronics.[15] Scalability is another challenge in current fabrication techniques that are time-consuming and expensive; hence new advanced manufacturing processes, including additive manufacturing such as 3D printing and roll-to-roll processing, can create large-scale spintronics devices.[16] Therefore, there is a great need for novel functional materials demonstrating high-spin polarization, large-orbit coupling, and low magnetic damping.[17] Furthermore, it is crucial to reassess and review current spintronics devices' performance, exploring novel measurement methods, and equally innovate approaches to fabrication and characterization to address current challenges that are the aim of this perspective.

2D materials based on Transition-metal dichalcogenides (TMDs) are fascinating due to their properties spanning different spintronics applications.[18] This material class possesses a considerable spin-orbit splitting, increasing with the metal and chalcogen atom size.[19] Recent studies demonstrated the marvelous induced magnetic moments in 2D TMD materials based on Fe_3GeTe_2, $FePS_3$, and $MnSe_2$ tunable with layer thickness.[20] Others revealed the spin-to-charge conversion based on 2D TMD, covering $NbSe_2$, MoS_2, $MoSe_2$, WS_2, and WSe_2,[20c,21] and spin-transport based on graphene/TMD, CrX_3/TMD.[22] The low Curie temperature (T_c) of these materials presents a significant challenge in utilizing them for practical spintronic devices operating at ambient temperature since the spin transport phenomenon has been demonstrated to be vastly enhanced when the operating temperature approaches Curie's, and decreased elsewhere.[23] Although there are ongoing discussions and debates surrounding spin relaxation mechanisms, addressing the 2D TMD materials' long spin lifetime, scalability, and device design and fabrication remain critical to overcoming the efficient operation of spintronic devices.[22a,24]

Here, we propose organic spintronics based on open-shell macroradical, liquid and soft crystals, and ionic liquids, which show promising magnetic and electrical properties, supporting different applications for spintronic devices. These properties include superconductivity, long coherent time, weak spin-orbit coupling and hyper interaction, and long spin-diffusion lengths, making these devices suitable for quantum computing, mass storage, and spintronics scanning and sensing.[2a,3a,4b,25] **Figure 1** summarizes properties, devices based on different mechanisms (e.g., spin pumping), and applications of organic spintronics based on open-shell macroradical, liquid and soft crystals, and ionic liquids.

2. New Class Materials for Organic Spintronics

Open-shell macroradicals refer to some carbon-based molecules carrying radical groups, making them highly reactive. They have been explored by manipulating their spin states to create new electronic devices with unique properties. In a recent study conducted by Poggini and coworkers,[26] nitronyl nitroxide radicals were utilized to alternate the magneto-transport properties in an organic spin valve, demonstrating a cost-effective wet chemistry-based method for hybrid architectures, paving the way for new molecular spintronics technologies. McGuire and

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coworkers used the redox-active dithiolene ligand radicals as a novel spin host for modular organic electron spin qubits, offering long phase memory times approaching 5.0 microseconds.[27] By altering the metal and ligand components of the molecule, the novel design and fabrication strategy enables the electrical activation of individual modular organic electron spin qubits, allowing the switch between different spin states and supporting entanglement scenarios. Other strategies, such as those elucidated in the research by Wasielewski and Evans, have exhibited the generation and subsequent optical readability of pure high-spin states.[28] Investigations into photoexcited organic chromophore-radical systems, as conducted by Rechirt, have unveiled significant promise for their potential use in molecular spintronics applications.[29] Additionally, Sessoli's employment of chirality-induced spin selectivity has demonstrated its efficiency in spin-specific electron transport.[30] Overall, the use of open-shell macroradicals in spintronics has shown great promise in recent years. Their unique electronic properties make them a promising candidate for numerous spin-based electronic devices.

Ionic liquids are organic salts in the liquid state, consisting of organic cations paired with organic or inorganic anions. They have recently emerged as a promising class of materials for spintronics applications due to their unique properties, especially when synthesized with other materials. Spin crossover (SCO) is one of the most important properties in spintronics based on ionic liquids with great potential in data storage.[31] A new route to the synthesis of magnetically switchable room temperature ionic liquid was reported by Fitzpatrick and coworkers, in which a paramagnetic ionic liquid made of mononuclear iron (III) complex cation, charge-balanced by a dicyanamide anion shows a range of spin states at room temperature.[32] Another important property is spin glass, where glassy magnetic behavior is reported in a wide range of crystalline magnetic materials.[33] In a recent study, Kofu and coworkers reported the spin glass behavior in a structural glass of a magnetic ionic liquid, C4mim$FeCl_4$ (1-butyl-3-methylimidazolium tetrachloroferrate).[34] Neutron Scattering based on a Cold Neutron Disk-Chopper Spectrometer and a near-backscattering Time of Flight (ToF) spectrometer DNA were employed, and collected data were analyzed to obtain the dynamic structure factor $S(Q,\omega)$ utilized along with other items of data to show the boson peak energy. Furthermore, ionic liquids have also been shown to be useful in spin manipulation, which is essential for spin-based logic and memory devices, providing a tuneable spin-orbit coupling. In a study by Akhgar and coworkers, it was demonstrated how ionic liquid was utilized in a gated dielectric at a two-dimensional hole gas to significantly enhance the spin-orbit interaction coupling, resulting in a more efficient spin manipulation.[35] The distinctive properties of ionic liquids make them highly promising for application in spintronics. Nonetheless, additional research is required to fully comprehend the fundamental mechanisms and optimize the efficacy of spintronics devices that utilize ionic liquids.

Liquid crystals are composed of ionic species arranged in a regular crystalline lattice, which provides them with unique properties. Liquid crystals have gained attention following the demonstration of the spin hall effect, a key enabler in the field of spintronics.[8a,36] Lekenta and coworkers demonstrated the control of spin currents by modulating the splitting between transverse electric and magnetic fields in liquid crystals integrated into microcavities.[37] The polarization pattern resulting from the developed converter analogized the spin hall effect in a photonic cavity, making it suitable for spin-based devices that depend on doping a liquid crystal with an emitter. Likewise, Panajotov and coworkers proposed a liquid crystal Spin-polarized Vertical-Cavity Surface-Emitting Lasers (VCSEL) with electro-optically controllable birefringence.[38] The liquid crystal-filled photonic cavity can be utilized in mimicking complex spin manipulation based on the coupling of the spin-orbit interaction by tuning synthetic Hamiltonian consisting of the Rashba-Dresselhaus and Zeeman terms.[39]

Soft crystals are a new material class that can respond to gentle stimuli while maintaining their structural order. They demonstrate noteworthy alterations in their appearance, encompassing their shape, color, and luminescent properties.[40] Vapochromic crystals are soft crystals that change color and/or emission when exposed to certain vapors or gases, exhibiting solid-state spin-switching properties.[41] A study by Kato and coworkers found that a Ni(II)-quinonoid complex demonstrates selective spin-state switching in response to methanol vapor.[42] The switchable paramagnetism property controlled by selective vapors can provide amazing features for storage devices based on spintronics. Yoshida and coworkers synthesized a liquescent Pt(II) complex 2-Cl, showing Thermo- and Mechano-Triggered Luminescence, ON/OFF switching, associated with the phase transition at ambient temperature.[43] Because of the very small Zero-Field Splitting (ZFS) values of the excited triplet sublevels, reflecting the level of the contribution of Pt(II) complexes to the emission state, their emission lifetimes exhibit "purer state emission display only weak temperature dependence. When the ZFS values become larger, causing the temperature dependence, this excited state is mixed with 3MLCT or 3(M+X)LCT states, owing to the spin-orbit coupling. Another class of materials is plastic crystals that pose distinctive ferroelectric properties compared to traditional molecular crystals.[44] These unique properties can be attributed to their inherent characteristics, such as the rotational motion of molecules and phase transitions accompanied by lattice-symmetry alterations.

Moreover, plastic crystals' intrinsic tunable crystal orientation, along with their mechanical properties, make them attractive functional materials for a wide variety of applications. Dragulescu-Andrasi and coworkers demonstrated the plastic crystalline phases based on bistable materials of radical dimerization.[45] Since plastic crystals possess an intermediate phase between liquid and solid, they have a low energy barrier to molecular rotation, allowing each molecule to spin around its center of mass, making it perfect for spintronic applications. Yet, the research area of liquid and soft crystals is still an unexplored frontier, offering a wealth of opportunities for the discovery of new materials; therefore, to establish this emerging field of soft crystals, a multidisciplinary approach that incorporates various domains such as material science, physical chemistry, computational modeling and simulation, material informatics, advanced physical measurements, to name a few, is imperative.

3. Conclusion and Outlook

In summary, It is imperative to discover novel organic materials, rethink several device designs, and experiment with different

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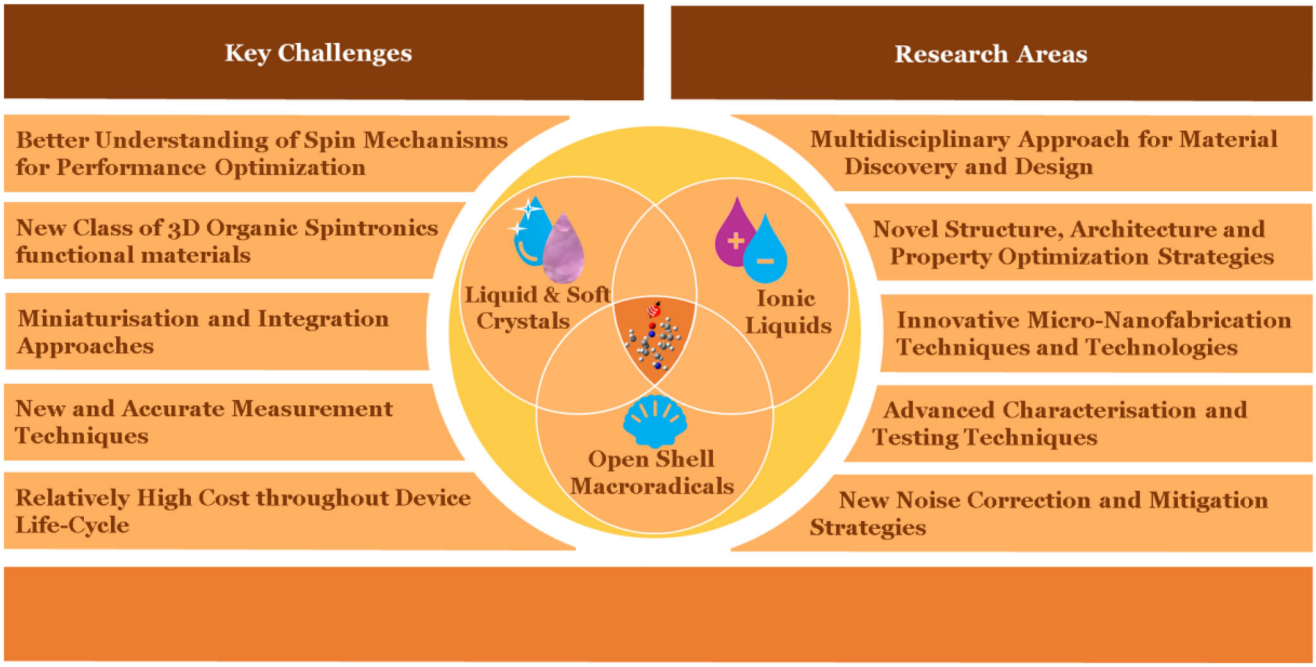

Figure 2. Summary of key challenges and opportunities in organic spintronics future research areas.

measurement approaches to solve current challenges in spintronic materials and devices. Additionally, a better understanding of the spin mechanisms can support performance optimization, for instance, enhancing the charge-to-spin conversion efficiency to fulfill various applications of low-power electronics, high sensitivity, and reduced-temperature dependency. Open shell macroradical, liquid and soft crystals, and ionic liquids can fulfill the tight requirements for the next generation of spintronics devices. In return, these new devices can accelerate the discovery of new materials with even superior properties. Nowadays, accurately representing the quantum mechanical states of moderately sized molecules on classical computers, for example, is challenging, making first-principles calculations for material discovery intractable; computation complexity grows exponentially with the number of simulated particles.[46]

While further development of current micro and nanofabrication approaches and scaling up is necessary to meet the new demands of organic spintronics, there is a high need for innovative methods and techniques to maintain their super properties. Current micro and nanofabrication approaches based on physical and chemical processes, including vacuum evaporation (e.g., electron beam and laser ablation), sputter deposition (e.g., ion beam), thermal growth, and chemical vapor deposition are primarily suitable for inorganic spintronics.[47] Most design and fabrication strategies for organic spintronics aim to protect the spin interface properties; hence, the selection of synthesis and the material design are highly important.[47d,48] Other strategies focus on the emergent interfacial properties, as demonstrated in the novel phenomena and functionalities of the work of Barraud, Raman, Sun, and Hu and coworkers.[10d,49] Some others focus on the bulk properties of the constituent materials, as revealed in the applications of structure-property relationships in the device-performance improvement of the work of Qin, Luo and coworkers.[50]

Nonetheless, these strategies are suitable for hybridized spintronics and functionalized interfaces, with little emphasis on organic spintronics design and fabrication innovation demonstrated elsewhere, including the molecular magnetic and electronic field-induced alignments.[51] Moreover, incorporating sophisticated characterization and material investigation strategies is vital to innovate high-performing functional materials with distinct structures and properties. For instance, investigating the operational effectiveness of newly designed spintronics at lower temperatures and analyzing their structural attributes may necessitate using intricate and costly cryogenic devices and complex characterization and measurement techniques. Another ongoing obstacle is the notably elevated expenses of synthesizing certain materials, such as Ionic Liquids. Likewise, utilizing materials based on hybrid spintronics as Molecular Quantum Bits (MQBs) based on copper (II), vanadium (IV), and chromium (III) can show a long coherence time; still, they need optimization of different materials and measurement setup.[52] For these challenges and alike, we found that adopting various computational modeling and simulation strategies, supporting proper handshaking between nano-micro level-specific approaches, can reduce experimental time and optimize fabrication cost apart from the device's total cost throughout its life cycle.

Significant research is drawn towards 3D spintronics and opto-spintronics implementations for fundamental studies and computing applications. Because its spin mechanism rests on the coupling of photonics and nanomagnetism/spintronics, increasing the lifetime of the photoinduced magnetic state of opto-spintronics at lower temperatures (i.e., $T > 200$ °K) still requires the development of novel functional materials.[53] Furthermore,

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integrating 3D nanomagnets made of high-quality materials into 2D microelectronic circuits poses significant challenges to 3D spintronics implementation, opening the door broadly for innovative fabrication processes and strategies and contributing to overcoming the effects of noise, temperature, and interference on spin coherence and stability.[16a] Similarly, diverse materials have been utilized in the development of spin torque diodes, which can operate without a direct current (DC) bias and have the potential to function as energy harvesters via spincaloritronics or electromagnetic radiation.[54]

Finally, organic spintronics has made significant progress in innovative materials and devices. Though, there is still a considerable distance to cover before they can be widely utilized in industrial applications since this research area is on the verge of a significant breakthrough soon. **Figure 2** summarizes key challenges and opportunities in future research areas.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ahmed Al-Qatatsheh was responsible for conceptualization, visualization, writing the original draft, reviewing, and editing. Saulius Juodkazis and Nishar Hameed reviewed and edited the work. This research received no external funding.

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