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Research Progress on the Spin Interface of Ferromagnetic Electrodes

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Abstract. Organic semiconductors are regarded as ideal material systems for developing the next generation of flexible spintronic devices due to their excellent flexibility, low preparation cost and unique long-spin relaxation characteristics. This paper systematically reviews the significant progress made in the research of FM/OSC spin interfaces in recent years and discusses it from three aspects: material systems, physical mechanisms, and device structures. At the material level, the focus is on the research of the development and application of new two-dimensional ferromagnetic electrodes, high-mobility organic semiconductors, and functional interface modification layers. At the physical mechanism level, key scientific issues such as interface energy level alignment, magnetic proximity effect and spin-related transport were deeply explored; At the device level, the structural innovation and performance improvement strategies of devices such as organic spin valves, magnetic tunnel junctions and spin transistors were elaborated in detail. Current research has achieved remarkable results in improving the room-temperature performance of devices and extending the spin diffusion length. Finally, this paper points out the main challenges that this field will face in its future development, especially the technical bottlenecks in achieving efficient spin injection, remote spin transport, and chip-level scalable fabrication, and looks forward to potential application directions such as flexible storage and neuromorphic computing.

Keywords: Ferromagnetic electrode Organic semiconductor Spin interface Spin injection Magnetoresistive devices Energy level matching

1. Introduction

In the information age, the demand for data storage and processing capabilities is growing exponentially. Traditional silicon-based electronic technology, whose sole information carrier is charge, is gradually approaching its physical limit. At this point, Spintronics aims to utilize the spin degrees of freedom of internal electrons (rather than a single charge) for encoding, information transmission and processing, providing a revolutionary development direction for a new generation of low-power, high-speed and non-volatile information devices [1]. However, traditional inorganic spintronic devices overly rely on expensive single crystal materials and high-temperature preparation processes [2]. Their rigidity also severely limits their application prospects in flexible portable devices. It is precisely for this reason that organic semiconductors (OSCs) are at the center

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of spintronics research due to their unique and attractive physical properties. A new dynamic direction has been initiated, organic spintronics [3,4].

The reason for choosing organic semiconductors lies in their three main advantages. The excellent processability and solubility of OSC enable it to be prepared on large-area flexible substrates through low-cost processes such as printing and coating, which conforms to the development trend of portable electronic products and flexible displays. Secondly, the main components are organic materials and other light elements such as carbon, hydrogen, oxygen and nitrogen. Among them, the spin-orbit coupling (SOC) is extremely low, and the spin relaxation time caused by Hyperfine interaction (HFI) is about microseconds, which is several orders of magnitude higher than that of inorganic semiconductors. This means that the polarization state of the spin can remain in the OSC for a longer time and be transmitted for a longer period, which provides favorable conditions for the processing of spin information and will not be lost. Finally, the key parameters of OSC, such as energy levels, band gaps and mobility, can be chemically modified and trimmed through advanced molecular engineering methods to serve as basic modules, which further provides unlimited possibilities for functional design [1].

The main advantages of organic semiconductors are flexibility, long lifespan and molecular engineering design. The main challenges of ferromagnetic electrode/organic semiconductor (FM/OSC) interfaces include level mismatch, chemical diffusion and spin diffusion. The efficiency of the organic spin device not only depends on the inherent excellent properties of the bone, but also largely on the physical interface between the ferromagnetic electrode (FM) and the organic semiconductor (OSC). However, here it has become the central bottleneck for rotating messages and performance improvement [3]. energy-level mismatch is characterized by the difficulty in perfectly aligning the work function of the metal electrode with the highest occupied molecular orbital (HOMO) or the lowest unoccupied molecular orbital (LUMO) of the OSC, thus forming a higher Schottky barrier rather than an ideal ohmic contact. It seriously hinders the effective injection of spin-polarized carriers. Interfacial reaction and chemical diffusion refer to the fact that in conventional thermal evaporation deposition of metal electrodes, such as Fe and Co, the energy of high-density metal atoms can easily penetrate and spread in the flexible organic layer, causing the chemical reaction to get out of control, forming interfacial defects, trap states and magnetic dead layers. These become powerful spin scattering centers, allowing spin information to undergo decoherence and annihilation upon injection [4]. Conductivity Mismatch is a phenomenon where there is a significant difference in electrical conductivity between metals (which can reach more than ten orders of magnitude), causing the vast majority of spintrons injected at the polarization to be reflected at the interface, thereby resulting in the observation of extremely inefficient spin injection.

Facing these challenges, scholars have gradually realized that it is difficult for any single discipline to break through and completely solve the problems. It is necessary to adopt a multi-level, strategic-level, and cross-disciplinary collaborative optimization approach, such as new types of electrodes like two-dimensional van der Waals ferromagnets and OSC(free radical polymers), to better connect from the source. Or at the physical mechanism level, advanced characterization techniques can be utilized to gain a deeper understanding of fundamental scientific issues such as interface energy level alignment, neighboring magnetic field effects, and spin relaxation. Alternatively, at the equipment structure level, new equipment geometric configurations (such as side spin valves, spin transistors) can be designed, and interface modification layers (such as tunneling barriers, SAMs) can be introduced [2] to optimize the spin transmission path.

Against this backdrop, this paper aims to systematically review and recall the latest progress made in the research of ferromagnetic/spin electrode interfaces of organic semiconductors in recent

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years. Analyze one by one how to overcome the above-mentioned technical bottlenecks through multi-dimensional collaboration methods. We will summarize the progress made in improving spin injection efficiency and equipment performance through the integration of two-dimensional materials and interface engineering. We will objectively analyze the real challenges that current research faces in achieving sustainable operation at ambient temperatures compatible with CMOS processes. Finally, this paper will envision the application blueprint of this interface in disruptive technologies such as flexible spin storage and neuromorphic computing in the future, with the aim of providing researchers in the field with a clear research roadmap and jointly promoting organic spintronics from the laboratory to industrialization [1].

2. Material progress

2.1. Electrode materials: from traditional metals to two-dimensional ferromagnets

Ferromagnetic electrodes are the source of spin-polarized carriers in organic spin devices, and their performance directly determines the initial efficiency of spin injection. At different stages of the development of organic spintronics, the selection of electrode materials has undergone an evolution from traditional metals to new two-dimensional ferromagnets. This evolution process reflects the continuous deepening of researchers' understanding of interface issues and their unremitting pursuit of high-performance devices.

Early research mainly used traditional ferromagnetic metals and their alloys as electrode materials, such as cobalt (Co), iron (Fe), and nickel-iron alloys (NiFe, also known as permalloy), etc [5]. These materials have the advantages of high Curie temperature, high spin polarizability and mature preparation process, and are widely used in inorganic spin devices. However, when these metals come into direct contact with soft organic semiconductor materials, during the thermal evaporation deposition process, high-energy metal atoms penetrate and diffuse into the organic layer, triggering uncontrollable interfacial chemical reactions. These reactions not only alter the molecular structure of organic semiconductors, generating chemical defects, but also produce a large amount of state density at the interface, which becomes the center of spin scattering. What is more serious is that this mutual diffusion will lead to the formation of a magnetic "dead layer" at the interface, that is, the surface magnetism of the electrode is significantly reduced, further weakening the spin injection efficiency. This interfacial reaction is the main factor restricting the performance of traditional metal electrodes and also the primary bottleneck faced by the early development of organic spin devices [3].

In recent years, the discovery of two-dimensional ferromagnetic materials has provided a revolutionary solution to the above-mentioned interface problems. This type of material is represented by Fe3GeTe2 (FGT), CrI3 and Cr2Ge2Te6, etc., and has a unique van der Waals layered structure. Compared with traditional metal electrodes, two-dimensional ferromagnetic electrodes have three significant advantages: Firstly, they offer a flat atomic surface without dangling bonds, enabling ideal van der Waals contact with organic semiconductors and fundamentally avoiding interface diffusion and damage. Secondly, these materials can be prepared by methods such as mechanical exfoliation or chemical vapor deposition, and can be integrated with organic semiconductors at low temperatures through transfer technology, fully meeting the process requirements of organic semiconductors. Most importantly, some two-dimensional ferromagnets such as Fe3GeTe2 exhibit high Curie temperatures and good spin polarization characteristics at low temperatures, providing the possibility for effective spin injection. Through reasonable interface

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engineering design, two-dimensional materials can achieve energy level alignment with organic semiconductors, further optimizing the spin injection efficiency.

Although two-dimensional ferromagnetic electrodes show great potential, they still face some challenges in practical applications. The first issue is the Curie temperature - the Curie temperature of most two-dimensional ferromagnets is lower than room temperature, and it is necessary to increase their operating temperature through methods such as element doping, electric field regulation, or heterostructure construction. Secondly, there is also the challenge of large-scale preparation. How to achieve the controllable preparation of high-quality and large-area two-dimensional ferromagnetic films still requires further exploration. In addition, the interface physical mechanisms between two-dimensional ferromagnets and organic semiconductors, especially the spin-related charge transfer processes and magnetic proximity effects, still require more in-depth research. Through ingenious interface engineering design, if appropriate intercalation molecules are introduced, the electronic structure and magnetism of two-dimensional ferromagnets can be effectively modulated, providing a new idea for achieving efficient spin injection [2].

In conclusion, the development of electrode materials has undergone a transformation from traditional metals to two-dimensional ferromagnets, which reflects the deepening understanding of interface issues in the field of organic spintronics. Although traditional metal electrodes are still used in some research due to their mature technology, two-dimensional ferromagnetic electrodes, with their unique van der Waals integration advantages and excellent interface characteristics, represent the future development direction. With the advancement of material preparation technology and the further clarification of interface physical mechanisms, organic spin devices based on two-dimensional ferromagnetic electrodes are expected to make breakthrough progress in the near future.

2.2. Semiconductor materials: from small molecules to free radical polymers

As the transport medium for spin-polarized carriers, the material properties of organic semiconductors directly determine the spin relaxation time and diffusion length, which in turn affect the performance of the entire device. According to the differences in molecular structure and physical properties, organic semiconductor materials can mainly be classified into small molecule semiconductors, polymer semiconductors and emerging free radical polymers, etc. Each type of material demonstrates unique advantages and challenges in the application of spintronics.

Small molecule semiconductors are characterized by high performance but limited flexibility. They have attracted much attention due to their clear molecular structure, high purity and good crystallinity. A review of the research progress of organic spintronic materials and devices in 2016 indicated that such materials are usually prepared by vacuum evaporation and can form structurally ordered films with high carrier mobility and relatively long spin diffusion length [1]. Small molecule semiconductors have unique advantages in fundamental mechanism research and high-performance device manufacturing due to their regular molecular structure and clear energy levels.

Polymer semiconductors show good processability, but their mobility needs to be improved. Compared with small molecule materials, conjugated polymer semiconductors such as P3HT, polyfluorene derivatives, and DPP polymers have excellent solution processing performance and mechanical flexibility. The influence of interface effects on the microstructure and magnetic resistance of Ni80Fe20/P3HT/Fe organic spin valves: Polymer materials can be processed into uniform films through solution methods such as spin coating and inkjet printing, and have good affinity with flexible substrates, making them highly suitable for large-scale, low-cost roll-to-roll production processes [3]. In addition, polymer films usually have good mechanical toughness and ductility, and can withstand certain bending and tensile deformations, which provides the possibility

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for the realization of flexible spin devices. However, a surface engineering study in 2019 on the preparation of phosphorene nanoribbons using transition metal heteroatoms in spintronics indicated that polymer materials also have problems such as relatively low carrier mobility and large molecular structure disorder, which can lead to strong charge scattering and spin relaxation. This limits the further increase of the spin diffusion length. The polydispersity and irregular chain structure of polymers can also introduce additional energy disorders, affecting the maintenance of spin polarization [6].

In recent years, a new type of material with an open-shell electronic structure - free radical polymers - has brought a new breakthrough direction to organic spintronics. This type of material molecule contains stable unpaired electrons and exhibits unique spin-related properties. Some chiral radical polymers not only possess inherent spin polarization characteristics but also exhibit chiral induced spin selectivity (CISS) effects, making the generation and transmission of spin polarization do not require traditional ferromagnetic electrodes [1]. The advantage of free radical polymers lies in that unpaired electrons provide an endogenous source of spin polarization, which may significantly enhance the spin injection efficiency. Secondly, many free radical polymers have good environmental stability and thermal stability, making them suitable for practical applications. Finally, through molecular design, its electronic structure and spin characteristics can be precisely regulated. These characteristics make free radical polymers an ideal choice for future organic spin devices [7].

2.3. Interface layer materials: from passivation isolation to energy level regulation

Introducing a functionalized interface layer between ferromagnetic electrodes and organic semiconductors is a key strategy to solve interface problems and improve spin injection efficiency. According to the differences in their functional mechanisms, interface layer materials can mainly be divided into two categories: insulating tunneling layers and self-assembled molecular layers. They improve interface properties through different approaches such as physical isolation or chemical modification, providing important technical means for achieving efficient spin injection.

Insulating tunneling layers, such as ultrathin alumina, lithium fluoride (LiF), magnesium oxide (MgO), etc., effectively address interface issues by introducing an extremely thin (typically 0.5-2 nm) insulating medium between the electrode and the organic layer. Self-assembled molecular layers (SAMs) represent a more refined interface engineering strategy. This type of material forms chemical bonds with the electrode surface through functional groups at the molecular ends (such as mercaptans, silanes, and phosphates), spontaneously assembling into highly ordered monolayers. SAMs have great potential in molecular spintronics. A study on chirality and symmetry in 2023 enabled the precise regulation of interfacial dipole moments through different molecular skeletons and terminal groups. Thus, the electrode work function can be adjusted to the state that best matches the energy levels of organic semiconductors. Some SAMs with chiral structures can also generate chiral-induced spin selectivity (CISS) effects, providing a new generation mechanism for spin polarization [8]. Compared with insulating tunneling layers, the advantage of SAMs lies in their precise controllability at the molecular level, enabling "customized" interface design. However, they have extremely strict requirements for preparation conditions and surface cleanliness [9].

In practical applications, insulating tunneling layers and self-assembled molecular layers are not mutually exclusive but can be combined to produce a synergistic effect. For instance, an ultrathin insulating layer can be deposited on the electrode surface first to prevent interfacial reactions, and then the SAMs can be modified to further optimize energy level alignment. This "dual modification" strategy has been proven to significantly enhance the performance and stability of the device.

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Table 1. Comparison of the characteristics of different types of interface layer materials [10]

Characteristics	Insulating tunneling layer	Self-assembled molecular Layer
Thickness	0.5-2 nm	1-3 nm
Advantage	The process is relatively simple and the isolation effect is remarkable	High regulation accuracy and the ability to introduce new functions
Limitations	It has high thickness sensitivity and may introduce additional potential barriers	The preparation conditions are harsh and the stability is challenging

3. Physical mechanisms and characterization

3.1. Core physics problem

The physical mechanism at the interface between ferromagnetic electrodes and organic semiconductors is a key factor determining the performance of spin devices. A thorough understanding of the energy level matching issue and interfacial magnetic interaction in the spin injection process is of great guiding significance for the design of high-performance organic spin devices.

Energy level alignment is essentially a competition between Ohmic contact and Schottky barrier. The energy level alignment problem is a core issue in FM/OSC interface physics and directly determines the efficiency of spin injection. The sun waits. The pioneering research in 2014, "Energy Level Alignment and Interaction Spin Polarization at Organic/ferromagnetic Metal Interfaces", systematically expounded the significance of interface energy level alignment. Their research indicates that the relative position of the Fermi level of the metal electrode to the frontier orbitals (HOMO and LUMO) of the organic semiconductor determines whether an ohmic contact or a Schottky barrier is formed at the interface [8].

The realization of Ohm contact is an ideal condition for achieving efficient spin injection. Precise interface engineering has demonstrated the possibility of achieving ohm-like contact between ferromagnetic electrodes and red fluorene single crystals. A study on the room-temperature ferromagnetism of organic semiconductors in 2022 found that by choosing appropriate electrode materials and interface treatment processes, the Fermi energy level of the electrode could be aligned with the HOMO energy level of the organic semiconductor, thereby achieving efficient hole injection and significantly improving the spin injection efficiency [11].

However, in actual systems, what is more frequently observed is the formation of Schottky barriers. Due to the interfacial dipole effect and the Fermi level pinning phenomenon, there exists a significant Schottky barrier at the interface between the nickel electrode and the red fluorene single crystal. The existence of the potential barrier increases the energy barrier of spin injection and reduces the efficiency of spin injection. Research shows that the height of the potential barrier depends on the temperature. At low temperatures, the tunneling effect is dominant, while at room temperature, thermal electron emission is more significant [12].

A study on organic spin devices in 2018 proposed an innovative solution, which is to use manganese oxide with electronic phase separation as the electrode material. By adjusting the phase composition of the material through an external field, the work function of the electrode can be dynamically regulated to achieve controllable adjustment of energy level alignment. This provides a new approach to solving the problem of energy level mismatch [13].

DOI: 10.54254/2755-2721/2026.KA29894

3.2. Key characterization techniques

Precise characterization of the interface characteristics between ferromagnetic electrodes and organic semiconductors is the foundation for understanding their physical mechanisms and optimizing device performance. In recent years, a series of advanced characterization techniques have been developed to study the FM/OSC interface, conducting in-depth research on it from multiple dimensions such as electronic structure, ultrafast dynamics, and atomic-scale spin states [14].

Ultraviolet photoelectron spectroscopy (UPS) is a core technique for characterizing the electronic structure at the FM/OSC interface. By measuring the photoelectric emission spectrum, UPS can precisely determine the changes in work function (detecting the changes in electrode work function before and after adsorbing organic molecules), ionization energy measurement (determining the HOMO energy level position of organic semiconductors), and interface dipole (analyzing the magnitude and direction of the interface dipole moment through band bending). Fermi level pinning (identifying interface states that cause failed level alignment) [15]

The time-resolved magneto-optical Kerr effect (TR-MOKE) is a powerful tool for studying spin relaxation and transport ultrafast dynamics. The theoretical framework of TR-MOKE was developed in the "ferromagneto-semiconductor junction and low-power ultrafast spin injection device", achieving precise detection of spin relaxation time (measuring the decay dynamics of spin polarization at different temperatures) and spin precession (observing the spin precession frequency and damping coefficient under the action of an external magnetic field). Interfacial spin transport (studying the time scale of spin passing through the FM/OSC interface), spin accumulation (detecting the spin accumulation and diffusion processes at the interface) [16].

Spin-resolved scanning tunneling microscopy and spectroscopy (STM/STS) [17] provide forces for characterizing spin states at the atomic scale. The force of L low-temperature STM characterizing the spin state of the metal-ligand interface at the molecular scale was demonstrated in "TM".

Table 2. Comparison of key characterization techniques for FM/OSC interface [18]

Technical	spatial resolution	temporal resolution	information depth	mainly obtain information
UPS	~100 μm	time-resolved	1-2 nm	work function, ionization energy, energy level alignment
TR-MOKE	~1 μm	<100 fs	10-20 nm	spin relaxation time, precession dynamics
Spin-STM	<0.1 nm	non-time-resolved	surface atom	atomic-scale Spin state and magnetic structure
Spin-STS	<0.1 nm	time-resolved	surface atomic	Spin polarization state density and energy gap

4. Equipment structure and application prospects

The development of organic spin devices has undergone an evolution process from the verification of basic principles to functional applications. With the enrichment of material systems and the advancement of interface engineering, organic spin devices are evolving from simple spin valves to more complex functional devices, demonstrating broad application prospects [19].

DOI: 10.54254/2755-2721/2026.KA29894

4.1. Organic Spin Valve (OSV)

The organic spin valve is the most fundamental and widely studied spin device. The core structure of OSV is a sandwich structure of ferromagnetic electrode/organic semiconductor/ferromagnetic electrode (FM/OSC/FM) [20]. The spin injection and spin transfer were investigated by measuring the resistance changes (magnetoresistance effect) when the magnetization directions of two ferromagnetic electrodes were parallel and antiparallel.

The structural evolution of OSV has evolved from the early vertical structure (mainly using vertical configuration, and the preparation process is relatively mature, but there are crosstalk and pinhole problems) to the transverse structure (using non-local transport measurement, effectively avoiding direct coupling between electrodes, but the signal is relatively weak) to the current van der Waals heterojunction (using two-dimensional materials as electrodes or interlayer layers to achieve atomic-level planar interfaces Significantly reducing the boundary, among which the NiTe2 scanning tunneling microscopy and spectroscopy research defect in 2022, the OSV device that can operate at room temperature through the photoelectric compensation strategy can further demonstrate the wide-range magnetic current regulation and multi-functional integration capabilities [21].

4.2. Organic magnetic tunnel junction

A 2010 article on the low-temperature STM single-molecule synthesis and characterization of metal-ligand complexes introduced a tunnel barrier layer on the basis of OSV, significantly improving the performance of organic magnetic tunnel junctions. Its performance advantages [22], for example, higher magnetoresistance ratio: due to the tunneling magnetoresistance effect, the magnetoresistance signal of OMTJ is stronger than that of OSV, and better thermal stability The barrier layer effectively suppresses interface diffusion, enhances device stability, and reduces power consumption: based on the quantum tunneling effect, the operating current density is relatively low.

There are traditional barriers in the development of the barrier layer, namely metal oxides such as AlO and MgO. The process is mature, but there are many interface defects.

Van der Waals barriers provide an ideal bond-free interface for two-dimensional insulators such as h-BN and MoS2 [23].

4.3. Organic spin transistor (OSFET)

Organic spin transistors represent a higher level of device integration and functionalization [24]. In terms of working principle, it adopts gate voltage regulation (regulating the channel carrier concentration and Fermi level position through the gate voltage), spin transport control (fully electrical control of the generation, transmission and detection of spin polarization), and non-volatility (combined with ferroelectric grid media to achieve non-volatile storage function).

In "organic conductors", organic conductors have great application potential in spintronics [25], especially their unique advantages in neuromorphic computing further demonstrate the application of organic-inorganic hybrid perovskite materials in spin devices. A study on room-temperature organic spintronic devices in 2022 Wide-range magnetic current tuning and multi-functional scenes are achieved through electro-optical compensation strategies. It provides new ideas for the development of multi-functional devices [26].

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Table 3. Comparison of types and performance of organic spin devices

Device type	Core structure	Working mechanism	Performance characteristics	Application field
OSV	FM/OSC/FM	Giant magnetoresistance effect	The structure is simple but the signal is weak	Basic research, sensors
OMTJ	FM/Potential barrier/OSC/Potential barrier/FM	Tunneling magnetoresistance effect	Strong signal and good stability	Memory, magnetic sensor
OSFET	Gate/FM/OSC/FM	Field effect regulation	Rich in functions and reconfigurable	Logic devices, neuromorphic computing

5. Summary and challenges

5.1. Research summary

In recent years, significant progress has been made in the research of ferromagnetic electrode/organic semiconductor spin interfaces, mainly reflected in two aspects: material innovation and structural optimization. Al-qatatsheh et al. pointed out that [27] the development of new material systems is a key driving force for the advancement of this field. Two-dimensional ferromagnetic materials (such as Fe3GeTe2, CrI3) offer atomically flat van der Waals contact interfaces, fundamentally avoiding the interfacial diffusion problem of traditional metal electrodes. Emerging organic semiconductor materials such as free radical polymers, due to their inherent spin characteristics, provide new mechanisms for spin injection and transport. The emergence of these materials has greatly enriched the range of material choices and provided more possibilities for performance optimization.

In terms of device structure, the introduction of interface state engineering such as van der Waals heterojunction integration technology has made it possible to prepare ideal interfaces that are non-destructive and have low defects. By precisely controlling the interface structure and energy level arrangement, researchers have successfully achieved a significant improvement in spin injection efficiency [28]. In addition, the design of multifunctional devices, such as photoelectric co-modulated spin transistors, has further expanded the application scope of organic spin devices.

These innovations in materials and structures have jointly driven a comprehensive improvement in device performance: the room-temperature magnetoresistance ratio has increased from less than 1% in the early stage to over 20%. The spin diffusion length has increased from tens of nanometers to over 200 nanometers. The operating temperature of this device has been extended from liquid nitrogen temperature to room temperature conditions. These advancements have laid a solid foundation for the practical application of organic spintronics.

5.2. Existing challenges

Despite significant progress made, this field still faces several key challenges that restrict the practical application of organic spin devices.

Insufficient room-temperature performance remains the biggest technical bottleneck. Although room-temperature operation has been achieved under laboratory conditions, the efficiency and stability of this device are still far from meeting the requirements of practical applications.

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Intrinsic disorder is an inherent limitation of organic semiconductors. The structural disorder of organic materials can lead to energy disorder and carrier localization, thereby limiting the spin diffusion length [29]. Although single-crystal organic semiconductors can partially alleviate this problem, their preparation is difficult and costly, making it hard to meet the requirements for large-scale applications.

The scalability and uniformity of the preparation process are also major challenges. "Focused ion beam nanostructures" demonstrate the complexity of preparing high-quality films [30]. The mechanical transfer and thermal evaporation processes adopted in the laboratory are difficult to be extended to wafer-level production, with issues such as large batch-to-batch variations and poor uniformity

5.3. Future development direction

Material innovation is the key to breaking through the existing performance bottlenecks in the face of current challenges [31]. In the future, it will be necessary to develop two-dimensional materials with room-temperature ferromagnetism, such as increasing the Curie temperature through element doping, strain engineering or heterostructure construction. At the same time, it is also crucial to design organic semiconductor materials with high mobility and long spin relaxation times. Molecular engineering strategies, such as introducing chiral centers or free radical functional groups, may offer new approaches for creating new spin-functional materials [32].

Exploring new physical mechanisms will provide new ideas for performance improvement. Topology-protected spin transport is expected to be achieved by utilizing novel quantum phenomena, such as the surface states of topological insulators and the flat-band effect of model superlattices. In addition, the research on molecular-level spin filtering mechanisms such as chiral-induced spin selectivity (CISS) effects may lay the foundation for the development of spin devices without ferromagnetic electrodes [33].

Technological innovation in processes is a necessary condition for achieving industrialization. The development of wafer-level van der Waals integration technology, the creation of low-temperature preparation methods compatible with CMOS processes, and the establishment of high-precision interface control processes are all key directions that need to be broken through in the future [34]. In particular, it is necessary to address key industrialization issues such as large-scale uniformity, process reproducibility and environmental stability.

Interdisciplinary cooperation will be the key to promoting the development of this field. It requires close collaboration among materials scientists, physicists, chemists and engineers to jointly address a series of challenges ranging from fundamental science to engineering technology. Only through such all-round collaborative innovation can organic spintronics truly achieve a leap from laboratory research to industrial application and make significant contributions to the development of the next generation of information technology [35].

In the next 5 to 10 years, organic spintronics is expected to make breakthrough progress in specific application scenarios such as flexible electronics, the Internet of Things, and neuromorphic computing, providing new solutions for the development of information technology.

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