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Mobility of Charge Carriers in Organic Semiconductors

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Abstract. Organic semiconductors are a class of semiconductors with carbon-based organic molecules or polymers as core materials. Their molecular usually contain conjugated π-electron systems, such as polythiophene, perylene diimide, etc., which achieve charge transport through electron delocalization Compared with silicon-based materials, organic semiconductors can be prepared into thin films through low-temperature processes (such as printing, spin coating), greatly reducing production costs. semiconductors have great advantages in flexibility, solution processability and low cost, so they have broad application prospects in flexible electronics, display technology and energy conversion. However, their carrier is generally lower than that of inorganic semiconductors, which has become a key factor limiting device performance. This paper systematically reviews the basic properties, influencing factors and improvement strategies carrier mobility in organic semiconductors, compares the differences between organic and inorganic semiconductors in mobility, analyzes the main challenges faced by current research, and prospects the future direction.

Keywords: Organic semiconductor, Carrier mobility, Molecular engineering, Thin film process, Device application

1. Introduction

The research of organic semiconductors began with the discovery of the conductivity of polyacetylene in the 1970s [1], and has undergone decades of development. The material system has been extended from the early small molecules (such as pentacene, phthalocyanine) [2] to the conjugated polymers (such as poly(3-hexylthiophene), indene-thiophene-benzothiadiazole-rodanine) [3], and the device performance has achieved significant breakthroughs, laying the foundation for flexible logic circuits and sensors.

In recent years, organic semiconductors have become a research hotspot in condensed matter physics, materials science, and flexible electronics because of their unique material properties and broad application prospects. Compared with traditional inorganic semiconductors (such as silicon, gallium arsenide), organic semiconductors take the carbon-based conjugated molecules or polymers [4] as the core, and achieve the carrier transport through π-π stacking and intermolecular charge transfer [5], with the advantages of solution processability, mechanical flexibility, and molecular structure designability. This characteristic makes organic semiconductors show great potential in flexible display, wearable electronics, low-cost photovoltaics [6], and provides a new idea for the development of a new generation of green electronic devices.

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However, organic semiconductors still face key challenges, such as low carrier mobility, insufficient environmental stability, and uniformity issues in large-area fabrication. These limitations mainly stem from the intrinsic characteristics of molecular disorder packing, high defect state density, and water/oxygen sensitivity. In recent years, the performance and stability of materials have been significantly improved by employing various strategies, such as molecular engineering [7] (e.g., fused-ring design, side-chain optimization), interface modification, and novel device structures (e.g., bulk heterojunctions, double-layer transport layers). Additionally, emerging methods like machine learning-aided molecular design and high-throughput screening [8] have also injected new impetus into the development of organic semiconductors.

Organic semiconductors are a class of materials based on carbon with a conjugated π-electron system, which can be chemically modified to regulate their optoelectronic properties [9]. Compared with traditional inorganic semiconductors, organic semiconductors have the advantages of simple preparation process, flexible processing, and low cost [10], and are widely used in devices such as organic light-emitting diodes (OLEDs), organic field-effect transistors (OFETs), and organic photovoltaic cells (OPVs) [11].

Carrier mobility is a key parameter to evaluate the charge transport capability in semiconductor materials, directly affecting the switching speed, luminous efficiency, and energy conversion efficiency of devices [12]. Although organic semiconductors exhibit significant advantages in device integration and flexibility, their mobility is generally low, typically ranging from 10-5 to 10 $cm^2/V \cdot s$, which is much lower than that of inorganic semiconductors such as silicon (>1000 $cm^2/V \cdot s$) [13]. This gap mainly stems from the weaker intermolecular interactions and disordered film structures in organic materials, leading to hopping-dominated charge transport with severe scattering [14].

Currently, enhancing the mobility of organic semiconductors has become a research hotspot in this field. This paper will systematically analyze the key factors affecting mobility from the aspects of material intrinsic properties, film structure, and external conditions [15], and review the progress achieved in recent years through strategies such as molecular design, process optimization, and development of new materials. Finally, the challenges and future development directions in practical applications will be discussed.

2. Comparison of mobility between organic and inorganic semiconductors

2.1. Carrier mobility in organic semiconductors

Organic semiconductors are a class of materials with a carbon-based π-conjugated system, and their carrier transport characteristics are essentially different from those of traditional inorganic semiconductors [16]. The carrier mobility in organic semiconductors is generally low, typically ranging from 10-5 to 10 $cm^2/V \cdot s$, which is much lower than that of inorganic semiconductors. The fundamental reason lies in the weak intermolecular interactions and the strong disorder in the solid state of organic semiconductor materials, causing the carrier transport to no longer follow the band transport mechanism but instead dominated by thermally-assisted hopping transport [17].

In the hopping transport model, carriers make transitions between localized states, which strongly depends on temperature, molecular spacing, and the degree of overlap of molecular orbitals. Therefore, the orderliness of molecular arrangement, crystallinity, and film morphology of organic semiconductor materials have a decisive influence on their mobility. For example, high-performance small molecule organic semiconductors such as pentacene and rubrene can achieve a hole mobility of 1~10 $cm^2/V \cdot s$ in single-crystal or highly ordered films [18], mainly benefiting from their close π–π stacking and effective molecular orbital overlap. In contrast, polymer semiconductors such as

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P3HT, due to the entanglement of molecular chains and the non-uniformity of intra- and inter-chain transport, usually have a mobility lower than 0.1 $cm^2/V \cdot s$ [19].

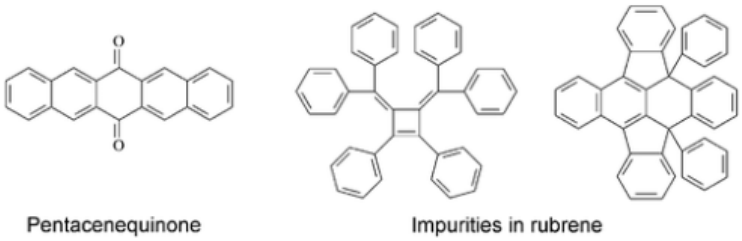

Figure 1. The structure of pentacenequinone and rubrene

In addition, charge carrier transport in organic semiconductors is also influenced by trap states, grain boundaries, interfacial defects, and other factors. Grain boundaries can scatter carriers, reducing the effective mobility; whereas chemical or structural defects may serve as capture centers for carriers, further restricting their mobility. Therefore, the key to enhancing the mobility of organic semiconductors lies in optimizing molecular structures, enhancing film orderliness, and reducing defect state densities.

It is worth noting that, despite the generally low mobility of organic semiconductors, they exhibit good solution processability, mechanical flexibility, and the ability to be prepared at low temperatures, making them uniquely suitable for applications in flexible electronics, large-area sensors, and wearable devices.

2.2. Carrier mobility in inorganic semiconductors

Inorganic semiconductors, such as silicon (Si), germanium (Ge), gallium arsenide (GaAs), and gallium nitride (GaN), possess highly ordered crystal structures and strong covalent or ionic bonding, and their carrier transport mechanisms are dominated by band transport [20]. In this mechanism, carriers (electrons or holes) move freely within continuous energy bands, with scattering primarily from lattice vibrations (phonons), ionized impurities, or crystal defects.

Due to the periodicity and high order of their crystal structures, inorganic semiconductors typically exhibit very high carrier mobilities. For instance, the electron mobility in single-crystal silicon at room temperature is approximately 1500 $cm^2/V \cdot s$, and the hole mobility is about 450 $cm^2/V \cdot s$; whereas, gallium arsenide has an electron mobility as high as 8500 $cm^2/V \cdot s$, making it particularly suitable for high-frequency, high-speed devices such as microwave amplifiers and high-electron-mobility transistors (HEMTs) [21]. Wide-bandgap semiconductors like silicon carbide (SiC) and gallium nitride (GaN), despite slightly lower mobility, exhibit outstanding performance in power electronics and optoelectronic devices due to their high breakdown electric field and high thermal stability.

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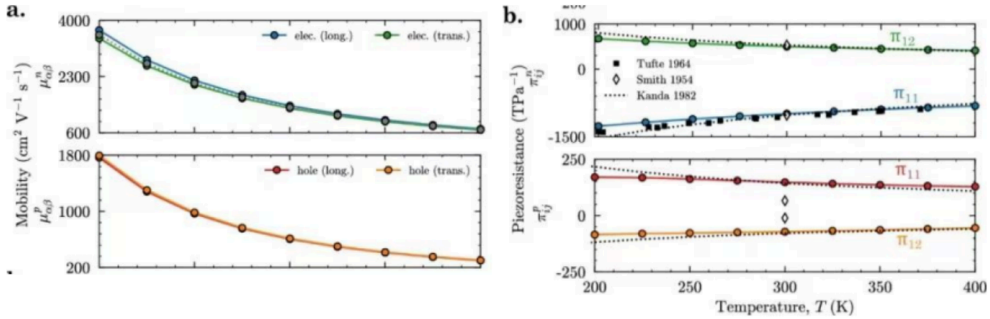

(a) Si carrier mobility (b) The piezoresistive coefficient of Si

Figure 2. Related properties of semiconductor silicon

The high mobility of inorganic semiconductors is mainly attributed to their long-range ordered lattice structure, large mean-free path of carriers, and low effective mass. Additionally, modern semiconductor processes such as molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) can prepare nearly perfect single-crystalline thin films [22], greatly reducing the defect density and further enhancing the performance of devices.

However, inorganic semiconductors also have some limitations, such as complex preparation processes, high cost, large material brittleness, and difficulty in large-area flexible integration. These factors limit their use in flexible electronics and some emerging applications to some extent.

2.3. Comprehensive review of mobility comparison between organic and inorganic semiconductors

There is a difference of orders of magnitude in carrier mobility between organic and inorganic semiconductors, which is ultimately determined by their material nature, molecular or atomic structure, and different carrier transport mechanisms [23].

From the structural point of view, inorganic semiconductors have a highly periodic lattice structure connected by strong chemical bonds, and carriers are delocalized and transmitted in the band, with phonon scattering and impurity scattering as the main scattering mechanisms. In contrast, organic semiconductors are stacked depending on weak van der Waals forces or π–π interactions, with weak intermolecular coupling, and carrier transport is dominated by phonon-assisted hopping models, which are highly localized and significantly reduce mobility.

From the performance point of view, the mobility of inorganic semiconductors usually ranges from hundreds to thousands of $cm^2/V \cdot s$, which is suitable for high-performance, high-frequency, and high-power application scenarios, such as microprocessors, power devices, and lasers. The mobility of organic semiconductors mostly ranges from 10-5~10 $cm^2/V \cdot s$, which is much lower than inorganic materials, but they have the advantages of good flexibility, solution processability, low-temperature preparation, and low cost, which are particularly suitable for emerging applications such as flexible displays, electronic skins, large-area sensors, and biodegradable electronic devices.

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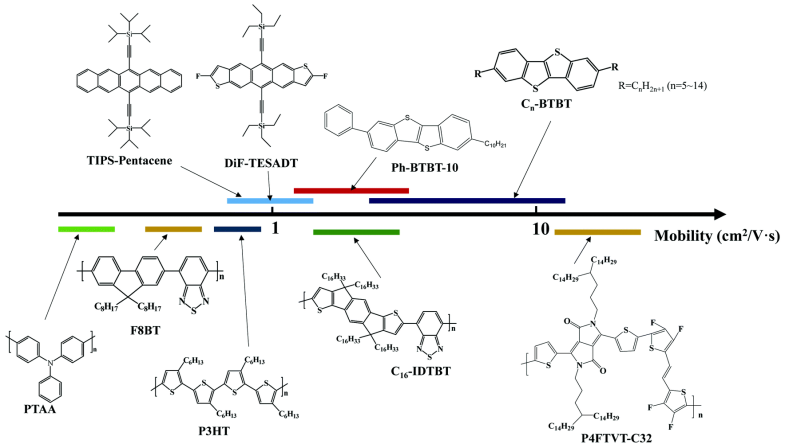

Figure 3. Comparison chart of electronic mobility performance of organic semiconductor materials

From the perspective of device application, the two are not simply substitutes but complementary. Inorganic semiconductors dominate traditional electronics, which pursues high performance and high reliability; while organic semiconductors, with their unique mechanical and processing advantages, open up new application directions such as flexible, stretchable, and transparent electronics [24].

In summary, the difference in mobility between organic and inorganic semiconductors reflects their fundamental differences in intrinsic physical mechanisms and material characteristics. When selecting material systems, it is necessary to consider the application scenario, performance requirements, and preparation cost comprehensively, to give full play to the advantages of various materials and promote the diversified development of electronic technology.

3. Key factors affecting carrier mobility in organic semiconductors

The magnitude of carrier mobility in organic semiconductors is constrained by multiple factors, including the intrinsic properties of the materials themselves, the morphology control during thin-film preparation, and the external environment in which the device operates. A deep understanding of the mechanisms of these influencing factors is of significant importance for the design of high-performance organic electronic devices [25].

3.1. Intrinsic properties of materials

The intrinsic properties of materials are the fundamental factors that determine carrier mobility in organic semiconductors, originating from the electronic structure of the molecules themselves and their stacking manner in the solid state [26].

3.1.1. Molecular structure and conjugated system

The electrical conductivity of organic semiconductors arises from their conjugated π-electron system. The length, planarity, and rigidity of the conjugated chain directly affect the degree of delocalization of molecular orbitals. Generally, a longer conjugation length and better planarity favor the delocalization of π electrons, enhancing the charge transport ability within the molecule and thus increasing the mobility. For example, compared to anthracene, pentacene has a longer conjugated structure, and its hole mobility is significantly higher [27]. However, excessively

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extending the conjugated chain can lead to decreased solubility and difficult processing, so a balance between conjugation length and solubility needs to be considered in molecular design.

3.1.2. Molecular energy level structure

The energy level positions of the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) are crucial for the efficiency of carrier injection and transport. For p-type semiconductors, the HOMO energy level should match the work function of the electrode to reduce the barrier for hole injection; for n-type semiconductors, the LUMO energy level needs to be sufficiently low to prevent electrons from being quenched by oxygen or water molecules in the environment. In addition, a smaller recombination energy is beneficial for the carrier to jump between molecules, improving the mobility [28]. The magnitude of the recombination energy is closely related to the rigidity of the molecular structure, with molecules that are more rigid generally having smaller nuclear relaxation and lower recombination energy.

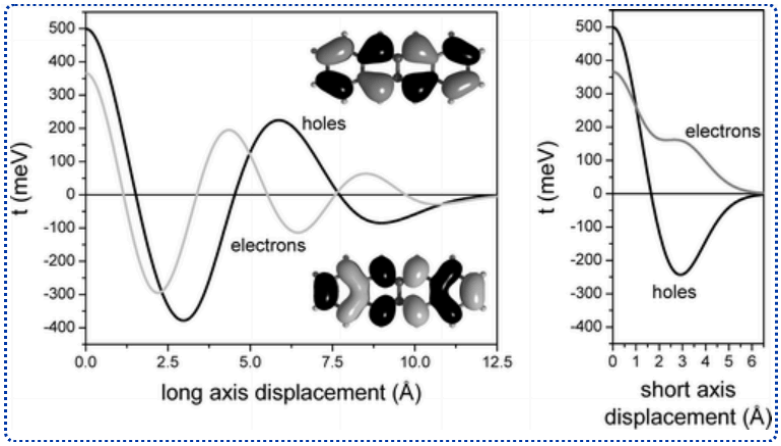

Figure 4. The change rule of charge transport capability of pentacenequinone molecules under stretching or compression

3.1.3. Substituent effects

The introduction of appropriate substituents is an important means to regulate the performance of organic semiconductors. Flexible substituents such as alkyl chains can improve the solubility and processability of materials, but alkyl chains that are too long or too branched may destroy the close packing of molecules and reduce the mobility instead. On the other hand, the introduction of strong electron-withdrawing groups such as fluorine atoms and cyano groups can modulate the energy levels, enhance the intermolecular interactions (e.g., dipole-dipole interactions), and promote the electron transport, which is a common strategy for the design of high-performance n-type semiconductors [29].

3.1.4. Molecular weight and polydispersity

For polymer semiconductors, molecular weight and polydispersity have a significant impact on the mobility. Higher molecular weight usually means longer conjugated chains and fewer chain end defects, which are beneficial to intrachain charge transport. However, excessive molecular weight may lead to severe chain entanglement, which is not conducive to the formation of an ordered microstructure [30]. A narrow molecular weight distribution (low polydispersity), on the other hand,

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helps to form a more uniform film, reduce the energy disorder, and thus improve the carrier mobility.

3.2. Film morphology and microstructure

The carrier transport in organic semiconductors strongly relies on the arrangement of molecules in the solid state, so the film morphology and microstructure are key factors affecting the mobility.

3.2.1. Crystallinity and molecular order

Highly ordered crystalline regions provide efficient transport pathways for carriers. The close π-π stacking between molecules and the face-to-face orientation are beneficial to orbital overlap, which reduces the hopping barrier and thus enhances the mobility [31]. Films with high crystallinity usually exhibit higher mobility and better electrical performance stability. The crystallization process is influenced by a number of factors such as molecular structure, solvent selection, and coating conditions.

3.2.2. Grain size and grain boundaries

Grain size is another important parameter that affects the mobility. Large grain sizes can reduce the number of grain boundaries, which are the major sources of carrier scattering and trapping, leading to a significant decrease in mobility. Therefore, obtaining large-sized, highly oriented grains through optimizing film formation processes, such as solvent vapor annealing, thermal annealing, etc., is an effective approach to enhance the mobility [32]. However, it is worth noting that in some cases, grain boundaries can also become favorable sites for charge separation, especially in photovoltaic devices.

3.2.3. Phase separation and microscopic phase state

In a blend system (e.g., donor-acceptor blends), the morphology of phase separation is crucial for the mobility. An ideal double-continuous interpenetrating network structure can provide efficient pathways for both electrons and holes transport, while excessive phase separation or too fine phase regions may be detrimental to the collection and transport of charges [33]. The morphology of phase separation can be regulated by adjusting the donor/acceptor ratio, selecting additives, controlling film formation kinetics, etc.

3.2.4. Defects and trap states

Defects in the film (e.g., molecular stacking faults, impurities, structural disorder, etc.) introduce local states that capture carriers, forming traps. The presence of trap states reduces the effective mobility, leading to non-ideal current-voltage characteristics, such as hysteresis phenomena [34]. Reducing defect density and passivating trap states are important means to improve device performance. High-purity materials, particle-free solutions, and clean processing environments are the basis for obtaining low-defect films.

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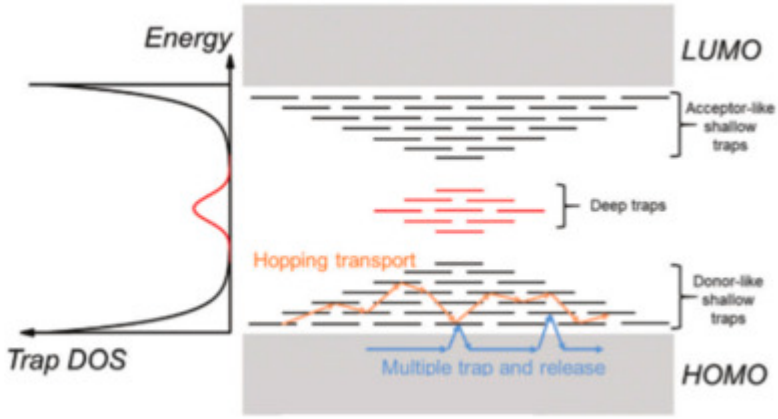

Figure 5. Trap states and carrier transport mechanisms in organic semiconductors

3.2.5. Molecular orientation and anisotropy

The orientation of organic semiconductor molecules on the substrate has an anisotropic effect on the mobility. For example, in OFET devices, it is desired to have the π-π stacking direction parallel to the charge transport direction (along the surface of the substrate) to maximize orbital overlap and charge transport efficiency [35]. The orientation of molecules can be regulated by selecting appropriate substrates, using surface modification layers (such as self-assembled monolayers), or employing external fields (such as temperature gradients during the solution-shearing process, electric field-induced), which can optimize device performance.

3.3. External conditions

In addition to the material itself and the film morphology, the external environment and working conditions also have an ineligible influence on the carrier mobility of organic semiconductors.

3.3.1. Temperature effect

The influence of temperature on mobility reveals its transport mechanism. In the hopping transport model, mobility usually increases with increasing temperature, following the Arrhenius relation ($\mu \propto e(-Ea/kT)$), where Ea is the activation energy. The increase in temperature provides the thermal energy needed for carriers to overcome the energy potential barrier between molecules. In the band transport model, mobility decreases with increasing temperature ($\mu \propto Tn$), as phonon scattering is intensified. In practical organic semiconductors, the relationship between mobility and temperature is often complicated, which may be the result of the joint action of various mechanisms.

3.3.2. Field dependence

Under high electric fields (typically > 105 V/cm), the mobility in organic semiconductors often exhibits field dependence, known as the Pool-Frenkel effect [36]. The electric field can reduce the potential barrier for hopping between molecules, leading to an increase in mobility with the enhancement of the electric field. This effect is particularly important in device operation, especially in short-channel devices or under high operating voltages, and needs to be considered in the model.

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3.3.3. Interface effects

Charge injection and transport strongly depend on the properties of the interfaces between the semiconductor and the electrode, the semiconductor and the dielectric layer. A high injection barrier can result in increased contact resistance, which can mask the intrinsic mobility of the material [37]. Charge injection can be improved and a more realistic mobility evaluation can be obtained by tuning electrode work function (e.g., using different metals, surface doping), introducing a modified layer at the interface (e.g., PFN, MoO3, etc.). In addition, the roughness, functional groups, etc., of the dielectric layer surface can also affect the film-forming and orientation of semiconductor molecules on it, and thus affect the mobility.

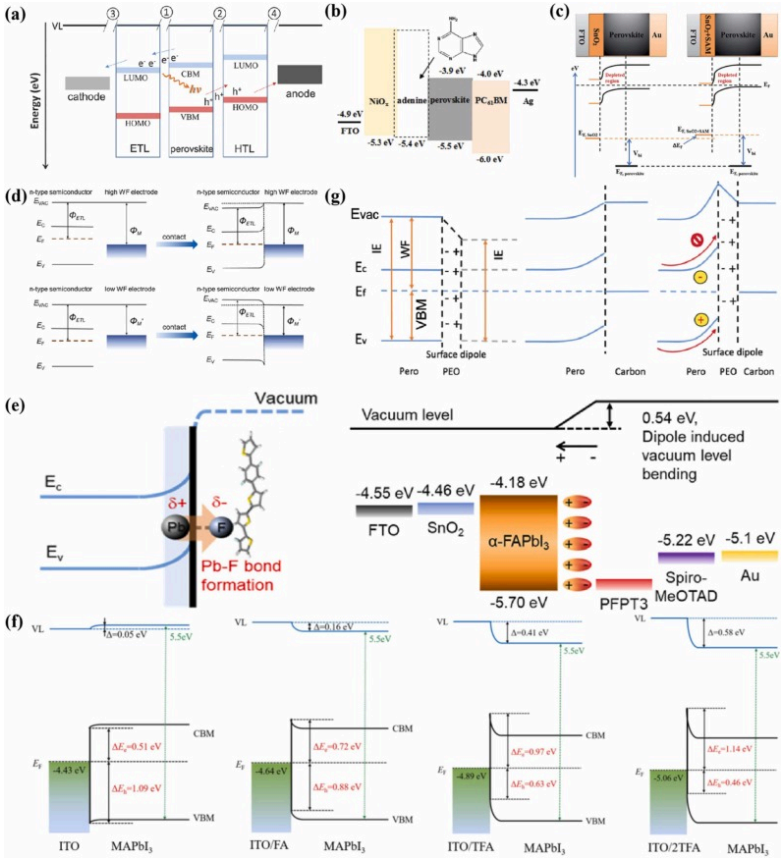

Figure 6. The mechanism of regulating the interfacial band structure in perovskite solar cells (or similar optoelectronic devices), especially the formation of interfacialoles and their crucial role in device performance.(a): Device structure;(b): Material band gap;(c): Ideal interface band alignment; (d): Fermi level pinning and unfavorable band bending;(e): Formation and effect of interfacial dipoles (taking perovskite/FTO as an example);(f): Comparison of interface decoration strategies and effects

3.3.4. Environmental ambiance

Many organic semiconductors, especially n-type materials and p-type materials with low HOMO energy levels, are highly sensitive to oxygen and water molecules in the environment [38]. These environmental impurities can act as electron traps, leading to device performance degradation and mobility decrease. Therefore, fabricating and testing devices in inert ambiances (e.g., nitrogen,

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argon) and effective encapsulation are crucial for obtaining stable and reproducible performance data.

3.3.5. Stress and mechanical deformation

In flexible electronic applications, organic semiconductor thin-films can be subjected to mechanical stresses such as stretching, bending, or compressing. Stresses can alter molecular spacing and stacking ways [39], thereby affecting mobility. Understanding the relationship between mobility and strain and developing strain-resistant elastic organic semiconductors are important research directions in the field of flexible electronics.

4. Strategies and advances in enhancing charge carrier mobility in organic semiconductors

Despite the great application potential of organic semiconductors in flexible electronics, their relatively low charge carrier mobility remains a major bottleneck restricting their commercialization. In recent years, researchers have proposed various effective strategies to improve the mobility of organic semiconductors by starting from multiple dimensions such as molecular design, process optimization, and development of new materials, and significant progress has been made.

4.1. Molecular engineering

Molecular engineering is a strategy to precisely regulate molecular structures through chemical synthesis means, fundamentally optimizing the performance of semiconductor materials. It is one of the most direct and effective methods to enhance mobility at present.

4.1.1. Design of rigid planar conjugated backbones

Enhancing the rigidity and planarity of molecules is an effective way to strengthen the π-π interaction between molecules and promote charge transport. Designing conjugated backbones with rigid fused ring structures (such as naphthalene, anthracene, and pentacene and their derivatives) [40] can reduce molecular conformational disorder, increase the reorganization energy barrier, and thus promote the delocalization and transport of charge carriers. For example, indole-based carbazole compounds exhibit excellent hole transport performance with a mobility of 1.0-2.5 $cm^2/V \cdot s$ [41] due to their high rigidity and planarity. In recent years, further enhancing molecular planarity through strategies such as introducing intramolecular hydrogen bonds, carbon-nitrogen bond locking, etc., has become an important direction for designing high-performance semiconductor materials.

4.1.2. Side-chain engineering and solubility regulation

Introducing appropriate flexible side chains (such as alkyl chains, alkoxy chains) on rigid conjugated backbones is an important means to solve the processability problem. The length, branch position, and topological structure of the side chains significantly affect the solubility, self-assembly behavior, and solid-state packing mode of the molecules. Straight-chain alkyl groups usually favor the formation of well-ordered lamellar structures, while branched alkyl groups, although they can enhance solubility, may destroy the close packing between molecules [42]. It was found that there is an optimal side-chain length that can ensure good solubility without significantly sacrificing intermolecular interactions. In addition, new strategies such as asymmetric side-chain design and the

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introduction of chiral side chains have been used to regulate the molecular stacking mode, reduce grain boundary defects, and thus improve mobility.

4.1.3. Energy level regulation and doping strategy

Precise regulation of HOMO/LUMO energy level position by molecular design can optimize carrier injection efficiency and reduce contact resistance. Donor groups (such as alkyl, alkoxy) can raise the HOMO energy level, which is beneficial for hole injection; acceptor groups (such as fluorine, cyano, carbonyl) can lower the LUMO energy level, which promotes electron transport [43]. The molecular internal D-A (donor-acceptor) structure design can regulate the energy level position, narrow the band gap, enhance the charge transfer within the molecule, and maintain a high mobility. Moreover, chemical doping strategies (such as using doping agents like F4TCNQ, NOBF4, etc.) can significantly improve the carrier concentration and conductivity, but the doping level needs to be carefully controlled to avoid mobility reduction caused by over-doping.

4.1.4. End group substitution and functional group modification

The introduction of specific functional groups (such as thiol, siloxane, cyano, etc.) at the end of the conjugated molecule can regulate intermolecular interactions, change molecular stacking patterns, and improve film morphology. For example, the introduction of a triphenylsilane ethynyl group (TIPS) at the end of the pentacene not only greatly improves solubility but also induces a unique "fishbone"-like stacking structure, significantly enhancing the crystallinity and mobility of the film. This "small molecule-large side chain" design concept has become an important design principle for high-performance solution-processed organic semiconductors.

4.2. Film process optimization

The microscopic structure and morphology of the film have a vital impact on the mobility. By optimizing the film formation process, the molecular arrangement mode can be effectively regulated, the crystallinity can be improved, and the defect density can be reduced, thereby significantly improving the device performance.

4.2.1. Solution-processing techniques

Solution-processing (such as spin coating, inkjet printing, blade coating, etc.) is the key technology for achieving large-area and low-cost preparation of organic electronic devices. By optimizing solvent selection (using mixed solvents, high-boiling point solvents), regulating solution concentration, and controlling film formation temperature and ambient humidity, the film formation kinetics process can be regulated to obtain a more uniform and ordered film. In recent years, solution shearing (Solution Shearing), slot-die coating (Slot-Die Coating), and other directed coating technologies have attracted extensive attention. These methods can generate shear force during the coating process, induce molecular directional arrangement, and form highly ordered crystal structures, which can improve the mobility by one order of magnitude or more.

4.2.2. Post-treatment methods

Post-treatment is an effective means to improve the morphology of the film. Thermal annealing is the most commonly used post-treatment method, which provides thermal energy to promote

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molecular motion and rearrangement, improving crystallinity, increasing grain size, and reducing grain boundaries. Solvent vapor annealing (SVA) is a more gentle treatment that partially swells the film surface by controlling the solvent vapor atmosphere, providing sufficient mobility for molecules to self-assemble and rearrange, forming higher quality crystalline structures while avoiding material degradation that may be caused by high temperatures. In addition, new post-treatment technologies such as microwave annealing, photothermal annealing, etc., also show unique advantages such as fast, energy-saving, and selective heating.

4.2.3. Interface engineering

The properties of the interface are crucial for charge injection and transport. The introduction of a modified layer (such as self-assembled monolayers, polymer interface layers, metal oxides, etc.) at the electrode/semiconductor interface can regulate the work function, reduce the injection barrier, and reduce the interface trap states. For example, in OFET devices, the OTS (octadecyltrichlorosilane) modified SiO2 dielectric layer has a lower surface energy, which is conducive to the orderly arrangement of semiconductor molecules, significantly improving the mobility. Constructing a molecularly flat surface at the semiconductor/dielectric interface can reduce scattering centers and improve charge transport.

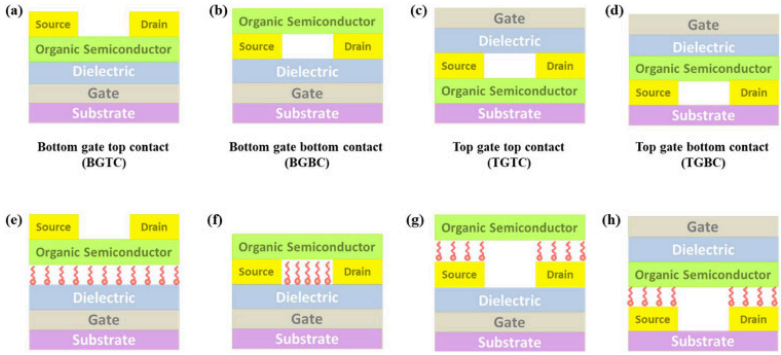

Figure 7. Eight core device structures of Organic Thin-Film Transistors (OTFTs)

4.2.4. Field-assisted assembly

The use of external fields (e.g., electric field, magnetic field, temperature field) to guide the oriented assembly of molecules is an emerging process strategy. The application of an external electric field during the film formation process can induce the orientation of polar molecules, enhancing the consistency between the π-π stacking direction and the charge transport direction. Magnetic fields can be used to regulate the orientation of molecules with anisotropic magnetic susceptibility. These field-assisted methods provide new approaches for precise manipulation at the molecular level.

4.3. New material systems

The development of new material systems is the fundamental way to break through the existing performance bottleneck and achieve a leap in mobility. In recent years, a number of new material systems have shown impressive performance.

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4.3.1. High molecular weight narrow distribution polymers

The performance of polymer semiconductors is closely related to their molecular weight distribution. High molecular weight and narrow distribution of conjugated polymers can be obtained by improving synthesis methods (e.g., GRIM method, CTRP, etc.). High molecular weight polymers have longer conjugated lengths and fewer chain terminal defects, which are beneficial to intrachain charge transport; narrow molecular weight distribution reduces energy disorder and promotes interchain ordered assembly. For example, donor-acceptor type polymers based on DPP (diketopyrrolopyrrole) have achieved a hole mobility of over 10 $cm^2/V \cdot s$ by precisely controlling the molecular weight, approaching the level of amorphous silicon [44].

4.3.2. Small molecule-polymer composite systems

Blending high-performance small molecule semiconductors with polymer matrices can combine the advantages of both: small molecules provide efficient charge transport channels, and polymers provide good film-forming properties and mechanical toughness. By regulating the mixing ratio, compatibility, and phase separation morphology, a interpenetrating structure can be formed in which small molecule crystals are embedded in a polymer network, achieving both high mobility and good mechanical flexibility. This type of composite material is particularly suitable for flexible electronics and large-area device preparation.

4.3.3. Two-dimensional organic semiconductors

Inspired by inorganic two-dimensional materials (such as graphene), two-dimensional organic semiconductors have attracted extensive attention in recent years. These materials typically possess extended π-conjugated planes and highly anisotropic charge transport characteristics. By designing large-area π-conjugated molecules and controlling their layer-by-layer self-assembly, organic ultrathin crystals with two-dimensional electronic characteristics can be prepared. For example, certain phthalocyanine and porphyrin derivatives can form two-dimensional structures similar to graphene under specific conditions, exhibiting high in-plane mobility and out-of-plane insulation characteristics, which provide a new material platform for future high-performance organic electronic devices [45].

4.3.4. Organic-inorganic hybrid materials

Organic-inorganic hybrid materials (such as perovskite materials) combine the processing advantages of organic materials with the high-performance characteristics of inorganic materials. Although typical perovskite materials (such as CH3, NH3, PbI3) are generally considered inorganic semiconductors, the presence of organic components provides unique dimensions for performance regulation. By regulating the structure and properties of organic components through molecular design, the crystallization process, dimensional control, and charge transport behavior of the materials can be influenced, achieving a significant enhancement in mobility [46]. These materials have exhibited revolutionary performance in the field of optoelectronics, and their design concepts have also provided important references for purely organic semiconductors.

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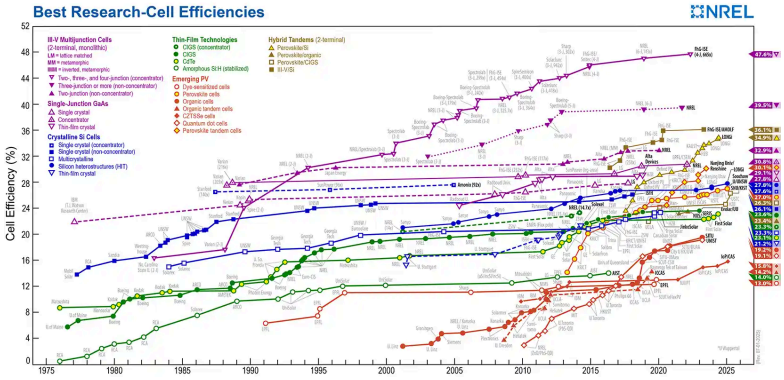

Figure 8. Best research-cell efficiencies

4.3.5. Single-crystal and wafer-level thin films

Although it is difficult to prepare, organic single crystals are still considered as the ideal system to investigate the intrinsic charge transport mechanisms and achieve the highest mobility. The mobility of high-quality organic single crystals prepared by physical vapour transport (PVT), solution-based epitaxy and other methods can be as high as 10~100 $cm^2/V \cdot s$ [47], or even higher. In recent years, the important breakthroughs have been made in the preparation of wafer-level organic single-crystal films. For example, the methods such as "double-wire source evaporation", "macroscopic sublimation" can prepare high-quality crystal films with large area and controllable thickness, which have laid a foundation for the commercial application of organic electronic devices [48].

5. Applications and challenges

5.1. Device application examples

Organic semiconductors, with their unique flexibility, solution-processability, and low cost advantages, have shown extensive application potential in various frontier electronics fields. In display technology, flexible OLED displays have achieved commercial production, widely used in high-end smartphones, foldable devices, and smart wearable products, where their lightweight and bendable characteristics greatly enrich the design dimension of consumer electronics. In the field of transistors, the development of high-performance organic field-effect transistors (OFETs) is rapidly advancing, particularly showing unique advantages in sensors, electronic tags, and low-cost integrated circuits, such as flexible gas sensors for environmental monitoring and pressure sensor arrays for the Internet of Things. In the energy field, organic photovoltaic cells (OPVs), with their lightweight, translucent, and customizable color features, have opened up new application directions in building-integrated photovoltaics (BIPV) and indoor light energy harvesting scenarios. Additionally, organic semiconductors also show important application prospects in emerging fields such as flexible memory devices, biochemical sensors, and artificial synapses.

5.2. Current technical bottlenecks

Despite significant progress in organic semiconductor technology, its further development and large-scale commercialization still face several key technical bottlenecks. Firstly, the carrier mobility of organic materials is generally lower than that of traditional inorganic semiconductors (such as silicon and oxide semiconductors), which limits the performance of organic devices in high-

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frequency and high-speed application scenarios. Secondly, organic semiconductors are more sensitive to environmental factors (such as oxygen, moisture, and light), leading to insufficient long-term stability and working life of devices, and increasing the complexity and cost of packaging technology. Furthermore, controlling the uniformity of thin films and consistency between batches during large-area preparation still poses challenges, as solution-based film formation can easily produce coffee ring effects, phase separation non-uniformity, and other issues, affecting device yield and performance distribution [49]. Additionally, the high cost of material synthesis and purification, the performance lag of n-type materials behind p-type materials, and the lack of unified theoretical models and performance characterization standards also collectively restrict the further development of the entire field.

6. Conclusions and prospects

Elevating the carrier mobility of organic semiconductors is a core challenge for achieving their high-performance and large-scale commercial applications. In recent years, significant progress has been made in the mobility of organic semiconductor materials through molecular engineering to optimize the energy level structure, side-chain design, and conjugated system, combined with the precise control of thin-film processes, such as solution shearing, epitaxial growth, and annealing techniques. Some high-performance material systems have approached the level of amorphous silicon. Additionally, the development of new materials, such as high-molecular-weight polymers, two-dimensional organic semiconductors, and organic-inorganic hybrid materials, has also provided new avenues for breaking through the mobility bottleneck.

Looking ahead, the development of organic semiconductors will increasingly rely on interdisciplinary collaborative innovation. Theoretical simulations and artificial intelligence-aided molecular design will accelerate the screening and development of high-performance materials; fine control of interfacial engineering and optimization of device structures are expected to further reduce the defect state density and improve carrier transport; and the integration of high mobility with good environmental stability and mechanical robustness will become a key research direction, especially for flexible, stretchable electronics, and bio-integrated devices. With the continuous development of wearable devices, the Internet of Things, and green energy technologies, organic semiconductors are expected to play a more critical role in flexible displays, large-area sensing, low-power electronics, and renewable energy, ultimately achieving the transition from laboratory innovation to industrial applications.

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