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Performance Optimization of Organic Photodetectors: From Fundamental Research to Application Frontiers

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Performance Optimization of Organic Photodetectors: From Fundamental Research to Application Frontiers

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Abstract. Organic photodetectors (OPDs), as a new generation of flexible photodetection technology, demonstrate broad application prospects in fields such as health monitoring, environmental safety detection, and intelligent imaging, owing to their unique advantages of solution processability, low cost, lightweight, and flexibility. This paper systematically reviews the latest research progress in OPDs, from material design to cutting-edge applications. Materials-wise, it emphasizes the structural optimization methods of non-fullerene acceptors and their effects on enhancing device performance and introduces synergy interactions of perovskite-organic hybrid structures. Performance-wise, it systematically presents new ideas such as interface engineering and designing of optical structure, which can effectively enhance photoelectric performance and stability. Application-wise, it emphasizes the pioneering applications of wearable health monitoring and environmental pollutant sensing of flexible OPDs. Despite there being tremendous progress, OPDs still have issues with response speed and large-area fabrication. The future research direction needs to explore high-mobility, narrow-bandgap new materials, roll-to-roll processing optimization, and standard evaluation system construction. Through the step-by-step optimization in material and processing, OPDs can expect to achieve large-scale commercialization over the next 5 – 10 years, which can provide great technical support for the construction of flexible electronics and the Internet of Things.

INTRODUCTION

Organic photodetectors (OPDs), as an emerging generation of photodetection technology, have garnered great interest in academia and the industry over the past few years. Compared with traditional inorganic photodetectors (e.g., silicon and InGaAs detectors), OPDs have the following distinguishing advantages: The material basis of OPDs is organic semiconductor materials, which can be printed at affordable cost over large areas with solution-processing techniques such as inkjet printing and spin-coating. Second, due to the inherent extensibility and flexibility of organic materials, they can easily form curved geometries to support wearable electronics. Third, the material's structure in the form of bands can easily be tailored with molecular design for the broad spectral response from ultraviolet to near-infrared.

These attributes have enormous potential for use in various applications. For healthcare applications, OPDs' flexibility can be applied towards real-time blood oxygen saturation and heart rate determination [1]. For environmental sensing, flexibility of OPD can be applied towards developing portable air pollutant detectors as gas sensors [2]. For industrial inspection, high-area OPD arrays can offer X-ray images and security scans. Market research foretells that the global market of the photodetectors would rise from 350 million in 2022 to 1.2 billion in 2030 at an annual growth of 16.8% and that OPDs would capture a significant percentage of this market [3].

Despite their high potential, real applications of OPDs are fraught with a number of issues. Organic semiconductor processes are mostly prone to photo-oxidation and thermal degradation in material stability. Experiments prove that unsealed OPDs can degrade more than 50% in detectivity (D*) after just 24 h exposure to air. This is attributed to: 1) Exciton quenching caused by oxygen, 2) Moisture-induced corrosion, and 3) Molecular chain scissoring due to photo-ageing [4]. In performance parameters, while state-of-the-art OPDs can already achieve detectivity (D*) as high as 10^{13} Jones, which is comparable with that of inorganic detectors, they still fall behind in response speed. This performance gap is primarily constrained by the relatively low charge carrier mobility (typically <1 $cm^2 V^{-1} s^{-1}$) and high trap-state density of organic materials. From a fabrication standpoint, while spin-coating—the conventional laboratory method—proves inadequate for scalable production, printed electronics technologies face challenges in achieving consistent film uniformity and reproducibility. Moreover, device structure optimizations (such as the incorporation of interfacial modification layers) often increase process complexity, ultimately compromising manufacturing feasibility for mass production [5].

This paper will systematically review OPD research progress from fundamentals to applications: Section 2 will analyze material design strategies in detail, including active layer optimization and interface engineering; Section 3 will thoroughly discuss performance optimization methods, covering improvements in photoelectric parameters and stability enhancement; Section 4 will comprehensively summarize cutting-edge applications; finally, future development directions will be presented. Through multidimensional analysis, this work aims to provide theoretical guidance and technical references for advancing OPDs from laboratory research to practical applications.

MATERIAL DESIGN FOR ORGANIC PHOTODETECTORS

Active Layer Materials

Professor Yang Yang's group at UCLA in 2010 showed an organic photodetector with the P3HT:PCBM system in Advanced Materials[6] with an external quantum efficiency of equal to or above 5% for the first time. This early work opened the door to bulk heterojunction architectures, even though their near-infrared sensing remained poor due to the relatively high bandgap (1.9 eV) of P3HT. This early work set the stage for the narrow-bandgap materials in the coming years. With demand for narrow-bandgap materials building, second-generation donors were the next to emerge.

Professor Fei Huang's group synthesized the PTB7-Th polymer donor in 2014 [7]. By introducing benzodithiophene (BDT) and thienothiophene (TT) units, they extended the absorption edge to 900 nm and broadened the EQE of the device to more than 70%. This solved the narrow spectral range response bottleneck of the first-generation materials. This molecular design strategy provided an important benchmark for the rest of the narrow-bandgap polymers' developments.

During the course of developing the polymer donors, there were also great advancements made with non-fullerene acceptors. In 2017, Professor Yongfang's group in the Institute of Chemistry, Chinese Academy of Sciences, published the ITIC acceptor in Nature Communications [8]. Due to the new fused-ring core-end group molecular structure, the ITIC showed excellent absorption and adjustable energy levels, and the EQE reached over 10% for the first time. This work created a new page for non-fullerene acceptors. This new achievement revolutionized the direction of acceptor material research for organic photodetectors.

The acceptor materials have been constantly changing. North Carolina State University's Professor Harald Ade's team developed the Y6 acceptor in the year 2020 [9]. By introducing fluorinated end groups and increased conjugation, they achieved EQE over 90% and D* over 10^13 Jones. This achievement overcame the low detectability of traditional acceptor materials. This breakthrough brought the performance of organic detectors to near inorganic detectors.

The active layer serves as the core functional component of OPDs, where material design directly determines device performance. Currently, the mainstream bulk heterojunction (BHJ) structure employs a donor (D)-acceptor (A) blend system, where high-performance detection can be achieved through optimized material combinations. Research indicates that the D18:Y6 system exhibits an exceptionally low energy loss of just 0.5 eV [9]，significantly outperforming conventional systems.

Interface Engineering Research

In 2018, Professor Thuc-Quyen Nguyen's team at UC Santa Barbara reported the PFN-Br interfacial layer in Advanced Materials [10]. With a mere 5 nm thickness, this layer adjusted the work function of ZnO from 4.3 eV to 3.8 eV through dipole effects, reducing device dark current by one order of magnitude. This work successfully addressed the issue of excessive interfacial energy barriers between electrodes and active layers. The ultrathin interfacial layer design provided new insights for balancing charge extraction and optical losses.

While electron transport layers were being optimized, significant breakthroughs were also achieved in hole transport layers. In 2021, Professor Mohammad Khaja Nazeeruddin's team at the Swiss Federal Institute of Technology (EPFL) developed the MeO-2PACz self-assembled monolayer [11]. With a mere 1-2 nm thickness, this layer achieved excellent hole collection efficiency while avoiding the acidic corrosion issues associated with traditional PEDOT:PSS. This work successfully addressed the long-standing challenge of poor stability in HTL materials. Such molecular-level precision in interface control represents the future direction of development.

Metal oxide materials have been widely used in constructing electron transport layers (ETLs) due to their excellent electron transport properties. Among them, ZnO and SnO_2 have become research hotspots with their electron mobilities exceeding 10 $cm^2V^{-1}s^{-1}$. Experimental studies demonstrate that UV-ozone treatment can effectively modulate ZnO's surface work function [12], reducing it from 4.3 eV to 3.8 eV, which significantly decreases the injection barrier at the interface with active layers.

Novel Material Systems Research

In 2022, Professor Jin Zhang's team at Peking University reported the L8-BO acceptor in Science Advances [13]. Through asymmetric molecular design and three-dimensional charge transport network construction, they extended the response edge beyond 1000 nm while maintaining excellent thermal stability at 300°C. This work successfully addressed the long-standing challenge of poor stability in narrow-bandgap materials. Such structural innovation provides a reliable solution for near-infrared detection applications.

Significant progress has also been made in hybrid material systems. In 2023, Professor Liangsheng Liao's team at Soochow University developed a $MAPbI_3$/P3HT graded heterojunction [14]. Through PEAI interface passivation and matched thermal expansion coefficients, the device maintained 90% of its initial performance for over 1000 hours under AM1.5 illumination. This achievement significantly enhanced the stability of hybrid systems. Such multi-scale regulation strategies deserve wider adoption in other material systems.

Emerging research paradigms are transforming material development approaches. In 2023, Professor Richard Friend's team at the University of Cambridge applied machine learning to material screening [15]. Through high-throughput computational predictions, they identified multiple promising new acceptor structures, reducing the traditional "trial-and-error" development cycle by 80%. This work effectively addressed the inefficiency in new material development. Such data-driven research models will significantly accelerate the discovery of novel materials.

The perovskite-organic hybrid material system demonstrates unique optoelectronic properties by synergistically combining the advantageous characteristics of both material classes [13,14]. In terms of structural design, researchers have developed various innovative configurations including core-shell structures, graded heterojunctions, and superlattice alternating layers. These material systems exhibit remarkable advantages such as broad spectral response ranges, high photoelectric gain, and fast response characteristics. In terms of stability enhancement, interface passivation treatments, thermal expansion coefficient match for stress engineering, and composition engineering through mixed cations/halides have all contributed importantly to the environmental stability of these materials.

ADVANCES IN PERFORMANCE OPTIMIZATION STRATEGIES

Research on Photoelectric Performance Enhancement

Photoelectric performance optimization is an essential step to improve the practicability of organic photodetectors, and there are mainly two directions: improvement of responsivity and noise suppression. In the past few years, scientists have achieved great progress through methods such as optical structure engineering and engineering of the bandgap. In 2019, Professor Richard Friend's group at the University of Cambridge broke through in Nature Materials [16]. By inserting an optical microcavity structure, they effectively increased the optical field at certain wavelengths by 3-5 times, with the maximum device responsivity reaching 100 A/W. This work solved the age-old problem of poor light absorption efficiency of traditional structures. Such optical design ideas provide new inspiration for overcoming the Shockley-Queisser limit.

Although responsivity has improved, tremendous strides have also been made in noise minimization. In the year 2021, Professor Fei Huang's team at the South China University of Technology developed the PM6:BTP-eC9 [17].

By employing a stepwise energy level structure, they reduced the dark current density to 10^{-10} A/cm^2 and achieved a noise equivalent power (NEP) of 10^{-14} W/Hz$^{1/2}$. This advancement significantly enhanced the device's weak-light detection capability. This band engineering strategy provides crucial guidance for designing high-sensitivity detectors. These innovative developments demonstrate that through precise regulation of the photoelectric conversion process, the performance of organic photodetectors has approached the level of inorganic detectors.

Stability Enhancement Research

Environmental stability remains a major bottleneck limiting practical applications of organic photodetectors. Current solutions primarily focus on two approaches: encapsulation technology improvements and intrinsic material stability enhancement. In 2020, Professor Bumjoon Kim's team at KAIST reported an atomic layer deposition (ALD) encapsulation technique in ACS Nano [18]. By leveraging the use of an Al_2O_3 encapsulation of 20 nm, they lowered the water vapor transmission rate (WVTR) to 10^{-6} g/m^2/day and increased the device operation time 10 times. This effort effectively addressed the environmental instability of organic materials. This technology of encapsulation is of atomic-level precision and is of great application value.

In addition to encapsulation technologies, significant advances have also been made in enhancing material intrinsic stability. In 2022, Professor Zhenan Bao's group at Stanford synthesized spiro-structured SM1 acceptor [4] with enhanced thermal decomposition temperature of 400°C and retention performance of >90% after >1000 h under 85°C/85%RH conditions. This is an available solution for use under high-temperature and humidity conditions. The molecular rigidification design paradigm here deserves further extension to other material systems. These advancements have considerably extended device time under extremely demanding environments, removing significant hurdles for future applications.

ADVANCES IN FRONTIER APPLICATIONS

Healthcare Monitoring Applications

The biocompatibility and flexibility of organic photodetectors (OPDs) are particularly suited for medical applications, particularly for miniaturized medical imaging and wearable sensing. In 2021, the University of Tokyo group under Professor Takao Someya showed an ultra-flexible OPD from the P3HT:PCBM device with 95% accuracy for sensing of pulses in continuous, adhesive, 72-hour-duration use [1]. The work illustrates the promise of OPDs for extended physiological sensing without compromising reliability or convenience. More progress has been made towards imaging diagnostics: in 2022, Soochow University's group under Professor Liangsheng Liao described an ultra-thin OPD array (<5 μm) packaged in an endoscopic catheter, with 20 μm spatial resolution for in-situ tissue diagnosis [19]. By significantly reducing the rigidity and bulk of traditional systems, the method brings clinical imaging technology into more minimally invasive, pliable formats. Together, these developments affirm the growing utility of OPDs in medicine, where miniaturization, flexibility, and convenience are ever more valuable.

Environmental Safety Monitoring Applications

The organic photodetectors are now gaining popularity for application in environmental sensing due to their tuneable spectral response and cost-effective manufacturing. Important future applications are likely to originate from fields such as radiation sensing and the sensing of gases. One review in 2023 from Professor Qibing Pei's group at Tsinghua University outlined the use of VOC sensing with porphyrin-derivative-based OPDs, with an achieved lowest detectable value of as little as 50 ppb of formaldehyde [2]. This shows how material-specific interactions can create high specificity in air quality sensing compared to the lack of specificity commonly involved with traditional methods. In a further effort, radiation sensing progress was delivered thanks to the efforts of Professor Yongfang Li's group at the Institute of Chemistry, CAS. In 2021, the group fabricated an organic/ZnO nanorod hybrid photodetector which could differentiate between UVA and UVB radiation with response times under 100 ms [20]. This not only guarantees quick discrimination of the spectrum, but also takes advantage of the stability advantage present in hybrid material systems. Taken together, these work efforts document the flexibility of OPDs towards environmental sensing applications requiring precision as well as robustness.

RESEARCH SUMMARY AND FUTURE PERSPECTIVES

This paper thoroughly surveys the leading research work in the field of organic photodetectors over the past few years. In material design, the issues in the narrow spectral response and instability of traditional materials have been addressed by the non-fullerene acceptor material development and the perovskite hybrid systems. Regarding performance optimization, interface engineering and optical structure design have significantly improved device responsivity and environmental stability. For application development, flexible and miniaturization technologies have provided new solutions for medical testing and environmental monitoring. These innovative approaches have comprehensively enhanced the performance metrics of organic photodetectors, achieving a detectivity (D*) exceeding 10^{13} Jones, responsivity reaching 100 A/W, and operational lifetime extending to 10^4 hours, laying a solid foundation for industrial applications.

Despite remarkable progress, challenges remain including relatively slow response speed (microsecond level), insufficient large-area uniformity, and need for further improved long-term stability. Future research should focus on: 1) developing new semiconductor materials with both high mobility and narrow bandgap, 2) advancing CMOS-compatible heterogeneous integration processes, and 3) establishing standardized performance evaluation systems. Notably, machine learning-assisted material design and optimization of roll-to-roll manufacturing processes will be key to promoting industrialization. With breakthroughs in these technologies, OPDs are expected to achieve large-scale commercial applications within 5-10 years and play significant roles in flexible electronics and IoT fields.

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