Next-Generation Organic Photodetectors: Hybrid Architectures and Applications

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Abstract. Organic photodetectors (OPDs) have attracted significant attention due to their flexibility, broadband sensitivity, and potential for integration with wearable electronics and 6G communications. Notably, their low-cost fabrication via solution processing further enhances their competitiveness compared to traditional inorganic photodetectors. This work reviews recent progress in OPDs and hybrid architectures including tandem perovskite, 2D perovskite, TMD (transition metal dichalcogenides), quantum-dot, graphene-plasmonic, and black phosphorus heterojunctions. The mechanisms of photon-to-current conversion, interfacial charge transport, and hybrid material integration mechanisms are discussed in detail. Research demonstrates that by tailoring dimensionality, energy alignment, and interfacial chemistry, the long-standing trade-off between speed, noise, and stability can be mitigated. These advances address critical issues such as high dark current, poor stability, and limited reproducibility, thus paving the way for the use of OPDs in healthcare monitoring, environmental sensing, and optical communication. The review highlights both achievements and challenges, emphasizing the need for scalable, defect-free fabrication and environmentally safe materials.

Keywords: Organic photodetectors (OPDs); wearable devices; optical communication applications.

1. Introduction

Organic photodetectors leverage solution-processable π-conjugated polymers and small molecules to offer mechanical flexibility, low weight, and broadband sensitivity from the visible to the near-infrared, yet unbalanced carrier mobility and interfacial defects still compromise their temporal response and noise performance when compared to inorganic counterparts [1]; therefore, advancing high-performance organic photodetectors (OPDs) will not only eliminate the weight and rigidity constraints inherent to conventional detectors and substantially reduce the fabrication cost of large-area arrays, but also establish a key sensing platform for flexible electronics, wearable diagnostics and spatial communication networks, while enabling conformal OPD arrays laminated onto 6G base-station reflectors to provide low-power fronthaul links [2]. Additionally, on-board short-wave-infrared imaging systems augmented by OPDs enhance pedestrian recognition under fog and rain, and ultra-thin OPD probes attached to endoscopic tips further support near-infrared fluorescence guidance for real-time intraoperative tumor-margin delineation [3].

Although organic photodetectors exhibit exceptional sensitivity and mechanical flexibility, their advancement remains constrained by three persistent bottlenecks [4]. First, the sustained imbalance between electron and hole mobilities prolongs carrier transit time and inevitably degrades temporal resolution. Second, nanometer-scale pinholes and interfacial energetic disorder facilitate defect-assisted recombination, markedly increasing dark current and electronic noise. Most critically, the solution-processed soft films that confer outstanding bendability are inherently susceptible to oxygen ingress, moisture penetration, and thermal drift, resulting in a pronounced decline in long-term stability and large-area reproducibility [5].

This research systematically investigates perovskites and low-dimensional quantum materials to uncover the fundamental interplay between carrier transport and interfacial charge transfer, thereby establishing a quantitative framework for the response-speed-noise trade-off; by co-designing these materials with on-chip photonic structures, it paves the way for higher-bandwidth 5G receivers [6-8]. Clinically, the resulting self-powered sensors enable painless, real-time detection of blood biomarkers

at picomolar levels, while environmentally, their light-harvesting operation eliminates battery dependence and supports zero-maintenance, distributed environmental monitoring networks for advancing carbon neutrality.

2. Organic Photoelectric Detector

2.1. Working Mechanism

Inside an OPD, photon-to-current conversion proceeds through a sequential process of absorption, diffusion, dissociation, transport, and collection. When visible-to-near-infrared light impinges on the active layer—typically a blend of a donor polymer and an acceptor small molecule—its energy is captured by π-conjugated backbones, promoting electrons from the valence band to the conduction band and producing bound electron-hole pairs termed excitons. These excitons possess lifetimes ranging from hundreds of picoseconds to a few nanoseconds and migrate by diffusion over distances of 10-20 nm. Consequently, the thickness of the active layer is engineered to match this diffusion length to minimize bulk recombination. Upon reaching the donor–acceptor heterojunction, the excitons encounter an energy offset of 0.3–0.5 eV combined with an intrinsic electric field, which promptly dissociates them into free charges: electrons are injected into the acceptor phase and holes remain in the donor phase [9].

Electrons then drift toward the cathode through the acceptor network, while holes drift toward the anode through the donor network; their mobilities are governed by molecular ordering and trap density. To maximize collection efficiency, an electron-transport layer (such as ZnO or SnO_2) is inserted at the cathode side and a hole-transport layer (MoO_3) at the anode side. These layers establish energy-level gradients that reduce injection barriers and passivate interfacial defects, enabling carriers to be collected by the metal electrodes within sub-microsecond timeframes, thus yielding a stable photocurrent. After low-noise trans-impedance amplification, the photocurrent is converted into a voltage signal that can directly interface with a 12-bit ADC or a Bluetooth SoC. In health-monitoring scenarios, a 50-μm-thin OPD patch attached to a fingertip outputs a voltage waveform that scales linearly with blood-oxygen saturation in real time. In environmental-monitoring scenarios, large-area flexible OPD arrays integrated with LoRa modules operate self-powered under 1000 lux indoor lighting, continuously uploading PM2.5 and temperature–humidity data to the cloud, thereby establishing a zero-battery, maintenance-free distributed sensor network [4].

Perovskite detectors utilize perovskite-structured semiconductors to convert high-energy radiation directly into measurable electrical signals. The key principle is as follows: when X- or γ-rays enter the crystal, photons interact with the lattice to generate a large number of energetic electron–hole pairs. Thanks to the high carrier mobility–lifetime product of the material, these charges are rapidly collected by electrodes under an applied electric field, forming a measurable current pulse. By optimizing crystal orientation and interfacial passivation, ionic migration noise is suppressed, enabling high-sensitivity, low-dark-current operation at room temperature [7].

From laboratory prototypes to system-level deployment, perovskite detectors now serve medical imaging, industrial non-destructive testing, security screening, and nuclear safety monitoring. Compared with traditional amorphous selenium, silicon, or CdZnTe devices, perovskites can be processed by low-temperature solution methods, allowing monolithic integration with flexible TFT arrays for large-area, lightweight, and low-cost flat-panel detectors. Their high atomic number and strong absorption coefficient both increase hard-X-ray absorption by more than an order of magnitude at the same thickness, significantly reducing patient or object dose. Moreover, superior tolerance to temperature and radiation damage enables stable long-term operation over a wide temperature range, opening new possibilities for portable imaging and on-site radiation monitoring [10].

2.2. Organic–Perovskite Tandem Detector

Organic-perovskite tandem detectors employ vertically stacked structures for complementary spectral detection [3]. The working principle relies on synergistic energy level design: the upper wide-

bandgap PM6 organic layer (Eg = 1.8 eV) preferentially absorbs 400–600 nm visible light, with excitons migrating to the perovskite interface via Förster resonance energy transfer (FRET); the lower narrow-bandgap $FA_{0.75}MA_{0.25}PbI_3$ perovskite (Eg = 1.55 eV) captures 600–800 nm near-infrared photons, enabling dual-band tandem absorption [4]. Driven by a 0.2 eV energy gradient established by the polyfluorene-based polymer (PFN-Br) dipole layer, exciton dissociation efficiency reaches 98%, with electron injection into the perovskite conduction band is 3× faster than in conventional structures while effectively suppressing phase separation caused by I^- ion migration. This architecture offers notable advantages: a peak external quantum efficiency of 95%, a spectral response covering 400–800 nm (enabling single-pixel visible-near infrared (NIR) dual-mode imaging), and 92% performance retention when flexed to a 3 mm radius on Polyethylene Terephthalate (PET) substrates—suitable for curved wearables like smart bands.

However, challenges include 40% efficiency degradation after 72 hours at 85% (relative humidity) RH, and stringent thickness requirements (150±5 nm for the organic layer and 250±10 nm for the perovskite layer) with processing reproducibility of only 65%. While 6 cm × 6 cm flexible modules (254 PPI pixel density) have been lab-validated, roll-to-roll production yields currently remain below 70%, requiring improved large-area perovskite crystallization uniformity for commercialization.

2.3. Organic–2D Perovskite Heterojunction

Organic-2D perovskite heterojunctions achieve efficient carrier separation through dimensionality engineering [5]. The fabrication involves spin-coating a PEDOT:PSS/PM6:Y6 bulk heterojunction on PET substrates, followed by the transfer of a monolayer of $(C_4H_9NH_3)_2PbI_4$ 2D perovskite sheets to form a Type-II band alignment (0.35 eV conduction band offset) [6]. Exciton dissociation at the interface enables electrons to transport through the high-mobility in-plane channel of the 2D perovskite (15 $cm^2\ V^{-1}\ s^{-1}$ at RT (room temperature)) while holes migrate through the organic layer, achieving spatial charge separation. The high dielectric constant ($\varepsilon \approx 8.5$) of the 2D perovskite passivates interface defects, suppressing dark current to 2×10^{-9} A cm^{-2}, with its 3 dB bandwidth exceeding 150 MHz due to 2D electron gas formation. This structure achieves 0.85 A/W responsivity at -0.5 V bias with 88% performance retention after 500 bending cycles. However, monolayer transfer yield remains 30–40% with frequent micrometer-scale cracks, and the extreme moisture sensitivity requires encapsulation with 10^{-5} g m^{-2} day^{-1} barrier films. While 2-inch flexible wafers have been validated in pilot lines (e.g., MIT and Swift Solar), commercial production lines have not yet been fully established.

2.4. Organic–TMD Hybrid

Organic-TMD hybrid detectors enhance performance through 2D material interface engineering. A monolayer MoS_2 charge transport layer deposited on a PM6:Y6 bulk heterojunction creates dual carrier transport pathways: photogenerated electrons are rapidly transported through MoS_2's high-mobility channel (>200 $cm^2\ V^{-1}\ s^{-1}$) to the cathode, while holes migrate through the organic layer to the anode [7]. The atomically smooth surface of MoS_2 reduces interface recombination, boosting responsivity to a 1.2 A/W at 680 nm and shortening response time to 0.8 ns. With Al_2O_3 atomic layer deposition encapsulation, devices show <5% performance degradation after 1000 hours at 85 °C/85% RH. However, CVD-grown monolayer MoS_2 costs ~\$200/cm^2, and weak interface adhesion (0.5 J/m^2) with the organic layers causes delamination during bending. Sulfur vacancy control requires precise H_2S annealing at 350±5 °C. While 4-inch wafer demonstrations exist, the per-pixel cost remains (5–8) × higher than silicon-based alternatives, preventing their adoption in consumer electronics.

2.5. Organic–QD Sensitized Detector

Organic-quantum dot sensitized detectors leverage quantum confinement effects to extend spectral response. CdSe/CdS core-shell QDs (4.2±0.3 nm diameter) embedded in a PM6:Y6 bulk heterojunction enable narrowband absorption at 520–700 nm (FWHM, full width at half maximum, ≈30 nm) via size tuning [8]. MPA ligand exchange reduces inter-dot spacing from 3.5 nm to 1.2 nm,

facilitating charge tunneling with 85% quantum efficiency. Multiple exciton generation of QDs yields 1.3 excitons per photon, boosting current density to 18 mA cm^{-2}. This structure achieves 1.8 A/W NIR responsivity at -2 V bias with zero performance degradation at 20% strain, ideal for skin-conformal monitoring. However, ligand exchange increases trap density, raising dark current to 5×10^{-8} A cm^{-2}, and Cd content exceeds the RoHS limits (200 ppm). While 1 cm × 1 cm flexible patches show 0.1% SpO_2 sensitivity in blood oxygen monitoring prototypes, FDA medical device certification remains pending during its preclinical validation.

2.6. Organic-Graphene Plasmonic Detectors

Organic-graphene plasmonic detectors integrate monolayer graphene with metallic nano-antennas to achieve near-single-molecule sensitivity in a flexible format. The architecture consists of a PM6:Y6 bulk heterojunction spin-coated on PET, onto which CVD monolayer graphene is then transferred, followed by electron-beam lithography of a periodic gold nano-antenna array (period 300 nm, height 50 nm) [9]. The antennas excite localized surface plasmon resonances that enhance the local electric field by 10^4 ×-fold, boosting photon absorption and hot-carrier generation within the graphene layer. Gate-voltage tuning of the Fermi level shifts the plasmon resonance of the antenna array, enabling narrowband detection at the telecom wavelength of 1.55 μm with a responsivity of 0.9 A/W and a specific detectivity approaching 10^9 Jones. Response times below 200 ps have been recorded, making the platform attractive for high-speed optical interconnects. Mechanical tests show no degradation after 1000 bending cycles at a 2 mm radius.

The key challenges are economic and lithographic: CVD graphene exhibits ±5% layer-number non-uniformity, and electron-beam patterning of the antenna array raises fabrication costs beyond \$50/cm^2, limiting its deployment to disposable wearable optical communication patches. Roll-to-roll nanoimprint lithography is under investigation to reduce cost by an order of magnitude.

2.7. Organic-Black Phosphorus Heterojunction Detectors

Organic-black phosphorus heterojunction detectors exploit the thickness-dependent direct bandgap of few-layer black phosphorus (BP) to extend detection into the short-wave infrared while maintaining polarization sensitivity [10]. Four- to six-nanometer-thick BP flakes are dry-transferred onto a PM6:PCBM bulk heterojunction, forming a Type-II band alignment in the heterojunction, with an interfacial electric field that drives efficient charge separation. The anisotropic in-plane mobility (1000 cm^2 V^{-1} s^{-1} along the armchair direction versus 200 cm^2 V^{-1} s^{-1} along the zigzag direction) enables polarization-resolved detection with an extinction ratio of 20:1 without external polarizers. Coupled with the organic layer, the device delivers a responsivity of 1.5 A/W at 1550 nm and a noise-equivalent power of 3 pW $Hz^{-1/2}$ under −1 V bias. The primary obstacles are environmental stability and manufacturing reproducibility: BP oxidizes rapidly in ambient air, requiring encapsulation with oxygen and moisture levels below 10^{-3} ppb. Furthermore, mechanical exfoliation yields only 10% of flakes within the desired thickness range (±1 nm), driving the cost per 4-inch wafer above \$200. Scalable synthesis via pulsed-laser deposition (PLD) is being explored to achieve wafer-scale uniformity and to satisfy cost targets for consumer electronics integration.

3. Conclusion

This comprehensive review has traversed six complementary hybrid platforms—tandem perovskite, 2D-perovskite, TMD, quantum-dot, graphene-plasmonic, and black-phosphorus heterojunctions—to articulate a coherent roadmap for the real-world deployment of next-generation organic photodetectors. By systematically manipulating dimensionality (bulk → layered → monolayer), energy-level alignment (Type-I → Type-II → cascaded), and interface chemistry (covalent → van der Waals → dipole-mediated), the community has converted the once-rigid trilemma of speed, noise, and mechanical flexibility into a continuously tunable parameter space. Central lessons include the pivotal role of energy cascades in accelerating exciton dissociation while

suppressing non-radiative recombination, the decisive advantage offered by atomically smooth 2D channels for sub-nanosecond carrier extraction, and the delicate balance between bendability and hermeticity that dictates long-term environmental stability. Outstanding challenges—scalable, defect-free transfer of monolayers; lead-free and RoHS-compliant compositions; and roll-to-roll integration of photonic cavities—have been explicitly itemized together with emerging solutions such as slot-die crystallization, pulsed-laser deposition, and nanoimprint lithography. When these final barriers are overcome, the resulting ultralight, conformal photonic front ends will seamlessly laminate onto 6G base-station reflectors for low-power fronthaul, adhere to skin as self-powered biochemical monitors, populate the zero-maintenance environmental grids for carbon-neutral cities, and equip autonomous vehicles with fog-penetrating vision systems—thereby catalyzing a convergent leap across information technology, sustainable energy, and precision healthcare.

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