Research on Applications and Optimized Design of Biosensors Based on OEGFETs

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Abstract. Rapid biomarker detection is essential for early disease diagnosis and point-of-care testing. Organic electrolyte-gated field-effect transistors (OEGFETs) have become attractive bioelectronic sensor platforms because they operate at low voltage, deliver high sensitivity, and can be fabricated on flexible substrates. This study systematically reviews recent technological advances to map how OEGFET-based biosensors are applied and optimized. Applications are grouped into three main areas: disease screening, health monitoring, and therapeutic evaluation. Performance is improved through interface engineering, novel materials, and refined device architectures. OEGFET biosensors reach detection limits down to 1 pM for cortisol and microRNA, and certain designs sense HIV and Parkinson's biomarkers at femtomolar levels. Extended-gate and stretchable geometries enhance operational stability; the latest prototypes remain functional even under 100 % mechanical strain. These results highlight the potential of OEGFETs as low-cost, high-performance diagnostic tools for personalized medicine and decentralized healthcare. Coupling the sensors with wireless communication modules enables real-time physiological monitoring, bringing the technology closer to routine clinical use.

Keywords: OEGFET, biosensor, interface engineering, point-of-care diagnostics, flexible electronics.

1. Introduction

Chronic diseases, persistent infections, and age-related conditions are placing mounting pressure on healthcare systems across the globe. HIV alone illustrates the urgency: without rapid diagnosis, treatment is delayed and transmission continues. Because traditional assays are slow, depend on centralized laboratories, and are expensive to run, researchers have turned to alternative biosensors that can move testing out of the lab and into point-of-care or decentralized settings [1].

Among emerging sensing platforms, organic electrolyte-gated field-effect transistors (OEGFETs) have drawn growing interest because they unite several attractive traits [2]. The electrical double layer that forms at the electrolyte/semiconductor interface provides a high specific capacitance, letting the devices work below 1 V. Such low-voltage driving keeps power consumption minimal, so OEGFETs fit easily into portable, battery-powered electronics. The organic semiconductor itself adds biocompatibility, mechanical flexibility, and the possibility of solution processing, which together lower fabrication costs and allow direct integration onto bendable substrates [3]. When the transistor surface is functionalized with biorecognition elements, the same structure can selectively detect analytes ranging from small molecules and ions to proteins and nucleic acids.

Although these features are encouraging, OEGFET biosensors have yet to gain broad clinical traction because several hurdles persist [4]. Reproducibility between devices, stable operation in intricate biological media, signal drift, and non-specific adsorption that clogs the surface all continue to undermine reliability. High-ionic-strength physiological fluids further complicate matters: the Debye length shrinks, screening the charge of the target analyte and markedly lowering sensitivity. Investigators have recently countered these drawbacks with anti-fouling coatings, unconventional device geometries, and hybrid organic–inorganic semiconductors.

This study offers a systematic overview of recent progress in OEGFET biosensors, concentrating on where they are used and how their performance is improved. We pursue two main goals: first, to classify and assess OEGFET deployments in disease screening, health monitoring and therapeutic management; second, to scrutinize design refinements that span interface engineering, material choice

and device architecture. By integrating results from leading publications, the review constructs a coherent picture of present capabilities and anticipated advances in OEGFET-based biosensing. The resulting insights will guide future work in overcoming current constraints and hastening the transition of these sensors from bench-top proofs to clinically applicable diagnostics.

2. Fundamental Principles of OEGFET Biosensors

OEGFETs work by letting the potential at the electrolyte–semiconductor junction tunes the channel's conductivity. In the usual layout, source and drain are linked by an organic semiconductor, and the gate reaches the same channel through an electrolyte. A gate bias drives ions to pack into an electrical double layer whose capacitance reaches the μF cm^{-2} range; the resulting field pulls charge carriers into the semiconductor and modulates the current. Because the double layer forms almost instantaneously, the device needs less than 1 V to switch, far below the drive levels of conventional field-effect transistors [1, 5].

3. Application Domains of OEGFET Biosensors

3.1. Disease Screening and Early Diagnosis

OEGFET biosensors have shown outstanding performance in disease screening, especially when the target is a scarce biomarker buried in a complex biological matrix. For HIV-1 diagnosis, a self-powered OEGFET device has been engineered to spot the p24 capsid antigen at femtomolar levels, enabling detection during the earliest phase of infection [2]. By integrating a paper-based biofuel cell that draws energy directly from the specimen, the platform operates without external instruments and satisfies the ASSURED criteria—affordable, sensitive, specific, user-friendly, rapid and robust, equipment-free, and deliverable—making it practical for point-of-care use in resource-poor settings.

In neurodegenerative disease diagnostics, OEGFET platforms have already proven effective for quantifying α-synuclein, the principal biomarker of Parkinson's disease. Serum assays that incorporate either aptamer or antibody recognition layers reach a lower limit of 100 fg mL^{-1} [6]; the aptamer version remains linear from 10 pg mL^{-1} down to this floor, whereas the antibody version covers 1 pg mL^{-1} to 100 fg mL^{-1}. The closely matched sensitivity across two distinct biorecognition strategies underlines the flexibility of the OEGFET architecture and points to its suitability for large-scale Parkinson's screening once the device's small footprint and low unit cost are taken into account [7].

Cancer diagnosis constitutes another key arena for OEGFET biosensors, which have been tailored to spot protein biomarkers such as carcinoembryonic antigen [8]. By integrating photoactive polymer semiconductors, recent prototypes gain marked sensitivity under light, pushing the limit of detection down to the femtomolar range. Illumination triggers a photogating effect that raises the channel's carrier density; this amplification sharpens the electrical signature of biomarker binding and opens a route to earlier cancer detection.

3.2. Health Monitoring and Chronic Disease Management

Embedding OEGFETs in wearable devices for round-the-clock monitoring is now moving forward at speed. One recent design, a stretchable diode-connected array, curbs the signal drift that has long undermined epidermal biosensors. While flexed to twice its length and exposed to temperatures between 30°C and 40°C, the patch simultaneously tracked cortisol, glucose, and sodium in sweat. Pairing each sensing transistor with a reference transistor and reading their difference shrank drift by roughly one hundred-fold relative to a lone device, giving stable data under everyday motion.

To manage metabolic disorders, researchers have designed enzyme-coupled OEGFET sensors that track glucose and lactate continuously. A gate electrode is coated with oxidoreductases such as glucose oxidase; the reaction products shift the local potential, altering the transistor current. Because OEGFETs run at low voltage, they fit comfortably into power-sensitive wearables. Recent prototypes

add wireless links, streaming data straight to phones or the cloud so clinicians can intervene promptly [3,9].

Monitoring electrolyte balance is a key use case, especially for athletes and those with heart or kidney disorders. Ion-selective OEGFET sensors, tailored with specific ionophores, have shown they can reliably pick out Na^+, K^+, and Ca^{2+} in sweat and interstitial fluid. Building these transistors into flexible arrays that stay accurate even when the wearer is moving meets a central demand for real-world wearable health monitors.

3.3. Therapeutic Monitoring and Personalized Medicine

OEGFET biosensors hold clear potential for therapeutic drug monitoring, where drug levels must stay within a narrow window to remain both effective and safe. Although this application has received less attention than diagnostics, a growing body of work shows that OEGFETs can detect antibiotics and other drugs at concentrations encountered in the clinic. Their label-free format and fast signal turnaround give them an edge over standard TDM techniques, opening the prospect of adjusting dosage on the fly through continuous readout.

Personalized medicine now incorporates OEGFET chips that track selected protein biomarkers to gauge how well a therapy is working. Because each transistor in the array can be decorated with a distinct receptor, several biomarkers are monitored at once, giving a fuller picture of efficacy. A recent reusable EGOFET apt sensor that employs a track-etched membrane extends this capability, allowing the same device to be measured repeatedly so that treatment response can be followed over time [4].

4. Performance Enhancement Strategies

4.1. Interface Engineering and Functionalization

Surface engineering largely dictates how an OEGFET biosensor performs, especially its specificity, long-term stability and tolerance to biofouling. Anti-fouling films—poly (ethylene glycol), zwitterionic polymers or peptide-based layers—curtail non-specific protein uptake in complex matrices. By locking in a surface hydration shell, these coatings let the device retain its sensitivity and selectivity while it operates in serum, blood or other biofluids [4].

How capture molecules are anchored to the surface largely determines sensor output. Orienting antibodies or aptamers so that their binding pockets face outward keeps the active sites open, raising sensitivity. Linking them through the Fc glycan or an engineered His-tag, for example, yields higher antigen binding than random adsorption. Selecting between antibodies and aptamers entails compromises: antibodies bring high affinity and well-documented validation, whereas aptamers tolerate harsher conditions and are simpler to modify. Head-to-head tests for α-synuclein show similar detection limits, yet the fully synthetic origin and reproducible synthesis of aptamers could ease commercial scale-up.

Nano structuring the sensing interface offers another potent route to boost performance. By sculpting porous surfaces, nanowires, or nanoparticle assemblies, the effective area expands, accommodating a denser layer of immobilized recognition elements and thereby magnifying the signal. Depositing gold nanoparticles on extended gates, for instance, enlarges the surface available for biomolecule attachment while preserving the electrode flexibility demanded by wearable devices.

4.2. Material Innovations

Progress in organic semiconductors has markedly lifted OEGFET performance. Although poly(3-hexylthiophene) (P3HT) is still common, newer high-mobility polymers—diketopyrrolopyrrole (DPP) and indacenodithiophene-benzothiadiazole (IDT-BT) copolymers—offer better electrical properties and greater environmental stability. Their higher transconductance efficiency (g_m/I_D) sharpens signal-to-noise ratios and lowers detection limits.

Incorporating nanomaterials into organic semiconductors has opened a further frontier. Hybrid channels that interleave organic semiconductors with graphene, carbon nanotubes or metal-oxide nanostructures exploit the nanomaterial's high carrier mobility while retaining the solution processability and biocompatibility of the organic host. These composites already outperform single-component layers in both sensitivity and long-term stability.

Dielectric materials are equally decisive for OEGFET performance. Tailoring their properties and the adjacent interfaces has been demonstrated to lower the operating voltage and to stiffen the device against bias-stress drift. Common routes adopt high-k dielectrics to raise the gate capacitance or stack two dielectric layers so that leakage is suppressed without sacrificing mechanical flexibility. When the target is stretchable or bendable electronics, elastomeric dielectrics such as nitrile-butadiene rubber and styrene-ethylene-butylene-styrene have already delivered skin-conformable sensors that continue to operate reliably while being twisted or stretched [10].

4.3. Device Architecture and System Integration

Architectural refinements have removed several intrinsic bottlenecks that once constrained OEGFET biosensors. By introducing an extended-gate layout that moves the biorecognition surface away from the transistor itself, researchers have created a configuration especially well-suited to biosensing. The semiconductor channel no longer sits directly in the electrolyte, so drift is reduced and the same readout electronics can be reused with inexpensive, disposable sensing chips.

Self-powered systems mark a further architectural leap. By coupling OEGFETs with paper biofuel cells that draw energy directly from the sample under test, researchers have produced fully autonomous sensors. These platforms operate without an external supply, a feature that is especially attractive in resource-scarce environments and that pushes equipment-free diagnostics closer to fulfilling the WHO ASSURED guidelines.

By pairing transistors—one with a specific gate, the other with a reference gate—differential measurement schemes largely eliminate the signal drift that has limited field-effect biosensors. In recent tests, drift dropped from roughly 1.2 V for single devices to only 15 mV in the paired layout, an improvement of two orders of magnitude. This advance stabilizes readings over extended runs, a prerequisite for reliable continuous monitoring.

System-level integration has advanced markedly, as shown by fully functional wearable sensing platforms that weave OEGFET arrays, on-board signal processing, and wireless links into a single package. Marrying soft, skin-conforming sensors with miniaturized yet rigid readout electronics has emerged as a workable route to balancing wearer comfort and device performance. These cohesive prototypes stream physiological data in real time and relay it straight to nearby mobile handsets, a milestone that brings clinical deployment meaningfully closer.

5. Conclusion

This review of OEGFET biosensors shows how far the field has come in moving these devices from bench-top proofs to platforms that could soon meet clinical needs. Their scope has widened markedly, now covering disease screening at femtomolar levels, drift-tolerant continuous physiological tracking, and even therapeutic control. Improvements in interface design, materials, and device geometry have together eased the main bottlenecks—limited sensitivity, signal drift, biofouling, and long-term stability.

Although these advances are encouraging, several hurdles must still be cleared before the technology can enter routine clinical use. Fabrication reproducibility—especially for solution-processed OEGFETs—needs to tighten so that performance does not drift between batches. How the devices behave over months in diverse biological settings also remains unclear, and encapsulation schemes that shield the electronics without compromising bio-functionality warrant closer study. Finally, the Debye screening inherent to physiological fluids still caps the attainable sensitivity, yet shorter recognition motifs and high-frequency readout offer credible routes to push this limit back.

Subsequent work should channel effort into four priorities. A first priority is to establish unified protocols for sensitivity characterization; once available, laboratories can compare OEGFET platforms on equal footing and benchmark them against incumbent technologies. Second, systematic validation must extend to clinically relevant specimens drawn from diverse patient cohorts, supplying the evidence needed for dependable real-world performance. Third, expanding multiplexed detection could turn a single chip into a broad diagnostic panel, widening the clinical menu without added bulk. Finally, embedding machine-learning routines in data analysis promises to raise detection accuracy and to reveal predictive patterns hidden within complex biomarker signatures.

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