Graphene and Two-Dimensional Material-Based Field-Effect Transistor Biosensors

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Abstract Field-effect transistor (FET) biosensors have attracted significant attention due to their ability to detect biological analytes with high sensitivity and real-time response. The performance of these sensors strongly depends on the channel material. Graphene and other two-dimensional (2D) materials have significant advantages because of their strong surface sensitivity, high carrier mobility, and atomic thickness. These characteristics enable the detection of minute variations in surface charge by graphene-based FET biosensors. These sensors exhibit great promise for use in wearable medical devices, biomolecule monitoring, and disease detection. Their practical application is constrained by a number of issues, such as fabrication constraints, device stability, and the Debye screening effect. This paper reviews the operating principles, material properties, applications, and challenges of graphene and 2D material-based FET biosensors, and discusses future research directions.

Keywords field-effect transistor, FET, 2D material, biosensors

1 Introduction

Biosensors play an important role in modern healthcare because they allow rapid detection of biological analytes for disease diagnosis and health monitoring [1], [2]. Among different biosensor types, field-effect transistor (FET)-based biosensors have attracted significant attention due to their ability to provide label-free and real-time detection [3], [4]. These sensors detect biomolecules by converting surface charge changes into electrical signals.

The performance of FET biosensors depends strongly on the channel material. Traditional silicon-based sensors have been widely studied and used, but their sensitivity is limited by material properties [5]. Therefore, two-dimensional (2D) materials became as alternative channel materials. Graphene is one of the most widely studied 2D materials due to its atomic thickness and high carrier mobility [6], [7], [19]. These properties allow graphene-based FET biosensors to detect small changes in surface charge with high sensitivity [11].

Other 2D materials, such as molybdenum disulfide (MoS_2), also show promising sensing performance due to their semiconducting properties [16], [17]. However, challenges such as Debye screening, device stability, and fabrication limitations still affect practical applications [10], [21].

This paper reviews the principles, materials, applications, and challenges of graphene and 2D material-based FET biosensors. The high sensitivity of 2D material-based FET biosensors originates from their strong surface coupling and atomic-scale thickness; Debye screening, signal drift arising from stability issues, and device-to-device variability significantly hinder practical implementation. Thus, future developments should focus on interface engineering and scalable fabrication strategies.

2 Fundamentals of Field-Effect Transistor Biosensors

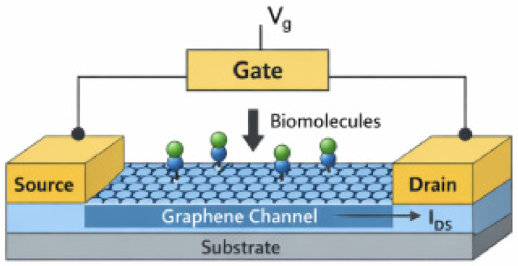

Figure 1. Schematic diagram of a graphene-based FET biosensor.

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Field-effect transistor (FET) biosensors detect biological analytes by monitoring changes in electrical conductance. A typical FET device consists of three main components: the source, drain, and gate electrodes. A semiconductor channel connects the source and drain electrodes. The gate voltage controls the carrier concentration in the channel. The gate voltage modulates the drain current [3].

In the linear regime of operation (i.e., at small VDS where higher-order terms can be neglected), the drain current (IDS) can be approximated as:

$$I_{DS} = \mu C_{ox} \frac{W}{L}(V_{GS} - V_{th})V_{DS}$$

In this expression, μ denotes the carrier mobility, Cox represents the effective gate capacitance (in liquid-gated configurations, corresponds to the electrical double-layer capacitance), W and L are the channel width and length, respectively, VGS is the gate-to-source voltage, VDS is the drain-to-source voltage, and Vth is the threshold voltage [3]. The way the electrical current reacts to variations in the gate voltage is determined by these parameters. Biological molecules attach to the sensor surface and add more electric fields in biosensing applications. The binding of charged biomolecules effectively shifts the threshold voltage (or the Dirac point in graphene), producing measurable changes in IDS or conductance under a fixed bias condition.

The sensitivity of FET biosensors is affected by the Debye screening effect. This effect occurs in electrolyte solutions such as blood or sweat. Ions in the solution reduce the effective electric field produced by biomolecules. Thus, only charges located very close to the sensor surface can influence the electrical signal. In high-ionic-strength physiological media, the Debye length is typically on the order of ~1 nm and varies significantly with ionic strength [9], [10]. This limitation makes it difficult to detect larger biomolecules.

Two-dimensional materials such as graphene provide important advantages for FET biosensors. Graphene has atomic-scale thickness and high surface sensitivity. This structure allows all charge carriers to interact directly with the surface. As a result, small changes in surface charge can produce measurable changes in conductance [5]. In addition, graphene has a characteristic Dirac point. Changes in this voltage point can indicate the presence of biomolecules.

Thus, the sensing performance of FET biosensors is fundamentally governed by the electrostatic coupling between surface-bound charges and the semiconductor channel, which can be significantly enhanced through the use of atomically thin 2D materials.

3 Channel Materials

The selection of channel material plays an important role in determining the performance of field-effect transistor (FET) biosensors. In recent years, researchers have explored two-dimensional (2D) materials as alternative channel materials. These materials have unique electrical and structural properties. Unlike conventional bulk semiconductors, 2D materials have atomically thin structures. This structure allows charge carriers to interact directly with biomolecules on the surface. As a result, 2D materials can improve sensing sensitivity [6], [7], [23].

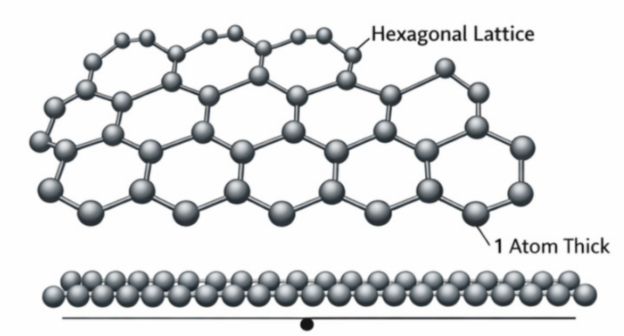

Figure 2. Atomic structure of graphene showing hexagonal lattice.

One of the most researched 2D materials for FET biosensing applications is graphene. Graphene consists of a single layer of carbon atoms arranged in a hexagonal lattice. This structure provides high carrier mobility, low electrical noise, and excellent conductivity [3]. In addition, graphene has atomic thickness. This property allows all charge carriers to respond directly to surface charge changes. Therefore, graphene-based FET (GFET) biosensors can detect biological analytes, such as proteins, DNA, and metabolites, at very low concentrations [4].

Another important feature of graphene is its ambipolar charge transport behavior. The characteristic Dirac point of graphene is the point at which the carrier density is at its lowest. The Dirac point voltage shifts when charged biomolecules adhere to the graphene surface. Researchers can measure this voltage shift to detect biological interactions. This mechanism allows graphene FET biosensors to perform label-free detection with high sensitivity and fast response [5].

Graphene does have some limitations, though. There is no bandgap in graphene. Consequently, graphene devices exhibit poorer switching performance and low on/off current ratios. This limitation can reduce signal clarity in some sensing applications [6]. Consequently, as substitute channel materials, scientists have looked into other semiconducting 2D materials like molybdenum disulfide (MoS_2). MoS_2 has a finite bandgap of approximately 1.8 eV in its monolayer form [15], [16]. This bandgap allows better control of electrical current and improves switching behavior [7]. In biosensing configurations, MoS_2-based FETs often exhibit higher on/off ratios and improved signal-to-noise characteristics. In addition, MoS_2 provides strong electrostatic control over carrier transport, which improves sensing performance.

Graphene offers exceptionally high carrier mobility and low electrical noise; however, its lack of an intrinsic bandgap results in a low on/off current ratio and a relatively limited signal window. In contrast, MoS_2 provides a finite bandgap and higher switching ratios that often improve signal-to-noise performance, although its comparatively lower mobility and interface-related defects may introduce drift and device-to-device variability.

Other emerging 2D materials, such as black phosphorus and transition metal dichalcogenides, also show promising properties for biosensing applications [8]. These materials provide tunable bandgaps and high surface sensitivity. Therefore, these materials offer additional options for improving biosensor performance.

Thus, graphene is particularly advantageous in applications requiring high surface sensitivity and rapid electrical response, whereas semiconducting 2D materials such as MoS_2 may be preferable when higher switching ratios and improved signal contrast are required.These 2D materials combine atomic thickness, high carrier mobility, and tunable bandgaps; however, their stability in aqueous and oxygen-containing environments remains a significant concern. Material selection should therefore be matched to the sensing task, with mobility, switching behavior, environmental stability, and fabrication scalability considered together.

Table 1. Comparison of Representative 2D Channel Materials for FET Biosensors (summarized qualitatively from Refs. [6], [7], [15], [16], [17], [18], [21])

Material	Bandgap	Mobility / Electrical Noise	Functionalization Difficulty	Stability in Liquid Phase	Fabrication Scalability
Graphene	0 eV (no intrinsic bandgap)	Very high mobility; low intrinsic electrical noise	Moderate (π–π interaction and covalent functionalization possible)	Good chemical stability; sensitive to environmental contamination	High (CVD scalable, though transfer uniformity remains challenging)
MoS_2	~1.8 eV (monolayer)	Moderate mobility; improved switching ratio	Moderate (surface defects assist but may induce variability)	Generally stable in aqueous environments	Increasing scalability; wafer-scale growth under development
Black Phosphorus (BP)	Tunable (~0.3–2 eV depending on thickness)	Moderate mobility; higher environmental sensitivity	More challenging due to surface oxidation	Poor stability in oxygen and water without encapsulation	Limited; stability and encapsulation remain bottlenecks
Other TMDs	Tunable bandgap	Moderate mobility	Moderate	Moderate stability	Emerging scalable synthesis methods

As summarized in Table 1, graphene offers superior mobility and surface sensitivity, whereas semiconducting 2D materials provide improved switching behavior, highlighting material-dependent trade-offs in biosensing design.

4 Applications

Graphene and other two-dimensional (2D) material-based FET biosensors have been applied in many biomedical areas. These devices have been explored primarily for disease diagnosis and continuous health monitoring [11], [20]. These applications require fast response and high sensitivity. This combination of rapid electrical readout and surface sensitivity makes graphene FET biosensors attractive for biomedical sensing [12].

One important application is cancer detection. Many cancers produce specific biomarkers, such as proteins and nucleic acids, in biological fluids [1]. Graphene FET biosensors can detect these biomarkers at low concentrations [11], [13]. For example, graphene FET biosensors have demonstrated detection limits in the femtomolar to picomolar range for protein biomarkers, with response times on the order of seconds under optimized conditions [11]. In addition, these sensors typically exhibit a wide linear detection range and high selectivity when functionalized with specific receptors, enabling reliable detection in complex biological environments. Graphene has high surface sensitivity due to its atomic thickness [6], [7]. As a result, small changes in surface charge can produce measurable electrical signals [12]. When biomarkers bind to the graphene surface, they change the electrical conductance of the device. The resulting conductance change can be monitored as an electrical readout of cancer-related molecular recognition [11]. After immobilized antibodies or aptamers capture specific cancer-related proteins or nucleic acids, the device response typically appears as conductance variations or shifts in the Dirac point (or threshold voltage), which serve as quantitative electrical readouts of the binding events. Early detection helps improve treatment outcomes and patient survival [1].

In addition, graphene FET biosensors can monitor biological molecules such as glucose [20]. Glucose monitoring is important for diabetes management. Traditional methods often require invasive blood sampling. However, graphene-based sensors can detect glucose in sweat or interstitial fluid [20], [25]. Most glucose sensing in FET-based platforms relies on enzyme-mediated reactions, particularly those involving glucose oxidase (GOx), which catalyze glucose oxidation and alter the local charge distribution or ionic environment near the channel surface. These changes are subsequently transduced into measurable current variations or voltage drift signals in liquid-gated FET configurations. Typical graphene-based glucose FET sensors exhibit detection limits in the micromolar range and have been successfully demonstrated in real samples such as sweat and interstitial fluid, highlighting their potential for non-invasive monitoring [20], [25]. Graphene sensors also operate at low power and provide high sensitivity [7]. Their low-power operation and high sensitivity also make them suitable candidates for integration into wearable devices. Such systems are particularly valuable for continuous, real-time physiological monitoring [25].

Another important application is infectious disease detection. Rapid detection of viruses and bacteria helps control disease spread [4]. Graphene FET biosensors can detect specific viral or bacterial molecules through surface functionalization [13]. Surface functionalization with selective receptors enables recognition of viral or bacterial biomarkers, and the resulting real-time conductance or voltage shifts can be directly monitored for point-of-care testing (POCT). These sensors produce fast electrical responses and allow real-time detection [4]. This real-time electrical response is especially relevant for point-of-care testing (POCT) applications.

Wearable graphene biosensors have attracted increasing attention because graphene combines electrical conductivity with excellent mechanical flexibility. This feature facilitates integration into soft and flexible electronic platforms that conform to the skin, enabling continuous monitoring of physiological signals [22], [25].

Taken together, graphene and other 2D material-based FET biosensors are particularly promising for applications requiring real-time, label-free detection [11], [12]. Their practical performance in complex physiological environments, however, still depends strongly on interface engineering, signal stabilization, and device robustness [20], [25].

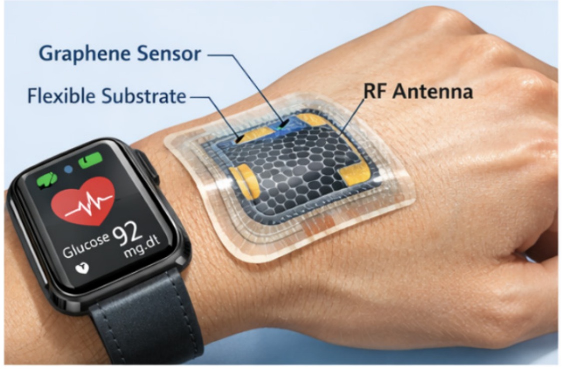

Figure 3. Example of a wearable graphene biosensor.

5 Challenges

Although graphene and other two-dimensional material-based FET biosensors show high sensitivity, several challenges still limit their practical use. These issues must be resolved before such devices can be translated into clinical and wearable applications [21].

One major challenge is the Debye screening effect. This effect occurs in biological fluids such as blood and sweat. Ions in the solution reduce the electric field generated by biomolecules [9], [10]. So only charges located very close to the sensor surface can affect the electrical signal. This effect reduces sensor sensitivity, especially when detecting larger biomolecules [10].

To mitigate this limitation, several strategies have been explored. These include lowering the ionic strength of the measurement buffer to increase the Debye length, employing shorter receptors or linker molecules to bring target charges closer to the sensing surface, and utilizing conformation-changing aptamer-based readouts that translate binding events into short-range charge redistribution. In addition, nanostructured surfaces and microfluidic designs have been investigated to locally reduce screening effects and enhance effective signal transduction.

Device stability is another important concern. Graphene is highly sensitive to environmental conditions due to its atomic thickness [6], [14]. Temperature changes, contamination, and electrical noise can affect its electrical properties. As a result, the sensor signal may drift over time. This problem makes reliable long-term measurements more difficult [14].

Surface functionalization also affects sensor performance. Selective detection generally requires the immobilization of receptors, such as antibodies or aptamers, on the graphene surface [11], [13]. However, improper surface modification or non-specific binding can reduce detection accuracy and introduce signal noise [13].

In addition, large-scale fabrication remains a challenge. Many graphene FET biosensors are still produced using laboratory fabrication methods [21]. These methods can cause variations between devices. As a result, device performance may not be consistent. More reliable and scalable fabrication methods are therefore essential for practical deployment [21].

Despite these challenges, ongoing advances in material engineering, interface design, and device architecture continue to improve performance and reproducibility [21]. Such progress is expected to support broader biomedical deployment in the future [20].

6 Future Directions

Future work can be organized around three major directions. First, improving material quality and device consistency through scalable fabrication methods and robust encapsulation strategies is essential for reducing device-to-device variability and enhancing long-term stability [21]. Second, optimizing the sensor–electrolyte interface and receptor design will be critical for mitigating Debye screening effects and improving selectivity under physiological conditions [10], [11], [13]. Third, integrating FET biosensors with wireless communication modules, low-power electronics, and flexible or stretchable substrates will enable wearable, continuous health monitoring systems suitable for real-world applications [18], [22], [24], [25].

With continued progress along these directions, graphene and 2D material-based FET biosensors may evolve from laboratory-scale demonstrations to reliable platforms for practical healthcare deployment [20], [25].

7 Conclusion

Field-effect transistor (FET) biosensors provide an effective method for detecting biological analytes. These sensors allow label-free and real-time detection with high sensitivity. The performance of FET biosensors depends strongly on the channel material. Two-dimensional materials, especially graphene, offer important advantages due to their atomic thickness and high carrier mobility. These properties improve surface sensitivity and detection performance.

Applications for wearable sensing, biomolecule monitoring, and disease detection exhibit great promise for graphene and other 2D materials. Their practical application is still constrained by a number of problems. These difficulties include fabrication constraints, device stability, and the Debye screening effect.

Continued progress in device engineering, material optimization, and system integration is expected to improve sensor reliability and accelerate practical translation. With further advances in fabrication and interface control, graphene and other 2D material-based FET biosensors may become important tools for next-generation biomedical diagnostics and health monitoring.

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