Proceedings of CONF-MSS 2026 Symposium: Mechanical Control and Automation
DOI: 10.54254/2755-2721/2026.BJ31418

Applications of Graphene-Based Flexible Field-Effect Transistors in Biomedical Sensing

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Abstract. Graphene is an ideal material for constructing high-performance flexible field-effect transistor (FET) platforms for biomedical sensing, thanks to its unique electrical, mechanical, and surface properties. This review systematically summarizes the research progress of graphene-based flexible FETs, with a focus on comparing two mainstream material systems—chemical vapor deposition (CVD) graphene and reduced graphene oxide (rGO)—and their impact on sensor performance. The operating principles and major sensing applications are also discussed, particularly in strain/pressure sensing and biomolecular detection. CVD graphene possesses high carrier mobility and excellent stability, making it suitable for high-sensitivity sensing; however, its zero-bandgap nature and transfer-induced defects limit the on/off current ratio and device uniformity. rGO offers advantages in solution processability and ease of surface functionalization, but its high defect density restricts electrical performance and consistency. Through mechanisms such as piezoresistance, gate-voltage coupling, and electrostatic gating, graphene-based flexible FETs have achieved highly sensitive detection of physiological strain, disease biomarkers, and viral nucleic acids. While promising for wearable and implantable healthcare devices, their practical adoption requires overcoming key challenges in device uniformity, long-term stability, and biospecificity. Future advances will depend on innovations in material engineering and system integration.

Keywords: Graphene Field-effect Transistor, Flexible Sensor, Biomedical Sensing, CVD Graphene, Reduced Graphene Oxide

1. Introduction

Flexible electronics has enabled real-time, continuous, and non-invasive health monitoring, while posing a key challenge: developing sensors that simultaneously offer high sensitivity, mechanical flexibility, and biocompatibility. Field-effect transistors (FETs), capable of converting biochemical events directly into electrical signals, provide an attractive architecture for high-performance biosensors. However, conventional silicon-based or organic-semiconductor FETs face limitations in carrier mobility, flexibility, and long-term stability, hindering their suitability for next-generation flexible, wearable, and implantable medical devices.

DOI: 10.54254/2755-2721/2026.BJ31418

Graphene, with its exceptional electrical properties, mechanical strength, atomic-layer thickness, and large specific surface area, has emerged as a transformative material for flexible FET biomedical sensors. Graphene-based flexible FETs (GFETs) retain the intrinsic signal amplification of conventional FETs while offering enhanced environmental sensitivity, mechanical flexibility, and potential for bio-integration. Research on GFETs aims to bridge the gap between high-performance flexible materials and highly sensitive biomedical detection, with significant implications for personalized medicine and smart wearable technologies.

This paper reviews the recent progress and application prospects of graphene-based flexible FETs in biomedical sensing.

2. Material system analysis

2.1. Synthesis pathways

2.1.1. Chemical vapor deposition graphene

Chemical vapor deposition, during the process, graphene nucleates and spreads across the surface of a metallic catalyst, and among the metals tested so far copper foil has become the everyday workhorse in most laboratories. The underlying idea is straightforward: a carbon-bearing gas flowing over the hot metal surface cracks apart, and because copper can hold almost no carbon in its bulk, the liberated atoms stay on the surface, hop around, and eventually lock together into an extended, seamless film that can be one or just a few atomic layers thick. This surface-adsorption route, rather than bulk dissolution and precipitation, is what lets the carbon self-assemble into large, almost defect-free graphene sheets [1].

Before graphene can actually be folded, bent, or stretched inside real-world flexible electronics, it first has to leave the rigid wafer on which it was grown and be relocated onto a soft plastic or rubber sheet. Among the handful of techniques that engineers have come up with so far, the wet-transfer route—where the metal foil or SiC is etched away in solution while the film is caught on a polymer support—has become the everyday workhorse in most university and industry labs.

2.1.2. Reduced graphene oxide

Reduced graphene oxide (rGO) is usually obtained by carrying out a reduction step on graphene oxide (GO), a sequence that begins with inexpensive natural graphite flakes. GO itself is first generated through an aggressive oxidation in concentrated acids, followed by intercalation and exfoliation, after which a subsequent reduction treatment peels away a large fraction of the oxygen groups and partially brings back the planar, conjugated network typical of pristine graphene. Because both the oxidation and reduction stages can be run in ordinary aqueous media, the whole pathway is fully compatible with solution-based coating, printing, or spraying operations and is therefore viewed as one of the few practical routes that can be pushed from laboratory scale to industrial tonnage without major equipment changes.

Oxidation and exfoliation are almost always performed through the modified Hummers method or one of its later variants, a route that is basically a combined chemical intercalation and oxidation reaction. During this step, a large number of sp^3-hybridized domains appear across the graphene basal plane, breaking up the original conjugated carbon network and turning the material into an electrical insulator while, at the same time, giving it pronounced hydrophilicity and ready dispersibility [2].

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The main purpose of the reduction step is to strip away the oxygen-containing functional groups that disrupt the sheet and, at the same time, to knit back at least part of the original sp^2 carbon network that gives graphene its hallmark conductivity, with chemical reduction still acting as the work-horse route in most labs. In a typical chemical reduction, the suspension (or the vapour above it) is dosed with common laboratory reductants such as hydrazine hydrate, ascorbic acid or a strong alkali; these reagents attack the epoxide and hydroxyl motifs anchored on the GO surface, detach them as small, soluble fragments and, in doing so, markedly raise the number of free π-electrons that can carry current. Because the whole reaction can be run in a beaker at atmospheric pressure and then simply washed, the protocol is viewed as bench-friendly and, more importantly, it can be carried out directly on plastic or other bendable supports without having to transfer the film afterwards. The downside is that traces of the reductant or its oxidation products often stay lodged between the sheets, and the sp^2 lattice is only patchily rebuilt, so the final conductivity, although much higher than that of starting GO, still falls short of pristine graphene [3].

2.2. Comparative analysis of key material properties

2.2.1. Electrical properties

CVD graphene owes its standout performance to an unbroken, sheet-wide sp^2 carbon lattice that contains hardly any native defects, a structure which hands the material exceptionally high carrier mobility and intrinsic electrical conductivity. Even at plain room temperature, the best CVD samples routinely deliver mobilities above 15,000 $cm^2\ V^{-1}\ s^{-1}$ [4]. Because the same material behaves as a zero-bandgap semimetal, a simple sweep of the gate voltage lets researchers flip the dominant carrier type and dial the concentration up or down without hitting a sharp threshold; in a standard FET layout this tunability shows up as the familiar, almost perfectly symmetric "V"-shaped ambipolar transfer curve [5].

While the oxidation-reduction cycle is running, the once-intact carbon scaffold inside rGO is chopped into a patchwork of tiny domains, so that a dense population of structural defects and oxygen-bearing functional groups suddenly appears. These freshly created imperfections behave like tiny roadblocks for charge carriers, and the resulting carrier mobility routinely lands one to three orders of magnitude below the value routinely reported for pristine CVD graphene. In most experimental reports, rGO behaves as a fairly stable p-type semiconductor: the hole density stays high, yet the window in which it can be further tuned remains rather narrow. When plotted, its transfer curve looks visibly lopsided, and the device reveals only a faint ambipolar response [6].

2.2.2. Chemical properties

The nearly complete sp^2 carbon network that characterises CVD graphene naturally gives the material a high level of intrinsic chemical inertness, a property that in turn translates into excellent long-term stability once the film is placed inside physiological environments; this combination of traits makes the material an appealing candidate for implantable sensors or for devices that are expected to carry out continuous monitoring over extended periods process [7]. However, because this same surface is both inert and hydrophobic, additional active sites usually have to be engineered before biorecognition molecules can be anchored effectively; typical routes include non-covalent modification schemes or the application of mild plasma treatments that introduce the necessary chemical handles without severely disrupting the underlying carbon lattice.

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The surface of rGO carries a high density of oxygen-containing functional groups and defect sites, a combination that naturally turns the sheet hydrophilic and, in turn, allows biomolecules to be anchored directly and efficiently through either covalent or non-covalent pathways, thereby streamlining the day-to-day assembly of sensing interfaces [8]. This convenience, however, is accompanied by a noticeable drop in chemical stability, so the same material can gradually undergo structural rearrangement or experience property drift once it is exposed to oxidative or enzymatic environments [9].

2.2.3. Mechanical properties

CVD graphene possesses exceptional intrinsic mechanical strength: a tensile strength of approximately 130 GPa and a Young's modulus of roughly 1 TPa [7]. When the material is integrated as a continuous film onto flexible polymer supports, its macroscopic mechanical behaviour is governed less by the lattice itself than by the quality of the transfer step and the resulting interfacial adhesion. Films that survive the transfer process with minimal wrinkles, cracks, or residues can routinely endure thousands of tight bending cycles while still delivering steady electrical and mechanical performance.

Owing to the fact that its carbon network is riddled with defects and breaks at multiple length scales, a single rGO flake ends up far weaker than the defect-free graphene lattice it tries to imitate, and any macroscopic film built from these flakes tends to develop cracks once the applied strain climbs past a fairly modest threshold. The practical edge that rGO still retains is its straightforward solution processability, which means it can be dispersed in common solvents and then blended with stretchy polymers without demanding complicated equipment, thereby giving composite films that bend and flex without snapping [10].

2.2.4. Summary

To visually compare the properties of two graphene materials, Table 1 summarizes the key characteristics of CVD graphene and rGO. These include electrical properties, surface properties, chemical properties, and mechanical performance.

Table 1. Comparison of core characteristics between CVD graphene and rGO

	CVD Graphene	Reduced Graphene Oxide (rGO)
Electrical Characteristics	High mobility, carriers can be bidirectionally and flexibly tuned	Low mobility, typically stable p-type, weak tunability
Surface Properties	Inert and hydrophobic, requires surface engineering modification	Rich in active functional groups, easy to functionalize directly
Chemical Properties	Extremely high intrinsic stability	Lower stability, susceptible to environmental factors
Mechanical Properties	High intrinsic strength, relies on high-quality transfer and integration	Low intrinsic strength, but easy to solution-process and composite

CVD graphene, thanks to its consistently high carrier mobility, mechanical robustness and low intrinsic noise, is usually picked whenever the sensing layer has to meet tight benchmarks on sensitivity, long-term drift and batch-to-batch reproducibility, a situation that frequently appears in high-end biomedical or environmental diagnostics. rGO, in contrast, can be decorated with thiol, amine or carboxyl groups in a beaker at room temperature and then spray-coated, spin-coated or ink-

DOI: 10.54254/2755-2721/2026.BJ31418

jet-printed on almost any substrate, so it is the material of choice for student teams, start-ups or pilot lines that need a cheap, fast turnaround or an intimate graphene–polymer interface without investing in vacuum equipment. Picking one form over the other therefore boils down to a conscious compromise among the absolute performance you truly need, the processing route your lab or fab can actually handle, and the unit cost the market or funding body is willing to accept.

2.3. Mechanisms impacting FET device performance

2.3.1. Chemical vapor deposition graphene

The exceptionally high intrinsic carrier mobility that CVD graphene possesses stands out as its most eye-catching advantage, and this very property equips the corresponding FET devices with strikingly fast response speeds so that they can keep up with and record rapid biomolecular interaction kinetics as they unfold in real time [11]. Yet, because its electronic structure lacks any bandgap, the resulting devices suffer from a very low on/off current ratio—usually staying below 10 [12], which in turn imposes a severe constraint on their usefulness in circuits that demand both a high signal-to-noise ratio and high-gain amplification.

Physical defects, contaminants, and interface problems that sneak in while CVD graphene is being transferred and integrated end up as the main performance bottlenecks. These defects behave like strong scattering centers and, in real devices, drive the carrier mobility sharply downward [13,14]. Because the defects are scattered at random, the electrical properties of each device jump around, which hurts array-level uniformity and makes wafer-scale reproduction much harder. Once the devices are placed in complex biological surroundings, the same fluctuations can show up as slow performance drift, so long-term reliability becomes shaky [14].

2.3.2. Advantages and bottlenecks of reduced graphene oxide

The core advantages of rGO lie in its tunable electrical properties and processing convenience. By controlling the reduction degree, its bandgap can be effectively tuned, enabling its FETs to achieve a relatively high on/off current ratio ($\geq 10^4$) [15]. This provides the possibility for its application in specific logic and sensing circuits. Its good solution processability also greatly simplifies device fabrication.

The high defect density of rGO is its fundamental limitation. Residual structural defects and functional groups act as strong scattering centers, resulting in carrier mobility far lower than that of CVD graphene [16]. The non-uniformity and randomness in the distribution of these defects within macroscopic films directly cause significant fluctuations in electrical properties such as mobility and on/off ratio between different devices or even different regions of the same device, severely compromising device consistency and reliability [16]. Therefore, despite advantages in on/off ratio and processability, the high-defect nature of rGO constrains its performance in high-end sensing applications that demand high mobility and high uniformity.

3. Sensing applications

3.1. Advantages of graphene FETs as a sensing platform

Graphene-based FETs, thanks to a bundle of material quirks that are hard to find in any single conventional semiconductor, have gradually become the go-to building blocks when students and labs try to assemble high-performance biomedical sensing platforms. Their sky-high intrinsic carrier

DOI: 10.54254/2755-2721/2026.BJ31418

mobility—electrons and holes zip through the sheet almost without scattering—guarantees that even a tiny dose of external stimulus can be turned into a crisp electrical pulse long before background noise starts to interfere, which is exactly the kind of rapid response clinicians hope to see at the bedside. At the same time, the film is only one atom thick, so any molecule that lands on the surface immediately nudges the local electronic landscape; in practical terms this means the device can register minute chemical or physical shifts that thicker channels would simply miss. Add to that the exceptionally large specific surface area—every square centimetre of a typical chip offers plenty of room for packing biorecognition elements at densities that would be impossible on a bulky silicon wafer—and end up with a transducer that can host a whole toolbox of probes without crowding. Because the graphene lattice is littered with π-bonds that are happy to react, the surface can be decorated with linker molecules in a matter of hours, allowing students to anchor antibodies, aptamers or even whole cells in a well-defined orientation. All of these features—speed, sensitivity, room for cargo and easy chemistry—feed into one another, so when a recognition event finally happens the transistor can translate it straight into a measurable current or voltage change without extra fluorescent tags or lengthy amplification steps, thereby laying a solid device-level foundation for label-free, real-time and impressively sensitive biomedical detection schemes.

3.2. Strain/pressure sensing

3.2.1. Piezoresistive effect

This is the most fundamental and ubiquitous intrinsic mechanism. When the graphene channel is stretched or compressed, changes in carbon-carbon bond lengths and angles cause distortion in its electronic band structure, leading to a shift in the Dirac point position. This significantly alters carrier concentration and mobility, ultimately manifesting as a sensitive and continuous change in channel resistance [17]. This effect is particularly pronounced in high-quality single-crystal CVD graphene, enabling highly sensitive static and dynamic strain detection.

High-precision wearable physiological monitoring. By exploiting this effect, researchers can produce ultrathin flexible sensors that sit almost unnoticed on the skin or over moving joints, quietly recording every tiny physiological whisper—whether it is the soft surge of pulse waves beneath the wrist, the minute tremor of vocal cords during speech, or the barely visible flicker of facial muscles that betrays expression.

3.2.2. Crack/wrinkle propagation mechanism

This mechanism primarily relies on the microstructural defects that are already present inside rGO or polycrystalline CVD graphene films. When the film is placed under macroscopic strain, these tiny imperfections—pre-existing microcracks or wrinkles—begin to grow, or fresh cracks nucleate right at the defect sites and then propagate outward. As this cracking or wrinkling unfolds, the network of conductive pathways inside the film is suddenly rearranged, producing sharp or nonlinear jumps in electrical resistance. Because of this abrupt switching behavior, the approach is especially well-suited for detecting events that involve either a high dynamic range of strain or very large mechanical deformation [18,19].

E-skin sensors that rely on this working principle can stretch by large amounts while still keeping track of mechanical inputs, so they register everything from a light fingertip tap to a deep bend, echoing the way human skin sorts out complicated touch cues. Because of that range, they have

DOI: 10.54254/2755-2721/2026.BJ31418

quickly spread into robot grippers that adjust on the fly, prosthetic hands that return a sense of force to the wearer, and everyday motion or posture-tracking gear.

3.2.3. Gate-voltage coupling effect

This mechanism makes active use of the gate structure already present in the field-effect transistor. By applying an external gate bias, one can switch the carrier type and continuously tune the carrier density inside the channel stability [20]. When the same gate control is combined with deliberate mechanical strain, the scattering events that strain normally creates can be electrostatically modulated in real time; this electro-mechanical co-design therefore adds an extra optimisation knob that simultaneously pushes sensor sensitivity, signal linearity and long-term stability well beyond the levels reachable by either electrical or mechanical tuning alone.

Active high-precision human-machine interfaces By continuously adjusting the gate voltage in real time, it becomes possible to build sensor arrays that can either compensate for drift on the fly or selectively amplify the desired signal, and these arrays are now being deployed in situations where both extreme accuracy and minimal hysteresis are non-negotiable—examples range from surgical robots that must translate a surgeon's hand motion into sub-millimetre tool movements, to virtual-reality gloves that need to recreate convincing force or tactile cues the moment a user's finger closes on a digital object, all the way to experimental setups that try to capture both the tiny bioelectrical spikes of a muscle fibre and the mechanical vibration of the surrounding tissue at the exact same instant.

3.3. Biomolecular detection

3.3.1. Electrostatic gating effect

This mechanism sits at the heart of every GFET biosensor. When target biomolecules that carry a net charge dock onto the carefully functionalised graphene surface, the extra charge—or the tiny interfacial potential that appears—electrostatically nudges the carrier density inside the graphene channel. The effect is much like sneaking in an extra, purely local gate voltage: the Fermi level of the graphene slides sideways, and the sheet's conductivity shifts in response, often by a clearly measurable amount biomolecules [21,22].

In the rapid detection of viral proteins, antibodies that specifically recognize the SARS-CoV-2 virus are first anchored onto the surface of the GFET channel; once the viral spike protein drifts in and binds, the electric charge it carries immediately nudges the channel's conductance through an electrostatic gating effect, turning the binding event into an electrical signal diagnosis [22].

3.3.2. Charge transfer and doping effect

This mechanism relies on direct electron exchange or on interfacial dipole interactions that form between the biomolecules and the graphene surface.Target molecules—ranging from small-molecule metabolites and metal ions to the redox products that emerge once these species react—can serve as either electron donors or acceptors, so they engage in charge-transfer events with the underlying graphene sheet. Such an exchange immediately rearranges the carrier density inside graphene, produces n-type or p-type doping, pushes the Fermi level noticeably upward or downward, and, as a direct consequence, creates a measurable, quantitative shift in electrical conductivity. This pathway is especially important for analytes that carry no net charge yet retain redox activity, or for species

DOI: 10.54254/2755-2721/2026.BJ31418

that trigger a conformational rearrangement in the recognition probe, an event that in turn exposes or shields local charges [23].

When neurotransmitters are analysed under dynamic conditions, their electrochemical oxidation products land on the graphene surface and engage in a reversible charge-transfer reaction; this reaction nudges the channel conductance up or down in real time, which in turn makes it possible to track, with high spatial and temporal resolution, how chemical signals are actually released inside the narrow synaptic cleft [23]. The underlying process is a mix of charge transfer and a doping-like effect: once the biomolecules bind, electrons or holes are passed either straight into the graphene lattice or through an indirect route, so the local carrier density changes, the Fermi level slides, and the sheet conductivity follows suit. In most cases this shift is accompanied by straightforward doping, because the extra charge that the molecules bring in can push the graphene toward either n-type or p-type behaviour, depending on the polarity of the transferred carriers.

4. Challenges and perspectives

4.1. Key challenges

Transfer defects that survive the CVD growth of graphene, together with the stubborn, high-density intrinsic defects that rGO never quite manages to heal, keep mobility and threshold voltage drifting from one small production batch to the next, so the electrical behaviour of finished devices can swing far beyond what most labs would call acceptable tolerance. At the same time, the material's perfectly gapless band structure refuses to deliver any meaningful current suppression at zero gate bias, which in practice locks it out of digital blocks that rely on clean, high on/off ratios for proper switching.

When devices have to operate inside the messy cocktail of real bodily fluids, they quickly run into two stubborn problemwhiss: proteins and cells stick to their surfaces in a thin, uncontrolled layer (the everyday nuisance everyone calls biofouling or non-specific adsorption), while at the same time the local ions slowly drift in and out of the sensing layer, nudging the electrochemical baseline up or down. Together these twin effects drag the signal-to-noise ratio downward and make it increasingly hard for the sensor to keep its readings steady over the long haul.

In real biological samples, sensor sensitivity and selectivity often degrade significantly; simultaneously, the response model to dynamic physiological environments, reliable calibration methods, and in vivo biocompatibility still require systematic investigation.

4.2. Future trends

Constructing graphene/2D material van der Waals heterostructures to tune electrical properties and enhance interfacial stability while maintaining high mobility is a crucial pathway to overcome intrinsic material limitations.

Putting effort into designing new antifouling coatings that borrow ideas from living organisms, together with reliable ways to lock biorecognition probes onto surfaces in a controlled and direction-specific fashion, and then coupling these surface tricks with up-to-date tools such as microfluidic chips, sits right at the heart of pushing both the specificity and the day-to-day reliability of detection assays whenever the sample background is messy and crowded with interfering substances.

If we want to keep an eye on health signals in real time and, when necessary, close the loop between diagnosis and therapy, the crucial step is to weave high-performance GFET devices tightly into stretchable or implantable foils that already carry wireless power coils, radio links, and custom

DOI: 10.54254/2755-2721/2026.BJ31418

ASICs, so that sensing, local processing, and outbound communication happen on the same soft platform instead of being scattered across separate modules.

5. Conclusion

This paper compares the properties of CVD graphene and rGO, outlining their respective advantages and disadvantages in a side-by-side manner. It outlines their advantages and disadvantages. The sensing mechanisms of graphene are explained. For physical sensing, these include piezoresistive effects, crack propagation, and gate-voltage coupling. For biomolecular detection, mechanisms involve electrostatic gating and charge transfer. Key challenges for practical use are also identified. These include improving material uniformity, ensuring interfacial stability, and achieving reliable in vivo performance.

Looking ahead, most of the coming work will probably revolve around three parallel tracks: first, tweaking the materials themselves and the way different layers meet so that the overall performance keeps climbing; second, carrying out ever more precise surface treatments so the sensors react only to the molecules we actually care about; and third, weaving these sensing elements into microfluidic chips and soft, bendable substrates that can talk to each other in real time. If these strands move ahead together, the long-promised picture of wearable or even implantable patches that both diagnose and treat should edge from prototype papers into gadgets people can actually strap on or slip under the skin.

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