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Graphene-Based Flexible Strain Sensors: A Comprehensive Review of Fabrication Methods, Sensing Mechanisms, and Wearable Applications

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ABSTRACT

Graphene, a two-dimensional carbon allotrope with exceptional electrical, mechanical, and thermal properties, has emerged as one of the most promising materials for next generation flexible strain sensors. This comprehensive review systematically examines the current state-of-the-art in graphene-based flexible strain sensors, covering synthesis approaches, functionalization strategies, piezoresistive and capacitive sensing mechanisms, and their integration into wearable platforms. We discuss key fabrication techniques including chemical vapor deposition (CVD), Hummers-derived graphene oxide reduction, inkjet printing, and screen printing on flexible substrates. The review further highlights recent advances in human motion detection, health monitoring, electronic skin (e-skin), and human-machine interfaces. Challenges such as sensitivity stretchability trade-offs, signal drift, and scalable manufacturing are critically analyzed. Finally, future research directions including self-healing composites, machine learning integration, and biodegradable sensors are outlined. This review aims to provide a holistic reference for researchers and engineers working at the intersection of nanomaterials and flexible electronics.

Keywords: Graphene, Flexible Strain Sensor, Wearable Electronics, Piezoresistive, Graphene Oxide, Electronic Skin, Nanomaterials.

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Introduction

The rapid advancement of flexible electronics and the Internet of Things (IoT) has created an unprecedented demand for lightweight, highly sensitive, and mechanically robust strain sensors capable of monitoring a wide range of deformations. Traditional metallic and semiconductor strain gauges, while reliable, suffer from limited stretchability (typically <5%), rigidity, and poor compatibility with curvilinear surfaces such as human skin or soft robotics components [1,2]. These limitations have spurred intensive research into novel nanomaterial-based alternatives that can simultaneously achieve high gauge factors and large strain ranges.

Graphene, first isolated in 2004 by Novoselov and Geim through mechanical exfoliation of graphite, has rapidly established itself as a transformative material in the field of flexible sensing [3]. Its unique two-dimensional honeycomb lattice structure confers extraordinary properties: an intrinsic carrier mobility exceeding 200,000 $cm^2\ V^{-1}\ s^{-1}$, a Young's modulus of ~1 TPa, ultimate tensile strength of ~130 GPa, and a theoretical surface area of 2,630 $m^2\ g^{-1}$ [4,5]. These properties make graphene an ideal candidate for piezoresistive sensing, where mechanical deformation induces measurable changes in electrical resistance.

Beyond pristine graphene, a rich family of graphene derivatives—including graphene oxide (GO), reduced graphene oxide (rGO), graphene nanoplatelets (GNPs), and heteroatom-doped graphene—has expanded

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the design space for sensor fabrication. These materials can be processed in solution form, enabling cost-effective deposition on diverse flexible substrates such as polydimethylsiloxane (PDMS), polyurethane (PU), thermoplastic polyurethane (TPU), and natural fibers [6,7]. The result is a versatile platform for wearable sensors capable of detecting subtle physiological signals—pulse rate, respiration, joint motion, and vocal cord vibration—as well as large mechanical deformations in structural health monitoring and soft robotics.

This review is organized as follows: Section 2 introduces graphene synthesis and key properties relevant to sensing; Section 3 discusses flexible substrate selection and composite fabrication; Section 4 details sensing mechanisms; Section 5 reviews fabrication techniques; Section 6 covers wearable and smart material applications; Section 7 addresses current challenges and limitations; and Section 8 presents an outlook for future research directions.

Graphene: Properties And Synthesis Methods

Understanding the structure-property relationships of graphene is fundamental to designing high-performance strain sensors. Graphene's sp^2-hybridized carbon atoms form a planar hexagonal lattice with a C–C bond length of 0.142 nm. The delocalized πelectron system is responsible for its exceptional in-plane electrical conductivity, while van der Waals interactions govern interlayer stacking in multilayer forms.

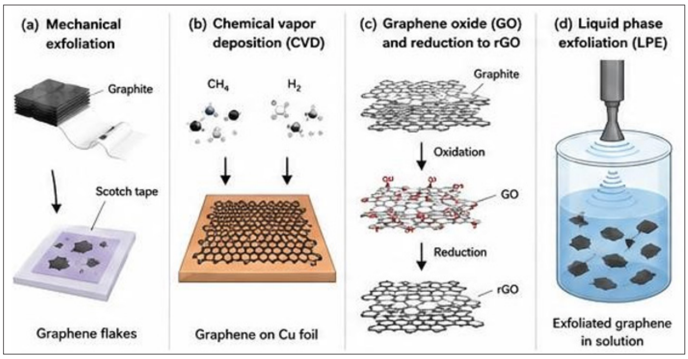


Figure 1: Main graphene production routes used for flexible strain sensor fabrication, including mechanical exfoliation, CVD growth, GO/rGO production, and liquid-phase exfoliation.

Mechanical Exfoliation

Mechanical exfoliation (scotch-tape method) remains the gold standard for producing pristine, defect-free graphene with the highest crystalline quality. While unsuitable for large-scale manufacturing, exfoliated graphene is invaluable for fundamental studies of intrinsic sensing mechanisms. Single-layer flakes produced by this method exhibit gauge factors (GF) exceeding 10^3 under uniaxial strain, attributed to crack formation and tunneling-dominated conduction [8].

Chemical Vapor Deposition (CVD)

CVD on catalytic metal substrates (Cu, Ni) represents the most scalable route to continuous, large-area graphene films. In a typical process, hydrocarbon precursors (CH_4, C_2H_2) are decomposed at 900–1050°C under low pressure, with carbon atoms segregating on the metal surface to form monolayer or few-layer graphene. Transfer to flexible substrates is achieved via polymer-assisted wet etching of the metal foil [9]. CVD graphene sensors benefit from uniform conductivity and controllable thickness, though transfer-induced wrinkles and grain boundaries can influence sensing performance.

Graphene Oxide (GO) and Reduced Graphene Oxide (rGO)

The Hummers method and its modifications produce GO through oxidative exfoliation of graphite using strong oxidants ($KMnO_4$, H_2SO_4). The resulting GO contains abundant oxygen-containing functional groups (epoxy, hydroxyl, carboxyl) that render it hydrophilic and processable in aqueous dispersions—ideal for solution-based coating and printing. Subsequent reduction via chemical (hydrazine, ascorbic acid), thermal (200– 1000°C), or electrochemical methods yields rGO with partially restored electrical conductivity (10^2–10^4 S/m) [10]. The residual defects and functional groups in rGO are advantageous for sensor sensitivity, as they create tunneling-dominated conduction pathways highly responsive to strain.

Liquid-Phase Exfoliation (LPE)

Ultrasonic or shear-force exfoliation of graphite in suitable solvents (N-methyl-2pyrrolidone, water-surfactant systems) produces stable graphene nanoplatelet dispersions. LPE is attractive for composite fabrication due to its scalability and compatibility with printing inks. Resulting GNPs typically have lateral dimensions of 0.1–10 µm and 2–10 layers, with electrical conductivity lower than CVD graphene but sufficient for piezoresistive sensing [11].

Flexible Substrates and Graphene Composite Design

The choice of substrate critically determines the mechanical compliance, stretchability, and durability of the resulting sensor. Elastomeric substrates based on PDMS are widely used due to their optical transparency, biocompatibility, low Young's modulus (~1–3 MPa), and stretchability exceeding 100% strain. However, PDMS's hydrophobic surface requires oxygen plasma or chemical treatment for adequate graphene adhesion [12].

Thermoplastic polyurethane (TPU) has gained increasing attention as a substrate due to its superior adhesion to graphene inks, higher abrasion resistance, and compatibility with melt-electrospinning and fused deposition modeling (FDM) 3D printing. Ecoflex, a platinum-catalyzed silicone, enables ultra-stretchable sensors (>400% strain) for prosthetics and soft robotics applications [13]. Natural substrates including cotton, nylon, and silk fibers have been explored for textile-integrated sensors, offering comfort and breathability essential for long-term wearable use.

Graphene composites are engineered by embedding graphene or rGO within elastomeric matrices (PDMS, Ecoflex, PU) or by creating layered structures (graphene film on substrate). Key design parameters include graphene loading fraction, dispersion homogeneity, and interface engineering. Hybrid composites incorporating graphene with carbon nanotubes (CNTs), silver nanowires (AgNWs), or MXenes have demonstrated synergistic improvements in both sensitivity and stretchability by constructing multiscale conductive networks [14,15].

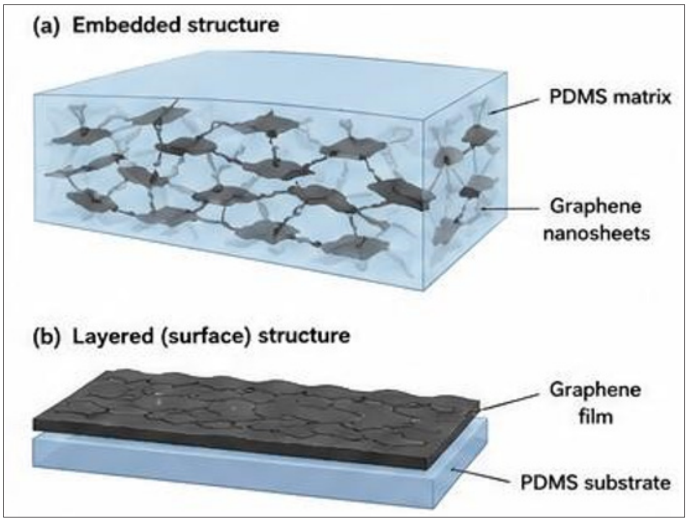


Figure 2: Schematic representation of embedded and layered graphene-based composite structures on flexible elastomeric substrates.

Sensing Mechanisms

Graphene strain sensors exploit two primary transduction mechanisms:
piezoresistivity and capacitance change. The gauge factor (GF = $\Delta R/R_0 / \varepsilon$, where ε is applied strain) is the primary figure of merit for piezoresistive sensors, while sensitivity ($\Delta C/C_0 / \varepsilon$) characterizes capacitive devices.

Piezoresistive Mechanism

In graphene films and composites, piezoresistivity arises from two concurrent phenomena: (i) geometric effects (change in conductor dimensions under strain) and (ii) changes in inter-flake contact resistance and quantum tunneling distance. For rGO-based sensors, the dominant mechanism involves the strain-induced disconnection of conductive pathways and increased inter-flake tunneling gaps.

This crack-propagation-assisted mechanism can yield exceptionally high GFs (10^3–10^6) at the cost of reduced stretchability [16]. Continuous CVD graphene films, by contrast, exhibit GFs of 2–6 at small strains, rising steeply near fracture due to crack nucleation.

Capacitive Mechanism

Capacitive strain sensors utilize graphene as a flexible electrode in a parallel-plate or interdigitated capacitor configuration. Applied strain changes the electrode area and dielectric layer thickness, modulating capacitance according to $C = \varepsilon_0 \varepsilon_r A/d$.

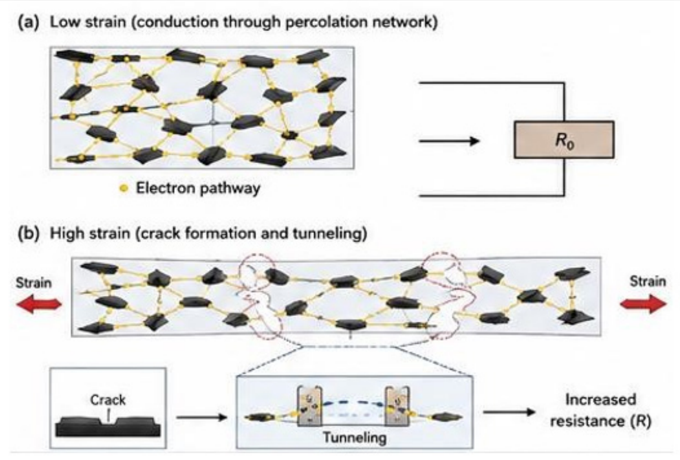
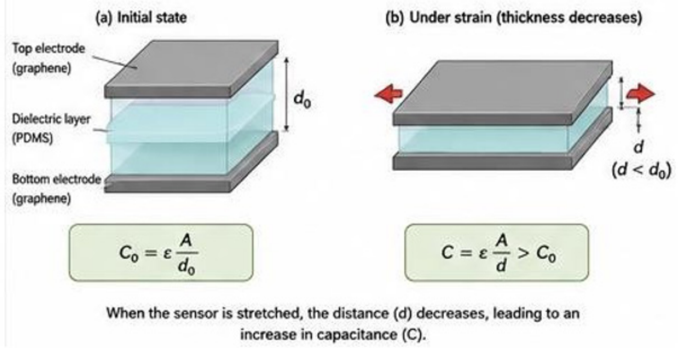


Figure 3: Piezoresistive sensing mechanism in graphene-based strain sensors based on crack formation, conductive pathway disruption, and electron tunneling.



When the sensor is stretched, the distance (d) decreases, leading to an increase in capacitance (C).

Figure 4: Capacitive sensing mechanism of graphene-based flexible strain sensors based on the variation of electrode distance and capacitance under applied strain.

Graphene's high conductivity and atomic thickness make it an ideal electrode material for capacitive sensors with low hysteresis and excellent frequency response. Recent work has demonstrated capacitive graphene sensors with linearity over 0–50% strain and response times below 10 ms [17].

Piezoelectric Mechanism in Hybrid Structures

While graphene itself is not piezoelectric, its composites with piezoelectric materials (PVDF, ZnO, $BaTiO_3$) have been explored for self-powered sensing. In these systems, graphene serves as a high-conductivity current collector that enhances charge transport from piezoelectric phases, enabling energy harvesting and simultaneous strain sensing without external power supply [18].

Table 1: Comparison of piezoresistive and capacitive sensing mechanisms in graphene-based flexible strain sensors

Parameter	Piezoresistive Mechanism	Capacitive Mechanism
Working principle	Change in electrical resistance due to deformation-induced variation in conductive pathways and tunneling distance	Change in capacitance due to variation in electrode distance, overlap area, or dielectric properties

Gauge factor (GF)	10^1 – 10^6 (can be very high depending on crack formation and tunneling effects)	10^{-1} – 10^2 (generally lower than piezoresistive sensors)
Typical stretchability	Up to ~100% (often lower in high-GF crack-based sensors)	Up to ~200% or higher depending on dielectric and structure
Sensitivity	Very high sensitivity, especially for small strain detection	Moderate sensitivity with good linearity over wide strain range
Response time	Fast (ms level)	Fast (ms level)
Advantages	Simple readout system, high sensitivity, suitable for detecting subtle physiological signals	Low power consumption, good stability, low hysteresis, suitable for large deformation sensing
Limitations	Signal drift, hysteresis, temperature sensitivity, limited durability in crack-based systems	Lower sensitivity, parasitic capacitance effects, more complex signal processing
Typical applications	Human motion detection, pulse monitoring, vocal cord sensing, electronic skin	Large-strain sensing, structural monitoring, soft robotics, wearable motion tracking

Fabrication Techniques for Graphene Strain Sensors

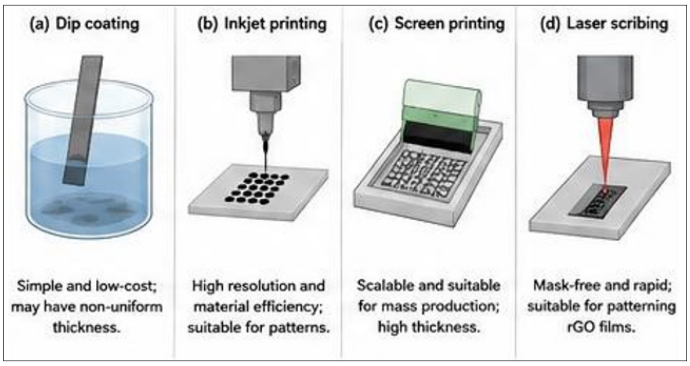


Figure 5: Common fabrication techniques for graphene-based flexible strain sensors, including dip coating, inkjet printing, screen printing, and laser scribing.

Dip Coating and Spray Coating

Dip coating of pre-stretched elastomeric substrates in rGO or GNP dispersions is a simple, scalable technique that produces crack-based sensors with ultrahigh sensitivity. The pre-stretch strategy induces controlled microcrack formation upon release, creating disconnected graphene islands whose reconnection/disconnection under cyclic strain generates large resistance changes. Spray coating offers faster deposition and better thickness uniformity for large-area applications [19].

Screen Printing and Inkjet Printing

Printing technologies enable precise patterning of graphene-based conductive inks on flexible and textile substrates with minimal material waste. Screen printing uses a mesh stencil to deposit viscous inks (graphene loading: 20–40 wt%) with resolutions of ~100 µm. Inkjet printing of low-viscosity graphene inks achieves finer resolutions (20–50 µm) and is compatible with roll-to-roll manufacturing. Post-printing sintering (thermal, photonic, or chemical) reduces sheet resistance to 10–100 Ω/sq [20].

CVD Transfer and Laser Scribing

Direct transfer of CVD graphene onto flexible substrates using PMMA or thermal release tape yields continuous films with excellent electrical uniformity. Laser scribing of GO films using CO_2 or infrared lasers is an emerging single-step technique that simultaneously reduces GO to laser-induced graphene (LIG) and patterns the conductive network. LIG sensors have demonstrated GFs up to 62 with stretchability of 30% and have been directly fabricated on polyimide, paper, and even wood substrates [21].

3D Printing and Electrospinning

Direct ink writing (DIW) and fused deposition modeling (FDM) with grapheneloaded filaments enable three-dimensional sensor architectures with complex geometries tailored for specific anatomical locations. Electrospun nanofiber mats incorporating rGO or GNPs create high-surface-area, porous sensing membranes with excellent breathability for skin-worn applications. These additive manufacturing approaches are increasingly combined with multi-material printing to integrate sensors, interconnects, and encapsulation in a single fabrication step [22].

Table 2: Electromechanical performance and properties of various graphene-based strain sensors.

Graphene Type	Substrate / Matrix	Fabrication Method	Gauge Factor (GF)	Stretchability (%)	Dominant Sensing Mechanism	Target Wearable Application	Key References
Pristine Graphene	Polyimide / PMMA	CVD Transfer	2 – 6 (at low strain)	< 5%	Geometric effect & crack nucleation	Highfrequency physiological monitoring	[9], [23], [24]

Reduced Graphene Oxide (rGO)	PDMS / Ecoflex	Dip / Spray Coating	103−106	10% – 30%	Crackpropagation & quantum tunneling	Subtle human motions (Pulse, vocal cords)	[12], [16], [19]
Graphene Nanoplatelets (GNP)	Polyurethane (PU)	Screen / Inkjet Printing	Low to Moderate	> 100%	Conductive network disconnection	Large-scale joint motions (Knee, elbow)	[7], [11], [20]
LaserInduced Graphene (LIG)	Polyimide (PI) Film	Direct Laser Scribing	Up to 62	~30%	Porous network deformation	Spatial pressure mapping & e-skin	[21]
Graphene Hybrid (CNTs/AgNWs)	Elastomeric Matrix	Multimaterial printing	Tailorable	> 100%	Multi-scale overlapping networks	Soft robotics & multimodal smart skins	[14], [15], [22]

Wearable and Smart Material Applications

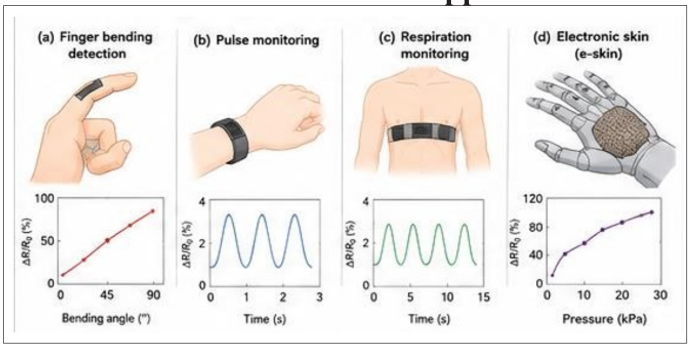


Figure 6: Representative wearable and smart applications of graphene-based flexible strain sensors, including finger motion detection, pulse monitoring, respiration monitoring, and electronic skin.

Human Motion Detection

Graphene strain sensors attached to joints (finger, wrist, elbow, knee) or integrated into gloves and compression garments have demonstrated accurate capture of both large-amplitude (≥30° joint angle change) and subtle motions (facial expressions, pulse waveform). Studies by Wang et al. and Chen et al. reported rGO/PDMS sensors with GF > 1000 and detection limits below 0.1% strain, sufficient for resolving individual finger joints during sign language gestures [23,24]. Real-time wireless transmission via Bluetooth-enabled microcontrollers has been demonstrated for continuous motion capture in sports biomechanics.

Physiological Signal Monitoring

The detection of subtle physiological signals—radial pulse (0–5% strain, 1–3 Hz), respiratory motion (1–15% strain, 0.1–0.5 Hz), and vocal cord vibration (0–2% strain, 80–1000 Hz)—demands sensors with high sensitivity, fast response, and reliable repeatability. Graphene sensors with microstructured surfaces (pyramidal, dome, or porous architectures) have achieved pressure sensitivities of 17.2 kPa^{-1} and response/relaxation times below 10 ms [25]. Wrist-worn graphene pulse sensors have been validated against clinical photoplethysmography (PPG) for heart rate variability (HRV) analysis.

Electronic Skin (E-Skin)

E-skin aims to replicate the distributed sensing capability of biological skin with multimodal detection of pressure, temperature, humidity, and strain. Graphene's large surface area, biocompatibility, and processability into ultrathin films make it a central material in e-skin development. Notable advances include transparent graphene e-skin arrays for spatial pressure mapping, self-healing graphene composites that restore conductivity within minutes of mechanical damage, and thermally sensitive graphene–PEDOT: PSS hybrid films for simultaneous strain-temperature dual sensing [26,27]. Integration with organic transistors has enabled active-matrix e-skin with sub-pixel spatial resolution (<1 mm^2).

Human-Machine Interfaces and Soft Robotics

Graphene strain sensors embedded in data gloves or exoskeletons enable intuitive control of robotic hands through gesture recognition, with classification accuracies exceeding 95% using machine learning algorithms. In soft robotics, proprioceptive graphene sensors integrated into pneumatic actuators provide real-time feedback on bending angle and contact force, essential for safe human-robot interaction [28]. Recent demonstrations include gripper fingers with embedded graphene sensors capable of discriminating object stiffness during manipulation tasks.

Current Challenges and Limitations

Despite remarkable progress, several fundamental and practical challenges impede the widespread adoption of graphene strain sensors in commercial wearable devices. The sensitivity-stretchability trade-off remains a central dilemma: high GF sensors typically rely on crack-based mechanisms that fail at modest strains (<30%), while highly stretchable designs (>100% strain) often sacrifice sensitivity (GF < 10). Engineering strategies such as serpentine geometries, kirigami patterning, and hierarchical crack control have partially mitigated this trade-off but have not yet fully resolved it [29].

Signal drift and hysteresis under cyclic loading represent persistent reliability concerns, particularly for long-duration health monitoring. Viscoelastic relaxation of elastomeric substrates and time-dependent rearrangement of graphene networks contribute to baseline resistance drift. Accelerated aging studies indicate that encapsulation strategies using parylene or waterborne polyurethane coatings can reduce drift by 60–80% but add fabrication complexity [30].

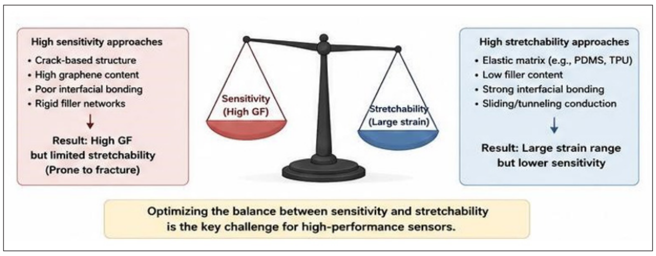


Figure 7: Key performance trade-off between sensitivity and stretchability in graphene-based flexible strain sensors.

Scalable, reproducible manufacturing of graphene sensors remains a significant barrier to commercialization. Batch-to-batch variability in GO reduction, ink rheology, and substrate surface energy leads to inconsistent sensing characteristics. Furthermore, the integration of power supply, signal processing, and wireless communication components into a compact, skin-compatible form factor requires advances in system level miniaturization and flexible circuit design. Biocompatibility and long-term skin irritation studies are also needed before clinical deployment.

Future Perspectives

The trajectory of graphene strain sensor research points toward several transformative directions. Self-healing graphene composites, inspired by biological skin, are expected to dramatically improve device longevity through autonomous restoration of electrical and mechanical properties after damage. Intrinsically stretchable, self-healing polysiloxane networks embedded with graphene have already demonstrated healing efficiencies exceeding 90% within 24 hours at room temperature [31].

The integration of artificial intelligence—particularly deep learning and neuromorphic computing—with graphene sensor arrays opens new frontiers in pattern recognition and adaptive sensing. Convolutional neural networks trained on graphene sensor time-series data have achieved >99% accuracy in activity recognition tasks, suggesting potential for clinical-grade continuous health monitoring systems [32]. Simultaneously, the development of biodegradable and transient graphene sensors using cellulose or silk substrates addresses growing concerns about electronic waste from disposable medical sensors.

Looking further ahead, the convergence of graphene strain sensors with energy harvesting (triboelectric and piezoelectric nanogenerators), near-field communication (NFC), and advanced biosensing functionalities (simultaneous biochemical and biomechanical monitoring) will enable truly autonomous, multi-modal health patches. Such systems could transform preventive medicine by providing continuous, personalized physiological data outside clinical settings, contributing to the vision of an interconnected, data-driven healthcare ecosystem.

Conclusion

This review has systematically examined graphene-based flexible strain sensors from materials synthesis to wearable system integration. The unique combination of graphene's exceptional electrical, mechanical, and chemical properties with the versatility of flexible substrate engineering has produced a rich landscape of sensor designs with performance metrics—gauge factor, stretchability, response time, and detection limit—that continue to improve rapidly. Key insights include: (1) rGO-based crack sensors offer unmatched sensitivity for subtle motion detection; (2) CVD graphene provides superior uniformity for high-frequency physiological monitoring; (3) hybrid composites with CNTs or AgNWs effectively decouple the sensitivity-stretchability trade-off; and (4) printing technologies are advancing toward industrial-scale fabrication.

Persistent challenges in signal stability, scalable manufacturing, and system integration must be addressed through interdisciplinary collaboration spanning materials science, electrical engineering, biomedical engineering, and data science. With continued advances in self-healing materials, AI-assisted signal processing, and sustainable fabrication, graphene strain sensors are poised to become foundational components of next-generation wearable health monitoring and human-machine interaction systems.

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