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Review Paper

Monolayer Graphene: Revolutionizing Graphene Field Effect Transistors (GFETs) and Graphene Hall Sensor Technologies in Biomedical Applications

Maryam Kahvazi Zadeh[1]

[1]**Department of Biomedical Science and Engineering, Koç University, Istanbul, Turkey, 34450**

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* Corresponding author: Maryam Kahvazi Zadeh (mzadeh22@ku.edu.tr)

Abstract

Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, exhibits extraordinary properties that have attracted widespread attention across various scientific disciplines. This paper explores the transformative impact of monolayer graphene in the field of sensor technology, specifically focusing on Graphene Field-Effect Transistors (GFETs) and Graphene Hall Sensors, and their applications in biomedical contexts. The unique combination of mechanical strength, electrical conductivity, and optical transparency in monolayer graphene has positioned it as an ideal material for sensor development. In the biomedical domain, graphene's biocompatibility and high surface area have opened avenues for applications in drug delivery systems, biosensors, and biomaterials for tissue engineering. The paper delves into the operational principles of GFETs, highlighting their ambipolar electric field effect, reduced short channel effects, and recent advancements in bandgap engineering.

GFETs offer versatility in high-frequency electronics, digital electronics, sensing applications, and flexible/wearable electronics. The fabrication process of GFETs involves synthesizing high-quality graphene, transferring it onto substrates, precise patterning, and electrode fabrication. These steps play a crucial role in determining the final performance and application potential of GFETs. Graphene Hall Sensors, another focus of this paper, leverage graphene's exceptional electronic properties for unparalleled precision in magnetic field detection. The advantages include high sensitivity, low power consumption, and compatibility with flexible substrates. The fabrication process involves synthesizing high-quality graphene, transferring it onto substrates, precise patterning, and final integration steps. The paper concludes by emphasizing the pivotal role of monolayer graphene in advancing sensor technologies, particularly in biomedical applications. The review underscores the potential of graphene-based sensors in enhancing sensitivity, specificity, and overall performance, thereby contributing to advancements in personalized medicine, health monitoring, and environmental sensing.

Keywords: Graphene, Graphene Field Effect Transistor, Graphene Hall Sensors, BioMedical Application

1. Introduction

Graphene, a single layer of carbon atoms arranged in a two dimensional honeycomb lattice, has captivated the scientific community since its first isolated and characterized [1]. The potential applications of graphene are vast and diverse, ranging from electronics to biotechnology. In the domain of sensor technology, graphene's high surface-to-volume ratio, along with its superior electronic properties, makes it an ideal candidate for developing highly sensitive and accurate sensors [2].

The allure of graphene lies in its remarkable combination of mechanical, electrical, and optical characteristics (Shown In **Figure 1**). Mechanically, it is about 100 times stronger than the strongest steel, with a tensile strength of over 130 GPa and an intrinsic strength of 42 Nm^{-1} [3]. Electrically, graphene exhibits extremely high electron mobility — up to 200, 000 $cm^2V^{-1}s^{-1}$ at room temperature — making it an excellent conductor of electricity [4]. Thermally, it has an exceptionally high thermal conductivity, around 5, 000 $Wm^{-1}K^{-1}$, surpassing that of a diamond [5]. Optically, graphene is almost perfectly transparent, absorbing a mere 2.3 percent of white light, which makes it suitable for applications in transparent electronics [6].

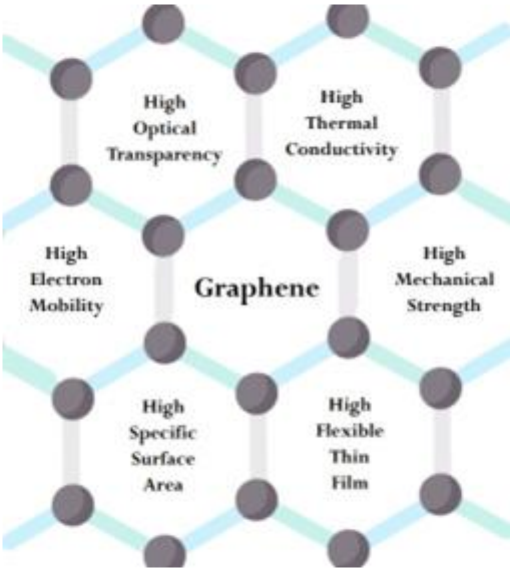

Fig. 1: Key Properties of Graphene

Graphene's versatility extends beyond its monolayer form. Bilayer and few-layer graphene have also been studied extensively, each exhibiting distinct properties. Bilayer graphene, for example, displays a tunable band gap, essential for applications in semiconductors and photovoltaic devices [7]. Few layer graphene, combining some properties of both monolayer graphene and bulk graphite, is being explored for use in energy storage systems, such as batteries and supercapacitors, and in composite materials due to its robustness and flexibility [8].

The scope of graphene's applications is vast. In electronics, its high conductivity and flexibility are being leveraged to develop advanced transistors, ultra-thin batteries, and flexible displays. Graphene's large surface area and electronic properties are particularly advantageous in solar cells and energy storage devices, potentially revolutionizing the field of renewable energy [8], [9].

In the biomedical realm, graphene's biocompatibility and high surface area make it a promising candidate for drug delivery systems, biosensors, and the development of novel biomaterials for tissue engineering [10], [11]. Its ability to interface with biological systems opens up new avenues in medical diagnostics and therapeutics. This review, however, narrows its focus to the utilization of monolayer graphene in the field of sensor technology and its biomedical applications. Graphene-based sensors, capitalizing on graphene's sensitivity to environmental changes, are being developed for the detection of gases, chemicals, and biomolecules, offering higher sensitivity and faster response times compared to traditional sensors [2]. In the biomedical sector, the use of monolayer graphene is particularly promising due to its unique interaction with biological molecules, enabling the creation of highly sensitive biosensors and innovative drug delivery platforms.

The extraordinary properties of monolayer graphene, such as its high surface-to-volume ratio, electrical conductivity, and mechanical strength, are pivotal in these applications. These characteristics enable the development of sensors with unprecedented sensitivity and specificity, crucial for environmental monitoring, healthcare, and industrial applications. Furthermore, in biomedical applications, graphene's biocompatibility and functionaliz ability allow for the development of next-generation diagnostic tools and targeted therapy techniques, which could significantly advance personalized medicine and health monitoring.

In this paper, we focus on biosensors that employ monolayer graphene, specifically examining Graphene Field-Effect Transistors (GFETs) and Graphene Hall sensors. Graphene's high electron mobility and sensitivity to external perturbations make it an ideal material for enhancing the performance of these sensors. In Hall-based sensors, graphene's high carrier mobility allows for the detection of magnetic fields with increased sensitivity and spatial resolution. These sensors capitalize on the Hall effect, where a magnetic field perpendicular to an electric current induces a voltage across the conductor. Graphene Hall sensors stand out due to their reduced noise and enhanced sensitivity compared to traditional Hall sensors [12]. On the other hand, in FET-based sensors, especially graphene-based field-effect transistors (GFETs), graphene's exceptional electrical conductivity and high surface-to-volume ratio are leveraged. GFETs are particularly sensitive to changes in their surrounding environment, making them suitable for detecting a wide range of substances, from gases to biomolecules [2].

2. GRAPHENE FIELD EFFECT TRANSISTORS (GFETS)

A. Introduction to GFETs

Graphene Field-Effect Transistors (GFETs) has emerged as a forefront innovation in the realm of nanoelectronics, leveraging the unique properties of graphene to offer capabilities beyond traditional semiconductor technology. Since the isolation of graphene, its integration into transistor design has been intensely pursued, driven by graphene's remarkable electron mobility, which exceeds 200, 000 $cm^2V^{-1}s^{-1}$, and its exceptional conductivity [13], [14]. These properties underpin GFETs' potential for high-speed and high-frequency operation, making them highly attractive for a range of advanced electronic applications.

GFETs are distinguished from conventional silicon-based FETs by their distinctive electronic properties. Graphene's ambipolar electric field effect enables both electron and hole conduction, offering unique opportunities for novel transistor designs [15]. Additionally, the atomic thickness of graphene contributes to GFETs' reduced short channel effects, which is a significant advantage in miniaturizing electronic components [16]. Recent advancements in GFET technology have addressed initial challenges related to graphene's zero bandgap nature, with developments in bandgap engineering and substrate interactions enhancing the on/off current ratio, a critical factor for digital applications [17], [18]. These innovations have opened new horizons for GFETs, ranging from high-speed digital circuits to flexible and transparent electronics (Shown in **Figure 2**).

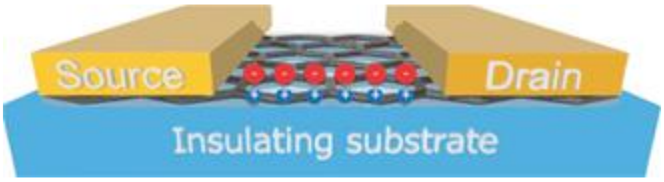

Fig. 2: Configuration of Graphene Field Effect Transistors (GFETs) showcasing the intricate arrangement of graphene layers synthesized through Chemical Vapor Deposition (CVD) or mechanical exfoliation. Following the transfer onto suitable substrates, precise patterning, and the addition of metal electrodes, the GFET structure highlights the unique ambipolar electric field effect of graphene

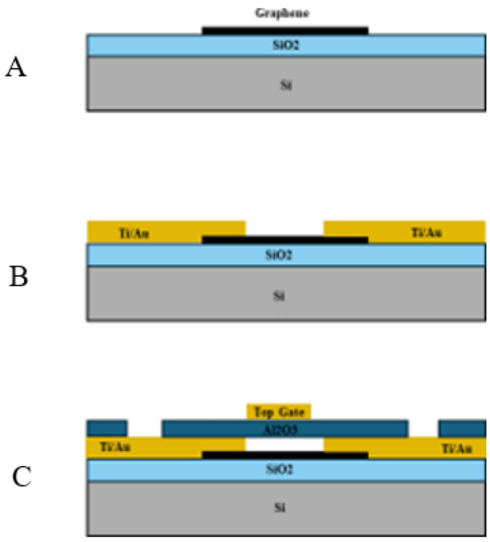

Fig. 3: Overview of the Fabrication Process for Graphene Field Effect Transistors (GFETs), involving synthesis of high-quality graphene, transfer onto substrates, precise patterning, and deposition of metal electrodes. The process concludes with the addition of a dielectric layer and gate electrode, ensuring optimal performance for applications like high-speed digital circuits and flexible electronics

B. Fabrication of Graphene Field Effect Transistors (GFETs)

The fabrication of Graphene Field Effect Transistors (GFETs), as shown in **Figure 3**, is a multi step process that plays a pivotal role in determining their final performance and application potential. Each step, from graphene synthesis to device assembly, is crucial.

Graphene Synthesis: The first step in GFET fabrication is the synthesis of high-quality graphene. There are several methods for graphene production, with Chemical Vapor Deposition (CVD) being among the most popular for its ability to produce large-scale and high-quality graphene films [19].

Transfer onto Substrate: Once synthesized, the graphene needs to be transferred onto an appropriate substrate, typically involving a wet transfer process. This process, while effective, can introduce wrinkles and contaminants, which are challenges currently being addressed in the field [20]. **(Figure 3 A)**

Patterning and Etching: After transfer, the graphene is patterned and etched to define the active area of the transistor. This is typically achieved through photolithography or electron beam lithography, which allows for precise control over the dimensions of the transistor [21]. **(Figure 3 A)**

Electrode Fabrication: The next step involves the deposition of metal electrodes to form the source, drain, and gate contacts. Metals such as gold or palladium are often used due to their good conductivity and chemical stability [19]. **(Figure 3 B)**

Dielectric Layer and Gate Electrode: Finally, a dielectric layer is deposited, and a gate electrode is added. The choice of dielectric material is crucial as it influences the device's carrier mobility and overall performance [22]. **(Figure 3 C)**

C. Application of Graphene Field Effect Transistors (GFETs)

Graphene Field-Effect Transistors (GFETs) have garnered significant interest due to their versatile applications, stemming from their exceptional electronic properties. Their high electron mobility and flexibility open up a range of possibilities across various technological domains.

High-Frequency Electronics: One of the most notable applications of GFETs is in high frequency electronics. Their exceptional electron mobility makes them highly suitable for radio frequency (RF) applications, such as mixers, amplifiers, and antennas. GFETs have been demonstrated to operate at terahertz frequencies, which is crucial for the next generation of wireless communication technologies [23].

Digital Electronics: In the realm of digital electronics, GFETs show promise as ultra-fast switches. Their high mobility and thin body allow for rapid switching capabilities, which is essential for high-speed processors and memory devices. The potential for low-voltage operation in GFETs also suggests a path toward energy-efficient electronics [14].

Sensing Applications: The sensitivity of GFETs to environmental changes makes them ideal for sensor applications. They have been used to develop sensitive and selective sensors for detecting gases, chemicals, and biological molecules. GFET-based biosensors, in particular, offer promising avenues for medical diagnostics and environmental monitoring [24].

Flexible and Wearable Electronics: The inherent flexibility of graphene paves the way for GFETs in flexible and wearable electronics. This application is particularly exciting for consumer electronics, where GFETs can be integrated into flexible displays, smart textiles, and health-monitoring devices [25].

3. GRAPHENE HALL SENSORS

A. Introduction to Graphene Hall Sensors

Graphene Hall Sensors (Shown in **Figure 4**) mark a pivotal advancement in the realm of sensor technology, harnessing the extraordinary characteristics of graphene to achieve unparalleled precision and versatility in magnetic field detection [1]. This section delves into the transformative impact of integrating graphene into Hall sensors, unlocking key advantages including heightened sensitivity, reduced power consumption, and enhanced adaptability to flexible substrates.

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, possesses remarkable electronic properties, including exceptional charge carrier mobility and high electrical conductivity. When harnessed in Hall sensors, these properties contribute to a new paradigm in magnetic field sensing. The utilization of graphene as a sensing material imparts unique advantages, making Graphene Hall Sensors stand out in terms of performance and functionality [26].

Advantages of Graphene Hall Sensors: High Sensitivity: The intrinsic properties of graphene, coupled with the Hall effect, enable Graphene Hall Sensors to exhibit unprecedented sensitivity in detecting magnetic fields. This heightened sensitivity makes them particularly suitable for applications requiring precise measurements [27].

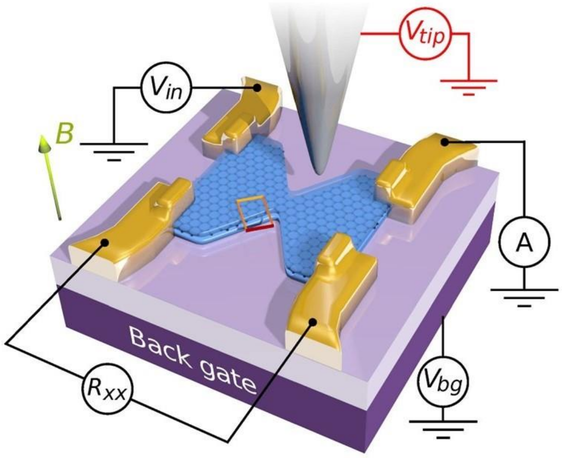

Fig. 4: Experimental Measurement Setup for Graphene Hall Sensor: Capturing the sensor's performance in action, this image showcases the measurement setup during testing

Low Power Consumption: Graphene's efficient charge transport characteristics contribute to low power consumption in Hall sensor operation. This feature is crucial, especially in scenarios where energy efficiency is a primary concern, such as in portable and battery operated devices [28].

Flexibility and Compatibility: A defining feature of Graphene Hall Sensors is their compatibility with flexible substrates. Graphene's flexibility allows for the integration of sensors into curved surfaces and conformable electronics, expanding their applicability in diverse environments [29].

The fabrication of Graphene Hall Sensors involves sophisticated processes, including the synthesis of high-quality graphene, transfer onto substrates, and precise patterning to define sensor structures. These fabrication techniques are critical in realizing the full potential of Graphene Hall Sensors [30].

This section will comprehensively explore the fundamental principles governing the operation of Graphene Hall Sensors, shedding light on their mechanisms, fabrication intricacies, and the expansive array of applications they encompass.

B. Mechanisms of Graphene Hall Sensors

The operational principle of Graphene Hall Sensors is rooted in the Hall effect, a fundamental phenomenon in physics that underpins their magnetic field detection capabilities. When an electric current flows through a graphene sheet subjected to a perpendicular magnetic field, the Hall effect comes into play, resulting in the generation of a Hall voltage. This voltage is directly proportional to the product of the applied magnetic field strength, the current passing through the graphene, and the charge carrier density within the graphene sheet [1].

Hall Effect in Graphene The Hall voltage generated in graphene is a consequence of the Lorentz force acting on charge carriers (electrons or holes) as they traverse the graphene sheet in the presence of a magnetic field. The resulting Hall voltage provides a measurable signal that serves as the basis for magnetic field detection. Importantly, the unique electronic properties of graphene, including its high charge carrier mobility, contribute to the exceptional sensitivity of Graphene Hall Sensors to changes in magnetic fields [31].

Charge Carrier Mobility Enhancement Graphene's exceptional charge carrier mobility is a critical factor influencing the performance of Graphene Hall Sensors. Charge carriers in graphene experience minimal scattering, allowing for efficient response to the applied magnetic field. This inherent property of graphene amplifies the sensor's ability to detect subtle variations in magnetic fields with high precision. Achieving and maintaining high charge carrier mobility is often realized through the careful selection of fabrication techniques, with methods such as chemical vapor deposition (CVD) and mechanical exfoliation being employed to produce high-quality graphene [32].

Optimization for Magnetic Field Detection: Graphene Hall Sensor performance optimization involves critical considerations:

Graphene Quality: The quality of the graphene layer is paramount in determining charge carrier mobility and, consequently, the sensor's sensitivity. Chemical vapor deposition (CVD) and mechanical exfoliation are techniques used to produce high-quality graphene layers, ensuring optimal performance in magnetic field detection scenarios.

Control of Charge Carrier Density: Precise control of charge carrier density within the graphene sheet is crucial for tailoring the sensor's sensitivity to specific magnetic field strengths. Techniques such as doping or the implementation of field-effect transistors (FETs) enable the modulation of carrier concentration, allowing for customized sensor responses.

Magnetic Field Calibration: Calibrating the Graphene Hall Sensor involves establishing a correlation between the applied magnetic field strength and the resulting Hall voltage. This calibration step is essential for ensuring the accuracy and reliability of magnetic field measurements [32].

4. FABRICATION OF GRAPHENE HALL SENSORS

The fabrication of Graphene Hall Sensors is a multi-step process (Shown in **Figure 5**) involving intricate techniques to harness the unique properties of graphene. The following subsections outline the key steps in the fabrication, including the synthesis of high-quality graphene, transfer onto substrates, and precise patterning to define sensor structures.

Electrode Fabrication:

The initial phase in creating Graphene Hall sensors involves designing the contact area on the Sio2/Si chip substrate. Following the design of this area, a layer of 5 nm of titanium (Ti) and 50 nm of gold (Au) is applied to the sample using electron beam (EBEAM) deposition. The next step is the liftoff process, which guarantees a precisely defined contact area. **(Figure 5b)**

Synthesis of High-Quality Graphene:

The crucial step in Graphene Hall Sensor fabrication is the synthesis of high-quality graphene. Chemical vapor deposition (CVD) and mechanical exfoliation are common methods employed for this purpose. CVD allows for the growth of large area, continuous graphene layers on metal substrates through the chemical reaction of hydrocarbons, while mechanical exfoliation involves isolating graphene layers from graphite using adhesive tapes. Both methods aim to produce graphene with minimal defects and high charge carrier mobility, ensuring optimal sensor performance [32].

Transfer onto Substrates:

Once synthesized, the graphene layer must be transferred onto a substrate suitable for sensor integration. Various transfer methods, such as wet transfer using polymers or dry transfer with supporting materials, are employed to ensure the preservation of graphene's integrity during the transfer process. The choice of substrate depends on the application requirements, with considerations for flexibility, compatibility, and thermal properties. Common substrates include silicon dioxide, poly-dimethylsiloxane (PDMS), and flexible polymers [30]. **(Figure 5c)**

Patterning for Sensor Structures: The next critical step involves precise patterning of the graphene layer to define the sensor structures. Lithographic techniques, such as photolithography or electron beam lithography, are commonly used to create well-defined patterns on the graphene surface. These patterns form the basis for Hall sensor structures, including the electrodes and the active sensing region. Careful attention is given to the resolution and precision of the patterning process, as it directly impacts the sensor's performance and sensitivity to magnetic fields [26]. **(Figure 5d)**

Encapsulation of Graphene:

The final stage in the fabrication of the Graphene Hall sensor involves encapsulation with SiO2. This critical step provides a protective layer over the entire structure, safeguarding the integrity of the sensor's components and enhancing its durability. The encapsulation process involves depositing a thin SiO2 layer over the graphene surface and the well-defined contact areas. This not only protects the sensor from environmental factors such as moisture and contaminants, which could degrade its performance over time, but also contributes to the stabilization of the sensor's electrical properties. By ensuring the sensor is encapsulated effectively, its reliability and longevity in various applications are significantly improved. **(Figure 5e)**

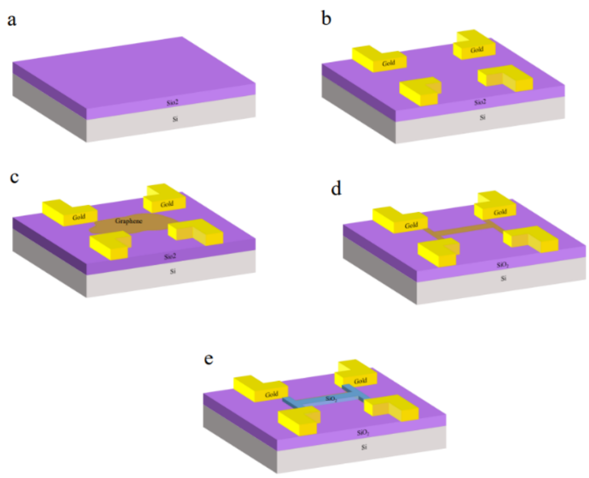

Fig. 5: Illustration of the Graphene Hall Sensor Fabrication process.

Integration and Finalization:

After patterning, additional processing steps involve the integration of the graphene Hall sensor into the desired device or system. This may include encapsulation for protection against environmental factors, connection to external circuitry, and calibration to establish the relationship between the applied magnetic field strength and the resulting Hall voltage. The finalization steps ensure that the Graphene Hall Sensor is ready for deployment in diverse applications, ranging from industrial magnetic field sensing to biomedical devices [32].

Conclusion

In conclusion, this paper highlights the transformative role of monolayer graphene in enhancing the capabilities of Graphene Field Effect Transistors (GFETs) and Graphene Hall Sensors, particularly within the realm of biomedical applications. Leveraging the exceptional properties of monolayer graphene—such as its superior electrical conductivity, mechanical strength, and optical transparency—these advanced sensors exhibit unparalleled sensitivity, specificity, and adaptability. These attributes are crucial for the development of sophisticated biomedical devices, enabling precise health monitoring and diagnostics. The discussions surrounding the fabrication and application of GFETs and Graphene Hall Sensors underscore the importance of high-quality graphene and meticulous device engineering in achieving optimal sensor performance. Moreover, the potential of these graphene-based technologies to revolutionize biomedical sensing and diagnostics is evident, though challenges related to scalability, integration, and stability remain to be addressed. This investigation into monolayer graphene's impact on sensor technology not only paves the way for future research and innovation but also highlights the material's significant potential in advancing personalized medicine and environmental monitoring. As the field of graphene research continues to evolve, the prospects for its application in sensor technology and beyond are both vast and promising.

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