

Graphene-Based Devices: Exploring Advantages, Challenges, and Multidisciplinary Applications

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Abstract. This study investigates the properties and possible uses of graphene, a two-dimensional material, in a variety of areas, such as electronics, optoelectronics, energy storage, and biomedicine. The study aims to explore the advantages of using graphene-based devices, identify potential applications in different fields, and assess the feasibility of incorporating graphene into these applications. The paper overviews the current state-of-the-art in developing graphene-based devices and describes their unique properties. Subsequently, the study delves into the potential applications of graphene in electronics, optoelectronics, energy storage, and biomedicine, each represented by a dedicated sub-section. The applications explored include graphene transistors, sensors, interconnects, photodetectors, solar cells, light-emitting devices, supercapacitors, batteries, biosensors, drug delivery systems, and tissue engineering. The paper concludes by summarizing the primary findings and offering a perspective on future research directions. The study highlights the potential of graphene-based devices in various domains and serves as a foundation for further investigation and development. The paper contributes to the growing body of knowledge on graphene and its applications, providing insights into the possibilities and challenges of incorporating graphene into different fields.

Keywords: Graphene, Electronics, Optoelectronics, Energy, Biomedicine.

1. Introduction

Since its isolation in 2004, graphene, a single layer of carbon atoms organized in a two-dimensional honeycomb lattice, has drawn much interest from the scientific community [1]. This exceptional substance is a hopeful option for numerous uses in electronics, optoelectronics, energy storage, and biology due to its extraordinary mechanical, electrical, and thermal characteristics. This article aims to comprehensively review the latest developments in graphene-based devices, focusing on their potential applications in the aforementioned fields.

The discovery of graphene has revolutionized the field of materials science due to its special properties, which include great mechanical strength, extraordinary electronic conductivity, and high optical transparency [2, 3]. The construction of graphene is made up of a single sheet of carbon atoms that are covalently bound in a hexagonal lattice, resulting in extraordinary properties [4]. The production and synthesis of graphene have evolved rapidly over the years, with chemical vapor deposition (CVD), liquid-phase exfoliation, and mechanical exfoliation employed to generate high-quality graphene sheets [5].

The potential applications of graphene in various fields have spurred a wealth of research aiming to understand and exploit its extraordinary properties. Several significant research has been made in exploring graphene's potential applications, with numerous studies uncovering new possibilities and pushing the boundaries of what this material can achieve. Pioneering work in the fields of electronics, optoelectronics, energy storage, composite materials, and biomedicine has led to the development of innovative graphene-based technologies such as transistors, supercapacitors, and drug delivery systems. These advancements have captured the attention of researchers and industries worldwide, fueling further research and investment in this fascinating material.

Despite remarkable achievements in graphene research, there still needs to be more to be addressed in its application. Key challenges include the scalable and cost-effective production of high-quality graphene. Current methods such as liquid-phase exfoliation, chemical vapor deposition (CVD), and

mechanical exfoliation present limitations in scalability, cost, and quality [6]. Additionally, understanding graphene's toxicity and environmental impact is crucial for developing safe and effective graphene-based technologies, especially in biomedical applications. Integrating graphene into existing technologies and materials also poses a challenge due to factors like interface compatibility, material purity, and structural integrity. Novel methods are needed for seamless incorporation into various applications. Lastly, the commercialization of graphene-based technologies is still in the beginning, with only a few products on the market. Overcoming barriers to commercialization and enabling the widespread use of graphene-based solutions requires further research and development and collaboration between academia, industry, and government.

This paper will delve into the main research questions and objectives concerning graphene-based devices, examining their advantages and challenges and exploring the potential applications of graphene in electronics, optoelectronics, energy storage, and biomedicine.

The main body of the paper will discuss several sub-sections that address different aspects of the research problem. First, this article will provide an overview of the current state-of-the-art in developing graphene-based devices, discussing their advantages and challenges. The following section will explore the potential applications of graphene in electronics, focusing on graphene-based transistors, sensors, and interconnects.

The subsequent section will delve into the potential applications of graphene in optoelectronics, covering graphene-based photodetectors, solar cells, and light-emitting devices. The next part will introduce the potential applications of graphene in energy storage, focusing on graphene-based supercapacitors and batteries. The Final section will examine the potential applications of graphene in biomedicine, including graphene-based biosensors, drug delivery systems, and tissue engineering.

In conclusion, the paper will summarize the main findings and provide an outlook on future research directions. The rapid advancements in graphene-based devices signify the material's potential to revolutionize various industries, from electronics and energy to healthcare. As researchers continue exploring and exploiting graphene's unique properties, this paper anticipates that developing novel graphene-based applications will significantly impact our lives in the coming years.

2. Applications of Graphene in Electronics

The unique properties of graphene, such as its exceptional electron mobility, high thermal conductivity, and remarkable mechanical strength, make it an attractive candidate for various electronic applications. This section will explore the potential applications of graphene in the field of electronics, focusing on graphene-based transistors and sensors.

2.1. Graphene Transistors

Silicon-based transistors have been the foundation of modern electronics for several decades. However, as device dimensions continue to shrink, silicon's limitations in electron mobility and heat dissipation become increasingly apparent. Graphene's high electron mobility, around 200 times higher than silicon, makes it a promising alternative for high-speed, low-power transistors [7].

The creation of the graphene field-effect transistor (GFET) is one of the critical developments in graphene transistors. GFETs can operate at high frequencies, exhibiting excellent switching characteristics. Additionally, GFETs exhibit a high on/off current ratio, making them suitable for digital applications, such as logic circuits, memory devices, and sensors. In digital circuits, transistors act as switches that turn on and off rapidly to represent binary information (0s and 1s). A high on/off current ratio ensures that the GFET can effectively switch between conducting and non-conducting states, allowing for fast, low-power operation. However, the absence of a bandgap in graphene presents a challenge in achieving low off-state leakage currents. Researchers have explored various approaches to engineering a bandgap, such as using bilayer graphene or graphene nanoribbons [1].

2.2. Graphene Sensors

Graphene's exceptional electrical and mechanical properties and large surface area make it a promising material for sensors with high sensitivity, low noise, and rapid response times. Graphene-based sensors have been developed for detecting various physical, chemical, and biological stimuli.

Graphene has a solitary sheet of carbon atoms, making it an extremely lightweight and thin material. This property is beneficial for wearable electronics, where minimizing the weight and thickness of devices is essential for user comfort. Moreover, lightweight and thin sensors can be easily integrated into structures without affecting their overall weight or performance in structural health monitoring [3]. Furthermore, graphene-based strain gauges have a high gauge factor (GF), or ratio of proportional change in electrical impedance to applied strain, a sensitivity measure. Moreover, Graphene-based strain sensors have fast response times, allowing for real-time monitoring of strain changes. This feature is essential in wearable electronics, where rapid response to body movements is required, and in structural monitoring, where quick detection of potential structural issues is crucial. The exceptional mechanical and electrical properties of graphene lead to a high GF, enabling the accurate detection of even small changes in strain with a faster time, which allows graphene-based strain sensors to have great potential for use in wearable electronics and structural health monitoring [8].

In the Biological aspect, graphene's biocompatibility and high electron mobility make it an attractive material for biosensors, capable of detecting biomolecules such as DNA, proteins, and glucose, allowing graphene can be used in medical equipment and drugs. Graphene-based biosensors have been developed for detecting specific DNA sequences. These sensors can sense target DNA segments sensitively and selectively due to the π - π stacking interaction between graphene and nucleobases. A graphene-based field-effect transistor (FET) biosensor, for instance, was created by He et al. and can be used to identify DNA hybridization events specifically [9]. Besides DNA detection, Graphene-based biosensors can be used for detecting proteins by immobilizing specific capture molecules, such as antibodies, onto the graphene surface. The binding of target proteins to these capture molecules induces changes in the electrical properties of graphene, allowing for label-free, real-time detection. For instance, Oh et al. created a graphene-based FET biosensor for detecting a prostate-specific cancer biomarker (PSA) [10]. Besides, Graphene-based field-effect biosensors can provide label-free, real-time detection of biomolecules, with potential applications in diagnostics, drug development, and personalized medicine.

In brief, the remarkable qualities of graphene, such as its high electron mobility, thermal transmission, and tensile strength, make it a promising material for various electronic applications. Graphene-based transistors, such as GFETs, offer the potential for high-speed, low-power devices while addressing the limitations of silicon. Graphene sensors, including physical and biological sensors, exhibit high sensitivity, low noise, and rapid response times, paving the way for innovations in wearable electronics, health monitors, and personalized medicine. As research continues to overcome challenges and develop new technologies, graphene holds the potential to revolutionize the field of electronics and contribute to the advancement of numerous industries.

3. Applications of Graphene in Optoelectronics

Optoelectronics involves studying and applying electronic devices that detect and control light. Due to graphene's special properties, such as significant electron mobility, broadband absorption, and mechanical flexibility, it has emerged as an ideal material for optoelectronic applications. This section will explore the potential applications of graphene in optoelectronics, explicitly focusing on graphene-based photodetectors, solar cells, and light-emitting devices.

3.1. Photodetectors

Graphene's exceptional electronic and optical properties have generated significant interest in optoelectronics, particularly concerning the development of photodetectors. A broad variety of uses,

including telecoms, imaging systems, and environmental monitoring, depend on photodetectors, which are devices that transform light into electrical impulses. Graphene-based photodetectors have demonstrated remarkable performance characteristics, such as high responsivity, broad spectral range, and fast response time. The strong light-matter interaction in graphene, which arises from its unique Dirac cone structure, enables efficient absorption of photons across an extensive range of wavelengths, from ultraviolet to infrared [11]. This broad spectral sensitivity makes graphene an attractive candidate for various photodetection applications. Furthermore, graphene photodetectors have been successfully integrated with silicon-based devices, offering a promising pathway for developing high-speed, flexible, and transparent optoelectronic devices.

3.2. Solar Cells

Graphene's exceptional properties, including excellent electrical conductivity, transparency, and mechanical flexibility, have generated considerable interest in its potential applications in solar energy conversion, particularly in the development of solar cells. Since graphene has been studied as a transparent conductive electrode in solar cell applications, providing a lightweight and cost-effective alternative to traditional indium tin oxide (ITO) electrodes [12]. Less than ten years after it was created, the graphene/silicon solar cell has reached up to 15% efficacy since 2004. The graphene layer also provided better surface passivation, contributing to improved device stability [13]. Incorporating graphene into solar cell designs has improved power conversion efficiency, device stability, and mechanical robustness.

Furthermore, researchers explored the use of compounds based on graphene in various components of solar cell architectures, such as electron-transport layers, hole-transport layers, and active layers. These explorations have led to the development of innovative solar cell technologies that leverage the unique advantages of graphene in improving device performance, energy conversion efficiency, and operational lifespan.

For instance, graphene quantum dots have been employed in dye-sensitized solar cells to enhance light harvesting and charge transport, resulting in increased device performance. Their excellent photoluminescence properties and tunable bandgaps enable more efficient solar spectrum utilization, leading to higher photocurrent generation and improved overall efficiency. Strongly luminous graphene quantum dots (GQDs) were produced using a one-step solvothermal method, as Zhu et al. showed, with a PL quantum yield of up to 11.4% [14]. Moreover, graphene has also been utilized to fabricate perovskite solar cells. It is an efficient charge transport layer, reducing charge recombination and improving device stability under various environmental conditions. This has led to the development of enhanced efficiency and stability of perovskite solar cells, making them more suitable for commercial applications.

Graphene's incorporation into organic and inorganic solar cells has also been explored. It plays a crucial role in improving interfacial charge transfer, reducing charge carrier recombination, and enhancing the overall device performance. This broad range of applications demonstrates the versatility of graphene-based materials in solar cell technology and highlights their potential to revolutionize the solar energy industry [15].

3.3. Light-Emitting Devices

Graphene's remarkable properties, such as high carrier mobility, flexibility, and transparency, make it an ideal candidate for light-emitting devices (LEDs). Researchers have been extensively exploring the potential of materials based on graphene in various types of LEDs, including organic LEDs (OLEDs), quantum dot LEDs (QLEDs), and perovskite LEDs (PeLEDs).

In the case of OLEDs, graphene has been investigated as an alternative to conventional indium tin oxide (ITO) electrodes due to its superior flexibility and mechanical stability. The use of graphene as a transparent conductive electrode in OLEDs could lead to the development of more robust, lightweight, and flexible devices, opening new possibilities in the design and fabrication of next-generation displays and lighting solutions [16].

Graphene-based materials have also been used in developing QLEDs, which contribute to enhanced charge transport and confinement. This results in improved device performance, such as higher brightness, better color reproduction, and increased device lifetime. Research reported that the quenching of luminescence at the junction between HTL (hole transport layer) and perovskite could be lessened with the adjusted GO (graphene oxide) quantity in PEDOT: PSS. In PeLED (Perovskite light-emitting diodes) with an optimized GO ratio (0.3), the luminance and current efficacy achieve their highest values of 3302 cd m^{-2} and 1.92 cd A^{-1} , respectively, increasing by 43.3% and 73.0% in comparison to the undoped device. The integration of graphene in QLEDs highlights its potential to address some challenges this emerging technology faces, such as charge carrier imbalance and efficiency roll-off [17].

Moreover, graphene has demonstrated potential in PeLEDs as an electron-transport layer, offering efficient charge injection and extraction and improved device stability. Incorporating graphene in PeLEDs could lead to the development of high-performance devices with superior operational lifetimes, making them more viable for commercial applications.

Overall, graphene-based photodetectors exhibit high-performance characteristics and broad spectral sensitivity, suitable for different uses. In the solar energy field, graphene has been explored as a transparent conductive electrode and component in various solar cell architectures, resulting in improved efficiency, stability, and mechanical robustness. Additionally, the application of graphene in light-emitting devices, such as OLEDs, QLEDs, and PeLEDs, demonstrates its potential to enhance device performance and enable the development of more robust, lightweight, and flexible devices. As research progresses, graphene's incorporation in optoelectronics will undoubtedly contribute to the advancement of this field and provide a foundation for next-generation technologies.

4. Applications of Graphene in Energy Storages

As was already stated, graphene has unique qualities that make it a desirable substance for energy storage uses, including strong electrical conductivity, a large surface area, and superb mechanical strength. This part will continue to cover the possible uses of graphene in energy storage, with a particular emphasis on batteries and supercapacitors made of graphene.

4.1. Supercapacitors

Supercapacitors, also referred to as ultracapacitors or electrochemical capacitors, are devices for energy storage that do so by accumulating electrical charge on their electrode surfaces. In comparison to batteries, they have an extended cycle life and can offer high power densities. Supercapacitor electrodes can benefit significantly from graphene's large surface area, exceptional electrical conductivity, and chemical durability.

Compared to conventional carbon-based supercapacitors, graphene-based supercapacitors exhibit remarkable energy storage efficiency, having a greater specific capacitance and energy density. At room temperature and 80°C , a supercapacitor with electrodes made of graphene was discovered to have a particular energy density of 85.6 Wh/kg and 136 Wh/kg , respectively. Graphene in supercapacitor electrodes can lead to faster charge and discharge rates and improved cycling stability. Moreover, due to graphene's mechanical elasticity, lightweight and flexible supercapacitors have been developed that are appropriate for a variety of uses, including portable devices and electric cars [18].

4.2. Batteries

In-depth research on graphene as an electrode substance for different batteries, such as lithium-ion, lithium-sulfur, and sodium-ion batteries, has also been done. Its high electrical conductivity, flexibility, and mechanical strength can significantly improve the performance of batteries by enhancing electron transport, accommodating volume changes during charge and discharge cycles, and increasing the overall stability of the electrode materials.

Furthermore, graphene's high surface area and porous structure can facilitate rapid ion transport, resulting in higher power density and faster charging rates for batteries. The unique properties of graphene have also been employed to develop advanced battery technologies, such as all-solid-state batteries and flexible batteries, which could revolutionize the energy storage landscape in the future.

Therefore, graphene-based supercapacitors demonstrate remarkable energy storage performance, faster charge and discharge rates, and improved cycling stability, making them suitable for various applications such as portable electronics and electric vehicles. Graphene has also been thoroughly investigated as an electrode substance for various batteries, resulting in improved efficiency, a higher power density, and quicker charging rates. The specific capacity of GNS was discovered to be 540mAh/g, which is significantly higher than that of graphite. By adding CNT (carbon nanotubes) and C60 (fullerenes) macromolecules to the GNS (graphene nanosheet), these specific capacities were raised to 730mAh/g and 784mAh/g, respectively. The ongoing research and development of graphene-based energy storage technologies have the potential to revolutionize the energy storage landscape and contribute significantly to advancements in various industries [19].

5. Applications of Graphene in Biomedicine

Due to its distinctive characteristics, including its large surface area and biocompatibility, graphene is an intriguing substance for a variety of biomedical applications. The possible uses of graphene in biomedicine will be covered in this part, emphasizing tissue engineering, medication delivery systems, and graphene-based biosensors.

5.1. Biosensors

Graphene-based biosensors have emerged as ideal analytical tools for detecting various biological analytes, including nucleic acids, proteins, and small molecules. The immobilization of biomolecules and the effective conversion of their interactions into quantifiable electrical signals are made possible by graphene's high surface area and superb electrical conductivity. Graphene-based biosensors have demonstrated high sensitivity, selectivity, and rapid response times, making them suitable for applications in disease diagnostics, environmental monitoring, and food safety [20].

5.2. Drug Delivery Systems

Graphene and its derivatives, such as graphene oxide, have been extensively studied as drug carriers for controlled drug release and targeted drug delivery. The large surface area of graphene allows for high drug-loading capacity. At the same time, its chemical functionality enables the attachment of targeting moieties, such as antibodies or peptides, for specific recognition of target cells. Graphene-based drug delivery systems have demonstrated improved therapeutic efficacy and reduced side effects in preclinical studies, highlighting their potential in treating various diseases, including cancer and neurological disorders [21].

5.3. Tissue Engineering

Due to their biocompatibility, mechanical strength, and capacity to support cell adhesion, proliferation, and differentiation, graphene and its derivatives have demonstrated significant promise as scaffold materials for tissue engineering use. Graphene-based scaffolds have successfully regenerated various tissues, including bone, cartilage, and neural tissues. Incorporating graphene into polymeric or hydrogel-based scaffolds can enhance their mechanical properties and electrical conductivity, promoting cell growth and tissue repair [22].

To sum up, Graphene-based biosensors have emerged as promising tools for detecting biological analytes, offering high sensitivity, selectivity, and rapid response times in disease diagnostics and environmental monitoring. In drug delivery systems, graphene and its derivatives have demonstrated improved therapeutic efficacy and reduced side effects, showing potential for the treatment of various diseases, including cancer and neurological disorders. Lastly, graphene-based scaffolds have shown

great promise in tissue engineering applications, supporting cell adhesion, proliferation, differentiation, and promoting tissue repair. As research progresses, graphene's incorporation in biomedicine will undoubtedly contribute to advancements in diagnostics, therapeutics, and tissue regeneration.

6. Conclusion

The enormous potential of graphene and its variants in a variety of uses, including electronics, optoelectronics, energy storage, and biomedicine, has been examined in this study. High electrical conductivity, a large surface area, and extraordinary mechanical strength are just a few of graphene's distinctive qualities that make it a hopeful substance for creating next-generation systems and devices.

Graphene-based transistors and sensors show great promise in revolutionizing the electronics industry. Graphene's applications in optoelectronics, including photodetectors, solar cells, and light-emitting devices, demonstrate its potential to address current limitations in these fields. Graphene's incorporation into supercapacitors and batteries in energy storage leads to enhanced performance, power density, and charging rates, which could significantly impact the energy storage landscape. Finally, in biomedicine, graphene-based biosensors, drug delivery systems, and tissue engineering applications highlight the material's potential in diagnostics, therapeutics, and tissue regeneration.

While considerable progress has been made in understanding and harnessing the remarkable properties of graphene, many challenges remain to be addressed to realize its potential in various applications fully. Future research should focus on overcoming these challenges, such as scalable and cost-effective production methods, engineering desired properties, and integrating graphene into existing technologies. As research in graphene and its applications continues to advance, this wonder material is expected to play a crucial role in shaping the future of science and technology across a wide range of industries.

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