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Advantages and Challenges of Graphene Transistors for High-Frequency Applications

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Abstract: Graphene is regarded as an ideal material for next-generation high-frequency (HF) electronic devices, attributed to its unique two-dimensional structure, high carrier mobility, and exceptional electrical properties. In recent years, the limitations of conventional silicon-based technologies for high-frequency applications have become increasingly apparent, resulting in heightened interest in graphene transistors, which exhibit significant potential for applications in wireless communications, radar systems, and terahertz technology. These transistors exhibit high cutoff frequency and low noise characteristics, along with favorable bipolar properties, which provide them with significant advantages in radio frequency (RF) applications. However, despite the significant theoretical advantages of graphene materials, their practical application is still restricted by multiple factors. Specifically, insufficient voltage gain from weak current saturation, material uniformity issues, and large-scale production challenges have restricted the widespread adoption of graphene transistors in high-frequency electronic devices. This paper reviews the relevant literature, examines the disparity between the electrical performance and practical applications of graphene transistors, and identifies the key factors influencing their implementation. The results demonstrate that targeted bandgap engineering, innovative device architectures, and the exploration of new materials can help graphene transistors can mitigate existing challenges and position themselves as key components in future HF electronic devices, driving significant advancements and broader integration of related technologies.

Keywords: Graphene, High Carrier Mobility, Zero Bandgap, High-Frequency Applications.

1. Introduction

As high-frequency (HF), radio frequency (RF), and terahertz technologies advance, the operating frequencies of electronic devices are continually increasing. As a result, the performance of traditional silicon-based semiconductor devices in high-frequency applications is approaching its physical limits, necessitating the exploration of novel materials and technologies to overcome this critical bottleneck. In this context, graphene has garnered significant attention due to its unique two-dimensional crystal structure and exceptional electrical and thermal properties. Graphene's high carrier mobility, broad spectral response, and exceptional electrical conductivity highlight its great potential in HF electronic devices, particularly in transistor design. Graphene-based transistors, as a new type of HF electronic device, exhibit higher carrier mobility and cut-off frequency (fT) than traditional silicon-based ones.

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Previous studies indicate that graphene transistors can sustain excellent electronic performance at very high frequencies, and their low noise and ambipolarity make them extremely promising for research in HF and RF bands. However, despite the numerous advantages of graphene materials, their practical applications encounter challenges such as weak current saturation and low voltage gain due to the zero bandgap, along with complex fabrication processes, which hinder large-scale commercialization and practical use. Thus, the paper reviews the research progress of graphene transistors in HF applications, analyzing breakthroughs and bottlenecks in material properties, the practical performance of electronic devices, and preparation technologies by examining the experimental results and technical solutions in the existing literature. This study aims to explore the feasibility and future development of graphene transistors in HF applications, highlighting its potential to promote technological development.

2. Unique Electrical Properties of Graphene

2.1. High Carrier Mobility

Graphene has become an important material in high-frequency applications due to its extremely high carrier mobility, which theoretically supports its widespread application in high-speed electronic devices. As a 2-D material composed of a single layer of carbon atoms, graphene's unique structure allows electrons to move freely in the plane, and the vertical movement is almost unrestricted [1]. This free movement results from the p-orbital electrons left by each carbon atom through sp^2 hybridization, forming a continuous π electron cloud, which significantly improves the mobility of electrons in the graphene layer [1,2]. Related research indicated that the carrier mobility of few-layer graphene can reach 10,000 cm^2/Vs, while that of multi-layer graphene can reach 150,000-200,000 cm^2/Vs. And this level of mobility is much higher than that of traditional silicon materials, about 10 times higher, which gives graphene a significant performance advantage in HF electronic devices. High mobility enables faster signal transmission and reduces energy loss from electron scattering, thus enhancing the overall efficiency of the device [3]. For example, in high-frequency communication devices, graphene's high carrier mobility can achieve faster signal transmission, which is essential for 5G base stations and future 6G networks. Meanwhile, in RF and microwave applications, graphene's superior performance makes it an ideal choice for efficient RF switches and amplifiers. Higher mobility can also reduce energy loss caused by electron scattering, thereby improving the overall efficiency of the device.

2.2. Zero Bandgap Characteristics

The zero bandgap characteristic of graphene can result in diminished switching speeds in switching applications, thereby leading to a lower switching efficiency at high frequencies compared to other semiconductor materials, such as silicon. This limitation hinders its application in digital circuits and high-performance computing, as the slower switching speeds compromise overall signal processing and transmission efficiency [4]. Additionally, the zero bandgap can make it difficult for graphene to achieve a complete "off" state in low-power applications, increasing power consumption and reducing device stability. However, in HF and RF applications, the influence of the zero bandgap on device performance is relatively limited. In these scenarios, graphene's barrier-free tunneling characteristic facilitates rapid signal transmission while minimizing energy loss. For example, in RF amplifiers and switches, the zero bandgap enables efficient signal amplification and transmission, making graphene well-suited for wireless communication and high-speed data transfer [1, 5]. Despite these challenges, the bandgap of graphene can be adjusted via techniques such as electric field modulation, chemical doping, or structural modifications, enhancing its performance. Therefore,

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while the zero bandgap poses limitations in certain applications, its remarkable electrical properties and tunability highlight its significance in high-frequency electronic devices.

3. Advantages of Graphene Transistors in High-Frequency Applications

3.1. High Cut-Off Frequency due to Unique Carrier Characteristics

The cutoff frequency (fT) is a crucial metric for evaluating the switching speed of transistors at high frequencies, indicating the frequency at which the current gain drops to one. The fT of graphene-based transistors is closely related to carrier mobility and gate length. Due to graphene's exceptionally high carrier mobility, typically ranging from 10,000 cm^2/Vs to 200,000 cm^2/Vs, carriers can move rapidly under an electric field, significantly enhancing switching speeds. Theoretically, higher carrier mobility diminishes scattering during motion, thereby enhancing current conduction efficiency. This allows graphene-based transistors to attain higher fT in high-frequency applications.For instance, by adjusting the gate length, designers can further optimize fT. A shorter gate length reduces the transistor's delay, thereby enhancing its frequency response [6]. Previous research showed that the fT of graphene-based transistors can reach up to 155 GHz, with advanced designs even exceeding 300 GHz. Notably, research has reported that graphene transistors with a channel length of 67 nanometers achieved a cutoff frequency of 427 GHz. These values demonstrate the tremendous potential of graphene for high-frequency signal transmission. Its structural advantages ensure barrier-free carrier transitions between the conduction and valence bands, facilitating rapid signal transmission under high-frequency conditions [7-9]. Importantly, the bandgap of graphene can be tuned through methods such as electric field modulation and chemical doping. This flexibility allows for performance optimization across various applications. For example, in RF applications, the zero bandgap characteristic of graphene enables efficient operation across a wide frequency range, thereby enhancing overall performance. This tunability, combined with its exceptional electrical properties, positions graphene favorably for future advancements in high-frequency electronic devices, capable of meeting current technological demands while laying the groundwork for innovative developments.

3.2. Superior Low Noise Performance

The low noise characteristics of graphene transistors arise primarily from their exceptional carrier mobility, which allows carriers to move at high speeds under an electric field, greatly reducing thermal noise caused by phonon scattering. Furthermore, the density of electronic states near the Dirac point in graphene approaches zero, which helps to minimize 1/f noise resulting from fluctuations in carrier concentration. These factors work together to enable graphene-based transistors to achieve excellent signal-to-noise ratios (SNR) in high-frequency applications, ensuring signal stability and accuracy. In comparison to non-graphene transistors, studies have shown that graphene-based transistors exhibit lower noise figures. For instance, the typical external noise of graphene-based transistors ranges from 3.3 dB to 7 dB, while intrinsic noise falls between 1 dB and 4 dB. These noise levels are particularly crucial in high-frequency applications. Related research indicated that bilayer graphene field-effect transistors (GFETs) grown on SiC substrates exhibited strong performance in input noise within the 10 GHz to 26 GHz frequency range, with external noise levels as low as 1.5 dB to 3.5 dB and internal noise reduced to 0.8 dB to 1.9 dB [10]. Moreover, the noise levels of GFETs are comparable to those of other high-performance material-based transistors, highlighting their competitiveness in low-noise applications. The low noise characteristics of graphene make it especially well-suited for low-noise amplifiers (LNAs) in high-frequency circuits. Compared to traditional non-GFET LNAs, GFETs have recorded a minimum noise figure of 1.34 dB, significantly outperforming similar devices and further establishing the importance of graphene in high-frequency electronic applications [11]. With its low noise properties, graphene transistors not

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only demonstrate superior theoretical electrical performance but also exhibit significant advantages in practical applications, making them an ideal choice for high-frequency electronic devices.

3.3. RF Applications of Bipolar Characterization

The zero bandgap characteristic of graphene enables excellent conductivity for both electrons and holes near the Fermi level. This bipolar conductivity offers graphene transistors unique advantages in high-frequency applications. By adjusting the gate voltage, these transistors can seamlessly switch between electron and hole conduction, providing a solid foundation for various RF applications.

3.3.1. Frequency Multipliers

The bipolar characteristics of GFETs streamline frequency multiplier design, enabling high gain efficiency and signal purity [12]. Frequency multipliers are critical in radio communication and broadcasting technologies. Since 2011, its bipolar transport properties have been utilized in the development of full-wave signal rectifiers and frequency multipliers, demonstrating promising applications. Research indicates that graphene-based frequency multipliers can effectively double signals at input frequencies of 10 kHz, achieving output signal purity as high as 90% at 20 kHz. This high purity positions graphene-based frequency multipliers as a highly promising choice for generating high-frequency signals [13]. With technological advancements, researchers have developed frequency multipliers based on triple and quadruple graphene, validating the application potential of graphene in this field. Moreover, GFET frequency multipliers achieve efficiencies exceeding 50%, significantly higher than the 3.66% to 11% efficiencies of non-GFET devices such as GaAs pHEMTs and InP DHBTs. This discrepancy highlights the exceptional performance of GFETs in frequency doubling and underscores their importance in RF applications. The simple design and fabrication of GFETs, along with their high-frequency capability, enhance their value in modern communication systems.

3.3.2. Frequency Mixers

The bipolar conductivity of graphene transistors facilitates the efficient conduction of both electrons and holes, greatly improving conversion efficiency and linearity in high-frequency signal mixers while minimizing mixing distortion. The performance of mixers is typically assessed by their conversion loss (CL), which directly impacts signal quality and processing capability. Graphene's high carrier mobility and low scattering characteristics allow it to outperform traditional materials in high-frequency applications. Experimental results indicate that graphene-based mixers achieve lower CL at high frequencies, improving signal fidelity and processing ability. For example, a mixer developed in 2010 achieved a CL of 35 dB at a 10 MHz fundamental frequency, highlighting graphene's potential in low-frequency applications [14]. Recent advancements have led to the development of a dual-gate Bernal stacked bilayer graphene FET mixer in 2019, which achieved a CL of 12.7 dB, underscoring its advantages in high-frequency mixer design. Moreover, graphene's thermal stability presents a significant benefit; studies demonstrate that even with an 80 K temperature variation, the performance of graphene-based mixers remains consistent, with CL decreasing by only 2 dB [15]. This temperature resilience allows graphene mixers to maintain high performance across various environments. With their high efficiency, low power consumption, and excellent thermal stability, graphene-based mixers possess significant potential for advancing high-performance wireless communication and signal processing systems. These theoretical and experimental findings indicate that GFET technology offers new directions and opportunities for mixer design.

4. Technical Challenges and Solutions

Despite the many advantages of graphene transistors for high-frequency applications, the problems should not be ignored.

4.1. Weak Current Saturation and Poor Voltage Gain

Despite the zero bandgap characteristic of graphene allowing it to achieve fT exceeding 400 GHz, providing significant advantages for high-frequency applications, this property also results in a very low switching ratio in traditional logic circuits, limiting the effective current cutoff. This directly leads to deficiencies in current saturation and voltage gain in graphene transistors, impacting their application potential. Voltage gain (AV) is determined by the ratio of transconductance (gm) to drain conductance (gd). The weak current saturation effect of gd becomes more pronounced at higher gm, further limiting the potential for increasing voltage gain [16,17]. In recent years, various innovative technologies have been developed to tackle the challenges of current saturation and voltage gain in graphene-based transistors. For instance, in 2022, Carsten Strobel and Carlos A. Chavarin developed a graphene-based three-terminal barrier transistor that modulates the quality factor of graphene through an electric field, achieving a switching ratio of approximately 106 and a current gain of up to 8×10^6, effectively resolving the issues of low switching ratio and inadequate current saturation in graphene field-effect transistors [18]. Additionally, in 2023, a research team focused on hot electron transistors, reporting a new device that achieved a significant improvement with an output saturation current of approximately 800 A cm^{-2} and a voltage gain (α) of up to 0.87 across a wide VCB window, providing new hope for advanced electronic applications [19].

4.2. Production Complexity and Mass Production Difficulties

The primary challenge in commercializing graphene transistors lies in the mass production of high-quality graphene. Current methods remain complex and costly, limiting scalability and often resulting in defects that negatively impact performance. Mechanical exfoliation, while capable of producing high-quality graphene, is not feasible for large-scale production due to its low yield and time-intensive nature. To overcome these limitations, recent advancements have introduced techniques like ball milling to produce high-concentration graphene dispersions with fewer defects, significantly enhancing both electrical and thermal conductivity [20][21]. Chemical vapor deposition (CVD) is the leading method for generating large-area, high-quality graphene. However, traditional CVD processes can be slow and complex, often affecting material properties due to low reaction temperatures and stringent conditions. Innovations such as steady-state atmospheric pressure CVD (SAPCVD) have demonstrated the potential for rapid batch production, yielding monolayer graphene with superior structural integrity and high carrier mobility, reaching up to 6944 $cm^2/V{\cdot}s$ [21]. And improvements in CVD systems through the use of rolled copper foils and various interlayer mediators have optimized growth rates and film quality, achieving production rates of 8.69 m^2/h and 15.57 m^2/h [22]. These theoretical analyses and experimental developments highlight the evolving landscape of graphene production technologies, reinforcing the necessity for continuous innovation to attain the scalability required for the broad adoption of graphene transistors.

5. Conclusion

This paper reviews the existing literature and examines the advantages and challenges of graphene transistors in high-frequency applications. Graphene exhibits exceptional optoelectronic performance in high-frequency scenarios due to its superior carrier mobility, bipolarity, and high cutoff frequency. However, inherent defects of graphene, particularly the weak current saturation and low voltage gain resulting from its zero bandgap, along with complex fabrication processes, remain significant barriers to practical applications. Despite these challenges, technological innovations and scientific research are driving graphene transistors to gradually overcome existing issues, thereby highlighting potential breakthroughs in band structure engineering and fabrication process improvements. It is important to note that this study is primarily based on existing literature and experimental data, and does not include personal experimental results, which may make some performance predictions difficult to validate in practical applications, thereby affecting the practical significance of the discussion. Furthermore, this paper provides a macro overview of the advantages and disadvantages of graphene transistors in high-frequency applications but does not delve into specific application scenarios such as wireless communications, radar, satellites, and aerospace. Additionally, the discussion focuses on the electrical performance of devices, overlooking other important characteristics such as mechanical and thermal properties. Lastly, this paper mainly concentrates on high-frequency applications without addressing other potential applications of graphene transistors, such as flexible sensors, thus failing to comprehensively showcase their diverse application prospects.

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