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Graphene Devices for Terahertz Communication Applications

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Abstract. The development of sixth-generation (6G) communication systems urgently demands terahertz (THz) devices with high speed, low loss, and efficient modulation capabilities. However, conventional semiconductor materials face severe performance bottlenecks in the THz band due to limited carrier mobility and significant high-frequency losses. This paper systematically reviews the properties, device architectures, and application status of graphene-based terahertz devices for 6G communication. Owing to its zero-bandgap Dirac structure, ultrahigh carrier mobility, and electrically tunable conductivity, graphene demonstrates strong outstanding potential for terahertz wave generation, detection, and modulation. Key challenges are also discussed, including large-scale high-quality graphene preparation, interface contact resistance, and system integration. The review demonstrates that graphene devices can effectively meet the core requirements of THz communication systems, providing a promising material platform for future 6G networks. This work aims to offer theoretical support and technical references for the further development and engineering application of high-performance graphene terahertz devices, thereby promoting the advancement of next-generation wireless communication technologies.

Keywords: Graphene, terahertz technology, 6G communications

1. Introduction

The rapid advancement of digital technologies has driven the transition from 5G to 6G mobile communication. 6G demands Tbps-level data rates, ultra-low latency, 100-fold bandwidth improvement, and space-air-ground-sea integrated coverage. Terahertz (0.1–10 THz) communication has become the core enabling technology for 6G due to its large bandwidth and strong directionality. However, conventional semiconductor materials feature low carrier mobility and incur substantial high-frequency loss within the terahertz band, leading to unsatisfactory efficiency of terahertz devices and forming a major bottleneck hindering practical deployment.

This paper aims to explore the application of graphene in 6G terahertz devices to overcome the material and performance limitations of conventional terahertz devices. A comprehensive review method is adopted to analyze the performance requirements of 6G, and the characteristics and challenges of terahertz communication, as well as the material properties, device architectures, and technical bottlenecks of graphene-based terahertz devices.

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This study confirms that graphene possessing a zero-bandgap Dirac structure, ultrahigh carrier mobility, and electrically tunable conductivity is well suited for terahertz wave generation, detection, and modulation. It clarifies the key challenges, including large-scale preparation, interface contact resistance, and system integration, and provides theoretical support and technical reference for the development and engineering application of high-performance graphene terahertz devices in future 6G communication systems.

2. Requirements and development of 6G communication

2.1. Key performance requirements of 6G

The global deployment of 5G began in 2020, supporting current demands for high-definition video and AI computing. To meet the needs of future intelligent and fully connected societies, 6G is expected to achieve substantial performance improvements over 5G [1]. Key requirements include Tbps-level peak data rates, sub-millisecond end-to-end latency, approximately 100-fold higher bandwidth, ultra-high connection density, enhanced energy and spectrum efficiency, sub-centimeter positioning accuracy, near-100% coverage, and AI-driven autonomous network management [2]. These requirements indicate that 6G represents not only an evolution in communication capacity but also a paradigm shift toward intelligent, ubiquitous, and fully integrated global communication systems.

2.2. Global development trends

Many countries have prioritized 6G research and development. The United States, China, the European Union, and Japan have formulated detailed plans for 6G technology. In 2019, the U.S. FCC opened the terahertz spectrum (95 GHz–3 THz) for future 6G experiments [3]. China launched 6G industry-university-research cooperation projects in 2019. The European Union and Japan released their 6G strategic roadmaps in 2020. These global efforts demonstrate a converging focus on terahertz communication, AI-native network architectures, and space–air–ground–sea integrated systems. 6G is expected to be commercially deployed around 2030, replacing existing 5G networks and holding strategic significance for national communication development.

3. Terahertz communication technology for 6G

3.1. Fundamental characteristics of terahertz communication

Terahertz refers to electromagnetic waves with frequencies ranging from 0.1 to 10 THz and wavelengths from 3 mm to 30 μm, representing a frequency range previously unexplored in wireless communications [4]. THz communication offers several key characteristics. First, it provides wide available bandwidth, enabling Gbit/s to Tbit/s transmission rates without relying on highly complex spectrum efficiency optimization technologies. Second, the short wavelength makes the antenna and device size smaller, which is conducive to miniaturization and integration. Third, THz exhibits strong directionality, which can reduce interference and enhance physical-layer security. In addition, terahertz waves have a certain penetration ability to smoke and dust and can adapt to special communication scenarios such as space and ocean [5].

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3.2. Current development and challenges

China's mobile communication bands have gradually risen from 2G (800/900 MHz) to 5G (2.6/3.5/4.9 GHz), and frequencies below 6 GHz are nearly fully allocated. Bandwidth demands grow from 4G's 20 MHz and 5G's 100 MHz to 6G's 1 GHz+, which can only be satisfied by terahertz bands above 100 GHz. Terahertz communication delivers high data rates without extra spectrum optimization, along with strong directivity, miniaturization, anti-eavesdropping, and better adaptability to space and ocean scenarios, making it vital for 6G.

However, terahertz systems still confront engineering bottlenecks: low efficiency of conventional semiconductor devices, severe atmospheric attenuation, and unsatisfactory integration and power consumption characteristics. These issues limit large-scale application and call for new materials and device structures.

4. Graphene-based devices for terahertz applications

Two-dimensional crystals were previously considered thermodynamically unstable in classic solid-state theory. However, in 2004, A.K. Geim and K.S. Novoselov successfully isolated single-layer graphene from graphite using the mechanical exfoliation method, which opened a new era of graphene research. Since then, multiple graphene preparation methods have been developed, including mechanical exfoliation, surface epitaxial growth on silicon carbide (SiC), and chemical vapor deposition (CVD) [6]. Among these methods, CVD is widely regarded as a promising method for producing large-area and high-quality graphene films suitable for industrial applications.

4.1. Properties of graphene relevant to THz devices

Graphene is composed of carbon atoms arranged in a hexagonal honeycomb lattice structure with sp2 hybridization, and its thickness is approximately 0.345 nm [7]. The carbon-carbon bond length in the lattice is 1.42 Å, with covalent bonds connecting atoms in the same plane, and π bonds connecting layers in the vertical direction. The structure of graphene is shown in Figure 1. Since the layers are connected by Van der Waals force, there are no dangling bonds, which reduces the occurrence of surface scattering. Therefore, graphene is recognized to have excellent carrier mobility, which can reach 15,000 $cm^2/(V \cdot s)$.

Besides, graphene has excellent optical transparency, absorbing only 2.3% of light. Its unique atomic structure provides excellent mechanical strength and flexibility, which is beneficial for flexible and integrated electronic devices. Its resistivity at room temperature is only about 10^{-6} $\Omega \cdot cm$, making it a promising material for future applications in the semiconductor industry.

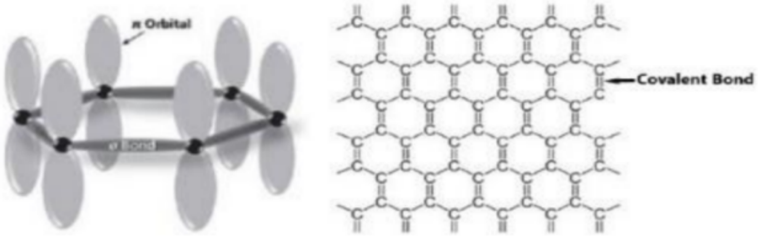

Figure 1. The structure of graphene

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In terms of electrical properties, graphene is an ideal zero-bandgap two-dimensional material. Its Fermi level can be modulated through doping, which gives graphene the characteristic of ambipolar carrier transport. Due to the conical symmetry of its band structure, the Fermi level lies at the intersection between the valence and conduction bands. Unlike three-dimensional systems, where parabolic band structures are described by the Schrödinger equation [8]. Semenoff utilized the Dirac equation to describe the electronic behavior of this energy state in 1984 [9]. Consequently, this intersection is defined as the Dirac point, and relevant discrepancies are illustrated in Figures 2 and 3. Although carrier transport appears absent at the Dirac Point, the phenomenon of Klein tunneling occurs at this state. Therefore, graphene still exhibits a minimum conductivity of σ=e2 /h at the Dirac Point.

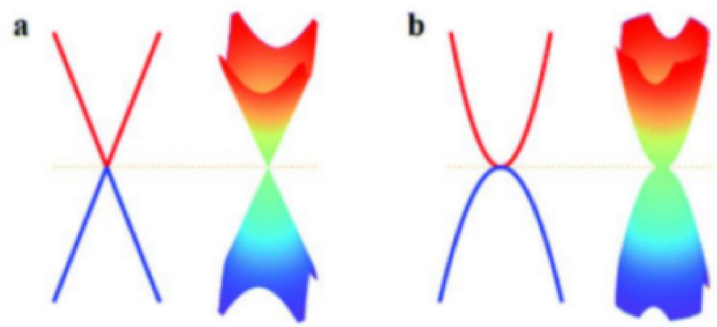

Figure 2. Energy band structure

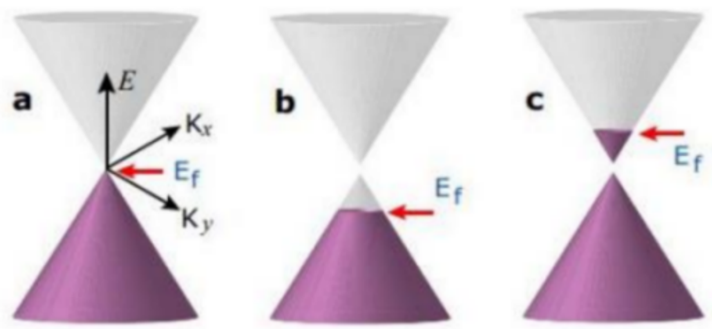

Figure 3. (a) Band structure diagram of intrinsic graphene (b) band structure diagram of p-type doped graphene (c) band structure diagram of n-type doped graphene

4.2. Graphene-based terahertz architectures

Graphene holds great promise for addressing technical challenges in terahertz communication. The zero-bandgap structure of graphene endows electrons with much higher mobility than most semiconductors used today. Therefore, electronic devices fabricated from graphene can realize high-frequency communications in the terahertz range (100-1000 times higher than gigahertz), potentially enabling data communication speeds ten times faster than current levels and supporting larger data transmission volumes.

Devices made of graphene can be used to regulate the propagation characteristics of terahertz waves. A common modulation approach employs a graphene-insulator-graphene structure, in which an external bias voltage is applied to adjust the Fermi level of graphene. This tuning process changes

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the optical conductivity via intraband carrier transitions and free-carrier absorption [10]. Recent studies on vertically stacked heterostructures composed of graphene, hexagonal boron nitride (h-BN), and other two-dimensional materials have further expanded the design possibilities of terahertz devices [11]. As an example, Figure 4 illustrates a bilayer graphene heterostructure reported by Yadav and co-workers [12]. In this structure, two graphene layers are separated by a thin h-BN tunnel barrier, enabling independent electrical control of each layer. Theoretical investigations on sandwiched bilayer graphene heterostructures have shown that such structures can be applied in high-efficiency and tunable THz/IR lasers and photodetectors (PDs), offering numerous advantages over devices based on interband radiative transitions in pristine bilayer graphene [13].

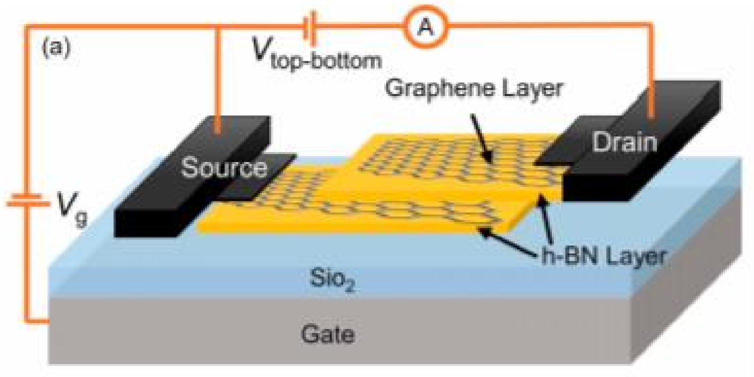

Figure 4. The bilayer graphene heterostructure [12]

4.3. Performance advantages and limitations

Graphene-based devices have a higher high-frequency response speed and lower loss than traditional semiconductor devices; the adjustable conductivity realizes active terahertz modulation; the small size is conducive to 6G terminal miniaturization; the heterostructure design can optimize emission, detection, and modulation performance.

However, large-area and high-uniformity single-layer graphene preparation is difficult; the contact resistance between graphene and metal electrodes is high, reducing device performance; and the service life and stability of graphene terahertz devices in complex environments need to be improved [14].

5. Challenges and future research directions

This paper introduces the development prospects of 6G, the current deployment status in various countries and regions, and the structural characteristics of graphene devices [15]. Although graphene exhibits excellent potential for terahertz communication devices, three core challenges still limit its large-scale engineering application: first, the large-scale preparation of high-quality graphene cannot meet the industrial demand, and the defect density affects device performance; second, the interface matching and contact resistance optimization between graphene and traditional semiconductor processes are difficult; third, the atmospheric propagation attenuation of terahertz waves needs to be cooperatively solved with graphene devices and system design [16].

Compared with traditional semiconductor materials such as silicon, gallium arsenide, and indium phosphide, graphene has obvious advantages in carrier mobility and high-frequency response and is more suitable for terahertz band work. However, traditional semiconductor materials have mature

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processes and high stability. The future development direction is the hybrid integration of graphene and traditional semiconductors to combine performance and process advantages.

In the future, low-cost, large-area, high-quality graphene preparation technologies can be developed, such as the optimized CVD method [17]. Another research approach involves designing novel graphene heterostructures to enhance the efficiency and stability of terahertz devices. It can also facilitate the integration of graphene terahertz devices with 6G base stations and terminals and conduct practical system verification.

6. Conclusion

This paper systematically explores the application prospects of graphene-based terahertz devices in 6G communications, aiming to alleviate the performance bottlenecks of 5G networks and support the high-demand application scenarios of emerging technologies. With the global deployment of 5G entering a mature stage, the development of 6G has become a strategic focus for major countries, requiring higher data rates, lower latency, and space-air-ground-sea integrated coverage, where terahertz technology serves as the core support due to its large bandwidth and unique propagation characteristics. As the primary candidate for the 6G spectrum, the terahertz band demands high-performance devices, and graphene, featuring a zero-bandgap Dirac structure, ultrahigh carrier mobility and electrically tunable conductivity, emerges as an ideal candidate material. Its superior electronic properties enable the fabrication of high-frequency terahertz devices, which can significantly improve data communication speed and capacity compared with conventional semiconductor-based devices. Relevant studies and device fabrications, such as bilayer graphene heterostructures, further verify the application potential of graphene in terahertz emission, detection, and modulation.

In summary, this study reveals the inherent correlation among 6G communication, terahertz technology and graphene materials, and validates the practical viability of graphene-enabled terahertz devices for 6G scenarios. It provides a new research direction for advancing future communication technologies. However, further studies are needed to optimize graphene preparation processes and device performance, which will lay a solid foundation for the practical application of graphene terahertz devices in 6G networks around 2030.

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