Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.35554

Research Progress on Fourth-Generation Semiconductor Materials in the Field of Communications

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Abstract. With the large-scale deployment of fifth-generation mobile communications (5G) and the ongoing evolution of sixth-generation communications (6G) towards the terahertz frequency band, the performance requirements for components in communication systems—in terms of high frequency, high power and high reliability—have increased significantly, and traditional silicon-based semiconductor materials are gradually becoming inadequate for such emerging technical demands. Against this backdrop, wide-bandgap (WBG) and ultra-wide-bandgap (UWBG) semiconductor materials have attracted extensive research attention. This paper employs a literature review approach to systematically analyse the key properties of fourth-generation semiconductor materials and the progress made in their application in high-frequency communication devices. Research indicates that improvements in device performance depend significantly on the optimisation of materials in terms of high mobility, wide bandgap and thermal management; material performance has thus become a key factor constraining the development of communications technology, whilst also providing important guidance for the design of future high-frequency devices.

Keywords: fourth-generation semiconductors, wide-bandgap materials, RF devices, high-frequency communications

1. Introduction

Since the advent of first-generation mobile communications (1G), wireless communication technology has undergone a leap forward, evolving from voice to high-speed data. With fifth-generation mobile communications (5G) commercial roll-out and sixth-generation communications (6G) research, communication frequency bands have expanded from the traditional MHz range to the millimetre-wave and even terahertz bands. Human-centred mobile communications remain a core 6G scenario, making security, confidentiality and privacy indispensable. Thus, wireless research must prioritize these capabilities [1]. 6G development is not limited to spectrum expansion but also convergent evolution of technological trends. As spectra extend to millimetre-wave and terahertz bands, stricter standards are imposed on semiconductor materials. However, traditional silicon approaches its limits under high-frequency, high-power conditions, failing to meet comprehensive requirements. Consequently, new material systems like GaN and ultra-wide bandgap semiconductors have become research foci, supporting high-frequency devices. This paper reviews

DOI: 10.54254/2755-2721/2026.35554

fourth-generation semiconductor materials and applications in high-frequency communication, providing insights for material selection in the 6G and terahertz era, and promoting synergistic development with 6G security.

2. Key performance requirements

2.1. Wide bandgap and breakdown electric field

In high-frequency communication systems, radio-frequency power amplifiers need to operate stably under conditions of high voltage and high power density.Consequently, the critical breakdown electric field of the material becomes one of the key parameters determining the performance of the device.Compared with conventional silicon-based materials, wide-bandgap semiconductors including silicon carbide (SiC) and gallium nitride (GaN) feature higher critical breakdown electric fields and better high-frequency performance, laying a solid material foundation for the fabrication of high-power and high-frequency communication devices.On this basis, gallium trioxide (Ga_2O_3), as a new-generation ultra-wide bandgap semiconductor material, has a Ballygao value far higher than that of SiC and GaN, demonstrating greater potential for breakdown electric field strength, and is expected to enable the development of high-voltage, low-loss power devices [2]. Furthermore, aluminium nitride (AlN), as a typical wide-bandgap semiconductor material, not only possesses a high breakdown electric field strength but also exhibits excellent thermal conductivity and good physicochemical stability, giving it significant potential for application in high-frequency, high-temperature and high-power electronic devices [3].

2.2. High electron mobility and saturation velocity

Electron mobility serves as one of the core indicators for evaluating the high-frequency application potential of semiconductor materials.In particular, due to its unique polarisation effect, GaN material can form a high-density two-dimensional electron gas (2DEG) at the heterojunction interface, thereby significantly enhancing carrier mobility, which has led to its widespread use in high-frequency RF devices [4]. With the continuous advancement of high-performance semiconductor technology, RF devices are evolving toward higher operating frequencies and stronger power-bearing capacity.Against this backdrop, ultra-wide bandgap semiconductor materials have gradually become a hot topic of research.Among these, gallium oxide (Ga_2O_3) has attracted widespread attention due to its bandgap width of approximately 4.8 eV; this characteristic theoretically endows it with a higher breakdown electric field strength and superior power handling capability, thereby opening up new possibilities for the realisation of high-voltage, high-power devices [5].

2.3. Thermal conductivity and power density

As high-frequency communication systems evolve towards the millimetre-wave and terahertz bands, the continuous growth in component power density renders thermal management an urgent technical challenge. For wide-bandgap semiconductor devices, such as those based on GaN, the self-heating effect has become one of the key factors limiting their high-frequency output performance and reliability [6]. At the nanoscale, heat transport processes exhibit pronounced size effects; the thermal conductivity in thin films and heterostructures may be significantly lower than that of bulk materials, which places greater demands on the thermal design of high-frequency devices.By introducing substrates with high thermal conductivity, optimising interface structures and designing

DOI: 10.54254/2755-2721/2026.35554

novel heat dissipation structures (such as microchannels or near-junction cooling), it is possible to effectively shorten the heat conduction path and enhance thermal diffusion capacity, thereby improving the device's output characteristics and extending its safe operating range.

2.4. High-frequency losses and interface scattering

At millimeter-wave and terahertz operating frequencies, device high-frequency loss becomes increasingly severe. Interfacial roughness and structural defects induce extra scattering mechanisms that substantially degrade carrier transport properties.Rough-surface scattering in GaN-based devices plays a dominant role in carrier transport and gain degradation, and is one of the key factors limiting the high-frequency performance of such devices [7]. In heterostructures such as GaN-on-Si, the chemical composition and charge distribution at the interface have a significant impact on radio-frequency loss.Relevant research indicates that a SiCxNy transition layer exists at the AlN/Si interface; its carbon content is closely related to the interfacial charge density and regulates the formation of parasitic conduction channels by influencing the interfacial potential distribution.

2.5. Radio frequency stability and reliability

Under high-frequency and high-power operating conditions, the degradation mechanisms of GaN-based devices are closely related to material defects and interface traps.Research has shown that carrier traps alter the distribution of the electric field within the device, thereby causing an increase in on-resistance and a deterioration in breakdown characteristics, which affects the long-term stability of the device [8]. Multiple characterization measurements reveal that non-uniform response zones mainly appear at high-field positions including gate edges, and these anomalies originate from crystalline defects like dislocations and impurity clusters.Atomic probe analysis has further revealed that impurities such as carbon and oxygen increase the trap density, thereby exacerbating the gate hysteresis and leakage hysteresis effects.Consequently, reducing the levels of defects and impurities is key to improving device reliability.

3. Fourth-generation semiconductor materials with ultra-wide bandgaps

Diamond is a representative ultra-wide-bandgap semiconductor with a bandgap of roughly 5.47 eV. It boasts record-high breakdown electric field and carrier mobility among all existing semiconductor materials. In particular, its thermal conductivity can exceed 2000 $W \cdot m^{-1} \cdot K^{-1}$, which is significantly higher than that of materials such as Si, SiC and GaN [9]. The high thermal conductivity of diamond is primarily due to its strong covalent bond structure and efficient phonon transport.Research has shown that the thermal transport properties of phonons are sensitive to applied electric fields; under the influence of a positive electric field, the mean free path of phonons increases, their lifetime is extended and phonon-phonon interactions are enhanced, thereby promoting an increase in the lattice thermal conductivity [9]. In actual devices, the interface and packaging structure also have a significant impact on the thermal performance of diamond.For example, at the metal-diamond interface, the interfacial thermal resistance limits the efficiency of heat transfer, thereby affecting overall heat dissipation performance.

β-Ga_2O_3 is a typical ultra-wide bandgap semiconductor material; with a bandgap width exceeding 4.5 eV and an extremely high theoretical breakdown electric field, it shows significant potential for application in high-power electronic devices [10]. Another key advantage of β-Ga_2O_3 is the feasible growth of large-size single crystals via the melt-growth method, which supports the low-cost

DOI: 10.54254/2755-2721/2026.35554

fabrication of power devices.However, in terms of the material's intrinsic properties, its thermal conductivity is relatively low, typically ranging from 10 to 30 $W \cdot m^{-1} \cdot K^{-1}$, which is significantly lower than that of materials such as GaN and SiC. Such material limitations bring severe thermal management challenges for devices operating under high-power-density conditions. 3.3 AlN and AlGaN.

Aluminium nitride (AlN) and its alloy, AlGaN, are typical Group III nitride ultra-wide bandgap semiconductor systems, and hold significant potential for application in high-frequency, high-power devices.AlN possesses excellent thermal stability, low dielectric loss and radiation resistance; its wurtzite structure and strong covalent bonds enable the material to maintain stable performance even under high-temperature and high-electric-field conditions [11]. By modulating aluminum composition, AlGaN alloys support flexible bandgap engineering and effectively strengthen the material polarization effect. Synergistic optimisation is required between bandgap tuning, polarisation effects and defect control in order to fully exploit the material's advantages.

4. Progress in communication devices based on fourth-generation semiconductors

4.1. High-frequency HEMT devices

The development of high-electron-mobility transistors (HEMTs) has placed greater demands on the performance of semiconductor materials.HEMT devices, typified by AlGaN/GaN heterostructures, rely on the material's high electron mobility, high breakdown electric field and high saturation drift velocity to achieve high-frequency, high-power output [12]. However, the defect density in the epitaxial layer, interfacial roughness and the polarisation effect have a significant impact on carrier transport.High-frequency operation imposes rigorous constraints on material thermal conductivity and lattice matching quality to suppress device self-heating effects. Furthermore, whilst materials with a high aluminium content and novel substrates can enhance performance, they also give rise to stress and defect issues.

4.2. THz emitters and detectors

The development of devices in the terahertz (THz) band places greater demands on semiconductor materials.As THz photons have extremely low energy, the signal is easily overwhelmed by thermal noise; consequently, devices typically rely on high-mobility carrier systems rather than conventional photoelectric response mechanisms, which places stringent demands on the electronic transport properties of the materials [13]. Currently, GaN/AlGaN heterostructure HEMTs have become a core technical solution for THz detection, whose performance is highly governed by the density and mobility of two-dimensional electron gas (2DEG). THz devices are particularly sensitive to the quality of semiconductor interfaces and the control of defects.New materials (such as graphene and GaN heterointegration) can further improve THz response characteristics by reducing phonon loss [13].

4.3. High-frequency power amplifiers

Advances in high-frequency power amplifiers have significantly driven the demand for improved performance in semiconductor materials.Power amplifiers, typified by GaN-based HEMTs, rely on the material's advantages—such as its wide bandgap, high breakdown electric field and high thermal conductivity—to achieve high power density and high efficiency [14]. However, the continuous

DOI: 10.54254/2755-2721/2026.35554

elevation of operating frequency and output power aggravates heat accumulation, interface degradation and leakage current deterioration, all of which are strongly associated with material intrinsic characteristics and interfacial quality. The performance of a power amplifier depends not only on carrier transport characteristics, but also to a large extent on the synergistic optimisation of a multi-layer material system comprising the substrate, buffer layer and gate dielectric.Research has shown that the introduction of high-thermal-conductivity substrates and high-k dielectrics can effectively improve thermal management and gate control capabilities, but this also places greater demands on material interface matching and defect control.

4.4. Satellite communication components

Advances in satellite communication components have placed increasingly stringent demands on semiconductor materials. GaN-based devices have been extensively validated in geostationary orbit environments and are able to maintain stable performance even under extreme conditions such as radiation, high temperatures and high electric fields, thanks to their wide bandgap characteristics and excellent radiation resistance [15]. Power devices based on GaN/SiC heterostructures achieve higher power density and superior thermal performance by combining a high breakdown electric field with high thermal conductivity; however, their performance remains highly dependent on the quality of the material interfaces and the degree of lattice matching.

4.5. AI RF front-end

The evolution of AI-enabled highly integrated RF front-ends toward higher operating frequencies puts forward stricter requirements for semiconductor material performance.Wide-bandgap semiconductor materials have become a key material foundation for radio-frequency front-ends due to their high breakdown electric field and excellent carrier transport properties.In AlGaN/GaN heterostructures, the two-dimensional electron gas (2DEG) induced by the polarisation effect can significantly enhance carrier concentration and mobility, thereby supporting performance improvements in high-frequency devices.Device performance is highly dependent on the epitaxial structure and interface engineering.The materials used for the gate dielectric and passivation layer have a critical influence on leakage current, interface state density and device stability, whilst the choice of substrate and buffer layer is directly related to thermal management capability and reliability.

5. Prospects for applications in 6G and THz communications

The development of millimetre-wave power devices demands higher semiconductor material performance. GaN-based MMIC power amplifiers offer high output power and efficiency in the millimetre-wave band, owing to wide bandgap, high breakdown field and high electron saturation velocity. Yet at higher frequencies, trapping, interface scattering and parasitic effects intensify, requiring more precise modelling and control. Integrated air-space-ground communications also raise material requirements: carbon-based nanomaterials with ultra-high carrier mobility enable efficient THz transmission, while silicon suffers from high-frequency limitations, and interface scattering demands better defect control and interface quality. Highly integrated systems need higher thermal conductivity and stability.

Advances in flexible and wearable RF technology further stress materials. Flexible substrates like polyimide and PET combine mechanical flexibility with low dielectric loss. Conductive materials

DOI: 10.54254/2755-2721/2026.35554

such as graphene, carbon nanotubes and metal nanowires are widely used for their conductivity and flexibility. Wearable applications require enhanced flexibility, conductivity and environmental stability; in fabric-based RF harvesters, substrate pore structure and conductive ink compatibility directly affect efficiency. Cyclic bending causes interfacial degradation, so rational optimization of interfacial structures and mechanical configurations is essential.

6. Conclusion

The aim of this paper is to provide a systematic analysis of the key performance characteristics of fourth-generation semiconductor materials in the field of high-frequency communications, as well as recent developments in their applications.Research has shown that materials such as GaN, Ga_2O_3 and AlN offer significant advantages in terms of wide bandgap, high breakdown electric field and high electron mobility, effectively supporting the development of high-frequency, high-power devices and validating the view that material properties are the key driver for enhancing the performance of communications devices.By comprehensively analysing the relationship between material properties and device requirements, this study remedies the research gap in the existing literature concerning the "material—device—system" synergistic mechanism, enriching the theoretical framework of wide-bandgap semiconductor applications for 6G and terahertz communication systems.In practical terms, this study provides a reference for the selection of materials and structural optimisation of high-frequency communication devices, and is of practical significance for advancing the development of next-generation communication technologies. However, this study is a literature-based review without original experimental data. In particular, the long-term operational reliability of relevant materials under extreme working conditions lacks in-depth discussion, which partially restricts the generalizability of the research conclusions.Future research could combine experiments with multi-physics simulations to explore in depth the mechanisms underlying the control of material defects and the optimisation of interface engineering, whilst expanding the application potential of novel material systems.Overall, this paper has deepened our understanding of the role of semiconductor materials in high-frequency communications and highlighted the crucial importance of optimising material properties in the development of communications technology.

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