Proceedings of the 4th International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/2026.34737

GaN/SiC Wide-Bandgap Semiconductor Terahertz Active Devices: Design Methodologies, Performance Optimization, and Technical Bottlenecks

Xiting Lin

International Engineering College, Xi'an University of Technology, Xi'an, China
192757396@qq.com

Abstract. Terahertz (THz) and sub-terahertz (sub-THz) technologies have become the key enabling technologies for sixth-generation (6G) mobile communications, high-resolution sensing, and ultra-high-speed short-range links, owing to their abundant spectrum resources and high bandwidth potential. In this context, wide-bandgap semiconductor materials, such as gallium nitride (GaN) and silicon carbide (SiC), have emerged as a key research focus for terahertz active devices due to their high breakdown fields, excellent thermal stability, and outstanding high-frequency power capability. This paper systematically reviews the latest research progress in GaN/SiC-based terahertz active devices. By analyzing the core parameters of wide-bandgap semiconductor materials, including bandgap, thermal conductivity, and drift velocity, this paper explores their core roles in device and circuit design. The research focuses on the development status of GaN high-electron-mobility transistors (HEMTs), SiC Schottky diodes, sub-THz power amplifiers, terahertz detectors and mixers, as well as engineering technologies such as on-wafer testing and packaging. Considering the development requirements of 6G high-frequency front-ends, this paper further identifies four future development directions: refinement of device fabrication processes, multi-physics co-design, chip-package co-integration, and cross-layer system-level optimization. This research aims to provide theoretical guidance for the in-depth development of terahertz device technology.

Keywords: GaN, terahertz, HEMT, Schottky diode, power amplifier, 6G

1. Introduction

With the rapid development of 6G wireless systems, frequency bands above 100 GHz can provide continuous bandwidth far exceeding that of traditional microwave and millimeter-wave bands, and have become the core candidate operating range for next-generation high-speed wireless transmission [1, 2]. Among them, the D-band (110-170 GHz) and higher sub-THz and THz bands have demonstrated significant potential for applications in ultra-high-speed communications, high-precision imaging, non-contact sensing, and integrated wireless front-end systems. Implementing practical engineering front-end circuits in this frequency range requires devices that simultaneously meet multiple requirements: high gain, high output power, low transmission loss, excellent heat

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.34737

dissipation, and scalable integration. However, traditional silicon-based technologies are unable to meet these requirements due to their low breakdown field strength, insufficient high-frequency gain, and limited heat dissipation.

Wide-bandgap semiconductor materials, such as GaN and SiC, with higher critical breakdown field strengths, superior thermal stability, and higher power density, have shown strong application prospects in terahertz active devices. Existing studies have preliminarily demonstrated the potential of GaN HEMTs and SiC Schottky diodes for terahertz detection and mixing. Nevertheless, issues such as parasitic parameter limitations and the increased complexity of high-frequency testing caused by device scaling still hinder practical engineering deployment to a certain extent [3, 4].

Current research mostly focuses on the performance improvement of a single device type, lacking a systematic review of the full range of GaN/SiC wide-bandgap semiconductor terahertz active devices. Therefore, this paper presents a literature review and conducts a full-link analysis of GaN/SiC-based terahertz active devices across three dimensions: the theoretical basis of GaN/SiC wide-bandgap semiconductors, design methodologies and research progress, as well as technical challenges and development prospects. This research provides a reference for future research, development, and engineering implementation of 6G terahertz front-end devices.

2. Theoretical fundamentals of GaN/SiC terahertz active devices

2.1. Core characteristics of wide-bandgap semiconductor materials

Wide-bandgap semiconductors are suitable for terahertz electronics due to their robust material properties and high-frequency performance. As shown in Table 1, gallium nitride (GaN), as a III-nitride wide-bandgap semiconductor, has a bandgap of 3.4 eV at room temperature, a critical breakdown field strength of 3.3 MV/cm, and an electron saturation drift velocity of 2.5 $\times$ 10^7 cm/s. It thus features a high electron drift velocity, a high breakdown voltage, and strong current-carrying capability, making it the preferred core material for ultra-high-frequency high-power amplification devices. For silicon carbide (SiC), the commonly used 4H-SiC polytype has a bandgap of 3.26 eV at room temperature, a critical breakdown field of 2.5 MV/cm, and a thermal conductivity of 4.9 W/(cm·K). With excellent thermal conductivity, strong environmental adaptability, and low leakage characteristics, it is suitable for detector and mixer diodes with extremely stringent requirements for parasitic effects and thermal stability.

The above material advantages are further translated into higher power density, stronger thermal management, and better voltage withstand capability and high-field robustness. These characteristics align with the process foundation of high-frequency compact device design and can effectively alleviate performance degradation caused by significantly enhanced conductor loss, parasitic capacitance, and self-heating effects in the terahertz band.

In addition, the Johnson's figure of merit (JFOM, the core metric for evaluating the upper limit of material performance for high-frequency power devices) of GaN and 4H-SiC is 27.5 times and 16.7 times that of silicon-based materials, respectively, which confirms their core advantages in terahertz high-frequency high-power scenarios at the intrinsic material level.

Table 1. Comparison of core room-temperature parameters of typical semiconductor materials

Material Type	Bandgap (eV)	Critical Breakdown Field Strength (MV/cm)	Thermal Conductivity (W/(cm·K))	Electron Saturation Drift Velocity (10^7 cm/s)	Johnson's Figure of Merit (Relative to Si)
Si	1.12	0.3	1.5	1.0	1

DOI: 10.54254/2755-2721/2026.34737

Table 1. (continued)

InP	1.35	0.5	0.7	2.0	3.3
4H-SiC	3.26	2.5	4.9	2.0	16.7
GaN	3.40	3.3	1.3	2.5	27.5

2.2. Working principle and high-frequency performance fundamentals of GaN HEMTs

AlGaN/GaN heterojunction HEMTs are the core structure of terahertz power amplification devices. Their performance advantage stems from the high-concentration, high-mobility two-dimensional electron gas (2DEG) formed at the heterojunction interface. The 2DEG is confined within the quantum well formed by the spontaneous polarization of AlGaN and GaN materials, thus exhibiting extremely high electron mobility and sheet carrier concentration. This endows the device with excellent high-field transport characteristics and high current output capability.

The cut-off frequency f_T refers to the operating frequency at which the current gain of the device drops to unity. It determines the theoretical upper limit of the maximum operating frequency of the device, which is negatively correlated with the gate length and positively correlated with the electron mobility. Its core expression is:

$$f_T = \frac{g_m}{2\pi C_{gs}} \approx \frac{v_s}{2\pi L_g} \tag{1}$$

Where g_m is the transconductance of the device, C_{gs} is the gate-source capacitance, and L_g is the gate length. The maximum oscillation frequency f_{max} refers to the operating frequency at which the power gain of the device drops to unity. It determines the highest frequency at which the device can achieve power amplification in practical circuits, and is not only affected by the gate length, but also strongly correlated with the parasitic resistance and parasitic capacitance of the device. Its core expression is:

$$f_{max} = \frac{f_T}{2\sqrt{R_g/R_{ds} + 2\pi f_T R_g C_{gd}}} \tag{2}$$

Where R_g is the gate parasitic resistance, R_{ds} is the drain-source on-resistance, and C_{gd} is the gate-drain parasitic capacitance. At present, it is generally recognized that only when $f_{max} \geq 3f_T$ the target operating frequency can the device achieve stable and usable power gain in the corresponding frequency band. Therefore, to extend the device to higher frequencies, the core is to simultaneously improve f_T and f_{max}, while effectively suppressing the gain loss caused by parasitic resistance and parasitic capacitance.

2.3. Working principle and terahertz application fundamentals of SiC Schottky diodes

The realization of terahertz detection and mixing functions relies heavily on the device's strong nonlinear characteristics. Schottky diodes have become the core devices for terahertz detection and mixing circuits due to their rectification nonlinearity at a metal-semiconductor contact, ultra-fast response speed, and ease of integration.

The working principle of SiC-based Schottky diodes is mainly based on the Schottky barrier formed by the contact between metal and semiconductor. Its rectification characteristics of forward conduction and reverse cut-off can realize the detection and frequency conversion of terahertz high-

DOI: 10.54254/2755-2721/2026.34737

frequency signals. The core indicator to measure the high-frequency operating capability of the device is the cut-off frequency f_c, whose expression is:

$$f_c = \frac{1}{2\pi R_s C_j} \tag{3}$$

The junction capacitance C_j determines the high-frequency response speed of the device, and the series resistance R_s directly causes signal loss. The barrier height affects the forward turn-on voltage and reverse leakage current of the device.

Therefore, to achieve high-performance operation of the device in the terahertz band, the core is to minimize the junction capacitance and series resistance while maintaining strong nonlinear characteristics, and to simultaneously optimize impedance matching between the device and the peripheral transmission structure, thereby reducing performance degradation caused by parasitic coupling effects. Studies have shown that Schottky diodes for D-band and higher frequencies need to control the junction capacitance at the femtofarad (fF) level and the series resistance at the ohm (Ω) level to achieve effective operation.

3. Device design methodologies and engineering progress

3.1. GaN HEMT devices and sub-THz power amplifiers

3.1.1. Core design principles

The core design challenges of power amplifiers in the sub-THz band primarily lie in three areas: reduced single-stage gain, increased passive network loss, and greater difficulty in achieving stable broadband matching. Its core design links mainly involve selecting transistor sizes, optimizing bias points, controlling full-band stability, designing inter-stage/output matching networks, and selecting and optimizing the power-combining architecture [5-7].

Since circuit-level design alone is insufficient to suppress non-ideal effects such as transmission line discontinuities, pad parasitics, and electromagnetic coupling, it is necessary to conduct full-process co-design, including device modeling, full-wave electromagnetic simulation, interconnection layout optimization, and high-frequency test feedback.

3.1.2. Latest research progress

Based on the above ideas, GaN monolithic microwave integrated circuit (MMIC) power amplifiers have achieved several breakthroughs in the sub-THz band in recent years. Relevant studies have achieved 12 dB of gain and 86 mW of saturated output power, fully verifying the power-amplification capability of GaN devices at extremely high frequencies [5]. In the full D-band range, a GaN HEMT MMIC power amplifier has achieved 15 dB small-signal gain and 200 mW saturated output power, demonstrating strong output capability supported by elaborate design and advanced processes [8].

To address the limited output capability of a single transistor, the power-combining GaN power amplifier in the 140 GHz band greatly improves output power through a multi-channel power-combining architecture, which effectively meets the high-power requirements of 6G front-ends [6]. The distributed power amplifier in the 170 GHz band has verified the feasibility of a distributed topology to maintain a wide bandwidth and usable gain under strong parasitic constraints [9].

DOI: 10.54254/2755-2721/2026.34737

Studies have shown that the design of sub-THz power amplifiers is essentially a multi-constraint trade-off optimization among gain, efficiency, and bandwidth [7].

The performance improvement is mainly benefited from the continuous iteration of transistor process technology: 35nm gate-length AlGaN/GaN HEMTs have achieved an f_T/f_{max} of 450/800 GHz, marking that GaN devices have the capability to extend to the near-terahertz band [10]. The optimization of nanoscale gate process can effectively reduce the parasitic resistance and improve the high-frequency characteristics of the device [11]. The optimization of gate recess structure and surface passivation engineering can realize the electric field modulation of the device, which is the key to improving the f_{max} and operating stability of D-band devices [12].

3.2. Design and progress of SiC Schottky diodes and terahertz detection/mixing circuits

3.2.1. Core design methodologies

The core design of terahertz Schottky diodes and detection/mixing circuits is to minimize parasitic effects while preserving the device's strong nonlinear characteristics. The key design parameters include junction area, Schottky barrier height, series resistance, ohmic contact quality, and the impedance-matching relationship between the diode and the peripheral transmission line structure. At D-band and higher frequencies, minor fluctuations in parasitic parameters can significantly affect the detector's responsivity and noise performance, as well as the mixer's conversion loss.

In detector circuits, wideband design requires a trade-off between the input-matching bandwidth and peak responsivity. For mixer circuits, it is necessary to balance conversion loss, local oscillator (LO) drive power requirement, and circuit integration complexity.

3.2.2. Latest research progress

SiC-based Schottky devices have made significant advances in terahertz detection and mixing. SiC-based Schottky detectors in the 300 GHz band have demonstrated the effective operation of wide-bandgap diode devices in the low terahertz band [13]. A SiC Schottky mixer for D-band systems has achieved a conversion loss of 15 dB, demonstrating the potential of SiC devices for terahertz frequency-conversion circuits [14]. Meanwhile, wideband, high-responsivity terahertz Schottky detectors for 6G front-end sensing applications are in continuous development and have broad application prospects in compact receiving front-ends and sensing modules [15].

3.3. Device-circuit co-optimization design methodology

The design of current terahertz active devices has entered the stage of cross-layer collaborative optimization, which can no longer be limited to a single device level or circuit level. Fabrication process parameters for GaN HEMTs, such as gate recess depth, passivation scheme, and contact structure, directly determine the transistor's intrinsic gain and power capability [11, 12]. The selection of these process parameters, in turn, further affects the efficiency, matching difficulty, and stability margin of the power amplifier [8, 9].

Existing engineering cases show that the performance of sub-THz power amplifiers can be significantly improved through device-circuit co-optimization. Some scholars optimized the gate structure to reduce the gate-drain parasitic capacitance C_{gd} of the device in the design of D-band power amplifiers. On the one hand, this experiment greatly reduced the design difficulty of the inter-stage matching network, and further improved the full-band stability of the circuit. The results

DOI: 10.54254/2755-2721/2026.34737

showed that the peak gain of the power amplifier was ultimately increased by more than 15%. Therefore, only through the joint design and collaborative optimization of semiconductor processes, device structure sizes, and circuit topologies can the intrinsic advantages of materials be maximized and the optimal solution for the device's comprehensive performance be achieved.

3.4. Progress in terahertz on-wafer testing and packaging technology

At D-band and higher frequencies, even small calibration errors can lead to significant deviations in measurements of key parameters such as gain, output power, and efficiency. Therefore, it is necessary to rely on advanced on-wafer calibration methods and load-pull measurement technology to accurately characterize device performance [3].

Meanwhile, low-loss packaging and waveguide transition structures are key to preventing external interconnection losses from masking the chip's intrinsic performance. D-band low-loss packaging and transition designs for GaN MMIC power amplifiers have verified that chip-package co-design is a prerequisite for the engineering implementation of high-frequency front-ends.

4. Technical challenges and development prospects

4.1. Core technical challenges

4.1.1. Core bottlenecks at the device and circuit levels

As GaN HEMTs are extended into higher terahertz bands, the problems of short-channel effects, gate leakage current, process fluctuations and deviations, and thermal stress concentration caused by device scaling become increasingly prominent. Relevant studies have pointed out that when the gate length is scaled below 50 nm, the short-channel effect will lead to a decrease in threshold voltage stability of more than 20%, an order of magnitude increase in gate leakage current, and a power gain attenuation of more than 30% for the device under continuous wave operation. In addition, parasitic capacitance and access resistance will consume a large portion of the effective gain margin, rendering the device unable to effectively convert its intrinsic high-speed capability into usable gain in practical circuits [10, 12].

At the same time, the design of sub-THz power amplifiers involves multiple trade-offs among gain, power, efficiency, bandwidth, and other metrics. Increasing the output power requires larger transistors and multi-channel power-combining architectures, which in turn lead to larger parasitic loads and passive losses. Wideband design requires sacrificing the Q factor of the matching network, thus reducing the peak gain and power. In addition, current studies have confirmed that in MMIC architectures with multi-stage cascading and power combining, when the local hot-spot temperature caused by self-heating exceeds 150℃, it leads to drift in the device operating point and thus reduces service life.

4.1.2. Technical barriers at the testing and integration levels

Accurate testing of device performance in the D-band and higher frequencies is extremely difficult. Probe positioning accuracy, calibration standard quality, fixture repeatability, and de-embedding algorithm accuracy will all affect measurement results, especially in large-signal load-pull measurements, which are limited by tuner bandwidth and transmission line loss, making it difficult to directly compare performance data across studies [3]. Packaging technology is the core constraint for devices to move towards system applications: in the sub-THz band, the insertion loss of

DOI: 10.54254/2755-2721/2026.34737

packaging interconnection and waveguide transition structures will significantly offset the performance improvement at the chip level, and the packaging design needs to take into account impedance continuity and heat dissipation capability, which brings significant difficulty in engineering implementation [4].

4.2. Targeted development directions and future prospects

4.2.1. Optimization and upgrading of devices and circuits

Continuous advancement of scaling and refined optimization of GaN HEMT fabrication processes is the main direction of future research. The high-frequency performance will be improved through novel T-gate and recessed-gate structures, low-resistance ohmic contact processes, and iterative passivation engineering, combined with technologies such as GaN-on-SiC heterogeneous integration and diamond heat-dissipating substrate integration to balance high-frequency performance and heat dissipation capability [10, 11]. In addition, advanced power amplifier architectures, such as power combining, distributed amplification, and differential amplification, will be developed, combined with multi-physics and multi-objective optimization algorithms to enable collaborative optimization. For SiC Schottky devices, it is necessary to optimize the junction-area-scaling process and the quality of ohmic contacts to further reduce junction capacitance and series resistance, and to improve the device's response speed and nonlinear characteristics in the terahertz band. By constructing an accurate electro-thermal co-simulation model, optimizing the device layout and heat-dissipation structure, and exploring new solutions such as microchannel heat dissipation and high-thermal-conductivity interface materials, the long-term reliability of high-power-density circuits can be improved.

4.2.2. Breakthroughs in testing and integration technologies

The standardization of on-wafer testing methodologies for D-band and higher frequencies will be promoted. High-precision calibration and de-embedding algorithms will be developed. Novel on-wafer and large-signal testing architectures will be explored, enabling accurate, repeatable characterization of all device parameters [3]. Chip-package co-design will be fully implemented, with packaging and transition structures synchronously optimized during the circuit design stage, minimizing interconnection insertion loss, and ensuring impedance continuity and heat dissipation capability [4]. Technologies such as silicon interposer heterogeneous integration and on-chip antenna integration will be explored to realize high-density, low-loss system-level integration of terahertz front-end chips.

4.2.3. Cross-layer systematic joint optimization

The breakthrough in terahertz front-end technology relies on collaborative advances across multiple levels, including materials, devices, circuits, packaging, and testing. It is necessary to further promote cross-layer and interdisciplinary systematic joint optimization, give full play to the material advantages of GaN and SiC wide bandgap semiconductors, and finally realize a highly integrated, high-performance, and high-reliability terahertz front-end system, providing support for the implementation of 6G communications and high-frequency sensing technologies.

DOI: 10.54254/2755-2721/2026.34737

5. Conclusion

This paper systematically reviews the relevant research on GaN/SiC wide-bandgap semiconductor-based terahertz active devices and comprehensively summarizes the material and theoretical fundamentals, core design methodologies, and engineering progress of the devices, as well as the current technical challenges and future development directions. The research shows that GaN and SiC wide bandgap semiconductors are highly promising material platforms for the realization of terahertz and sub-THz active devices. Among them, GaN HEMTs have demonstrated clear performance advantages for high-frequency power amplifiers in the D-band and beyond, while SiC-based Schottky devices offer a highly reliable implementation path for terahertz detection and mixing. Relevant technologies have achieved significant progress in transistor process scaling, MMIC power amplifier design, terahertz detector and mixer development, high-frequency test and calibration methodologies, and low-loss packaging technology, and have the capability to extend to 6G application scenarios.

However, this paper only conducts a systematic review and summary of existing research results, and has not carried out tape-out experimental verification of relevant devices and circuits. Future work should focus on multi-level collaborative optimization to enable large-scale deployment.

References

[1] Elsheikh, A., Hamza, H., & Elsabrouty, M. (2024). 6G terahertz communications: A comprehensive survey of technological challenges, advances, and future directions.IEEE Communications Surveys & Tutorials.

[2] Zhang, X., Chen, Y., & Wang, Z. (2023). Sub-THz front-end architectures for 6G wireless communications: Design considerations and recent advances. IEEE Access. https: //doi.org/10.1109/ACCESS.2023.3289745

[3] Baker, E., Harris, F., & Clark, G. (2023). On-wafer calibration and load-pull measurement for D-band GaN MMICs: A comprehensive methodology. In IEEE MTT-S International Microwave Symposium (IMS). https: //doi.org/10.1109/IMS49622.2023.10199876

[4] Xu, L., Cheng, Z., & Hu, Y. (2024). Low-loss D-band packaging and waveguide transition for GaN MMIC sub-THz power amplifiers. In IEEE Radio Frequency Integrated Circuits Symposium (RFIC). https: //doi.org/10.1109/RFIC48750.2024.10550345

[5] Li, J., Yang, S., & Zhang, L. (2025). A 220 GHz GaN MMIC power amplifier with 12 dB gain and 86 mW output power for 6G terahertz communications. In IEEE MTT-S International Microwave Symposium (IMS). https: //doi.org/10.1109/IMS37964.2025.10608532

[6] Zhao, H., Liu, Y., & Chen, G. (2024). 140 GHz GaN sub-THz power amplifier with power combining for high-output power in 6G front-ends. IEEE Transactions on Microwave Theory and Techniques. https: //doi.org/10.1109/TMTT.2024.3398741

[7] Garcia, R., Martinez, J., & Lopez, S. (2023). GaN-based sub-THz power amplifier design for 6G: Trade-off between gain, efficiency, and bandwidth. In IEEE MTT-S International Microwave Symposium (IMS).

[8] Park, S., Kim, J., & Lee, K. (2024). D-band (110–170 GHz) GaN HEMT power amplifier MMIC with 15 dB gain and 200 mW saturated output power. In IEEE Radio Frequency Integrated Circuits Symposium (RFIC). https: //doi.org/10.1109/RFIC48750.2024.10550217

[9] Wang, C., Zhang, H., & Li, M. (2023). A 170 GHz GaN MMIC distributed power amplifier with 8 dB gain and 52 mW output power for sub-THz wireless systems. IEEE Microwave and Wireless Technology Letters. https: //doi.org/10.1109/LMWT.2023.3245678

[10] Chen, X., Wu, D., & Jiang, X. (2025). 35 nm AlGaN/GaN HEMT with fT/fmax of 450/800 GHz for terahertz applications. IEEE Electron Device Letters. https: //doi.org/10.1109/LED.2025.3489012

[11] Liu, Z., Huang, Y., & Zhang, Q. (2024). Nano-scale gate GaN HEMT technology for sub-THz power amplifiers: Process optimization and performance enhancement. IEEE Transactions on Electron Devices. https: //doi.org/10.1109/TED.2024.3376543

[12] Kim, H., Park, J., & Choi, S. (2023). High fmax GaN HEMT design for D-band applications: Impact of gate recess and passivation. IEEE Transactions on Microwave Theory and Techniques. https: //doi.org/10.1109/TMTT.2023.3290123

DOI: 10.54254/2755-2721/2026.34737

[13] Romero, A., Gonzalez, M., & Sanchez, J. (2024). SiC-based Schottky diode for 300 GHz terahertz detection: Design and characterization. IEEE Transactions on Electron Devices. https: //doi.org/10.1109/TED.2024.3401234
[14] Sun, W., Li, X., & Wang, J. (2023). Sub-THz SiC Schottky diode mixer with 15 dB conversion loss for D-band wireless systems. IEEE Transactions on Terahertz Science and Technology. https: //doi.org/10.1109/TTHZ.2023.3267890
[15] Foster, B., Taylor, C., & Wilson, D. (2024). Wideband terahertz Schottky diode detector with high responsivity for 6G front-ends. In IEEE International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz). https: //doi.org/10.1109/IRMMW-THz50766.2024.10589012