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Review on the Properties and Comprehensive Application Development of Novel Semiconductor Materials based on GaN, InP, and GaAs

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Abstract

With the rapid development of 5G/6G communications, data centers, new energy vehicles, autonomous driving, and high-performance optoelectronic systems, traditional silicon-based semiconductors are gradually approaching their performance limits in application scenarios such as high frequency, high power, high temperature, and high-speed photoelectric conversion. Compound semiconductor materials have become key enablers for new-generation devices. Gallium arsenide (GaAs) and indium phosphide (InP) offer high electron mobility and excellent optoelectronic properties for high-frequency communication and photonic applications. Gallium nitride (GaN), distinguished by its wide bandgap and high breakdown field strength, further extends these capabilities to high-power electronics and ultraviolet optoelectronics.This paper focuses on three typical compound semiconductor materials, GaAs, InP, and GaN, and reviews their material properties, current technological development status, and main application directions. It emphatically analyzes the application progress of GaAs and InP in radio frequency (RF) front-ends, microwave and millimeter-wave multifunctional integrated circuits, optical communications, and optoelectronic devices, discusses the development potential of InP/CMOS heterogeneous integration in high-frequency communications above 100 GHz, radar detection, and optoelectronic integration, and outlines the application prospects of GaN in vertical power devices, driver integrated circuits, new energy vehicles, and 6G communications. Finally, it analyzes the challenges faced by compound semiconductors in large-size substrate preparation, process compatibility, device reliability, manufacturing costs, and large-scale applications, and prospects their future development trends toward multi-material collaboration, heterogeneous integration, and system-level integration.

Keywords

Gallium Arsenide; Indium Phosphide; Gallium Nitride; New Compound Semiconductors; Heterogeneous Integration; Power Devices.

1. Introduction

Semiconductor materials are the foundation for the development of the modern electronic information industry. Semiconductor materials have gone through three development stages: the first-generation elemental semiconductors represented by silicon (Si) and germanium (Ge), the second-generation semiconductors represented by gallium arsenide (GaAs) and indium phosphide (InP), and the third-generation wide-bandgap semiconductor materials represented by gallium nitride (GaN), silicon carbide (SiC), and zinc oxide (ZnO)[1].

First-generation semiconductor materials represented by silicon (Si) and germanium (Ge) have long dominated integrated circuits and low-to-medium power electronic devices relying on mature preparation processes and a complete industrial ecosystem. However, with the

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increasing performance requirements for devices in fields such as wireless communications, optical communications, intelligent vehicles, data centers, and high-end equipment, traditional silicon-based devices have gradually shown limitations in high frequency, high voltage, high temperature, high power density, and high-speed photoelectric conversion. Against this background, compound semiconductor materials have attracted extensive attention due to their excellent physical properties and application adaptability[2]. As second-generation III-V compound semiconductors, GaAs and InP have high electron mobility, large electron saturation drift velocity, and excellent optoelectronic performance, making them suitable for high-frequency, high-speed, and optoelectronic devices. GaAs has mature applications in RF power amplifiers, low-noise amplifiers, digital phase shifters, digital attenuators, VCSELs, and microwave and millimeter-wave multifunctional integrated circuits; InP, with its advantages in high-speed transmission and photoelectric conversion, is widely used in optical communications, data centers, lasers, detectors, and high-frequency devices above 100 GHz. In recent years, with the continuous improvement of communication rates and system integration, GaAs and InP-related devices are developing from single-function devices to multifunctional integration and system-level applications. Meanwhile, third-generation wide-bandgap semiconductor materials represented by gallium nitride (GaN) have developed rapidly. GaN features a wide bandgap, high breakdown field strength, high thermal conductivity, and high electron saturation velocity, showing significant advantages in high-frequency and high-power RF devices, power electronic devices, and high-temperature and high-voltage applications. Especially in 5G/6G communications, on-board power supplies for new energy vehicles, fast-charging adapters, wireless charging, and high-power-density power conversion systems, GaN devices have demonstrated good application prospects. Compared with lateral GaN devices, vertical GaN power devices have potential advantages in voltage resistance, current density, and chip area utilization, and are considered one of the important development directions for high-performance power devices in the future[3].

With the increasing complexity of application systems, a single material platform can hardly fully meet the comprehensive requirements of high speed, high frequency, high power, and high integration. Heterogeneous integration technology provides a new path for the development of compound semiconductors by complementing the advantages of different materials and process platforms. Among them, InP/CMOS heterogeneous integration can combine the advantages of InP in high-frequency, optoelectronic, and high-speed devices with the advantages of CMOS in digital circuits, high integration, and low-cost manufacturing, and has important research value in 6G communications, terahertz detection, radar imaging, silicon photonic interconnects, and high-performance computing[4]. Although significant progress has been made in compound semiconductor materials and devices, their further development still faces various challenges. For example, the preparation of large-size high-quality substrates is difficult, and material defect and dislocation control still need to be optimized; there are problems of thermal expansion coefficient mismatch, lattice mismatch, and process compatibility in heterogeneous integration; GaN power devices still need breakthroughs in gate reliability, vertical structure processing, and driver circuit co-design; meanwhile, manufacturing costs, yield, and large-scale production capacity restrict the industrialization process of related technologies.

Based on the above background, this paper focuses on three typical compound semiconductor materials, GaAs, InP, and GaN, reviews their material properties, device development, and application status, emphatically analyzes their development trends in microwave and millimeter-wave integrated circuits, optoelectronic devices, heterogeneous integration, power devices, and 6G communications, and discusses the current key issues and future development directions.

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2. Research Background and Current Status

2.1. Overall Progress in Compound Semiconductor Materials Research

With the rapid development of 5G/6G communications, data centers, new energy vehicles, and intelligent systems, traditional silicon-based semiconductors are gradually showing performance bottlenecks in high frequency, high power, high temperature, and high-speed photoelectric conversion, so compound semiconductor materials have attracted extensive attention. At present, compound semiconductors represented by GaAs, InP, and GaN constitutes a critical material foundation for new-generation electronic and optoelectronic devices.

Among them, GaAs and InP, as second-generation compound semiconductor materials, have mature applications in high-frequency communications and optoelectronics. GaAs has high electron mobility and a mature process foundation, and is widely used in RF front-ends, microwave and millimeter-wave integrated circuits, power amplifiers, VCSELs, and other devices. InP has obvious advantages in high-speed optical communications, lasers, detectors, and high-frequency devices above 100 GHz, and shows good development potential in the direction of InP/CMOS heterogeneous integration. Overall, GaAs focuses more on RF and integrated applications, while InP is more suitable for high-speed optoelectronic and ultra-high-frequency systems. As a third-generation wide-bandgap semiconductor material, GaN has the advantages of wide bandgap, high breakdown field strength, and high thermal stability, and has developed rapidly in high-frequency and high-power communications and power electronics. In particular, vertical GaN power devices are considered an important development direction for high-performance power devices in the future due to their greater advantages in voltage resistance, current density, and chip area utilization. Meanwhile, with the expansion of GaN devices to system-level applications, the importance of driver integrated circuit and device co-design is increasing.

GaAs, InP, and GaN are not simply substitutive in applications, but complement each other in the fields of RF, optoelectronics, and power electronics. In the future, the development of compound semiconductors will pay more attention to multi-material collaboration, heterogeneous integration, and system-level applications.

2.2. Current Research on the Application of Third-Generation Semiconductors in 6G Communications and New Energy Vehicles

Against the background of the rapid development of new-generation communications and electric vehicles, the application value of third-generation semiconductor materials has become increasingly prominent. From the perspective of 6G communications, Zhou Honglin analyzed the applications and challenges of third-generation semiconductor materials, pointing out that materials such as GaN and SiC have obvious advantages in high frequency bands, high power, and resistance to extreme environments, and are important candidate materials supporting 6G's high bandwidth, low latency, and large connectivity. Compared with silicon and second-generation semiconductors, third-generation semiconductors have better performance in high-frequency, high-temperature, and radiation-resistant scenarios, and are especially suitable for millimeter-wave and even terahertz communication systems[6].

However, relevant studies also pointed out that third-generation semiconductors still face various challenges in 6G applications, including technological maturity, reliability, spectrum resource adaptation, and cost. High-frequency band signals are more susceptible to rain, fog, occlusion, and propagation loss, which puts forward higher requirements for material, device, and system co-design. Meanwhile, device power consumption increases and heat dissipation pressure rises under high-frequency operation, further highlighting the importance of material and packaging technologies[9]. Therefore, the current literature generally believes that in the future, it is necessary to support the engineering application of third-generation

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semiconductors in 6G communications by improving material preparation processes, optimizing device structures, developing advanced packaging, and enhancing system-level design capabilities.

In addition to communications, the application of third-generation semiconductors in new energy vehicles has also attracted great attention. Relevant materials show that GaN has gradually entered on-board OBC, DC/DC, electric drive, and high-voltage fast-charging systems, mainly relying on its advantages of high switching frequency, high efficiency, and miniaturization. Especially with the rapid development of 800 V high-voltage platforms, GaN and SiC are becoming important supporting materials for the upgrading of electric vehicle power electronic systems. Compared with traditional silicon-based MOSFETs and IGBTs, GaN devices are expected to further reduce power loss, reduce system volume, and improve thermal management.

Third-generation semiconductor materials are gradually expanding from single-device applications to communications, automotive, power supply, intelligent systems, and other fields, and their research focus is gradually shifting from "material availability" to "system availability" and "industrial availability".

2.3. Literature Review

Synthesizing the existing literature, it can be seen that domestic and foreign research on GaAs, InP, and GaN compound semiconductors has formed a clear development context. First, in the field of GaAs and InP, research has gradually expanded from material growth and device preparation to large-size substrates, industrial chain layout, and system applications. Foreign countries still hold advantages in high-end substrates, optical communication devices, and high-frequency chips, while China has achieved rapid catch-up in material preparation and some segmented applications. Second, in the field of microwave and millimeter-wave integrated circuits, GaAs technology is relatively mature and suitable for realizing high-integration, multifunctional RF front-ends; GaN, with its advantages of high power and high efficiency, shows greater development potential in high-performance T/R components and phased array systems. Research in this field is developing from single-chip functional integration to heterogeneous system integration. Third, in terms of InP/CMOS heterogeneous integration, international research has gradually entered the stage of engineering platforms and system demonstrations, while China is still focused on key process breakthroughs and prototype verification. Improving process compatibility, reducing interconnection loss, enhancing thermal stability, and establishing a standard system will be the keys to promoting the further development of this direction in the future. Fourth, in terms of GaN power devices, the vertical structure is generally regarded as an important development direction for high-performance power devices in the future. Current research not only focuses on the performance improvement of the device itself, but also pays increasing attention to driver circuits, thermal management, and system-level application adaptation.

In summary, existing research has fully revealed the advantages of compound semiconductors in high-frequency communications, optoelectronics, and power electronics, but there are still deficiencies in cross-material collaboration, heterogeneous integration process maturity, large-scale manufacturing, and application system verification. Therefore, follow-up research needs to further strengthen the collaborative design of materials-devices-circuits-systems, and promote compound semiconductor technology from performance breakthroughs to high-reliability, low-cost, and large-scale applications.

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3. Basic Characteristics and Performance Comparison of GaN, InP, and GaAs

GaN, InP, and GaAs are all important compound semiconductor materials with wide applications in high-frequency communications, optoelectronic devices, and power electronic systems. Although the three belong to high-performance semiconductor materials, they have obvious differences in bandgap width, electron mobility, breakdown field strength, thermal conductivity, and applicable scenarios. It is these differences that determine their technical advantages and application positioning in different fields.

3.1. Basic Material Characteristics

GaAs and InP belong to second-generation semiconductor materials, with high electron mobility and good high-frequency response capability, suitable for high-speed, RF, and optoelectronic devices. Among them, GaAs is an earlier industrialized III-V semiconductor material, with mature applications in microwave RF, power amplifiers, low-noise amplifiers, lasers, and photodetectors. InP has more advantages in high-speed optical communications, edge-emitting lasers, photodetectors, and ultra-high-frequency devices, especially suitable for high-frequency and high-speed optoelectronic applications above 100 GHz.

GaN is a third-generation wide-bandgap semiconductor material, characterized by a wide bandgap, high breakdown field strength, and good thermal stability, capable of maintaining good working performance under high-temperature, high-voltage, high-frequency, and high-power conditions. Compared with GaAs and InP, GaN is more suitable for high-voltage power devices, high-frequency and high-power amplifiers, and high-power applications in new energy vehicles and 6G communications. In recent years, with the progress of GaN epitaxy technology and device processes, it has shown strong development potential in both RF electronics and power electronics.

From the perspective of material generation and application direction, GaAs and InP are more focused on high-frequency, high-speed, and optoelectronic applications, while GaN has both high-frequency and high-power advantages and performs more prominently in extreme working environments.

3.2. Comparison of Key Performance Parameters

The performance of semiconductor materials is usually measured by indicators such as bandgap width, electron mobility, breakdown field strength, electron saturation drift velocity, and thermal conductivity. According to existing literature, the typical performance parameters of GaN, InP, and GaAs vary greatly.

First, in terms of bandgap width, GaN is about 3.4 eV, significantly higher than 1.42 eV for GaAs and about 1.34 eV for InP. A wider bandgap means stronger high-temperature, high-voltage, and radiation resistance, so GaN has more advantages in high-voltage, high-power, and high-temperature environments, while GaAs and InP are more suitable for medium and low voltage but high-frequency and high-speed working conditions.

Second, in terms of electron mobility, GaAs and InP perform more prominently. GaAs has a high electron mobility, and InP's electron mobility is also significantly better than traditional silicon materials, giving both natural advantages in high-speed signal transmission, high-frequency amplification, and optoelectronic response. In particular, InP, due to its excellent electron transport properties, shows high potential in ultra-high-speed and terahertz band devices. In contrast, GaN's electron mobility is lower than that of GaAs and InP, but its high electron saturation drift velocity and high breakdown field strength make up for this deficiency, making it still highly competitive in high-frequency and high-power devices.

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Third, in terms of breakdown field strength, GaN is significantly better than GaAs and InP. GaN's breakdown field strength is usually above 3 MV/cm, while GaAs and InP are at a low level. This means that under the same voltage resistance requirement, GaN devices can adopt a thinner drift layer and smaller chip size, which is conducive to improving power density and conversion efficiency. Therefore, GaN has more obvious application value in power electronics, on-board power supplies, high-voltage fast charging, and other fields.

In terms of thermal conductivity, GaN is generally better than GaAs and has good thermal stability. High thermal conductivity helps devices dissipate heat in a timely manner during high-power operation, reducing performance degradation and reliability problems caused by local overheating. GaAs has excellent high-frequency performance but relatively low thermal conductivity, so it faces greater heat dissipation pressure under high-power continuous operation. Although InP has obvious advantages in high-speed optoelectronic applications, its thermal management capability is also inferior to GaN, which is an important reason for its limitation in high-power applications.

Overall, GaAs and InP have advantages in high-speed, high-frequency, and optoelectronic performance, while GaN performs better in voltage resistance, temperature resistance, power density, and system efficiency.

Table 1. Comparison of Key Physical Parameters of GaAs, InP and GaN

Parameter	GaAs	InP	GaN
Material generation	Second-generation compound semiconductor	Second-generation compound semiconductor	Third-generation wide-bandgap semiconductor
Bandgap / eV	1.42	1.35	3.4
Electron mobility / ($cm^2 \cdot V^{-1} \cdot s^{-1}$)	8500	5400	1000–2000
Electron saturation drift velocity / (cm/s)	2.0×10^7	2.2×10^7	2.5×10^7
Breakdown field / (MV/cm)	0.4	0.5	3.0–3.5
Thermal conductivity / ($W \cdot cm^{-1} \cdot K^{-1}$)	0.46	0.68	1.3–2.3

The values listed in the table are typical reference values and may vary depending on substrate type, epitaxial conditions and device structure.

3.3. Advantages and Limitations of Different Materials

As can be seen from Table 2-1, GaN is significantly better than GaAs and InP in terms of bandgap width, breakdown field strength, and thermal conductivity, and is more suitable for high-voltage, high-temperature, and high-power applications; GaAs and InP have advantages in electron mobility and high-frequency and high-speed performance, and are more suitable for RF and optoelectronic devices.

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The main advantages of GaAs lie in its relatively mature process, excellent RF performance, and complete application system, especially suitable for mobile communication RF front-ends, microwave and millimeter-wave multifunctional chips, VCSELs, and other devices. Its main disadvantages are low bandgap width and breakdown field strength, which limit its application scope under high-voltage and high-power conditions. Meanwhile, GaAs material is brittle and has low thermal conductivity, making heat dissipation and reliability design difficult in high-power density systems.

The outstanding advantages of InP are high electron mobility, high cutoff frequency, and excellent direct bandgap characteristics, so it occupies an important position in high-speed optical communications, lasers, photodetectors, and ultra-high-frequency devices above 100 GHz. Especially in the directions of data center high-speed interconnects, coherent optical communications, and high-frequency radar detection, InP plays an irreplaceable role. However, InP devices have complex processes, small substrate sizes, high manufacturing costs, and large-scale integration capabilities inferior to CMOS platforms, which restrict their widespread popularization to a certain extent.

The advantages of GaN are mainly reflected in wide bandgap, high breakdown field strength, high thermal stability, and high power density, so it is particularly suitable for high-frequency and high-power RF devices and high-efficiency power switching devices. In recent years, GaN's application popularity has continued to rise in fast-charging adapters, on-board power supplies, wireless charging, base station RF, and 6G cutting-edge communications. However, GaN also has problems such as difficult material defect control, high substrate costs, and still needs to improve device consistency and gate reliability, especially in vertical devices and large-scale integrated applications, there is still considerable development potential.

It can be seen that these three materials do not have absolute advantages or disadvantages, but each has the best application scenarios under different application requirements. GaAs is more suitable for mature RF systems and medium and high-frequency integrated circuits, InP is more suitable for ultra-high-speed optoelectronic and ultra-high-frequency applications, and GaN is more suitable for high-voltage, high-power, and high-efficiency systems[7].

3.4. Comparison of Application Adaptability

From the application perspective, GaAs, InP, and GaN have a clear division of labor. GaAs is the most mature in consumer electronics, mobile communication RF front-ends, and microwave and millimeter-wave multifunctional chips, with a good balance of cost and performance. InP is mainly oriented to high-speed optical communications, photoelectric detection, terahertz devices, and some high-end military electronic systems, and plays an irreplaceable role in high-end communications and high-performance optoelectronics. GaN is widely used in high-frequency power amplifiers, power electronics, on-board charging systems, fast-charging adapters, and new-generation high-power-density energy conversion equipment.

It is worth noting that with the improvement of system complexity, a single material is often difficult to meet all performance requirements at the same time. For example, in wireless communication systems above 100 GHz, front-end amplifiers may be more suitable for InP devices, while digital baseband and control parts still rely on CMOS processes; in highly integrated RF systems, GaAs is suitable for undertaking multifunctional RF modules, while GaN is more suitable for high-power output stages. For this reason, the future development trend is not only the continuous improvement of single material performance, but more importantly, the functional complementarity and heterogeneous integration between different materials.

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Table 2. Comparison of Typical Applications of GaAs, InP and GaN

Item	GaAs	InP	GaN
Main performance advantages	Excellent high-frequency performance, mature process, high integration capability	Excellent high-speed optoelectronic performance, suitable for ultra-high-frequency applications	Wide bandgap, high breakdown strength, high power density, good high-temperature performance
Main limitations	Low breakdown field, limited high-power capability	High cost, small substrate size	Complex process, defect control and reliability still need improvement
Typical devices	Power amplifiers, low-noise amplifiers, phase shifters, attenuators, VCSELs	DFB/EML lasers, PIN/APD photodetectors, high-speed optical modules	HEMTs, power amplifiers, fast chargers, onboard chargers, DC/DC converters, vertical power devices
Main application fields	RF front-end, microwave and millimeter-wave integrated circuits, mobile communications, consumer electronics	High-speed optical communication, data centers, terahertz devices, heterogeneous integration systems	5G/6G communications, new energy vehicles, power electronics, industrial power supplies
Typical application scenarios	Medium- and high-frequency, medium- and low-power, highly integrated systems	High-speed, high-sensitivity, ultra-high-frequency systems	High-voltage, high-power, high-efficiency systems
Future development directions	Higher-frequency and higher-integration MMICs	InP-CMOS heterogeneous integration, high-speed optoelectronic integration	Vertical GaN devices, driver co-design, high-reliability power systems

It can be seen from Table 2 that GaAs, InP, and GaN are not mutually substitutive, but complement each other for different application scenarios such as RF, optoelectronics, and power electronics. In the future, multi-material collaboration and heterogeneous integration will become important development directions.

3.5. Summary of This Chapter

Comprehensively, as three representative compound semiconductor materials, GaN, InP, and GaAs have their own characteristics in performance and application directions. GaAs has a mature RF process foundation and strong microwave and millimeter-wave integration capability; InP performs prominently in high-speed optoelectronic and ultra-high-frequency devices; GaN, relying on its wide bandgap and high breakdown field strength, shows strong potential in high-frequency and high-power applications, particularly in power electronics. The development of the three is not mutually substitutive, but forms a complementary relationship for different needs. With the further increase of communication frequency, continuous improvement of system integration, and continuous expansion of new energy applications in

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the future, the collaborative application and heterogeneous integration of GaN, InP, and GaN will become important development directions.

4. Typical Application Status of GaAs, InP, and GaN

As typical representatives of compound semiconductor materials, GaAs, InP, and GaN have formed a clear division of labor in practical applications due to different material properties. Overall, GaAs has mature applications in RF and microwave and millimeter-wave integrated circuits, InP has outstanding advantages in high-speed optical communications and heterogeneous integration, and GaN has developed rapidly in high-frequency and high-power devices and power electronic systems. With the continuous increase of communication frequency, system integration, and the rapid expansion of new energy and intelligent applications, the engineering applications of these three materials are evolving from single devices to system-level, multifunctional, and high-integration directions.

4.1. Application of GaAs in RF and Microwave Millimeter-Wave Integrated Circuits

GaAs is one of the earlier III-V compound semiconductor materials to be engineered and industrialized. Due to its high electron mobility, fast electron drift velocity, and good high-frequency characteristics, GaAs has long been widely used in RF front-ends, microwave and millimeter-wave circuits, and optoelectronic devices. Especially in mobile communications, satellite communications, radar, and phased array systems, GaAs devices have formed a relatively mature technical system and industrial chain foundation[3].

In the field of RF and microwave and millimeter-wave integrated circuits, the most representative application of GaAs is multifunctional monolithic integrated circuits. Relevant studies show that integrating power amplifiers, low-noise amplifiers, switches, phase shifters, attenuators, and digital control circuits on the same substrate can significantly reduce the volume of T/R components, improve assembly efficiency, and reduce loss and solder joint failure risks caused by external interconnections. GaAs process is particularly suitable for realizing such high-integration multifunctional chips due to its good frequency response performance and mature integration scheme. At present, GaAs multifunctional chips have been applied in multiple frequency bands such as Ku-band, K-band, Ka-band, and X-band. Its typical products include transceiver integrated chips, amplitude-phase control chips, and limiting low-noise amplifier chips[8]. Among them, transceiver multifunctional chips usually integrate transmitting and receiving links on the same chip, which can effectively reduce module size and system complexity; amplitude-phase multifunctional chips integrate digital phase shifters and digital attenuators for phased array radar and communication beam control systems; limiting low-noise amplifiers are suitable for scenarios requiring both receiving sensitivity and large-signal protection capability.

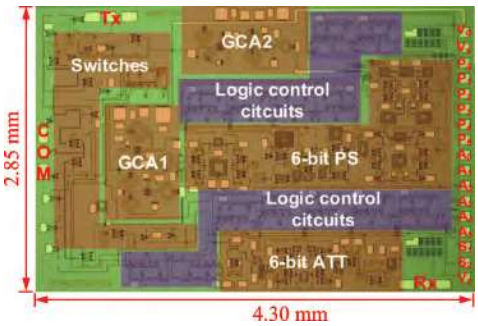


Figure 1. High-precision amplitude-phase multifunctional GaAs chip with switchable transmit/receive states for the X-band (image adapted from Ref. [8])

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In addition to microwave and millimeter-wave front-ends, GaAs is also widely used in consumer electronics and optoelectronic devices. For example, GaAs-based VCSELs are widely used in 3D sensing, short-distance optical communications, and some vehicle-mounted sensing systems; GaAs power amplifiers and RF switches maintain a high application proportion in mobile communication terminals. Overall, GaAs has a good balance of performance and cost in high-frequency and medium-low power applications, and is one of the important material platforms in the current RF front-end field. However, GaAs also has certain limitations. Due to its relatively limited breakdown field strength and thermal conductivity, it is gradually challenged by materials such as GaN in higher voltage and higher power density scenarios. But at this stage, GaAs still has strong competitiveness in mature RF systems, multifunctional microwave and millimeter-wave chips, and medium and high-frequency communication front-ends.

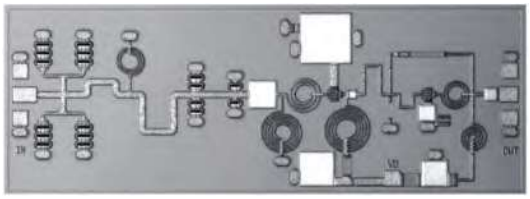


Figure 2. Photograph of a 5–13 GHz GaAs limiter-LNA integrated chip (image adapted from Ref. [8])

4.2. Application of InP in High-Speed Optical Communications and Heterogeneous Integration

InP is an important basic material for high-speed optoelectronic devices and ultra-high-frequency electronic devices. Compared with GaAs, InP has more obvious advantages in high-speed transmission, cutoff frequency, and photoelectric conversion performance, so it plays an irreplaceable role in high-speed optical communications, data centers, terahertz devices, and high-end detection systems.

In the field of optical communications, the most typical application of InP is lasers and photodetectors. Edge-emitting lasers, DFB lasers, EML lasers, and PIN/APD detectors based on InP materials are one of the core devices of current medium and long-distance optical fiber communications and high-speed optical modules. With the continuous upgrading of data center networks and backbone transmission networks to higher bandwidth, optical module rates have gradually evolved from 100G to 400G, 800G, and even higher rates, which directly promotes the growth of demand for InP optoelectronic devices. Due to InP material's direct bandgap characteristics suitable for communication band operation and its ability to achieve high-performance laser emission and high-sensitivity detection, it has always occupied an important position in high-speed optical interconnects and coherent optical communication systems.

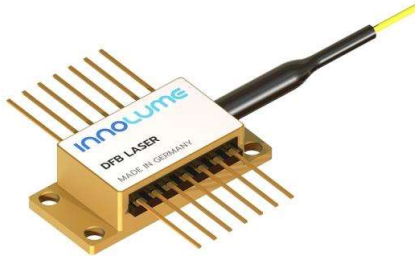


Figure 3. DFB semiconductor laser manufactured by Innolume, specifically the DFB09XX000YY030MFXXX series.

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In addition to optical communications, InP also performs prominently in ultra-high-frequency electronic devices. Relevant studies show that InP-based high-electron-mobility transistors and heterojunction bipolar transistors can support operation above 100 GHz and even higher frequencies[4], so they have important application value in the fields of millimeter-wave, sub-millimeter-wave, and terahertz detection. This makes it not only suitable for high-end communication systems, but also for radar imaging, remote sensing detection, high-resolution sensing, and other directions.

In recent years, InP/CMOS heterogeneous integration has become an important research hotspot in this field. Its core idea is to use InP's excellent high-frequency and optoelectronic performance combined with CMOS's advantages in digital processing, high integration, and low-cost manufacturing to achieve collaborative integration between different material platforms. This method can improve system integration and functional complexity while maintaining high-speed and high-frequency performance, so it is considered an important implementation path for wireless communications above 100 GHz, silicon photonic interconnects, terahertz sensing, and high-performance hybrid systems in the future. At present, foreign countries have conducted early research on InP/CMOS heterogeneous integration, and have gradually developed from process verification to engineering platforms and system demonstration stages. In recent years, China has also made certain progress in InP thin film transfer, silicon-based template construction, fan-out packaging, high-frequency transceiver chips, and other aspects. Although China is still in the catching-up stage in terms of platform processes, standard systems, and large-scale applications on the whole, InP heterogeneous integration has shown good application prospects.

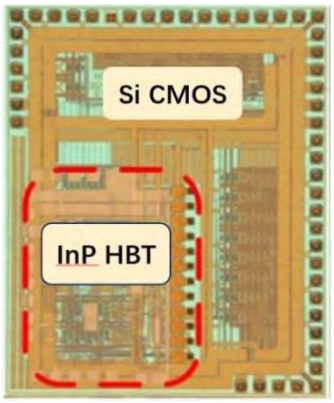


Figure 4. Schematic diagram of heterogeneous integration (image adapted from Ref. [4])

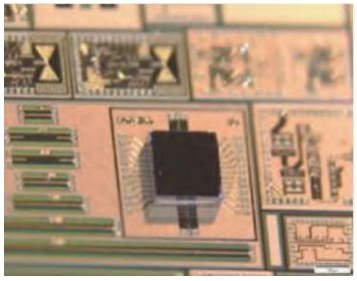


Figure 5. Micrograph of an InP chip on a BiCMOS carrier (image adapted from Ref. [4])

However, it should be pointed out that although InP has superior performance, it also faces problems such as high manufacturing costs, small substrate sizes, and high process complexity, which limit its large-scale popularization to a certain extent. Therefore, the future development

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of InP will rely more on high-value application scenarios and in-depth integration with silicon-based platforms.

4.3. Application of GaN in Power Devices and High-Frequency Communications

As one of the representatives of third-generation wide-bandgap semiconductor materials, GaN has developed rapidly in high-frequency and high-power communications and power electronics in recent years. Compared with GaAs and InP, GaN's most prominent advantages are wide bandgap, high breakdown field strength, high thermal stability, and high electron saturation drift velocity, making it very suitable for high-voltage, high-frequency, high-temperature, and high-power working environments.

In the field of high-frequency communications, GaN has become an important material for high-power RF front-ends. Due to its high power density, high efficiency, and strong voltage resistance, GaN devices are particularly suitable for base station power amplifiers, phased array radars, satellite communications, and millimeter-wave high-power transceiver systems. Relevant studies show that GaN process has been used in the design of S-band, C-band, and Ka-band transceiver multifunctional chips[8], showing better performance than traditional GaAs process in output power and power added efficiency. With the evolution of 5G to higher frequency bands and the demand of future 6G for sub-terahertz and high-frequency communications, GaN's application prospects in high-power RF front-ends will be broader.

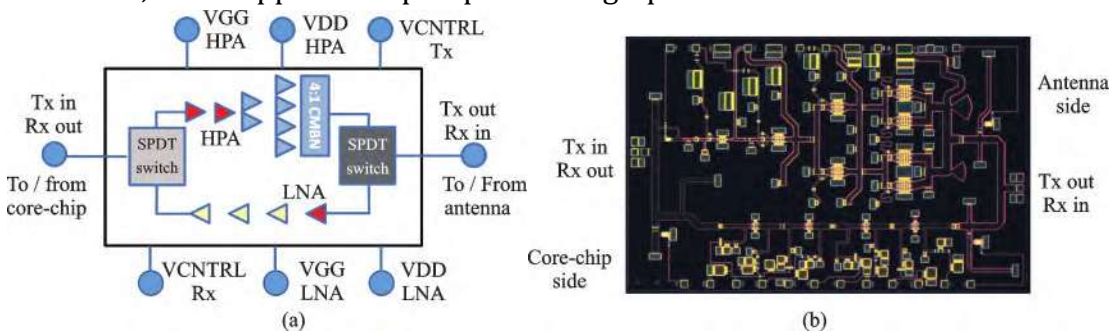


Figure 6. Ka-band GaN transceiver chip: (a) structural diagram; (b) photograph (image adapted from Ref. [8])

In the field of power electronics, GaN applications are also very active. With low on-loss and high switching speed, GaN devices have gradually entered fast-charging adapters, wireless chargers, on-board chargers, DC/DC converters, motor drives, and other systems. Especially in the consumer electronics fast-charging market, GaN devices can operate at high switching frequencies, thereby reducing the size of magnetic components and filters, improving power density, and reducing system weight. Compared with traditional silicon-based devices, GaN chargers are usually smaller in size, higher in efficiency, and better in heat dissipation performance, so market acceptance has been increasing in recent years[9].

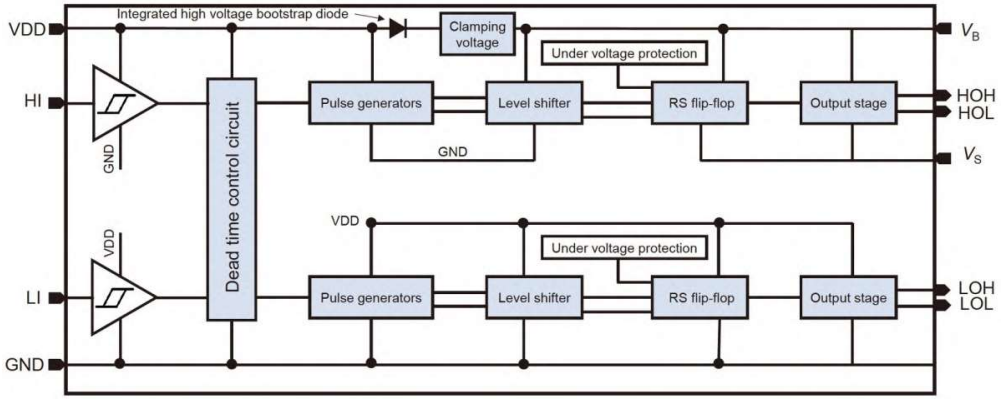


Figure 7. Internal block diagram of a typical GaN power device driver chip (image adapted from Ref. [5])

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In the field of new energy vehicles, GaN is mainly used in on-board power supply systems and auxiliary power conversion links, such as OBC, DC/DC converters, and some high-frequency drive modules. With the development of new energy vehicles towards high-voltage platforms, high efficiency, and miniaturization, GaN devices' advantages in medium and low voltage high-frequency power supply systems have become increasingly prominent[9]. Although SiC still has stronger competitiveness in ultra-high voltage main drive inverter and other scenarios, GaN has shown high application value in high-frequency, high-power density auxiliary power supply systems.

In addition, vertical GaN power devices are considered an important development direction in the future. Compared with traditional lateral GaN devices, vertical structures have greater potential in voltage resistance, current density, and chip area utilization, suitable for higher power level application requirements. At present, vertical GaN devices are still in the stage of continuous research and development and optimization, but their application prospects in high-performance power electronics have attracted widespread attention.

Overall, GaN is gradually expanding from a single high-frequency device material to a core material platform covering both RF electronics and power electronics, and its application scope is also extending from communication equipment to new energy vehicles, industrial power supplies, intelligent energy systems, and other fields.

4.4. Comparison of Application Characteristics of the Three Materials

In terms of typical application status, GaAs, InP, and GaN have formed a relatively clear technical positioning in different fields. GaAs has mature processes and wide applications, suitable for mobile communication RF front-ends, microwave and millimeter-wave multifunctional chips, and some optoelectronic devices, and is one of the most mature materials in high-frequency and medium-low power systems. InP has obvious advantages in high-speed optical communications, ultra-high-frequency electronic devices, and heterogeneous integration systems, especially suitable for high-end high-speed, high-sensitivity, and high-frequency applications. GaN, relying on its wide bandgap and high-power characteristics, has developed rapidly in high-frequency and high-power communications and high-efficiency power conversion, and has become an important supporting material for the third-generation semiconductor industry.

The application differences among the three essentially come from different material properties. GaAs emphasizes the balance between high-frequency characteristics and process maturity, InP emphasizes ultimate high-speed and high-frequency performance, and GaN emphasizes high voltage, high power, and high efficiency. At the current stage of technological development, the three materials are not in a simple competitive relationship, but jointly serve electronic and optoelectronic systems of different levels and requirements. Meanwhile, with the increasing complexity of systems, the situation where a single material independently completes all functions will become less and less in future applications. On the contrary, the collaborative use of different materials will become more common. For example, in high-speed wireless communication systems, InP devices may be responsible for ultra-high-frequency front-ends, GaAs for some intermediate frequency RF functions, and CMOS for digital processing; in high-power communication and energy systems, GaN may be responsible for output stage power devices. Therefore, multi-material collaboration and heterogeneous integration will become an important trend in the next stage of application development.

4.5. Summary of This Chapter

This chapter analyzes the typical application status of three compound semiconductor materials, GaAs, InP, and GaN. GaAs has mature technology in the field of RF and microwave and millimeter-wave integrated circuits, and has been widely used in multifunctional

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transceiver chips, amplitude-phase control chips, and RF front-end systems; InP, with its excellent high-speed and optoelectronic performance, plays an important role in optical communications, detectors, and heterogeneous integration; GaN, relying on the advantages of high breakdown field strength and high power density, has shown a rapid development trend in high-frequency communications and power electronics. The three materials have their own focuses and have formed a clear application pattern in communications, optoelectronics, power electronics, and other fields. With the further increase of communication frequency, continuous improvement of device integration, and rapid development of new energy vehicles and intelligent systems in the future, the collaborative application and system-level integration of GaAs, InP, and GaN will become important development directions.

5. Main Problems Faced by the Development of Compound Semiconductors

Table 3. Comparison of Major Challenges Faced by GaAs, InP and GaN

Item	GaAs	InP	GaN
Substrate and material preparation	High cost of large-size high-quality substrates; material brittleness	Small substrate size, difficult single-crystal growth, high cost	Difficulty in obtaining high-quality substrates; strict requirements for epitaxial defect control
Device fabrication	Reliability and thermal management issues under high-power conditions	Complex fabrication process; limited compatibility with large-scale integration processes	Complex process; device uniformity and gate reliability still need improvement
Integration capability	Limited system-level integration capability	Difficulty in heterogeneous integration with CMOS platforms	Large-scale monolithic integration and driver co-design are still immature
Thermal management and reliability	Relatively low thermal conductivity; difficult heat dissipation design	High requirements for stability under high-speed and high-frequency conditions	Thermal management and long-term reliability issues are prominent under high power density
Manufacturing cost	High cost of advanced device manufacturing	High overall cost of materials and devices	High cost of substrates, epitaxy and packaging
Industrialization challenges	High-end products and core technologies still depend on foreign suppliers	Relatively small industrial chain; applications mainly concentrated in high-end fields	Mass production, consistency control and standardization still need improvement

Although compound semiconductor materials such as GaAs, InP, and GaN show obvious advantages in high-frequency communications, optoelectronic devices, and power electronic systems, from the current development stage, their further promotion and industrial

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application still face many constraints. These problems include not only basic problems at the material and process levels, but also practical challenges related to device reliability, system integration, manufacturing costs, and industrial chain supporting. Overall, the development of compound semiconductors is no longer just a simple pursuit of material and device performance improvement, but has gradually entered a new stage where performance, reliability, cost, and large-scale capacity are equally important.

To intuitively compare the main problems faced by GaAs, InP, and GaN in the development process, this paper summarizes them from the aspects of material preparation, device process, integration capability, thermal management, manufacturing cost, and industrialization, as shown in Table 3.

It can be seen from Table 3 that GaAs, InP, and GaN all face problems in material preparation, device process, thermal management, integration capability, manufacturing cost, etc., but the focus of contradictions is different. The main problems of GaAs focus on heat dissipation and reliability under high-power conditions; InP is more prominent in high cost, small-size substrates, and heterogeneous integration difficulty; GaN mainly faces challenges in high-quality material preparation, device reliability, and large-scale applications. Overall, these problems restrict the further promotion of compound semiconductor materials to a certain extent, and also indicate that future research needs to pay more attention to the collaborative optimization of materials, devices, and systems.

5.1. Problems in Substrate Preparation and Epitaxial Growth

Substrate and epitaxial material quality are the basis for determining the performance of compound semiconductor devices. For GaAs, InP, and GaN, the size, dislocation density, impurity content, surface roughness, and crystal uniformity of single-crystal substrates will directly affect the subsequent epitaxial growth quality and device performance. At present, although certain progress has been made in substrate preparation for these materials, the stable supply of large-size, high-quality, and low-cost substrates is still one of the key issues restricting the development of the industry.

For GaAs and InP, although leading international enterprises have achieved commercial supply of large-size substrates, the high-end product market is still concentrated in a few manufacturers. Although domestic enterprises have made significant progress in single-crystal growth and substrate processing, there is still a certain gap compared with the international advanced level in terms of consistency, yield, and batch stability of large-size substrates. Especially for InP materials, due to the difficulty of single-crystal growth, relatively small substrate size, and high cost, it is strongly restricted in large-scale applications.

For GaN, the problem is more prominent. Due to the difficulty of preparing high-quality GaN free-standing substrates, it has mainly relied on epitaxial growth on heterogeneous substrates such as Si, SiC, and sapphire for a long time. Although this method can reduce costs, due to lattice mismatch and thermal mismatch between different materials, high dislocation density, cracks, and residual stress are easily generated in the epitaxial layer, thus affecting the voltage resistance level, reliability, and service life of the device[10]. In recent years, although the quality of GaN free-standing substrates has improved and costs have gradually decreased, on the whole, substrate preparation and high-quality epitaxial growth are still important bottlenecks for GaN devices to further approach the theoretical limit of materials.

Therefore, from the perspective of material foundation, the development of compound semiconductors still needs continuous breakthroughs in large-size crystal preparation, defect control, dislocation reduction, and epitaxial quality improvement.

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5.2. Problems in Device Process and Integration Compatibility

Although compound semiconductors have advantages in material performance, their device manufacturing processes are usually more complex than silicon-based processes, and process maturity and standardization are relatively low. GaAs, InP, and GaN generally have problems such as narrow processing windows, insufficient process stability, and difficult consistency control of key steps in device preparation, which will affect device performance and production yield.

GaAs process is relatively mature, but under higher frequency and higher integration conditions, parasitic effects, thermal effects, and interconnection loss problems caused by device size reduction become more prominent. Although InP devices have excellent high-frequency performance, their process platforms are mostly built on small-size wafers and complex experimental processing conditions, with high process costs and large differences from standard CMOS processes, limiting their large-scale integration and industrial manufacturing. For GaN devices, lateral devices are relatively mature, but there are problems such as electric field concentration, current collapse, and surface traps under high voltage; although vertical devices have greater development potential, there are still many technical difficulties in trench processing, interface quality control, threshold stability, gate dielectric reliability, and other aspects. Especially in vertical GaN devices, the matching problem between structural design and process implementation has not been completely solved, affecting their further engineering application.

In addition, with the development of systems towards high integration, the compatibility problem between different materials has become increasingly prominent. Especially in InP/CMOS heterogeneous integration, the mismatch of lattice constant, thermal expansion coefficient, and process temperature window between different materials can easily cause interface delamination, thermal stress accumulation, interconnection failure, and other problems during bonding, transfer, and subsequent processing[4]. This shows that to achieve higher-level integrated applications, compound semiconductors need to break through the key technologies of multi-material collaborative manufacturing and heterogeneous interconnection in addition to optimizing single-device processes.

5.3. Reliability and Thermal Management Problems

Reliability has always been one of the core issues for compound semiconductors to move from laboratory research to practical applications. For high-frequency communications, optical communications, and power electronic systems, devices must not only have high performance, but also maintain stable operation under high-temperature, high-frequency, high-power density, and long-term working environments.

GaAs devices are mature in high-frequency RF applications, but their thermal conductivity is relatively limited, and local overheating is prone to occur under high-power continuous operation, thus affecting amplifier gain, output power, and long-term stability. Although InP devices have outstanding advantages in high speed and high frequency, they also have problems of limited heat dissipation capacity and obvious heat accumulation, especially in highly integrated optoelectronic systems, temperature rise will directly affect laser wavelength stability, detector noise performance, and device life.

For GaN devices, although the material itself has good high-temperature and high-power resistance, they still face many reliability problems in practical applications. For example, GaN devices are often accompanied by significant transient thermal effects and electric field stress under high-speed switching and high-power operation, which may lead to gate degradation, threshold drift, and performance attenuation. Especially in vertical GaN devices and high-density power modules, unreasonable thermal design can easily affect device safety and system life due to local hot spots.

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Meanwhile, it should be noted that in heterogeneous integration systems, thermal management problems will become more complex. Due to the different thermal conductivity and thermal expansion characteristics of different materials, uneven thermal stress distribution is easy to occur during operation, thereby affecting interface stability and interconnection reliability. Therefore, the future development of compound semiconductors not only needs to improve reliability at the material and device structure levels, but also needs to improve the overall application stability through packaging design, heat dissipation path optimization, and system thermal management collaboration.

5.4. Cost Control and Industrialization Challenges

Compared with traditional silicon-based semiconductors, compound semiconductor materials still have obvious deficiencies in manufacturing costs and industrialization capabilities. The reasons for high costs mainly include expensive substrate materials, long epitaxial growth cycles, complex process flows, high equipment requirements, and relatively low production yield.

Although GaAs and InP have formed a certain scale of industrial chain, the high-end substrate and key epitaxial material markets are still mainly dominated by a few international manufacturers, affecting cost control and supply chain security to a certain extent. Especially for InP, due to small substrate size and high process complexity, its unit area cost is significantly higher than that of silicon-based platforms, so it is more suitable for high-value-added and high-performance application scenarios, and not easy to quickly popularize in large-scale low-cost markets. The industrialization challenges of GaN are more typical: on the one hand, GaN devices are growing rapidly in consumer electronics fast charging and RF front-ends and other fields, but high-quality substrates, epitaxial consistency, device packaging, special driver circuits, and other links still increase the overall system cost; on the other hand, to further expand the market, GaN devices still need continuous improvement in device consistency, long-term reliability, standardized testing, and batch manufacturing capacity. For applications such as new energy vehicles, industrial power supplies, and communication base stations, performance advantages are not enough; only when cost, reliability, and supply stability meet engineering application requirements can related technologies truly achieve large-scale implementation.

In addition, although China's compound semiconductor industrial chain has developed rapidly, it still needs to improve in high-end equipment, core process platforms, EDA tools, testing standards, and upstream and downstream collaboration. Especially in key links such as high-end substrates, advanced processes, packaging platforms, and system verification, there is still a certain gap compared with the international advanced level. It can be seen that the development of compound semiconductors is not only a technical issue, but also closely related to industrial ecological construction.

5.5. Summary of This Chapter

This chapter analyzes the main problems faced by the development of compound semiconductors from four aspects: substrate preparation and epitaxial growth, device process and integration compatibility, reliability and thermal management, and cost control and industrialization. Overall, although GaAs, InP, and GaN have obvious advantages in high-frequency, high-speed, and high-power applications, they still face many challenges in large-size high-quality substrate preparation, key process stability, heterogeneous integration compatibility, long-term reliability, and low-cost large-scale manufacturing. These problems indicate that the future development of compound semiconductors cannot only stay in the improvement of single material performance, but needs to be promoted collaboratively from multiple levels of materials, devices, packaging, circuits, and industrial chains. Only by continuously improving reliability, reducing costs, and enhancing industrialization capabilities

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while ensuring performance advantages can compound semiconductor technology achieve sustainable development in a wider range of application scenarios.

6. Development Trends and Prospects of Compound Semiconductors

With the rapid development of new-generation communications, intelligent sensing, data centers, new energy vehicles, and high-efficiency power electronic technologies, the importance of compound semiconductor materials is constantly increasing. Relying on their outstanding physical properties, GaAs, InP, and GaN have formed a clear application pattern in RF communications, optoelectronic devices, and power electronic systems. Meanwhile, with the increasing requirements of system performance, single material or single device optimization can hardly fully meet the development needs of the future electronic information industry. The research and application of compound semiconductors are gradually shifting from material performance competition to a new stage of parallel advancement of multi-material collaboration, heterogeneous integration, system-level optimization, and industrial ecological improvement.

6.1. Development Trend of High Performance and High Integration

The primary direction of the future development of compound semiconductor technology is still high performance. For GaAs, InP, and GaN, improving device performance has always been the core driving force for their application expansion. GaAs will continue to develop towards higher-frequency and higher-integration microwave and millimeter-wave monolithic integrated circuits to meet the requirements of radar, satellite communications, and high-performance RF front-ends for multifunction, miniaturization, and low loss. InP will play a more important role in higher-rate optical communications, ultra-high-frequency electronic devices, and terahertz systems, especially in devices above 100 GHz and high-speed optoelectronic integration, its advantages are still very obvious. GaN will continue to make breakthroughs in high-frequency and high-power RF devices and high-efficiency power electronic devices in the future, especially with broad development space in higher voltage resistance, lower on-loss, and higher switching frequency.

While developing high performance, high integration will also become an important trend. In the past, compound semiconductors were mostly used in single high-performance devices, while future systems have put forward higher requirements for volume, weight, energy consumption, and functional complexity, promoting devices to develop towards multifunctional integration and system-level integration. For example, in RF front-end systems, the integration degree of power amplification, low-noise amplification, switching, phase shifting, attenuation, and control units will be further improved; in optical communication systems, transmitting, modulating, detecting, and signal processing modules will also evolve towards a tighter integration form. It can be seen that the development direction of compound semiconductors will not only be reflected in the improvement of single device indicators, but also in the optimization of overall system performance and integration efficiency.

6.2. Heterogeneous Integration and System-Level Collaborative Development

Heterogeneous integration is one of the most representative directions for the future development of compound semiconductor technology. Due to the obvious differences in material properties and application scenarios among GaAs, InP, and GaN, it is not necessarily that one material will completely replace other materials in the future, but it is more likely to build a system-level solution with better performance and stronger functions through the complementary advantages of different material platforms. Among them, InP/CMOS heterogeneous integration has become a research hotspot in high-speed communications and high-frequency electronic systems. By combining InP's excellent high-frequency, high-speed,

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and photoelectric conversion performance with CMOS's mature digital logic processing and large-scale integration capabilities, the limitations of single material platforms in speed, power consumption, and cost can be effectively broken. In the future, such heterogeneous integration technology is expected to be more widely used in 6G communications, terahertz detection, high-speed optical interconnects, and intelligent sensing systems.

In addition to InP and CMOS, GaAs and GaN will also be more involved in heterogeneous system design. For example, in microwave and millimeter-wave front-ends, GaAs is suitable for undertaking multifunctional intermediate and high-frequency RF circuits, while GaN is more suitable for high-power output stages. This division is conducive to balancing system efficiency, output capability, and integration. With the continuous development of packaging technology, wafer-level interconnection technology, and chiplet design, multi-material, multi-chip, and cross-platform collaborative design will become an important path for the realization of complex systems in the future.

It can be predicted that the future competition focus of compound semiconductors will no longer be limited to a single material itself, but will be more reflected in who can more effectively achieve multi-material collaboration, heterogeneous integration, and system-level performance optimization.

6.3. Development Prospects in 6G Communications, New Energy Vehicles and Other Fields

From the application level, 6G communications and new energy vehicles are one of the most representative growth directions of compound semiconductors in the future. First, in the field of 6G communications, the system's demand for higher frequency bands, larger bandwidth, lower latency, and higher energy efficiency will promote the further upgrading of RF devices and high-speed optoelectronic devices. GaAs will still maintain an important position in medium and high-frequency RF front-ends and microwave and millimeter-wave integrated circuits; InP will play an irreplaceable role in ultra-high-frequency communications, terahertz devices, high-speed modulation, and detection; GaN will show greater application potential in high-power base stations, satellite communications, and millimeter-wave power amplifiers. With the gradual extension of 6G to higher frequencies and more complex scenarios, the collaborative application of different compound semiconductor materials will become more common[12].

In the field of new energy vehicles, the value of wide-bandgap semiconductors will be further highlighted. GaN and SiC have become important supporting materials for the upgrading of on-board power supply systems, and GaN's advantages in high-frequency, high-efficiency, and miniaturized power conversion are especially suitable for on-board chargers, DC/DC converters, fast-charging modules, and auxiliary power supply systems. With the development of 800 V high-voltage platforms and high-power density fast-charging technologies, the market demand for high-efficiency, low-loss, and lightweight power devices will continue to grow, providing good conditions for the promotion of GaN devices.

In addition, compound semiconductors will also maintain high development potential in data centers, satellite Internet, intelligent sensing, industrial control, high-end medical equipment, and other fields. With the popularization of artificial intelligence, large-scale interconnection, and intelligent terminals, the system's requirements for high speed, high sensitivity, high stability, and low power consumption will continue to increase, which will further promote the in-depth application of GaAs, InP, and GaN in their respective advantageous fields.

6.4. Summary of This Chapter

This chapter analyzes the development trends and future prospects of compound semiconductors. Overall, the development of GaAs, InP, and GaN will present the characteristics

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of high performance, high integration, heterogeneous integration, and system collaboration. GaAs will continue to maintain advantages in high-frequency RF and microwave and millimeter-wave integrated circuits, InP will play a more important role in high-speed optical communications and ultra-high-frequency devices, and GaN will continue to expand its application scope in high-frequency and high-power communications and power electronic systems. In the future, the development focus of compound semiconductors will no longer be limited to the improvement of single material or single device performance, but will pay more attention to functional complementarity, heterogeneous integration, and system-level collaborative optimization between different material platforms. With the sustainable development of 6G communications, new energy vehicles, data centers, and intelligent systems, compound semiconductors are expected to play a key supporting role in a wider range of fields and become an important foundation for promoting the progress of new-generation electronic information technology[11].

7. Conclusion

This paper systematically sorts out the material characteristics, performance differences, typical applications, current development status, and main problems faced by three typical compound semiconductor materials, GaAs, InP, and GaN, combined with relevant domestic and foreign literature, and analyzes the future development trends.

First, from the perspective of material properties, GaAs, InP, and GaN have their own characteristics in bandgap width, electron mobility, breakdown field strength, thermal conductivity, etc. GaAs has a mature process foundation and good high-frequency performance, and is widely used in RF and microwave and millimeter-wave integrated circuits; InP has outstanding advantages in high-speed optical communications, detectors, and ultra-high-frequency electronic devices, especially suitable for high-speed, high-sensitivity, and high-frequency applications; GaN, relying on wide bandgap and high breakdown field strength, shows strong development potential in high-frequency and high-power communications and power electronics. The three do not have a simple substitution relationship, but complement each other under different application requirements.

Second, from the perspective of application status, GaAs has formed a relatively mature application system in RF front-ends, amplitude-phase control chips, transceiver multifunctional chips, VCSELs, and other fields; InP shows important value in high-speed optical modules, lasers, detectors, and the direction of heterogeneous integration with CMOS; GaN has developed rapidly in high-power RF front-ends, fast-charging adapters, on-board chargers, DC/DC converters, vertical power devices, and other aspects. This indicates that compound semiconductor materials are gradually evolving from a single high-performance device platform to a system-level supporting material for complex application scenarios.

This paper analyzes the main problems faced by the development of compound semiconductors. At present, although GaAs, InP, and GaN have obvious advantages in performance, they still face great challenges in large-size high-quality substrate preparation, epitaxial defect control, device process stability, heterogeneous integration compatibility, reliability and thermal management, and low-cost large-scale manufacturing. These problems determine that the future development of compound semiconductors not only depends on the optimization of materials and devices themselves, but also needs the simultaneous improvement of process platforms, packaging technologies, driver circuits, and industrial chain collaboration capabilities. From the perspective of development trends, the future development of compound semiconductors will present the characteristics of high performance, high integration, heterogeneous integration, and system collaboration. With the continuous development of emerging fields such as 6G communications, new energy vehicles, data centers, satellite

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Internet, and intelligent sensing, the application space of GaAs, InP, and GaN will be further expanded. Among them, multi-material collaboration and heterogeneous integration will become an important path to improve system performance and a key direction for the development of electronic information technology in the future. Compound semiconductor materials are becoming an important foundation for supporting the progress of new-generation communications, optoelectronics, and power electronics technologies. In the future, with the continuous improvement of material preparation, device design, system integration, and industrialization capabilities, GaAs, InP, and GaN are expected to achieve in-depth applications in a wider range of fields and play a more important role in promoting the upgrading of the electronic information industry.

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