Performance Comparison and Future Prospects of Silicon-Based and Compound Semiconductor Substrates

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Abstract. Silicon-based substrates have long dominated the IC industry with their mature manufacturing processes and low costs, but are limited by narrower bandgaps and lower thermal conductivity, high-temperature and high-frequency scenarios that are becoming more common today. Compound semiconductor substrates represented by Gallium Nitride (GaN) and Silicon Carbide (SiC) show significant advantages in new energy, 5G communications and high power fields due to their wide bandgap, high breakdown field strength, high thermal conductivity and other characteristics. This paper systematically compares the material properties of silicon-based substrates with those of compound semiconductor substrates and analyses their impact on device performance. Research shows that: silicon-based substrates will still dominate in low and medium frequency, low voltage scenarios with the advantages of cost and integration density; GaN has become an ideal choice for high frequency RF devices with its high electron mobility and polarization effect; and SiC has achieved energy-efficiency breakthroughs in high-voltage high-temperature scenarios, such as electric vehicle inverters, due to its ultra-high thermal conductivity and high-temperature stability. Future technologies need to focus on compound semiconductor mass production and silicon-based III-V heterogeneous integration technology to drive the development of emerging fields such as high-performance computing and 5G radio frequency.

Keywords: Silicon-based substrate, Compound semiconductor, Gallium nitride (GaN), Silicon carbide (SiC).

1 Introduction

In today's era of ever-changing electronic technology revolution, semiconductor substrates, as the physical basis for manufacturing various types of electronic components, are becoming more and more important for scientific progress; their characteristics will have a direct impact on the electrical performance, temperature management capability and reliability of the related devices. Since the invention of integrated circuits in the 1960s, the traditional substrate represented by silicon (Si) has dominated the IC industry for a long time by virtue of its mature manufacturing process and low-cost advantage; and its process nodes have been shrinking under the impetus of Moore's Law.

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The compound semiconductor substrates represented by gallium nitride (GaN) and silicon carbide (SiC), on the other hand, have shown irreplaceability in high-power and high-frequency applications due to their excellent characteristics such as wide bandgap, high breakdown field strength, high thermal conductivity, and so on; and since the 21st century, SiC and GaN substrates have rapidly gained popularity in the fields of new energy and 5G communications [1].

Nowadays, the main direction of research on substrates in academia focuses on the continuous miniaturization of silicon-based technologies and the improvement and application of compound semiconductors in emerging scientific fields, such as using SiC's radiation resistance and high-temperature tolerance to develop high-temperature and high-irradiation fields such as space and nuclear power, or using GaN's high-frequency performance to develop 5G/6G wireless communication systems with enhanced frequency and reduced power consumption. However, few studies have systematically compared the material characteristics of both types through specialized analyses.

In this paper, we will compare the performance of silicon-based substrates and compound semiconductor substrates represented by GaN and SiC, and through the comparison, we may be able to more intuitively see the development potential of the two and provide a basis for material selection for future device design.

2 Fundamental properties of silicon-based and compound semiconductor substrates Introduction

2.1 Fundamental properties of silicon-based and compound semiconductor substrates

Silicon is a major material for semiconductor substrate fabrication due to its relatively good properties at room temperature and the ability to grow a high-quality silicon oxide layer by thermal oxidation; its large reserves in the earth's crust (~27.7%) reduce the cost of obtaining it, and also make silicon materials available for semiconductor fabrication significantly more cost-effective than other semiconductor materials [2].

Silicon has a bandgap of 1.11 eV and an electron mobility of about 1350 $cm^2/(V \cdot s)$, which makes it suitable for medium-frequency applications in logic devices. Its greatest advantage lies in the formation of high-quality SiO_2 insulating layers, whose low dielectric constants down to 3.9 and very low interfacial state densities make it an ideal gate insulating material, which is fundamental for the fabrication of MOS devices [3]. However, despite the improvement over germanium, silicon's thermal conductivity (150 $W/m \cdot K$) and breakdown field strength (0.3 MV/cm) make it difficult to meet the heat dissipation and voltage withstand requirements in high-power scenarios, limiting its application in high-voltage, high-temperature scenarios. Its narrow bandgap also leads to a significant increase in leakage current at high temperatures, restricting its maximum operating temperature.

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Table 1 shows the performance comparison between Si and the two mainstream compound semiconductor substrate materials, GaN and SiC, in terms of their own properties.

Table 1. Comparison of the performance of the three materials in terms of their properties

Properties	Si	GaN	SiC
Bandgap（eV）	1.11	3.4	3.3
Electron mobility（$cm^2/(V\cdot s)$）	1350	2000	700
Saturated electron drift velocity（$\boldsymbol{10^7 cm/s}$）	1.0	2.5	2.0
Breakdown field strength（MV/cm）	0.3	3.3	2.0
Thermal conductivity（W/(m·K)）	150	230	450
Melting point（℃）	1412	3360	2830

A comparison of the data in Table 1 clearly shows that the band gaps of GaN and SiC are approximately three times higher than silicon’s; as another important factor in measuring the performance of electronic devices, GaN and SiC are also basically ten times the value of Si in terms of breakdown field strength. On the other hand, the electron mobility of GaN significantly exceeds the other two materials, being nearly twice that of Si and nearly three times that of SiC; its saturation drift velocity is also in the lead. However, while GaN does not differ much from Si performance in terms of thermal conductivity, SiC has a thermal conductivity that is about three times higher than

Si. Moreover, the melting points of GaN and SiC are significantly higher than that of Si, which provides a wider thermal process window compared to silicon

3 Impact of different substrate material properties on device performance

3.1 Advantages of silicon CMOS devices

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CMOS technology boasts high integration density as a key advantage. Over the past few decades, the development of silicon-based semiconductor processes has followed Moore's Law, which states that the number of transistors that can be accommodated on a single chip doubles every two years, as shown in Fig 1.

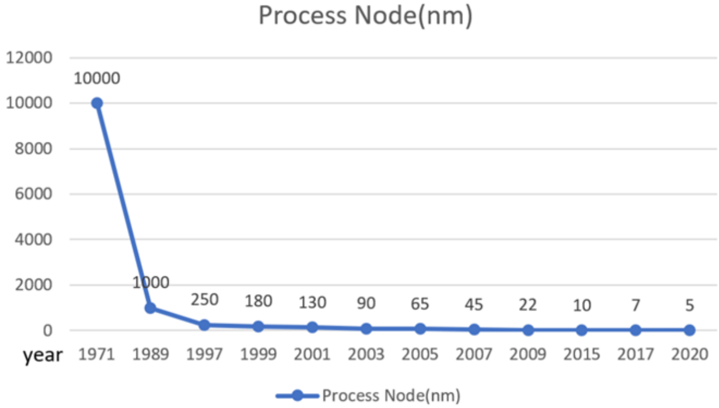

Fig. 1. Evolution of IC process node scaling.

Since the first CMOS integrated circuit was born in the United States in 1968, the minimum feature size of semiconductor manufacturing technology remained at approximately 10^4nm as of 1971, and after decades of development, by 2015, the process node of CMOS has reached 10nm [4-6].

Although Si, as a first-generation semiconductor material, occupies a disadvantage in many properties relative to the two third-generation semiconductor materials of GaN and SiC, its low production cost and extremely mature scale production process bring great advantages that cannot be ignored. The Semiconductor Equipment and Materials International (SEMI) released a report in January 2024 stating that global monthly wafer production capacity will reach a staggering 30 million wafers in 2024 [7], something compound semiconductors are unlikely to reach anytime soon

3.2 Advantages of GaN power devices

After nearly 60 years of development in semiconductor devices, the silicon material has been unable to meet the growing demand for device performance, rather than spending a lot of time and resources in the improvement of silicon materials, people will focus on the material performance is more outstanding compound semiconductor materials. GaN, with its larger bandgap relative to Si, higher breakdown field strength (critical field strength), lower on-state resistance (R_{on}), and its relatively high thermal conductivity and melting point, has been able to achieve higher operating temperature tolerances, higher withstand voltages, and system efficiency [8].

In addition to this, in the AlGaN/GaN heterojunction structure, which is unique to GaN power devices, the polarization effect due to the difference in the bandgaps of the two results in a high density, high electron mobility (up to 2000 cm^2/V-s) two-dimensional electron gas (2DEG) at the interface [9], which results in lower channel resistance for GaN devices. At the same time, GaN's high electron mobility and electron saturation drift velocity of up to 2.5×10^7 cm/s enable GaN materials to maintain good performance in high electric field environments, making GaN devices the preferred choice for high-power and high-frequency applications.

3.3 Advantages of SiC power device

The foremost advantage of SiC lies in its exceptionally high thermal conductivity (450 W/m·K), enabling SiC devices to operate at significantly lower temperatures than their counterparts at equivalent power dissipation, to prolong its service life [10]; conversely, under the condition of ensuring that the heat dissipation effect remains unchanged, the use of SiC power devices will greatly simplify the thermal system, thus achieving the purpose of reducing the size and weight. Thus achieving the purpose of reducing the size and weight. This, together with SiC's high bandgap (3.3eV), allows SiC power devices to maintain a good working condition in high temperature environments, which can theoretically withstand temperatures as high as 600°C [11], granting SiC power devices dominant advantages in high-temperature applications.

At the same time, SiC's relatively high breakdown field strength and electron saturation drift velocity allow SiC power devices to have a thinner drift layer design, which greatly reduces the on-resistance of the device; the high electron saturation drift velocity also endows it with superior high-frequency switching performance, and the switching loss of SiC power devices is only 35% of that of Si IGBTs in the same frequency range [12]. These two superior properties have also led to SiC power devices being commonly used in inverters and boost converters for electric vehicles, such as Toyota's Mirai car equipped with SiC-based FC boost converters, resulting in an 8% to 10% improvement in energy efficiency [13].

3.4 Comparison of the advantages of the three devices

Table 2 systematically summarises the differentiated positioning of the three types of devices, namely, silicon-based CMOS devices, GaN power devices and SiC power devices, through the dual dimensions of performance advantages and application areas.

Table 2. Comparison of the main performance advantages and areas of strength of the three devices.

Comparison Criteria	Silicon CMOS devices	GaN Power Devices	SiC Power Devices
Key Performance Benefits	Proven technology and lower costs	High electron mobility and high electron saturation drift velocity	High thermal conductivity, high breakdown field strength and electron saturation drift velocity
Key Areas of Strength	Low-frequency, low-voltage, low and medium-power applications	High frequency, medium and high power applications	High temperature and high power applications

Based on the information in Table 2, it can be seen that in low-voltage applications (<500V) and other areas with limited requirements for device performance, silicon-based devices will occupy an absolute advantageous position with their highly standardized manufacturing processes and the economic advantages brought about by the effect of large-scale production; the high-frequency performance and low conduction loss of GaN power devices compensate for silicon's limitations, but their thermal conductivity constraints cause heat dissipation challenges in high-voltage applications, in the medium and high-voltage (900V or so and the following) applications will be dominated by its; the SiC power devices will be mainly used in high voltage applications above 1200V due to its core advantage of ultra-high thermal conductivity and high voltage tolerance [14]. Meanwhile, high-frequency applications will choose between SiC and GaN based on different requirements for performance and efficacy. In the future, with the breakthrough of compound semiconductor mass production technology, the three will deepen the application in their respective areas of strength, establishing a multi-material co-optimized semiconductor landscape

4 Potential and Outlook for Future Substrate Technologies

4.1 Mass production of large-diameter compound semiconductor substrates

Compared to silicon-based substrates, which have easy access to materials, mature mass production technology and low production costs, compound semiconductor substrates such as GaN and SiC have been limited in their development by their high costs and low yields. Achieving the mass production of compound semiconductor substrates has become an essential pathway for future substrate technology development.

GaN power devices can be grown on Si, SiC, sapphire, where GaN-on-Si epitaxial wafers grown on Si-based substrates have relatively low cost and can be an alternative to Si substrates, and China has been carrying out research on the mass production process of the relevant technology. China's total production of GaN-on-Si wafers reached 600,000 wafers in 2023, a 35 per cent increase from the previous year. In 2023, China's total GaN-on-Si wafer production reached 600,000 wafers, a 35% year-on-year increase from the previous year. 6-inch wafers accounted for 70% of the total, and it is expected that China's production of GaN-on-Si wafers will exceed 1 million wafers by 2025, and the proportion of 8-inch wafers will be increased to 20% [15], progressing toward larger wafer sizes and higher production volumes.

At the same time, Substantial global R&D efforts have been directed toward the mass production readiness of SiC substrates. The SiC substrate has a bright market outlook driven by synergies with 800V EV applications. Wolfspeed has transitioned to an 8-inch SiC fab in 2024 and is expanding its materials capacity in line with its strategic vision, which will effectively reduce the cost of large-diameter SiC substrates. It is expected that the n-type SiC substrate market share will likely exceed 40% by 2029.

4.2 Silicon-based III-V heterogeneous integration technology

As the silicon-based CMOS integrated circuit technology node scaling gradually approach the physical limit, instead of allocating excessive R&D resources to seek breakthroughs in the process limit, exploring alternative approaches may prove more viable, while certain III-V compound semiconductors offer unique performance metrics unattainable with silicon. The silicon-based materials also have advantages in terms of integration and some physical properties that compound semiconductors cannot match. If two or more semiconductor processes can be combined, the limitations of a single semiconductor process in the face of difficulties can be solved. Heterogeneous integration technology is an emerging technology developed to address this problem. It allows the integration of individually fabricated components into a system at a higher level of packaging, obtaining more functionality at a lower total cost, with better operating characteristics relative to any of the materials involved in the heterogeneous integration [6].

5 Equations and mathematics

5.1 A Subsection Sample

This paper systematically compares the material properties of silicon-based substrates and compound semiconductor substrates (GaN, SiC) and their impact on device performance, and reveals the technical advantages and development potential of the two in different application scenarios. The study shows that:

With mature mass production manufacturing processes, low-cost advantage and high integration capability, silicon-based substrate is still the dominant material in logic devices and consumer electronics, but material characteristics such as its relatively narrow bandgap and limited thermal conductivity constrain its application in high-voltage and high-temperature scenarios. While compound semiconductor substrates represented by

GaN and SiC show significant performance advantages, GaN has become an ideal choice for high-frequency RF devices due to its high electron mobility (2000 cm^2/V-s) and polarization effect; SiC, with its ultra-high thermal conductivity (450 W/m-K) and high-temperature stability, has been used to achieve system-level energy efficiency improvement in high-voltage and high-temperature scenarios such as electric vehicle inverters and boost converters.

On this basis, future technological development needs to focus on two major directions: the first is to develop the mass production of compound semiconductors, through the mass production of 8-inch SiC substrates (e.g. Wolfspeed 2024 production) and GaN-on-Si epitaxial technology optimization, to reduce costs and expand the scope of application; the second is to develop heterogeneous integration technology, combining the high integration of silicon-based and compound semiconductor performance advantages to promote the development of emerging fields such as 5G RF front-end and high-performance computing.

Despite the revolutionary potential of compound semiconductors in terms of performance, their industrialization still faces dual challenges of cost and process maturity. Future research should further explore the synergistic optimization of material properties and device design, and through the combination of material selection and technological innovation, semiconductor substrate technology will continue to promote the development of electronic devices in the direction of high efficiency, high integration and high reliability. Meanwhile, with the continuous progress of wide-bandgap semiconductor technology and the further maturity of heterogeneous integration technology, the complementary integration of silicon-based and compound semiconductors may become the core paradigm of the next-generation power and RF devices, which will provide a key technological support for the development of new energy sources and the digitalization of society under the goal of carbon neutrality.

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