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Beyond Silicon Semiconductors: Material Pathways, Application Demands and Engineering Challenges

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Abstract. Silicon (Si) has sustained the semiconductor industry for more than half a century, but it is rapidly approaching fundamental physical limits. Its ~1.12 eV band gap and the approaching end of Moore's law, together with the "power wall" of conventional electronic computing, make it increasingly difficult for silicon alone to satisfy emerging applications — AI data centers with extremely high power density, energy-efficient power electronics for electric vehicles and renewable energy, and high-frequency components for 5G/6G communications. This paper reviews the motivations and landscape of "beyond silicon" semiconductor materials. It first analyzes the driving forces, including the end of Moore's law, soaring data-center energy consumption, and the changing demands of new applications, and then examines the pathways of material transition. Wide band gap semiconductors — gallium nitride (GaN) and silicon carbide (SiC) — are highlighted for their large band gaps, high breakdown fields and superior thermal properties: GaN excels in high-frequency and high-power-density applications such as fast chargers, 5G base stations and data-center power supplies, while SiC, with a breakdown field about ten times that of silicon, dominates high-voltage domains including EV drive inverters and renewable-energy converters. Two-dimensional materials such as MoS_2 and emerging WSi_2N_4 are discussed as candidates for extending transistor scaling beyond silicon. Finally, the paper addresses the engineering challenges — process controllability, heterointerface compatibility, extreme-environment adaptability and device reliability — and concludes that the future lies not in outright replacement of silicon, but in a complementary, multi-material landscape of Si, SiC, GaN and emerging materials.

Keywords: Beyond Silicon; Wide Band Gap Semiconductors; GaN; SiC.

1. Introduction

Since the mid-20th century, Si has been employed to produce integrated circuits and power devices. Electronics have mature fabrication technology, are low-cost, and have good semiconductor properties. Silicon is also near its physical limits now. Its band gap is about 1.12 eV restricts device performance in high-voltage, high-temperature, and high-frequency applications, transistor scaling towards atomic dimensions has reached the end of Moore's Law. It is becoming increasingly difficult, and leakage current and power dissipation are also rising. At the same time, the new applications of semiconductors are demanding. Data centres for the new system need to be high-power-density and are moving towards electrification and renewable energy require high-efficiency power electronics, and 5G and future 6G communications require components operating at higher frequencies. These requirements can no longer be satisfied with silicon alone, and the semiconductor industry will reach a turning point beyond Silicon. As a result, other materials have begun to appear. Wide-bandgap semiconductors have shown good results. GaN and SiC have a large breakdown field and high saturation. They have good thermal conductivity and is suitable for high-power, high-frequency applications; therefore, it is now being used in commercial production. Two-dimensional Molybdenum disulfide (MoS_2) is also expected to extend the scaling of transistors beyond research on the limits of silicon is still in its infancy. Silicon will not be gone but a diversified landscape of "silicon-based plus multi-material" semiconductors is about to be formed. unavoidable trend of future development.

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2. Silicon Semiconductor Replacement

2.1. New-type Semiconductor Materials

2.1.1. Reason of Using Other Materials.

Currently, artificial intelligence is advancing rapidly, driving a sustained surge in computing power demand. Optical computing has emerged as a globally prioritized frontier direction. Traditional electronic computing chips have encountered a "power wall"; facing the high energy consumption that inevitably accompanies high-performance computing, soaring electricity costs have become a primary constraint on the future development of artificial intelligence. The International Energy Agency's report "Energy and Artificial Intelligence" predicts that by 2030, global data center electricity consumption will reach approximately 945 terawatt-hours, approaching Japan's total annual electricity usage [1]. For over 50 years, Moore's Law has been the driving force behind progress. However, silicon materials are now reaching their physical limits. As transistor sizes shrink, leakage currents increase, power consumption and heat become difficult to control, and reliability is compromised.

New applications are continually pushing the limits of silicon materials. The AI revolution necessitates data centers with extremely high power densities; the global transition to electric vehicles and renewable energy requires power electronics with greater energy efficiency; and 5G and future 6G communications require components that can operate at higher frequencies. These demands urgently call for the development of semiconductor technologies that "go beyond silicon." Machine learning models such as those powering ChatGPT and Gemini represent a typical class of AI systems. These systems demand extremely high computational resources and consume substantial amounts of energy, a fact that becomes particularly evident when they run on existing hardware. New applications—AI systems like ChatGPT and Gemini, EVs and renewable energy, and 5G/6G communications—are pushing silicon to its physical limits, urgently driving the development of "beyond silicon" semiconductor technologies.

Material transitions. Firstly, wide band gap semiconductors such as GaN and SiC, which offer exceptional performance for high-power and high-frequency applications and are now ready for commercial use. Secondly, two-dimensional materials like MoS_2, which hold promise for significantly expanding the scalability of transistor sizes beyond the limits of silicon materials, although they are still in the early stages of development.

Band gap means different materials have different band gaps, such as metal (0eV), silicon (1.12eV), diamand (5.47eV). Band gap illustrates that how many energy should be gained for electrons to jump between the valence band and the conduction band by vibrate, heat or light. A higher band gap which means the electrons are more difficult to pass through the materials. Therefore a material with a high band gap is suitable for a higher operating voltage and affordable more power consume. Fig.1 shows that a wider band gap raises the energy required for electrons to jump from the valence band to the conduction band, enabling higher operating voltages, temperatures and frequencies.

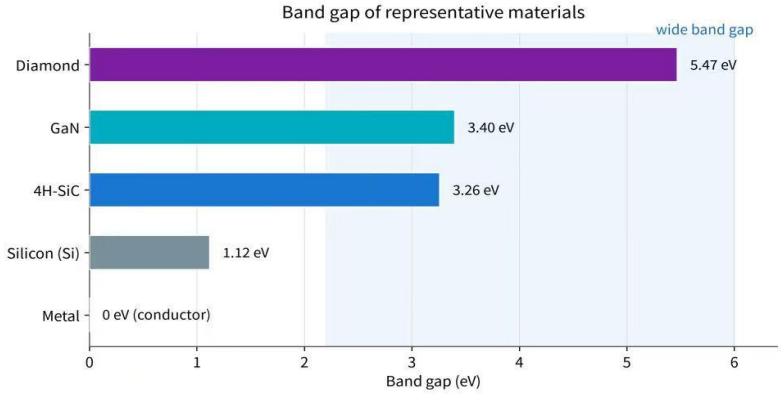

Fig. 1 Band gap of representative materials

2.1.2. Wide Band Gap Materials.

Wide band gap semiconductor for now are changing. GaN and SiC are no longer just theoretical concepts; they are continually reshaping the industry landscape and emerging as key players of the future. The advantages of GaN and SiC stem from their fundamental material properties. As shown in this table, their larger bandgap, significantly higher breakdown electric field compared to silicon, and excellent thermal conductivity directly translate to devices that can operate at higher voltages, temperatures, and speeds, with significantly reduced energy losses compared to silicon.

Single-material substrates can no longer meet the demands of such multi-performance synergy: while SiC substrates exhibit excellent thermal conductivity, their fabrication is costly and large-scale single-crystal growth remains challenging; GaN heavily relies on heteroepitaxial growth, where there is a pronounced conflict between substrate and epitaxial layer performance matching. By combining materials with different properties through specific processes, it achieves "1+1>2.". In the laboratory, their losses in circuits were simulated using Saber. The results showed that the average losses of SiC MOSFETs are 30% to 48% lower than those of Si MOSFETs [2]. In short, GaN and SiC leverage their wider bandgaps and superior thermal properties to cut device losses, and through material integration they will overcome the limits of single substrates to become the core of future power devices. Fig.2 illustrates that normalized comparison of key material properties for Si, SiC and GaN. SiC leads in thermal conductivity; GaN leads in band gap, breakdown field, electron mobility and saturation velocity (typical values).

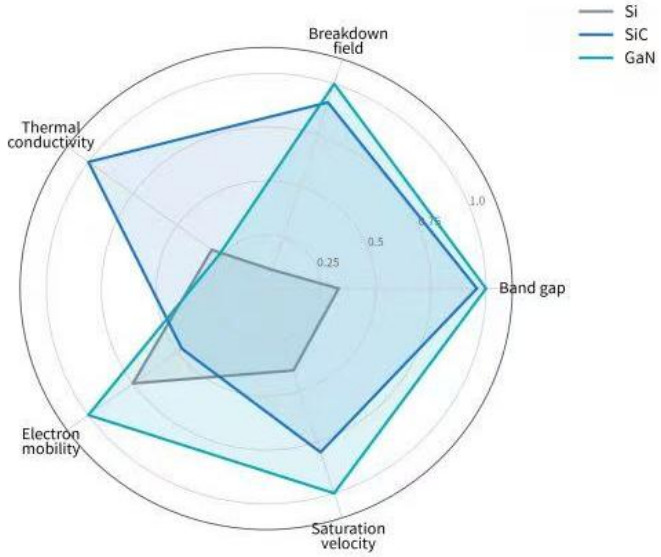

Fig. 2 Properties of three main semiconductors

GaN is characterized by high speed and high frequency, with fast electron mobility and extremely rapid switching, which can significantly reduce energy conversion losses. It is in the latest fast chargers, which are not only smaller and more powerful but also more efficient. Beyond the realm of consumer electronics, GaN is driving revolutionary changes in data centers and 5G communications, and is gradually making its way into automotive systems. An abrupt-GaN-composition heterojunction source yields a lower specific on-resistance, while the semi-superjunction barely affects R_on,sp but reshapes the drift-region electric field, boosting breakdown voltage by 114.71% and reducing parasitic capacitance and switching delays (t_off by 33.04%, t_on by 25.28%) compared with a device without the semi-superjunction, offering a new scheme for high-performance HFET design [3] .This market is experiencing exponential growth, driven largely by the cost reductions resulting from increased wafer sizes and innovative technologies such as vertical GaN. A GaN-based two-way Doherty power amplifier targeting 5G NR n78 band is designed and implemented. Using an integrated unequal Wilkinson divider with λ/4 phase delay, the amplifier obtains 42.5 dBm peak power, 13.3 dB gain and 83% peak PAE at 3.5 GHz, with harmonics suppressed below −30 dBc. Simulations and measurements validate this broadband high-efficiency solution for 5G base station transmitters [4].

Therefore, it is commonly used in ultra-compact fast-charging adapters rated at 65W/100W for consumer electronics, as well as in precision power supplies for data centers and next-generation AI servers.

Because of the exceptional voltage and temperature resistance, the breakdown electric field strength is approximately 10 times that of traditional silicon, making it suitable for handling high-voltage environments of several thousand volts. Owing to differences in material systems, conduction mechanisms, and device structures, Si, SiC, and GaN power semiconductors exhibit contrasting behavior at low temperatures: Si MOSFETs show reduced on-resistance but degraded threshold stability and breakdown voltage, SiC MOSFETs suffer from increased on-resistance due to reduced free-carrier concentration and interface traps, while GaN HEMTs—conducting via polarization-induced 2DEG—improve their on-state performance and demonstrate superior low-temperature adaptability over SiC [5].SiC is a key player in high-voltage and high-power applications. Its most significant impact is seen in the field of electric vehicles, where SiC is used in the main inverter to improve efficiency and driving range. It is also crucial for renewable energy systems. The SiC market is expected to experience significant growth, although the sector has faced supply chain challenges due to the difficulty of manufacturing high-quality wafers. The efficiency curve of the SiC system at a 700V input voltage shows that the SiC system has relatively low efficiency at light loads, only 0.9316. As the load increases, the efficiency gradually rises, reaching a maximum of 0.9838, which is 0.5% to 1% higher than that of the silicon system. This represents a significant improvement in energy conversion systems. For the application of mobile energy storage stations, two products were selected for testing and analysis of their losses, efficiency, and power density. The results indicate that compared to the silicon system, the SiC system has an overall efficiency 2.68% higher, losses 11% lower, operating temperature 50% lower, and power density increased by 0.95 times [6]. Also, In the manufacturing of third-generation SiC power devices, the high-temperature annealing process faces challenges such as thermal radiation nonlinearity and multi-zone dynamic coupling, leading to insufficient impurity activation. An intelligent temperature monitoring system based on multi-physics state-space modeling and adaptive fuzzy neural network control employs fiber-coupled dual-color spectral sensing and Kalman filtering technology. It constructs a comprehensive thermal field model incorporating cavity heat capacity, radiative conduction, and gas convection, and introduces a feedforward decoupling strategy to eliminate thermal flow interference across different temperature zones. Research results indicate that after applying this system, the temperature difference within the wafer surface is less than 0.8°C, interface defects caused by step beaming are significantly reduced, and device manufacturing yield is improved to 93.5%. This design can be extended to high-temperature precision heat treatment processes for large-sized SiC wafers [7]. So it is common use in Drive inverters for electric vehicles (EVs), onboard chargers, and large-scale power converters for renewable energy sources (solar and wind power).

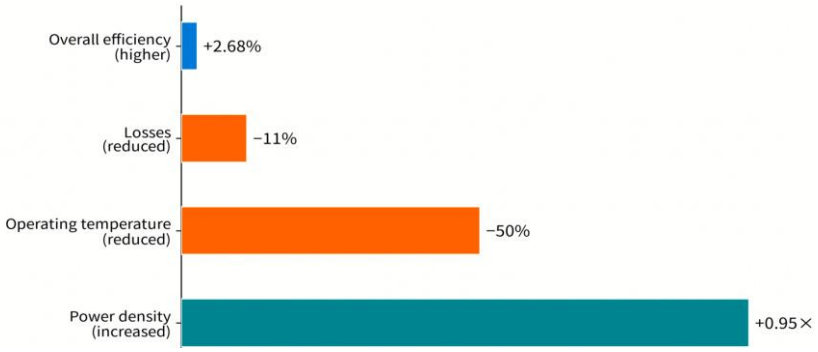

Fig. 3 Performance gains of SiC system

Fig. 3 shows that the performance gains of the SiC system over the Si system in power converters overall efficiency +2.68%, losses −11%, operating temperature −50%, power density +0.95×.

Essentially, it functions like a small parallel data processing factory, equipped with a 4-bit parallel processor capable of executing 8 different instructions simultaneously. It also features four core

modules, including an instruction decoder, a register file, an arithmetic logic unit, and a multiplexer [8] .A joint team led by Zhu Mengjian together with Prof. Ren Wencai and Prof. Xu Chuan from the Institute of Metal Research, CAS, has developed a CVD method using liquid Au/W bimetallic films as the growth substrate, enabling wafer-scale, doping-tunable growth of monolayer WSi_2N_4 with sub-millimeter single-crystal domains and a growth rate about 1,000 times faster than previously reported; combining high hole mobility, large on-state current density, high strength, good thermal dissipation, and chemical stability, the material is promising for 2D-semiconductor CMOS integrated circuits and post-Moore chip technologies [9].Chinese manufacturers such as Tianyu Advanced have rapidly gained market share, particularly in the critical substrate market. This trend is reshaping the competitive landscape in the global silicon carbide sector. While GaN and SiC are addressing current challenges, 2D materials represent the next frontier. These atomically thin materials play a crucial role in extending Moore's Law beyond the physical limits of silicon.

2D materials have been proved that it is work in hospital. In the AQA test, there was no statistically significant difference in the total deviation between the two tools under the Fixed mode ($P > 0.05$), while a statistically significant difference was observed under the MLC mode ($P = 0.008$); however, all measurements fell within the clinically acceptable error range. In the Iris QA test, the maximum standard deviation of the collimator size measurement results was 0.04 mm, and the maximum deviation was 0.08 mm, which is well below the deviation requirements specified in WS 667-2019 "Quality Control and Inspection Specification for Robotic Radiotherapy Devices." In the Beam QA test, the symmetry difference between SRS MapCHECK and the 3D water tank was ≤0.52%, and the flatness difference was ≤1.82%, demonstrating good consistency with the 3D water tank (gold standard). Conclusion: The 2D semiconductor matrix SRS MapCHECK can replace EBT3 film and 3D water tanks for AQA, Iris QA, and Beam QA tests on the CyberKnife system, enabling rapid completion of QA work for the M6-type CyberKnife system [10].A van der Waals γ-InSe nanosheet photodetector fabricated by mechanical exfoliation, dry transfer, and electron-beam lithography achieves a responsivity of ~12.9 mA/W, an external quantum efficiency of ~2.5%, and a specific detectivity of 9.6×10^7 Jones at 532 nm under room temperature, with photocurrent scaling with intensity and reproducible under periodic illumination, demonstrating good transient photoresponse, stability, and promise for room-temperature photodetection [11]. Overall, 2D semiconductor devices have proven practically viable — the SRS MapCHECK matrix can replace film and 3D water tanks for CyberKnife QA within clinically acceptable error, while γ-InSe nanosheet photodetectors show stable, reproducible room-temperature photodetection with promising performance.

2.2. Challengings

All of the today's mainstream semiconductor materials have their strong points and weakness points in their respective areas. Si is mature and cheap, but has a band gap of ~1.12 eV and scaling limits are rapidly being hit; SiC has very high breakdown field and high thermal conductivity, but has issues with carrier freeze out, interface traps, high fabrication costs; promising 2D materials such as MoS_2 are still at an early stage; GaN has excellent performance at high frequency and low temperature due to the 2DEG, but is not suitable for vertical devices, thermal management, long term reliability, or thermal runaway under transient fields. While 2D semiconductors are good candidates for channels in next generations of electronics, the performance of 2D transistors is well below theoretical expectations, with most of the limitations coming from the interfaces. This review systematically investigates the three key interfaces: metal/2D semiconductor, dielectric/2D semiconductor, and encapsulation (substrate)/2D semiconductor, as well as the important issues and challenges of these interfaces, and summarizes the most recent advances in contact engineering, dielectric engineering, surface encapsulation, and substrate optimization to push the device performance of 2D semiconductors to their full potential to enhance their performance and facilitate their transfer from laboratory research to industrial applications [12]. No single material will be able to satisfy the requirements—the future is a multi-material (Si, SiC, GaN, emerging materials) framework of complementary materials.

The engineering implementation of cutting-edge new materials and intelligent algorithms faces significant challenges. Novel materials such as heavily doped silicon, carbon-based/nitride-based compounds, and wide-bandgap semiconductors are constrained by practical bottlenecks including poor controllability of coating processes, inadequate thermodynamic compatibility at heterojunction interfaces, and immature production lines, making industrial-scale replacement difficult in the short term. There are shortcomings in the adaptability of extreme operating conditions and new concept devices. In extreme environments such as high-low temperature cycles, strong mechanical overload, and intense electromagnetic/particle irradiation, issues like stress distortion in packaging systems and heterointerface failures are prominent. Multi-physics field environments can easily lead to unintended device triggering and detonation energy drift [13]. To summarize, despite their performance promise, advanced materials and intelligent algorithms still face engineering hurdles — from poor process controllability and heterojunction incompatibility to immature production lines and failure under extreme conditions — that make near-term industrial replacement difficult.

TCAD multiphysics simulations of GaN Schottky diodes under transient intense electromagnetic fields reveal that heat accumulates most readily at the lightly/ heavily doped layer interface; when the pulse interval is shorter than the device's thermal relaxation time, severe heat buildup induces thermal runaway and device failure [14] .When hydrogen enters the device, it primarily enhances the output current by passivating gallium vacancies and other traps, suppressing capture effects, and forming a dipole layer at the metal/AlGaN interface. Under a hydrogen atmosphere, applying thermal electron stress induces "dehydrogenation," reactivating traps and dominating device degradation. In nitrogen, low thermal conductivity can lead to heat accumulation and thermal burnout. Deep-level traps generated under high-temperature operating stress can be partially restored by hydrogen. Under RF over-stress, high-energy thermal electrons reactivate traps and induce new defects, with strong electric fields being the primary cause of local channel burnout, while ambient temperature has limited influence. Based on this, this paper establishes an RF-accelerated life assessment process, confirming that RF stress damage is significantly more severe than DC stress at the same junction temperature, and constructs an RF over-stress lifetime model based on the Arrhenius equation, yielding an activation energy of 0.76 eV. The research findings can provide mechanistic understanding and experimental method support for enhancing the reliability and over-stress survival capability of GaN microwave devices [15]. Taken together, these studies clarify the failure mechanisms of GaN devices — from interface heat accumulation and hydrogen-related trap passivation to RF over-stress defects — and provide a lifetime model and assessment framework for improving their reliability under extreme conditions.

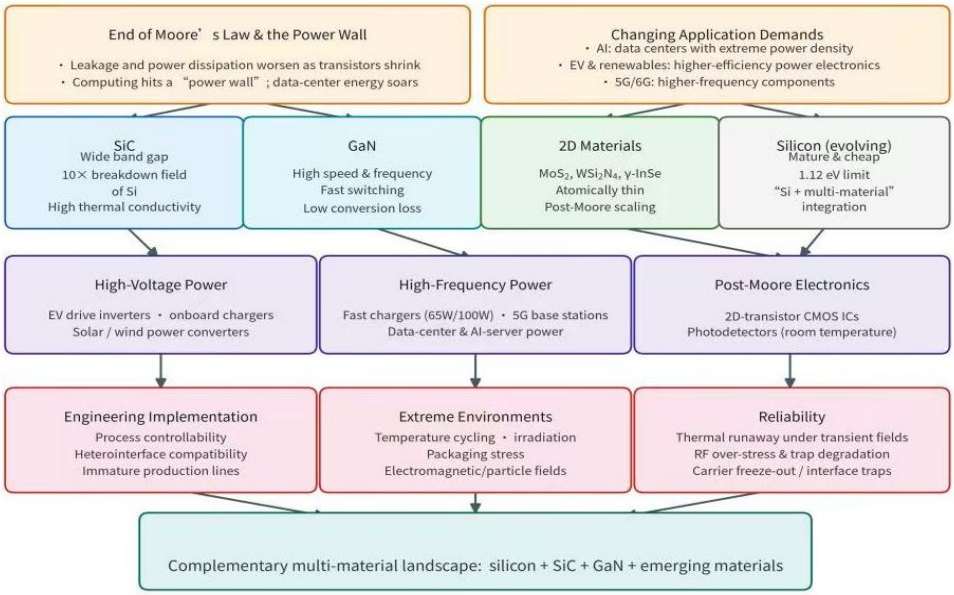

Fig. 4 The "beyond silicon" technology landscape and the resulting complementary multi-material landscape

3. Conclusion

The "beyond silicon" technology landscape: driving forces, material branches, application domains, engineering challenges, and the resulting complementary multi-material landscape.

Due to limitations in experimental conditions and sample scope, the theoretical assertions in this paper are primarily based on the cross-verification of macroscopic electrical parameters, low frequency noise, electroluminescence, and multiphysics field simulations. The microscopic dynamics of hydrogen diffusion, passivation, and thermal desorption within the device, as well as the energy level structure of deep-level traps and atomic-scale characteristics of dipole layers, still require further confirmation through direct characterization methods. The lifetime model is based on a thermally activated form, with limited consideration for electric field acceleration terms and electrothermal coupling. The existing data also lacks sufficient coverage in terms of process batches, sample quantities, and stress conditions. Future work can be pursued in three directions: first, introduce micro-characterization to identify the existence states of hydrogen and trap energy levels, verifying and refining the mechanisms of passivation, dehydrogenation, and dipole formation; second, expand the temperature and bias stress matrices, increase sample numbers and process batches, incorporate an electric field acceleration factor into the model, and include actual radar modulation signals and varying standing wave ratios as operating conditions; third, based on the correlation between burnout points and local strong electric fields, evaluate the practical effectiveness of passivation and field structure improvements in suppressing local burnout and enhancing the device's over stimulation survival capability. Fig. 4 gives the conclusion of current semiconductor materials.

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