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Hardware Development and Application of Silicon Carbide and Gallium Nitride in Integrated Circuit Detection Systems

Boran Li*

GRGTEST Group Co., Ltd., Guangzhou 510000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: Silicon carbide (SiC) and gallium nitride (GaN) are used as wide-bandgap semiconductor materials in the hardware development of integrated circuit detection systems. The impact of material characteristic differences on system performance needs to be considered, and hardware platforms should be adapted to construct a three-dimensional technology management system. In addition, interdisciplinary team collaboration, heat dissipation structure design, long-term reliability assessment and other management aspects, as well as supply chain collaboration, packaging technology selection are of great significance to research and development, and technical management can provide scientific guidance.

Keywords: Silicon carbide; Gallium nitride; Integrated circuit testing system

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1. Introduction

With the development of the semiconductor industry, the application of wide-bandgap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) in integrated circuit (IC) testing systems has become increasingly important. The "Several Policies on Promoting the High-quality Development of the Semiconductor Industry" issued in 2021 emphasizes the importance of promoting technological innovation and application of semiconductor materials, providing policy support for the research, development, and application of SiC and GaN in testing systems. These two materials have distinct physical characteristics and significantly impact the performance of testing systems. From hardware platform adaptation to the construction of technical management systems, from multidisciplinary team collaboration to thermal design, in-depth research on their applications can better leverage the advantages of these materials, enhance the performance and reliability of testing systems, and promote the development of hardware research and development for IC testing systems.

2. Characteristics of SiC and GaN materials and advantages of detection system applications

2.1. Comparative analysis of characteristics of wide bandgap semiconductor materials

SiC and GaN, as wide-bandgap semiconductor materials, each have their own characteristics in terms of physical properties. In terms of thermal conductivity, SiC has a higher thermal conductivity, which enables it to dissipate heat more efficiently in detection systems and helps maintain stable system operation, while GaN has a relatively lower thermal conductivity but can still meet certain heat dissipation requirements. In terms of breakdown field strength, SiC has a higher breakdown field strength and can withstand higher voltages, reducing the probability of system breakdown faults. The breakdown field strength of GaN is also considerable, which is conducive to achieving high-voltage applications. In terms of electron saturation rate, GaN has a high electron saturation rate and fast signal processing speed, which can improve the response speed of the detection system. Although the electron saturation rate of SiC is not as good as GaN, it still has good electron transport capability. These characteristic differences have a significant impact on the performance of the detection system, such as the heat dissipation effect affecting system stability, breakdown field strength affecting system safety, and electronic saturation rate determining system response speed. Therefore, during development, materials should be selected reasonably based on the specific requirements of the detection system [1].

2.2. Research on hardware platform adaptability of detection system

In terms of hardware platform adaptability in the detection system, it is necessary to focus on high-frequency response, power density, and heat dissipation requirements. SiC and GaN have excellent high-frequency response characteristics, which can meet the high-speed signal processing requirements of detection systems, adapt to high-frequency hardware platforms, and effectively improve detection efficiency and accuracy [2]. In terms of power density, both have significant advantages, which enables detection equipment to operate at higher power in a compact space, adapt to small volume and high integration hardware platform designs, and optimize the overall system layout. In response to the heat dissipation requirements, the good thermal conductivity of these two materials provides reliable heat dissipation guarantee for high heat flux density hardware platforms, which can avoid performance degradation and failures caused by overheating, ensure stable operation of the detection system in complex working environments, achieve efficient adaptation of hardware platform and material characteristics, and fully play their application value in integrated circuit detection systems.

3. Analysis of technical management requirements for integrated circuit testing system

3.1. Design of technical management system architecture

To meet the hardware development and application of SiC and GaN in integrated circuit detection systems, a three-dimensional technology management system architecture is constructed. In terms of R&D resource allocation, it is necessary to allocate human, material, and financial resources reasonably to ensure the smooth progress of hardware R&D in all aspects, such as accurately investing funds in the purchase of detection equipment related to SiC and GaN. Technical risk assessment focuses on identifying material adaptation and performance stability risks caused by the characteristics of SiC and GaN, and developing response strategies in advance. Intellectual property management should strengthen the protection of research and development achievements and apply for patents in a timely manner. At the same time, highlighting the decision-making mechanism for technology route selection and iterative updates, flexibly adjusting technology routes based on industry development trends and market demand to adapt to the constantly changing application needs of SiC and GaN in integrated circuit detection systems [3].

3.2. Cross-disciplinary technology collaboration mechanism

In the hardware development of integrated circuit detection systems, collaboration among multidisciplinary teams such as semiconductor technology, detection algorithms, and mechanical automation is crucial. There are differences in professional knowledge and technology in different fields. Without effective collaboration, it is easy to form an "island" effect, which hinders the hardware development process. It is necessary to establish an effective cross disciplinary technology collaboration mechanism to promote information sharing and deep cooperation among teams. On one hand, building a unified communication platform enables team members to communicate research progress, encountered problems, and solutions in a timely manner, enhancing mutual understanding. On the other hand, clarify the responsibilities and task boundaries of different teams in each stage of hardware development to prevent confusion caused by unclear responsibilities. Through these collaborative mechanisms, knowledge can be smoothly transferred between interdisciplinary teams, breaking down disciplinary barriers, improving hardware development efficiency and quality, and enabling SiC and GaN to better play their roles in integrated circuit detection systems [4].

4. Key challenges and countermeasures in technical management practice

4.1. Challenges in thermal management and reliability technology

4.1.1. Management of heat dissipation technology under high temperature conditions

During the continuous operation of integrated circuit testing systems, the distribution of thermal stress can have a significant impact on system performance and reliability. Under high temperature conditions, heat dissipation becomes a key challenge. The detection system operates for a long time, and each component continuously generates heat. If it cannot effectively dissipate heat, it can lead to performance degradation, shortened component life, and even system failure. Analysis of the distribution characteristics of thermal stress shows that there are significant differences in thermal stress in different parts, and traditional heat dissipation methods are difficult to meet the requirements. Based on this, a topology optimization based heat dissipation structure design management scheme is proposed [5]. Through topology optimization, it is possible to accurately design heat dissipation structures based on the distribution of thermal stress, making the distribution of heat dissipation materials more reasonable and improving heat dissipation efficiency. This solution can effectively address the heat dissipation problem under high temperature conditions, ensure stable operation of the detection system under continuous working conditions, improve its reliability and service life, and provide strong support for the hardware development and application of SiC and GaN in integrated circuit detection systems.

4.1.2. Construction of long term reliability assessment system

The construction of a long-term reliability assessment system is crucial for the hardware development and application of SiC and GaN in integrated circuit detection systems. A reliability management process covering accelerated life testing and failure mode analysis needs to be established. Accelerated life testing strengthens stress conditions, shortens test cycles, and quickly obtains device life data, providing a foundation for long-term reliability evaluation [6]. Failure mode analysis aims to identify the possible failure modes of hardware under various operating conditions, explore the root causes of failure, and provide a basis for improving design. At the same time, it is necessary to establish admission standards for the technical validation stage, clarify the quantitative indicators that hardware needs to achieve in terms of performance, stability, etc. Only hardware that meets these standards can enter the next stage of research and development, in order to ensure the reliability of hardware in long-term use and improve the application quality of SiC and GaN in integrated circuit detection systems.

4.2. Breakthrough in difficulties of supply chain collaborative management

4.2.1. Quality management of special material suppliers

Quality management of special material suppliers is crucial in the hardware development of integrated circuit detection systems using SiC and GaN. The key challenge lies in how to develop a scientifically reasonable evaluation standard for the defect rate of semiconductor wafer epitaxial layers and a supplier grading management system. If the evaluation criteria for the defect rate of epitaxial layers are not precise, it may lead to the inability to accurately measure material quality and affect subsequent hardware performance. On the other hand, an imperfect supplier grading system can make it difficult for high-quality suppliers to stand out, which is not conducive to establishing long-term stable cooperation. In terms of countermeasures, it is necessary to collaborate with industry experts, research institutions, and other multiple forces, based on a large amount of experimental data and practical experience, to jointly develop practical and forward-looking defect rate evaluation standards [7]. In the meantime, a comprehensive supplier grading index system is constructed from multiple dimensions such as product quality stability, supply capacity, and research and development innovation. Suppliers are regularly evaluated and graded to incentivize them to improve their quality and service levels, and achieve coordinated development of the supply chain.

4.2.2. Optimization strategy for inventory of supporting components

In the supply chain collaborative management of integrated circuit detection systems, optimizing the inventory of supporting components is a key link. Applying the ABC classification method to construct a dynamic inventory management model for key components of detection equipment can effectively address this challenge. By ABC classification, the key components of the testing equipment are classified into three categories: A, B, and C based on factors such as importance and frequency of use. For Class A critical and high usage components, it is necessary to focus on monitoring and management, maintain low inventory levels while ensuring supply stability, such as establishing long-term partnerships with high-quality suppliers and shortening supply cycles. For Class B components, the management intensity should be appropriately relaxed. C-class components with low usage and low importance can maintain high inventory to simplify management processes. This dynamic inventory management model can make the inventory structure more reasonable, reduce inventory costs, improve supply chain collaboration efficiency, and break through the difficulties of component matching inventory management [8].

5. Implementation cases of technical management in R&D practice

5.1. Research and development case of SiC power module detection system

5.1.1. Key technology path selection

In the development of SiC power module detection system, careful decision-making is required for the key technology path selection of packaging technology. Direct bonding technology has good electrical performance and thermal conductivity, which can effectively reduce the parasitic parameters of modules. However, it has strict requirements for process conditions and relatively high costs. Silver sintering technology performs well in high-temperature reliability, can withstand higher operating temperatures, and provide good mechanical strength, but the control difficulty of sintering process is relatively high. By conducting multidimensional comparative analysis of the two, including performance parameters, process complexity, cost-effectiveness, etc. From a technical management perspective, considering the performance requirements, production scale, and long-term reliability requirements of the detection system, a suitable packaging technology selection is made after weighing the pros and cons to ensure that the SiC power module detection system can meet performance indicators in hardware research and development, as well as have economic feasibility and process operability [9].

5.1.2. Application of risk management tools

In the development of SiC power module detection systems, the FMEA method has shown significant effectiveness in preventing electromagnetic compatibility design defects. The R&D team uses FMEA to systematically analyze the possible failure modes of various hardware components of the detection system in electromagnetic environments. For example, regarding the signal acquisition circuit of the detection system, potential problems such as signal distortion and acquisition errors that may be caused by electromagnetic interference are carefully explored, and the impact on the performance of the entire detection system is evaluated. Key risk points are determined based on the risk priority number. By identifying these potential hazards in advance, the R&D team has developed targeted preventive measures, such as optimizing circuit layout and adding shielding measures. Consequently, after practical testing and verification, the use of FMEA method significantly reduced the occurrence rate of faults caused by electromagnetic compatibility issues in the detection system, effectively improving the stability and reliability of the system [10].

5.2. Management practice of GaN RF device testing equipment

5.2.1. Optimization of R&D resource allocation

In the development and practice of GaN RF device testing equipment, it is of great significance to achieve dynamic allocation and management of simulation computing resources and experimental verification resources. For example, in the development of a new GaN RF power amplifier testing equipment, the device characteristics and circuit performance were initially analyzed through simulation calculations, and computing resources were concentrated to quickly establish an accurate model. With the advancement of research and development, when it is necessary to conduct experimental verification of key performance indicators, resources should be promptly tilted towards experimental verification, and experimental equipment and venues should be allocated to ensure the smooth progress of verification work. Simultaneously, based on experimental feedback, the simulation calculation parameters were re-optimized, and computing resources were reallocated to further improve the model. By dynamically allocating simulation computing resources and experimental verification resources in this loop, the efficiency and quality of testing equipment development have been significantly improved, ensuring that the final product meets high-performance requirements.

5.2.2. Intellectual property layout strategy

In the development and practice of GaN RF device testing equipment, intellectual property layout strategy is crucial. In terms of high-frequency probe cards, enterprises need to comprehensively search for existing patents, clarify technical gaps and competitive situations. For example, analyzing the performance parameters, applicable scenarios, and other related patents of different types of high-frequency probe cards in the market to identify underutilized technical points. Concurrently, actively participate in standardization work and integrate the advantageous technologies developed by oneself into industry standards. Taking a well-known semiconductor company as an example, it has promoted the standardization process of its independently developed high-precision high-frequency probe card technology through cooperation with industry associations and research institutions. This not only enhances product recognition, but also builds a patent portfolio around the technology, occupying a favorable position in market competition and achieving coordinated development of technology research and intellectual property protection, laying a solid foundation for the long-term development of GaN RF device testing equipment.

5.3. Standardized process management of detection system

5.3.1. Technical document management system

In a hardware development project for an integrated circuit detection system, a standardized document cloud platform covering design specifications, process parameters, and test records was established to achieve effective management of technical documents. The design specification document specifies in detail the requirements for SiC and GaN in circuit board layout, wiring, and other aspects to ensure that hardware design meets performance and reliability standards. The process parameter document records the key parameters of two materials during the manufacturing process, such as etching time, temperature, etc., providing accurate guidance for production. The test record document retains the results and data of each test for analyzing product performance and optimizing improvements. With the help of cloud platforms, R&D team members can easily access, share, and update documents, greatly improving information flow efficiency, avoiding R&D delays caused by inconsistent or missing document versions, and effectively promoting the hardware development process of integrated circuit detection systems based on SiC and GaN.

5.3.2. Technical personnel capability assessment

In the hardware development of integrated circuit detection systems using SiC and GaN, it is crucial to evaluate the capabilities of technical personnel as follows:

(1) Consider the technical personnel's mastery of the characteristics of SiC and GaN materials and related hardware design knowledge, and evaluate their theoretical basis;

(2) Examine its hands-on ability in practical circuit design, wiring, debugging, and other operational processes, and verify it through actual project operations;

(3) Pay attention to the adaptability of technical personnel to solve unexpected problems in research and development, such as whether they can quickly analyze and propose solutions when facing circuit abnormalities caused by the unique electrical properties of SiC and GaN;

(4) Evaluate the team's collaboration ability, as hardware development requires the cooperation of multiple technical personnel, and good communication and collaboration can ensure project progress;

(5) Provide strong support for technical team optimization and project advancement through comprehensive capability assessment.

6. Conclusion

The hardware development and application of new semiconductor materials such as SiC and GaN are of great significance in integrated circuit detection systems. Extracting the methodological value of technical management in the development of testing equipment provides scientific guidance principles and processes for hardware research and development, helps optimize R&D resource allocation, and improves R&D efficiency and quality. A technology management improvement framework based on the PDCA cycle, through a continuous cycle of planning, execution, inspection, and processing, can continuously discover and solve problems in the hardware development process, and promote the iterative upgrading of technology. The application prospects of intelligent decision-making systems in R&D management are broad. With the help of big data and artificial intelligence technology, it can analyze complex data in hardware R&D, provide accurate support for R&D decisions, and help achieve more efficient and innovative hardware R&D of SiC and GaN in integrated circuit detection systems.

Disclosure statement

The author declares no conflict of interest.

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