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Power Semiconductor Device Humidity Reliability Study

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ABSTRACT

This paper aims to study the aging mechanism of power semiconductor devices in high humidity environments, propose anti-humidity optimization design methods, and explore the humidity reliability of these devices in-depth. The reliability of the devices can be examined through High Humidity High Temperature Reverse Bias Testing to simulate aging in high humidity environments and evaluate their performance. By analyzing the performance of power semiconductor devices under humidity stress, this research reveals the humidity aging mechanism and failure points, providing a theoretical basis for optimizing the design to enhance humidity resistance and lifespan [2]. Research on humidity reliability has gained frequent attention in recent years, but the causes and mechanisms of failure in chips are still unclear. Therefore, similar tests are required to analyze and summarize the failure parts. Simulations can be used to model the working conditions of devices in high humidity environments, simulating the diffusion of water vapor into chips, identifying failure patterns, analyzing moisture diffusion mechanisms, and improving the weak points of failure through comparative analysis using different materials. Finally, the most suitable anti-humidity materials can be identified for device improvement.

KEYWORDS

Power Semiconductor Devices; Humidity Reliability; Aging Mechanism; Anti-humidity Design.

1. INTRODUCTION

Power semiconductor devices are widely used in outdoor working conditions such as photovoltaic power generation, new energy vehicles, and offshore wind power. Their long-term reliability is influenced by humidity stress. As the core components of modern power electronics technology, power semiconductor devices are extensively used in energy conversion, motor drive, and renewable energy fields [2]. With the continuous development of electronic power technology, the performance requirements for power semiconductor devices are increasing, especially in harsh conditions such as high temperature and high humidity. Under high humidity conditions, water vapor diffuses into the devices, resulting in a significant decrease in insulation performance. As a result, device lifespan and stability are greatly compromised. Although humidity reliability research has gained attention in recent years, the humidity aging mechanism, failure points, and testing standards and principles remain unclear. Therefore, this paper aims to study the aging mechanism of power semiconductor devices in high humidity environments, propose anti-humidity optimization design methods, and provide theoretical foundations for understanding the impact of humidity on power device reliability, researching pressure resistance reliability under humidity environments, optimizing anti-humidity design, and enhancing humidity resistance and lifespan. Therefore, conducting humidity reliability tests on power semiconductor devices is of significant theoretical and engineering value.

2. SIGNIFICANCE AND RESEARCH STATUS

Power semiconductor devices are negatively affected by humidity stress in long-term outdoor working environments, leading to decreased reliability. Although humidity reliability research has gained attention in recent years, the aging mechanism, failure points, and other related aspects remain unclear. Moreover, there are various testing standards for humidity reliability, but the principles for determining testing conditions are not well-defined, which presents challenges for evaluating the humidity reliability of power semiconductor devices. Conducting humidity reliability tests can ensure the stability and consistency of device performance during actual operation, and evaluate and improve their durability during long-term operation. It also helps identify and address potential problems that may accelerate the aging of devices under extreme conditions such as avalanche and short circuits, thus improving the dynamic reliability of devices. Reliable wide bandgap semiconductors are required to operate under harsh conditions such as high temperature, high humidity, and high vibration, and humidity reliability testing can help ensure the normal operation of devices.

Since the stability of silicon PN junctions under environmental humidity was first proposed in 1959, the influence mechanism of humidity on power semiconductor devices has gradually been revealed [3]. With the development of power electronic technology, especially the increasing demand for high voltage and high power IGBT devices in areas such as high voltage direct current transmission and electric locomotives, the reliability requirements for these devices are becoming increasingly demanding. Researchers have developed various methods to diagnose IGBT device failures, such as acoustic microscopy, infrared inspection mirrors, infrared detectors, and X-ray detectors, to discover failure modes and mechanisms. As the packaging of IGBT devices varies, their main failure modes and mechanisms also differ. In the 1970s, extensive research was conducted on integrated circuits, aluminum, silicon, and other elements' electrochemical migration, surface conductivity, and coating protection [3]. The history of the evolution of modern silicon-based power semiconductor devices and the research progress of new devices is one key focus. In addition, research on wide bandgap semiconductor materials and devices is also progressing. These new devices and materials are expected to enhance the operating capabilities of power semiconductor devices in high temperature and high humidity environments. In terms of theoretical research, many scholars have analyzed the impact of humidity on semiconductor device reliability and proposed comprehensive practices to reduce temperature effects and achieve high module reliability. Research has also focused on the research progress of new device structures and the current status of wide bandgap semiconductors and devices. With the development of device miniaturization, high power density, and various high-voltage power devices, the reliability of devices under harsh conditions such as high temperature and high humidity has received widespread attention. However, simulation related to power device water vapor diffusion is still in its infancy internationally.

3. RESEARCH OBJECTIVES, CONTENTS, AND KEY PROBLEMS TO BE SOLVED

The main objectives of this research are to study the aging mechanism of power semiconductor devices in high humidity environments, propose anti-humidity optimization design methods, and establish humidity reliability testing standards and evaluation systems. To achieve these objectives, this paper will focus on the following aspects:

(1) Research on humidity aging mechanisms: Through in-depth research on the aging process of power semiconductor devices in high humidity environments, the humidity aging mechanism and failure points will be revealed.

(2) Anti-humidity optimization design methods: Based on the research results of the humidity aging mechanism, anti-humidity optimization design methods for power semiconductor devices will be proposed to improve their resistance to humidity and lifespan.

(3) Humidity reliability testing and evaluation: A comprehensive humidity reliability testing and evaluation system will be established to provide a scientific basis for evaluating the humidity reliability of power semiconductor devices.

The key problems to be solved include clarifying the humidity aging mechanism and failure points, proposing effective anti-humidity optimization design methods, and establishing unified humidity reliability testing standards and evaluation systems.

4. RESEARCH METHODS AND TECHNICAL ROADMAP

This research will adopt a combination of theoretical analysis, experimental research, and simulation modeling methods. Firstly, relevant literature and data will be reviewed to summarize the present research status of humidity reliability in power semiconductor devices. Secondly, experimental observations and analyses will be conducted on the aging process of power semiconductor devices in high humidity environments to reveal the humidity aging mechanism and failure points. Simultaneously, simulation modeling techniques will be used to simulate the diffusion of water vapor into the device during actual operation, providing a theoretical basis for anti-humidity optimization design. Through electrical performance testing, the electrical characteristics of the devices will be evaluated under harsh conditions by measuring and recording parameters such as conduction resistance and leakage current. Material properties, such as the coefficient of thermal expansion and bond strength, may change with varying air humidity conditions. Mechanical performance testing will provide a better understanding of material characteristics. Long-term device operation will simulate the real-life use of devices and better predict their long-term reliability. By analyzing the performance degradation and failure parts through physical and chemical analyses, the failure causes and mechanisms can be determined. Finally, based on the experimental and simulation analysis results, anti-humidity optimization design methods will be proposed, and a humidity reliability testing and evaluation system will be established. Optimization can be conducted on the failure parts based on the experimental test results to improve the humidity resistance of materials. The encapsulation of power devices can be optimized for humidity resistance, improving device operational capabilities under extreme conditions. Mathematical statistical methods can be used to scientifically analyze the experimental data and identify failure patterns. Mathematical models can be established based on these patterns to predict the effects of humidity and clearly reveal performance trends and expected lifespan.

5. EXPECTED RESULTS AND CONTRIBUTIONS

This research is expected to reveal the aging mechanism and failure points of power semiconductor devices in high humidity environments, propose effective anti-humidity optimization design methods, and establish unified humidity reliability testing standards and evaluation systems. This will help reduce the impact of humidity on power device reliability, improve their pressure resistance reliability in humidity environments, and optimize anti-humidity design. Conducting humidity cycling tests on power semiconductor devices can increase their lifespan. The experimental data can help discover potential issues such as chip passivation, identify weak areas, and improve devices to enhance their market competitiveness. Conducting humidity reliability testing provides more rigorous standards for the industry, promotes the improvement of product quality, and advances the industry as a whole. Analyzing failure causes can effectively reduce the maintenance costs of future products and increase user satisfaction. This can enhance trust in the products and improve brand awareness. Testing on new materials such as wide bandgap semiconductors can effectively promote research on the failure mechanisms of wide bandgap semiconductors. Furthermore, this research will provide new ideas and methods for the reliability assessment and optimization design of power semiconductor devices, promoting their extensive application and development in outdoor working environments. In-depth research on humidity reliability testing can provide a better understanding of performance changes with changing environmental conditions, promoting the development of environmentally friendly devices. Regarding passivation layer design, traditional passivation layer designs use SiO2 as the material. However, traditional SiO2 is prone to increased leakage current and decreased blocking characteristics, reducing device reliability. Therefore, improving passivation layers with Si3N4 material, which has good water resistance [4], is recommended. By adding a pressure-dispersing material at the interface between Si3N4 and the polyimide material, crack formation can be suppressed, thereby improving device lifespan [5]. For package anti-humidity optimization design, since devices operate in different environments in real life, consideration should be given to high humidity and high-temperature aging. The first approach is to apply a polyether fluoride liquid, such as FR3, on the surface of the silicone gel, effectively preventing water vapor penetration at high temperatures [6]. The second approach involves using epoxy resin and other materials to create a model [7], as epoxy resin has strong anti-humidity capabilities and low thermal resistance, allowing the device to operate more effectively [8].

6. CONCLUSION AND OUTLOOK

Through the study on humidity reliability of power semiconductor devices, this paper has explored the aging mechanism of humidity, anti-humidity optimization design methods, and humidity reliability testing and evaluation. Through humidity reliability testing, it was found that passivation layer optimization focuses mainly on improving anti-humidity and removing contamination ions. For package material design, the main consideration is improving resistance to humidity. However, the main reason for IGBT device failure is metal corrosion and charge distribution abnormality. Although certain research achievements have been made, many issues still need further research and exploration. In the future, we will continue to deepen our research on humidity reliability in power semiconductor devices, explore more effective anti-humidity optimization design methods, and establish more comprehensive humidity reliability testing and evaluation systems to provide a more scientific and accurate basis for the reliability assessment and optimization design of power semiconductor devices.

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