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Research Status of Heat Dissipation Technology of High-Power Electronic Devices

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Abstract:
With the continuous advancement of high-power power electronic devices, the thermal management technology of these devices plays a pivotal role in their practical application. In order to address the heat dissipation challenges associated with power electronic technology, this study focuses on four key aspects: the impact of temperature on power electronic devices, commonly employed heat dissipation techniques, relevant equipment for power electronic thermal management, and the utilization of novel materials for enhancing heat dissipation capabilities in power electronic devices. The application of conventional heat dissipation technology has been found to enhance the thermal management performance of high-power density power electronic devices.The continuous advancement in semiconductor materials has led to the emergence of numerous materials with excellent thermal conductivity.In order to enhance the heat dissipation efficiency of power electronic devices, it is imperative for researchers to further investigate the development and application of novel material technologies. The application of advanced semiconductor materials will be expanded in power electronic devices to enhance thermal management capabilities.

Keywords: Power electronic devices; heat dissipation technology; high power density

1. Introduction

The continuous advancement of high-power power electronic devices towards higher power and density results in the conversion of work-generated losses into heat energy.The thermal dissipation of high-power electronic devices has emerged as a significant challenge. If the temperature is too high, the junction temperature of the power electronic device may be too high, and the power electronic device may be burned or thermal failure. The study of heat dissipation technology for high-power power electronic devices is therefore of utmost importance. The heat dissipation issue is effectively addressed through the implementation of forced air-cooling, air-cooling fin heat dissipation, phase change heat dissipation,

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micro-channel cooling heat dissipation, and the utilization of innovative materials. Implementing effective measures to dissipate heat can lower the operating temperature of these devices, thereby enhancing their reliability and stability. Zhuzhou Institute and Institute of Microelectronics, Chinese Academy of Sciences jointly set up a research and development center for new power electronic devices to carry out comprehensive research on the technology and industrialization of new power electronic devices based on SiC materials. At present, the center has successfully developed a SiC Schottky diode sample and combined into a hybrid IGBT module. Professor Zhang Ping from Guilin University of Electronic Science and Technology conducted experimental research on four different sizes of rectangular aluminum microchannel structure cold plates. The heat transfer performance of the cold plate is found to be closely correlated with the microchannel width, exhibiting an exponential increase in heat transfer coefficient as the microchannel width decreases. Neglecting the influence of cold plate volume, higher aspect ratios of channels result in improved heat transfer performance of the cold plate. Additionally, the heat transfer coefficient of the micro-channel cold plate exhibits a rapid increase with increasing liquid flow rate [1]. The Laboratory of Power Electronic Devices at the School of Electrical Engineering, Zhejiang University, has successfully developed a novel vertical gallium nitride (GaN) power electronic device with an impressive power quality factor of 825 MW/cm^2. This groundbreaking achievement marks the first instance where the device exhibits impeccable performance in terms of “no current collapse” under high voltage and high-speed switching conditions [2]. The accomplishment effectively addresses the persistent issue of dynamic performance degradation that has long plagued conventional planar devices, thereby offering crucial support for the application of GaN devices in the realm of power electronics.Therefore, this study primarily focuses on investigating common heat dissipation methods for high-power power electronic devices, including air-cooled fin heat dissipation, phase change heat dissipation, forced air-cooled heat dissipation, and micro-channel cooling heat dissipation. Additionally, the application of new materials such as SiC and GaN in power electronic devices is a key research area. By employing these advanced heat dissipation technologies, it is possible to effectively reduce the failure rate of high-power power electronics. Simultaneously, cutting-edge semiconductor materials and technologies are utilized in power electronic equipment to address the thermal management challenges associated with high-power devices.

2. Effects of Temperature on Power Electronics

When the temperature exceeds the recommended limit, it can expedite material aging and structural damage within power electronic devices, ultimately reducing their lifespan. The operating life of a power electronics chip may be reduced by half when its temperature rises by 10°C. Excessive temperature can exacerbate thermal stress, leading to fatigue damage in power electronic devices. The rapid fluctuations between hot and cold temperatures can cause significant thermal stress, leading to material fatigue and the formation of cracks within the device. This inconsistency in expansion and contraction ultimately impacts the reliability and lifespan of the device. The presence of insulation materials (such as MOSFETs, IGBTs, transformers) in power electronic devices renders them susceptible to aging and deterioration in insulation performance when exposed to high temperatures. The insulation materials are susceptible to decomposition, oxidation, and polymerization at elevated temperatures, thereby accelerating the aging process. The increase in thermal motion of the insulating material molecules due to high temperature leads to a decrease in dielectric constant and insulation strength, consequently increasing the risk of leakage current. The aforementioned effects will heighten the likelihood of device failures, such as breakdowns and short circuits, thereby impacting the overall lifespan of the device.

The electrical parameters of power electronic devices, including resistance, capacitance, and inductance, may also be influenced by temperature variations. The modification of these parameters may impact the device’s regular functioning and potentially result in operational failure. The temperature increase typically leads to a reduction in the threshold voltage and an elevation in leakage current for MOSFETs, thereby impacting their opening and closing characteristics and diminishing device efficiency and stability. The temperature rise in power semiconductor devices, such as IGBTs, can enhance the switching speed; however, it also leads to an increase in both switching losses and reverse leakage current [3]. The temperature increase, in addition to reducing the on-resistance of the device, may also contribute to a decrease in on-loss. However, it is important to note that this could potentially lead to increased heat generation and device failure.

3. Power Electronics Cooling Technology Related Devices

The radiator is an essential heat dissipation device for high-power electronic devices, primarily utilized to dissipate the heat generated during their operation. The prevention of component damage and reduction in service life caused by high temperatures leading to overheating is essential[4]. The heat sinks are typically fabricated from materials possessing high thermal conductivity and are designed in various configurations to augment the dissipation area, employing convection and radiation principles for swift dispersion of heat into the surrounding environment. This facilitates reduction in the operational temperature of electronic components, thereby enhancing their stability and reliability.

The thermal gap gasket is a high-performance material with excellent thermal conductivity, specifically designed for use in electronic equipment and as an interface for heat sink or product housing transfer. The thermal gap gasket is a high-performance material with excellent thermal conductivity, primarily utilized as an interface for heat transfer between electronic devices and heat sinks or product housings. The presence of air significantly hampers heat transfer efficiency due to its poor thermal conductivity. By filling these gaps, the contact thermal resistance is reduced, thereby enhancing heat transfer efficiency. The gap gasket exhibits excellent thermal conductivity, facilitating rapid heat transfer from the heat source to the radiator and subsequently to the surrounding environment. The efficient heat transfer mechanism facilitates temperature reduction of the heat source and mitigates the risk of overheating, thereby safeguarding power electronic devices from potential damage[4].

The heat pipe is a device that facilitates heat transfer by utilizing the phase change of the working medium within the tube, effectively and rapidly transferring thermal energy from a hot object to the external environment. The heat pipe typically consists of a housing, a liquid wick structure, and an end cap. The shell is typically constructed from a metallic material, housing a porous suction core that utilizes capillary action to facilitate movement of the working liquid within the core, irrespective of the heat pipe's location [5]. The interior of the heat pipe is evacuated to a negative pressure state, and subsequently charged with an appropriate quantity of working fluid possessing a low boiling point and facile volatility.

Cooling plate is a common cooling device for high power electronic devices. The material composition of this product includes high-performance heat-conducting materials such as copper, aluminum, and their alloys. It is comprised of a substrate and a heat. The substrate is in direct contact with the heat source, while the heat sink is affixed to the surface of the cooling plate in order to augment the device's heat dissipation area and enhance its thermal efficiency. The surface of the cooling plate may be coated with black pigment or other radiation-enhancing materials in certain applications to augment thermal radiation and further enhance heat dissipation performance.

4. Common Heat Dissipation Method

4.1 Air-cooled Fin Heat Dissipation

The air-cooled fin radiator consists primarily of three components: the fin tube, heat sink, and fan. Among these, the main function of the fin tube is to facilitate heat transfer, thereby playing a crucial role in determining the radiator's overall thermal dissipation performance[6-7]. The fin in the fin tube is also a crucial component, which effectively enhances the heat dissipation area of the radiator and facilitates the quick and efficient transfer of heat generated by the device to the heat sink. The performance of the finned tube, however, must consider the principles of convective heat transfer and heat conduction theory to efficiently and uniformly dissipate heat. The heat sink is a crucial component of the air-cooled fin radiator, as it is primarily affixed to the exterior of the finned tube and serves the purpose of absorbing and dissipating thermal energy from the finned tube into the surrounding air. The heat sink must therefore establish a substantial heat exchange area on the surface of the finned tube in order to facilitate rapid dissipation of heat into the surrounding air. The performance of the air-cooled fin radiator fan also impacts heat dissipation, as it enhances airflow velocity and improves overall cooling efficiency, when the fan's wind speed exceeds a certain threshold, it leads to an increase in flow resistance and subsequently generates significant noise. The wind speed should not exceed a certain threshold, as it can hinder the radiator's heat dissipation efficiency and result in power loss.

The air-cooled fin heat dissipation is more mature and widely adopted compared to the conventional water-cooled cooling method, featuring a relatively simple structure that facilitates easy installation and maintenance. The system is both secure and reliable, eliminating the need for additional cooling mediums and mitigating risks such as media leakage. It offers a cost-effective solution with excellent heat dissipation capabilities, effectively meeting the thermal requirements of various equipment, making it widely applicable.

4.2 Phase Change Heat Dissipation

The process of phase change heat dissipation involves the utilization of substances to absorb or release heat during phase transition, thereby achieving efficient thermal management. In the field of phase-change heat dissipation, the selection of phase-change materials by researchers plays a

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crucial role. These materials can typically be categorized into two groups: organic and inorganic materials. The organic phase change materials primarily consist of paraffin, fatty acids, esters, and alcohols [8]. The phase transition temperature of these materials is predominantly below 150 degrees Celsius, classifying them as medium to low temperature phase change materials. The change in latent heat of phase transition is closely correlated with the carbon atom count in the molecule, which is worth noting as straight-chain paraffins.

Inorganic phase change materials, including hydrated salts, inorganic salts, and metal-based materials, are widely utilized for building heating energy conservation. Among these options, crystalline hydrated salts exhibit similarities to organic phase change materials and have become a popular choice. The properties of these materials render them a significant selection for both research and practical applications.

The phase change heat dissipation exhibits high efficiency in dissipating heat, ensuring more precise temperature control, and promoting environmental protection and energy conservation [9]. These characteristics are attributed to the utilization of characteristic materials. The phase change heat dissipation technique exhibits high stability and adaptability due to its superior temperature control precision and a wider range of applicable materials, thus holding great potential for efficient heat dissipation in electronic devices.

4.3 Forced Air Cooling

The forced air cooling heat dissipation system primarily comprises of fans and heat sinks. The heat sink is primarily utilized for direct thermal conduction with the heat source. The enhancement of overall heat dissipation efficiency in the system necessitates an increase in the heat sink's dissipation area. The function of the fan is to generate a substantial airflow, enabling the heat sink to efficiently dissipate a significant amount of heat into the surrounding air. Therefore, the primary process of heat dissipation in a forced air cooling system involves: Firstly, the power device generates heat during operation and dissipates it through the power chip to the device housing, which is surrounded by a large area of heat sink. Subsequently, solid conduction facilitates the transfer of heat from the power device housing to the cooling substrate via thermal interface material. Secondly, solid conduction enables the transmission of heat from the radiator substrate to the heat sink. Finally, the airflow generated by a fan allows for the dissipation of heat from the heat sink to its surrounding environment.

The forced air cooling method, as opposed to natural cooling, utilizes a fan to facilitate targeted heat dissipation by actively circulating air. Revised sentence: "Forced air cooling is not dependent on specific external conditions (such as temperature difference) to function, resulting in high heat dissipation efficiency and fast operation speed." The forced air cooling design incorporates simultaneous dissipation of the fan and heat pipe, resulting in enhanced heat dissipation effectiveness and improved stability compared to natural air cooling.

4.4 Micro Channel Cooling

The utilization of micro-channels in cooling technology enhances thermal efficiency by capitalizing on their high specific surface area and compact size. The micro-channel features a minute size with a diameter at the micron level, enabling it to possess an extensive contact area with heat within the channel. Consequently, it facilitates rapid heat transfer to the fluid and ensures highly efficient heat dissipation. The micro-channel cooling and heat dissipation technology, however, relies on fluid dynamics to enhance the channel structure and contact area, minimize resistance, and optimize heat dissipation efficiency[10]. The micro-channel cooling technology features a narrow cross-sectional area, leading to an elevation in internal temperature during the heat transfer process. This thermal rise may result in uncontrolled or damaged electronic devices due to abrupt temperature spikes, thereby impacting the stability of power electronic devices. The micro-channel cooling radiator, due to its compact size and high thermal efficiency, finds extensive application in the aerospace industry.

5. Application and Advantages of New Materials in Heat Dissipation of Power Electronic Devices

5.1 The Applications and Advantages of Wide Band Gap Devices Based on Silicon Carbide (SiC)

The third-generation semiconductor material, silicon carbide (SiC), possesses several distinguishing characteristics when compared to the first-generation semiconductor material, silicon, and the second-generation semiconductor material, gallium arsenide. These include a wide band gap, high critical breakdown electric field strength, exceptional thermal conductivity, and an elevated saturation migration rate. The doping range of silicon carbide materials is extensive for both N-type and P-type doping. The silicon carbide material is currently the sole compound semiconductor material capable of naturally forming an oxide layer (SiO2) [11-12].The silicon carbide power semiconductor device holds significant potential for application in aerospace, new energy vehicles, energy exploration drilling, nuclear power, and other industries due to its exceptional attributes including high pressure resistance, elevated temperature endurance, and radiation resilience.

5.2 Gallium Nitride (GaN) Wide Band Gap Device Applications and Advantages

The advantages of gallium nitride (GaN) lie in its ability to combine the high breakdown electric field characteristics of silicon carbide (SiC) with the materials gallium arsenide (GaAs), germanium silicon alloy (GeSi), and indium phosphide (InP) for manufacturing high-frequency devices [13]. The material preference factor of gallium nitride is generally higher compared to silicon carbide, offering the potential for enhanced performance in power electronic devices, particularly at microwave frequencies. This highlights its significant prospects and application possibilities.

5.3 The Applications and Advantages of 2D Materials

The utilization of graphene as a superior substrate is prevalent in the manufacturing of transparent conductive films. The application value of this type of membrane electricity is significant, particularly in the context of smartphones, tablet computers, and other touch screen devices.Traditionally, tin oxide or yttrium oxide has been commonly used as the material for transparent conductive films [14]. However, these materials exhibit suboptimal conductivity and are prone to thermal expansion issues when heated. The contrasting nature lies in the fact that graphene can be synthesized at low temperatures using techniques such as chemical vapor deposition or mechanical exfoliation, thereby rendering it a more optimal choice due to its exceptional electrical conductivity and high temperature resilience. The exceptional conductive properties of graphene make it a preferred choice for serving as electrodes in silicon transistors, thereby contributing to the production of high-performance microelectronic components.

6. Conclusion

The findings of this study indicate that the continuous advancement of high-power power electronic devices can result in excessive power dissipation, leading to elevated temperatures which subsequently impact the lifespan and parameters of these devices. The thermal dissipation of high-power electronic devices is of utmost importance. After conducting research, it has been determined that power electronic cooling technology devices (such as heat sinks, thermal gap gaskets, heat pipes, cooling plates, etc.) and associated heat dissipation technologies (such as air-cooled fin heat dissipation, phase change heat dissipation, micro-channel cooling heat dissipation, forced air cooling heat dissipation) can effectively expedite the distribution of device-generated heat to the surrounding air. This serves to mitigate potential issues arising from excessive temperatures and prevent device malfunction or damage. After further investigation, it has been determined that the existing heat dissipation technologies have limitations in terms of cost, environmental impact, noise level, and size. Therefore, it is crucial for researchers to conduct extensive research on new materials such as graphene, sic, GaN, etc., in order to address the heat dissipation issues faced by electronic devices in the future. The utilization of new materials with high thermal conductivity and low thermal resistance characteristics can greatly enhance the effectiveness of heat dissipation. For instance, cutting-edge technologies and materials such as phase change materials for heat dissipation, two-dimensional materials like graphene, and semiconductor refrigeration technology should be employed in electronic equipment to address the heat dissipation issue arising from high power density. The researchers should also investigate intelligent cooling systems to enable high-power electronic devices to automatically regulate the balance between power and heat dissipation. Additionally, interdisciplinary integration should be pursued to develop efficient, reliable, and environmentally friendly technologies for addressing the heat dissipation issue in high-power electronic devices.

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