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Thermal Optimization of Polycrystalline Aluminum Nitride Ceramic Substrates for Power Electronic Packaging

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Abstract. The power devices in artificial intelligence computing equipment and new energy vehicles require substrates that possess both electrical insulation and heat dissipation capabilities. The heat dissipation performance of polycrystalline aluminum nitride (AlN) is influenced by both the preparation of the ceramic and the packaging structure. This article compares the results and limitations of related studies along four paths: powder oxygen control and debinding, sintering additives and grain boundary phase regulation, sintering and post-processing, and packaging interface. Existing research indicates that reducing lattice oxygen requires considering densification; additives and sintering processes also change pores, second phases, and mechanical properties, so it is not advisable to directly compare thermal conductivity values without considering the raw materials and test conditions. After entering the power module, the thermal conductivity of the substrate or the strength of the joint may increase, but this cannot alone prove that the module junction temperature has decreased; thermal cycling may also cause cumulative deformation. The selection of high-power chip substrates requires a comprehensive evaluation of the ceramic matrix properties, interface thermal resistance, module junction temperature, and joint stability.

Keywords: aluminum nitride ceramic substrates, thermal conductivity, lattice oxygen, packaging interfaces

1. Introduction

Power devices used in artificial intelligence computing systems and new energy vehicles are increasingly integrated and operate at higher power levels. Heat generated by the chips must be efficiently transferred through the packaging structure. An increase in temperature can impair device operation and increase thermal stress in packaging materials. Therefore, the heat dissipation substrate not only needs to provide electrical insulation and mechanical support, but also needs to provide an effective heat-conduction path for chip cooling. A reported gallium nitride (GaN) half-bridge module integrating multiple power devices on a multilayer polycrystalline aluminum nitride (AlN) substrate demonstrates the practical use of AlN substrates in high-voltage, highly integrated power packages [1].

For polycrystalline AlN substrates, surface oxygen on the powder, aqueous processing, and debinding conditions can influence oxygen incorporation, and the oxygen entering the lattice and the

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residual pores may both limit the thermal conductivity of the ceramic matrix [2-5]. Sintering additives, temperature and post-processing can improve densification, but they can also change the grain-boundary phases, grain structure and bending strength, and cannot be judged solely by the highest thermal conductivity [6-8]. In addition, thermal cycling of AMB-AlN substrates has been associated with cumulative deformation, while brazed-joint studies have reported changes in joint strength [9, 10]. These findings concern specific structures and conditions; they do not establish a general increase in package thermal resistance.

This paper focuses on polycrystalline AlN substrates and discusses four thermal-optimization paths: powder and oxygen control during debinding, additive-based grain-boundary control, sintering and post-treatment, and packaging-interface optimization. It combines thermal conductivity, strength and reliability to evaluate their effects.

2. Power-module structure and role of the heat-dissipation substrate

For readers who are not familiar with the packaging structure, the power module can be regarded as a system where the chip, chip connection layer, metallized ceramic substrate and external heat dissipation structure are stacked sequentially. When the chip works, it generates heat, which first passes through the chip connection layer, then enters the ceramic substrate, and is subsequently dissipated through the lower metal layer or heat sink. Thermal resistance in an actual package does not arise only from the substrate itself, but may also come from the connection layer and various interfaces. Therefore, the substrate's thermal conductivity is an important factor for heat dissipation capability, but it cannot by itself represent the thermal performance of the entire module.

The ceramic substrate in the power module usually needs to achieve a balance between thermal conductivity and electrical insulation. Taking the active metal brazing (AMB) substrate as an example, the ceramic layer is connected to the metal layer on both sides, and the metal layer is used for circuit interconnection or connected to the heat sink; the ceramic layer provides insulation and bears part of the mechanical load. Different packaging designs have different metallization methods, layers and chip arrangements. Kuring et al. [1] reported a half-bridge module that uses a multi-layer polycrystalline AlN substrate to integrate GaN devices and their gate-driving components in a compact structure. This case shows that the AlN substrate is not only a thermally conductive layer, but also participates in the electrical layout and structural design of the module.

When transitioning from materials to packaging, it is necessary to distinguish between the substrate's own thermal resistance and interface thermal resistance. Even if the substrate material itself has a high thermal conductivity, the interface state between the chip connection layer, metal–ceramic junctions, or between the substrate and the heat sink may still limit the entire heat flow path. The material's thermal conductivity reflects the heat conduction ability of the ceramic matrix, while the module's junction temperature or total thermal resistance is also affected by the substrate thickness, metalization layer and connection interface. When the module undergoes temperature changes, the thermal expansion difference between metal and ceramic may cause the substrate to deform or generate interface stress. Zhang et al. [9] conducted a thermal cycling experiment on AMB-AlN substrates and observed bending-height hysteresis and accumulation during thermal cycling from 20 to 200 to 20 °C. This indicates that the evaluation of the substrate also needs to pay attention to connection strength and thermal cycling stability [9, 10]. The packaging interface and heat flow path will be discussed as the fourth optimization path, together with the three ceramic-substrate optimization routes. Figure 1 illustrates the module heat-flow path and the four optimization routes discussed in this review.

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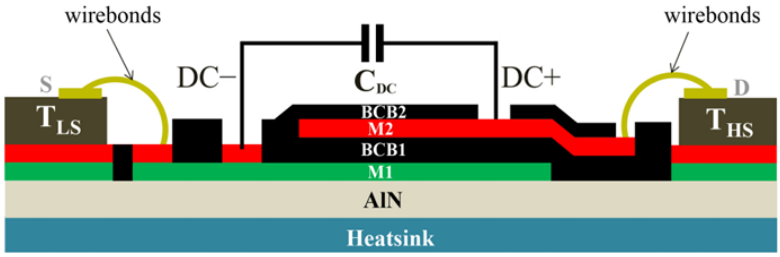


Figure 1. Cross-sectional structure of a GaN half-bridge module integrated on an AlN ceramic substrate [1]

3. Thermal optimization paths of AlN ceramic substrates

3.1. Oxygen control in powder and debinding processes

Reducing oxygen input is the starting point for improving the thermal conductivity of polycrystalline AlN ceramic substrates. The surface oxide layer of AlN powder introduces oxygen into the sintering system. When the particle size decreases, the sintering activity may increase, but the larger specific surface area also increases the likelihood of surface reactions. Chen et al. [8] compared different powders and sintering parameters and found that powder properties are related to the formation of second phases, density, and thermal conductivity simultaneously. Therefore, raw materials should not be selected based on particle size or total oxygen content; the powder packing and subsequent sintering conditions also need to be considered. Oxygen control and densification are interrelated from the raw material stage [8, 11].

Pre-treatment further changes the surface state of the powder. AlN is prone to hydrolysis in water, and if the water-based slurry is exposed for a long time, more oxygen-containing products may be produced. Li et al. [4] treated the powder with hydrolyzed polymaleic anhydride (HPMA) and improved its resistance to hydrolysis and dispersion stability during the aqueous tape-casting process. This study showed that the powder state during the forming process can be improved, but it did not separately prove that this treatment increased the thermal conductivity of the sintered ceramic. Lu et al. [11] compared AlN from different grinding routes and found differences in debinding, sintering behavior, and final thermal conductivity; these differences cannot all be attributed to oxygen content.

Zhang et al. [5] provided more direct evidence of oxygen control: reducing the original powder oxygen content and using protective debinding conditions helped limit lattice solute oxygen. Under the specific processing conditions, the sample thermal conductivity reached 220 $W \cdot m^{-1} \cdot K^{-1}$.

However, the total oxygen content of the powder, the total oxygen content of the sintered body, and the lattice oxygen are not the same quantity. When evaluating this path, the oxygen content of the raw materials and particle size should be recorded, the states before and after debinding should be compared, and the thermal conductivity changes should be explained in combination with the post-sintering lattice parameters, relative density, and phase composition. Including the changes in pores and grain boundaries in the analysis will enable a more reliable assessment of the contribution of pre-treatment oxygen control [3, 5, 8].

3.2. Sintering additives and grain-boundary phase regulation

The role of sintering additives is not only to make the body denser. High-purity AlN is difficult to directly densify under normal pressure. Adding additives such as yttrium oxide (Y_2O_3) can enable

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the surface oxides of the powder to participate in reactions and form yttrium aluminate second phases, and the distribution of oxygen in the lattice and grain boundaries also changes [2]. The reduction of lattice solute oxygen is beneficial for reducing defect scattering; however, if the second phase is continuously distributed along the grain boundaries, heat may still be hindered when passing through the polycrystalline body. Therefore, the effect of the additive depends on whether the densification, lattice purification, and grain-boundary phase control can be achieved together.

Kobayashi et al. [3] estimated the oxygen content using lattice parameters and found that the lattice oxygen of samples with different additives was related to thermal resistance. Huang et al. [6] compared Y_2O_3 with several yttrium aluminate additives under similar sintering conditions and observed changes in phase composition, thermal conductivity, and flexural strength as the formulation changed; among them, the tape-cast sample made from Grade-H AlN powder with 8 wt% Y_2O_3, pressurelessly sintered for 10 h at approximately 1850 °C, reached 205 $W \cdot m^{-1} \cdot K^{-1}$ and a flexural strength of 295 MPa. When choosing additives, not only should their ability to promote sintering be examined, but also the final residual phase and its distribution should be considered. Zhang et al. [5] promoted the formation of $Y_4Al_2O_9$ through oxygen control of raw materials and process and reported lower lattice oxygen and higher thermal conductivity. The powders and processes of these two studies are different, and the thermal conductivity values should not be directly ranked. The same additive may form different quantities and morphologies of grain boundary phases at different addition amounts; reporting only the additive name is insufficient to explain the performance differences [2, 6].

Phase composition analysis also needs to correspond to the measurement object of oxygen. When the total oxygen content does not significantly decrease, oxygen may still transfer from the lattice to the second phase. The reduction of grain boundary phases does not automatically imply a decrease in lattice oxygen. Discussing the lattice parameters, the distribution of second phases, density, and thermal conductivity together is necessary to determine the actual effect of additives on the thermal conduction of the ceramic matrix [3, 5, 6].

3.3. Sintering conditions and post-treatment

The sintering conditions determine whether the powder can be fully densified and also affect the degree of reaction between oxygen and additives. An insufficient temperature or holding time may result in residual pores and grain boundary impurities maintaining a high thermal resistance; increasing temperature and prolonging holding time will promote grain growth and changes in the second phase. Chen et al. [8] observed that the relative density and thermal conductivity could be simultaneously improved with process adjustments. However, when multiple variables change simultaneously, the benefits cannot be attributed solely to the sintering temperature.

Post-treatment provides another means to coordinate oxygen control and mechanical properties. Zhang et al. [7] reduced oxygen content through hot-press pre-sintering and annealing. During the pre-sintering stage, the sample density decreased, and after subsequent optimization, the final sample achieved a thermal conductivity of 204 $W \cdot m^{-1} \cdot K^{-1}$ and a flexural strength of 376 MPa. Therefore, when comparing processes, it is necessary to distinguish between the intermediate stage and the final ceramic, and not to confuse the indicators of the two. Miyata et al. [12] used spark plasma sintering to prepare AlN, and under their research conditions, the thermal conductivity of the sample at 1850 °C reached 163 $W \cdot m^{-1} \cdot K^{-1}$, and the estimated solute oxygen value was correlated with the thermal resistance. Different studies use different powders, additives, and testing methods, and these values cannot be used to determine that a certain sintering method is universally superior.

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The effects of sintering and post-treatment need to be judged in combination with the final microstructure. When the temperature, holding time, or annealing conditions change, the pores, grains, and grain boundary phases may change simultaneously, and the increase in thermal conductivity cannot be attributed to a single factor [7, 8, 12]. The orientation of the microstructure also affects the measured thermal conductivity. Okazaki et al. [13] found in low-temperature sintered ceramic with AlN whiskers that the thermal conductivity in the parallel direction of the whiskers was higher than that in the perpendicular direction. The orientation of the whiskers is not a direct result of annealing, but this example highlights the need to specify, when comparing sintering processes, the reinforcing phase and testing direction of the sample, and to verify the density, oxygen content, and strength of the final sample. Digital light processing offers another example in which shaping and sintering conditions must be considered together. Rauchenecker et al. [14] reported room-temperature thermal conductivities above 160 $W \cdot m^{-1} \cdot K^{-1}$ for printed AlN sintered at 1700 °C, while Tang et al. [15] obtained 168 $W \cdot m^{-1} \cdot K^{-1}$ after sintering printed AlN at 1720 °C under 0.6 MPa nitrogen. Their different powders and processing conditions preclude a direct ranking.

3.4. Packaging interface and heat-flow path

After the substrate enters the packaging process, the heat dissipation is no longer solely determined by the thermal conductivity of the ceramic body. Heat is transferred from the chip to the heat sink, passing through the chip connection layer, metallization layer, AlN ceramic, and bonding interface. For the same material, the thicker the ceramic layer, the greater the thermal resistance across that layer; the effective heat transfer area, metal layer layout, and interface contact state will also change the heat flow. If there are pores in the connection layer or uneven interface bonding, the improvement in the thermal conductivity of the ceramic body may not translate into a decrease in the module junction temperature. Therefore, the optimization route should first clearly define the direction of heat flow and the geometric dimensions of each layer, and then distinguish between material thermal resistance and interface thermal resistance. Kuring et al. [1] integrated GaN devices and the gate-driving components onto a multilayer polycrystalline AlN substrate and verified the heat dissipation capability in their module design. This result indicates that AlN can simultaneously perform insulation, wiring, and heat conduction tasks, but the module performance is also affected by the overall packaging structure and cannot be solely attributed to the improvement in the thermal conductivity of the substrate.

Interface optimization must also consider stability during operation. The thermal expansion behaviors of metals and AlN are different. Repeated heating and cooling may cause plastic deformation of the metal layer and solder, and form cyclic stress in the bonding area between the ceramic and metal. Zhang et al. [9] observed bending-height hysteresis and accumulation after five experimental heating and cooling cycles from 20 to 200 to 20 °C in AMB-AlN substrates; their finite-element calculations evaluated stress after five cycles and the effects of copper and filler-layer thickness. These results document early-cycle deformation under the tested conditions, without establishing long-term joint lifetime. For joints, Lv et al. [10] added titanium nitride (TiN) to the AlN/Cu brazing system and observed that the brittle reaction layer thinned and the joint strength increased. Accordingly, process design should consider the composition of the solder and the thickness of the reaction layer, and the copper-layer thickness should be considered when assessing cyclic deformation, to avoid only pursuing initial strength. However, the strength improvement reported in this study cannot be directly equivalent to the decrease in interface thermal resistance, nor can it prove that the same level is maintained after thermal cycling. When comparing packaging schemes, the module junction temperature or total thermal resistance can be measured under the

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same ceramic thickness, metallization area, and chip operation conditions, while recording the joint strength, deformation, and interface defects, and repeating the tests before and after thermal cycling. Evaluating thermal performance and connection reliability within the same framework is necessary to determine whether the substrate performance benefits brought by additives, sintering, and packaging processes can be retained in the actual module. For the packaging interface path, the existing evidence is still insufficient to make a universal ranking of the total heat dissipation performance of different joint schemes. The representative findings and limitations of the four optimization paths are summarized in Table 1.

Table 1. Representative evidence for the four optimization paths

Path	Controlled variable and process	Thermal conductivity	Mechanical or reliability evidence	Source
Powder and oxygen	Powder oxygen and protected debinding	220 $W \cdot m^{-1} \cdot K^{-1}$	Lower lattice oxygen; cycling not tested	Zhang et al. [5]
Additive and grain boundary	8 wt% Y_2O_3; ~1850 °C, 10 h	205 $W \cdot m^{-1} \cdot K^{-1}$	295 MPa flexural strength; 3.30 $g \cdot cm^{-3}$ density	Huang et al. [6]
Sintering and post-treatment	Hot-press pre-sintering and annealing	204 $W \cdot m^{-1} \cdot K^{-1}$	376 MPa flexural strength; cycling not tested	Zhang et al. [7]
Packaging interface	AMB-AlN cycling; TiN/AgCuTi brazing	Module value not reported	Early-cycle warpage [9]; joint-strength gain [10]	Zhang et al. [9]; Lv et al. [10]

Note: Conductivity values come from different studies and are not directly comparable. Huang et al. [6] did not specify the heat-flow measurement direction; Zhang et al. [9] and Lv et al. [10] did not report module junction temperature.

4. Conclusion

The thermal optimization of polycrystalline AlN substrates encompasses powder preparation, sintering, and packaging. Controlling raw materials and oxygen during debinding helps reduce oxygen dissolved in the AlN lattice, but it is still necessary to maintain adequate densification; additives regulate the distribution of oxygen between the lattice and grain boundaries, and sintering and post-treatment also change pores, grains, and strength. Therefore, comparing only the peak thermal conductivity is insufficient; comprehensive evaluation of lattice oxygen, phase composition, density, and mechanical properties should be conducted under similar test conditions. After the material enters the power module, the connection layer and metallization interface also form a heat flow path. Improvements in joint strength or ceramic body thermal conductivity cannot directly prove a reduction in module junction temperature; cumulative deformation during thermal cycling may also affect the service stability. Future research should uniformly set the substrate thickness, metallization layout, and cooling conditions, measure interfacial thermal resistance and module junction temperature, and compare the joint states before and after thermal cycling. At the same time, tracking the changes in oxygen content and grain boundary phases with the process is necessary to distinguish the contributions of material improvement and packaging design, providing a basis for the selection of high-power chip substrates. A further limitation is that many studies report ceramic-level thermal conductivity without measuring module-level junction temperature or interface resistance under matched conditions. Future studies should use common reporting

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protocols for powder grade, additive content, density, specimen direction, and test method, and should validate material-level improvements in complete modules before drawing conclusions about service-level heat dissipation.

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