DELAMINATION ANALYSIS OF AN ALN (DIRECT BOND COPPER SUBSTRATE) USING FINITE ELEMENT ANALYSIS (FEA)

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ABSTRACT

This study investigates the behavior of AlN direct bond copper (DBC) substrates used in power modules. The focus is on understanding substrate delamination, thermal expansion mismatch, and stress distribution within the substrate. The simulation results are compared with the findings from a Thermal Shock Test (TST) to validate the observed stress concentration behavior. The results indicate that stress concentration primarily occurs at the edges of the copper layer, emphasizing the need for careful design considerations in these areas. The simulations also reveal that varying the copper thickness influences stress distribution, with higher stress levels observed with increased copper thickness. This highlights the importance of optimizing the copper thickness to minimize stress concentrations and enhance substrate stability. Additionally, the study demonstrates temperature-dependent stress variations within the substrate, with maximum principal stress occurring at -40°C and lowest stress levels at 125°C. These findings underscore the significance of considering thermal effects when evaluating mechanical behavior and potential failure mechanisms. Based on the results, recommendations are made for design optimization, copper thickness optimization, material selection, and further research on novel substrate materials and thermal management techniques to improve power module reliability and performance.

1. 0 INTRODUCTION

A power module is an electronic device that is designed to convert and regulate electrical power from one form to another. These modules are typically used in power electronic applications, such as inverter systems, motor drives, and power supplies. Power modules can range in complexity from simple rectifiers and regulators to more advanced modules that incorporate multiple components such as diodes, transistors, and capacitors. They are used in a variety of industries including automotive, aerospace, telecommunications, and consumer electronics. The design and performance of a power module are critical to the overall efficiency and reliability of the electronic system it is used in.

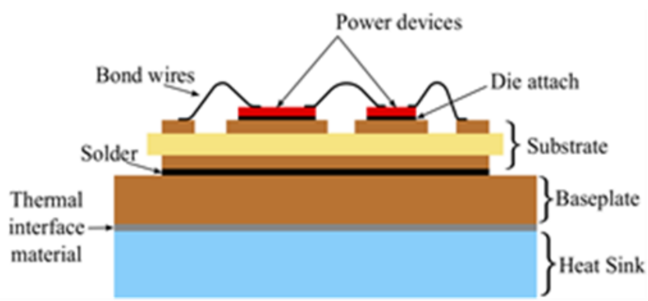

Figure 1. Power Module Structure by Yang, Y., Dorn-Gomba, L., Rodriguez, R., Mak, C., & Emadi, A. (2020). Automotive Power Module Packaging: Current status and future trends. IEEE Access, 8, 160126–160144.

1.1 Power Module Substrate

Power modules can vary in their specific components depending on their intended application, but here are some common parts that can be found in a power module:

1. Power semiconductors
2. Thermal interface materials
3. Substrate
4. Gate drivers
5. Capacitors
6. Inductors
7. Protection circuitry
8. Connectors

In a power module, the substrate is the physical foundation upon which the other components are mounted. The substrate is typically a thin, flat, and rigid material that provides mechanical support for the power semiconductor devices, as well as electrical insulation between the devices and other components.

The substrate is also an important component in thermal management, as it helps to conduct heat away from the power semiconductors and dissipate it into the surrounding environment. The substrate material should have a high thermal conductivity, low thermal resistance, and be able to withstand high temperatures without degradation.

Common substrate materials for power modules include ceramics such as aluminum oxide, aluminum nitride, or silicon nitride, which have good thermal conductivity and mechanical strength. Other materials, such as copper or aluminum, can also be used as substrates in some cases.

Overall, the substrate plays a critical role in the performance and reliability of power modules, helping to ensure that the power semiconductors operate within their specified temperature range and that the module can withstand the mechanical stresses associated with normal operation.

1.1.1 Substrate Delamination

Delamination in DBC substrates can occur due to a variety of factors, including thermal cycling, mechanical stress, and poor adhesion between layers. Delamination can compromise the thermal and electrical performance of the substrate, leading to reduced heat dissipation efficiency.

A thermal shock test was conducted to compare the Al_2O_3 and AlN substrate materials subjected to 50 and 500 cycles. The primary objective of the study was to examine the potential delamination between the two ceramic materials. The results are presented in Figures 2 and 3.

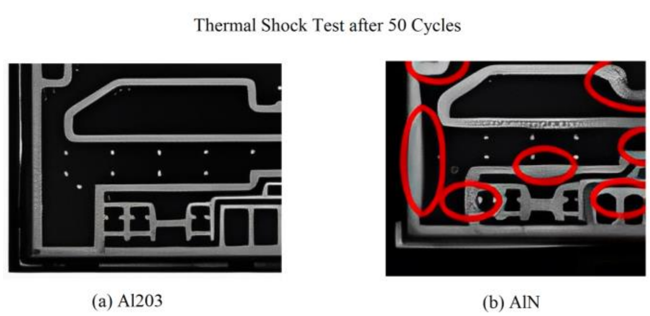

Figure 2. SAM inspection (Ceramic to Copper) of (a) Al_2O_3 and (b) AlN Substrate after 50 TST Cycles.

Figure 2 reveals that the Al_2O_3 substrate exhibited no signs of gap, delamination, or cracks on the ceramic to copper interface even after 50 TST cycles. Conversely, the AlN substrate showed delamination on the ceramic to copper interface after 50 TST cycles.

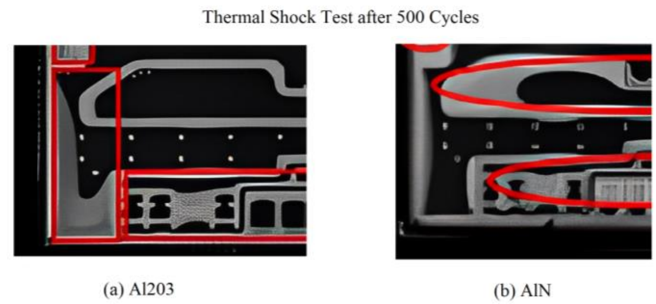

Figure 3. SAM inspection (Ceramic to Copper) of (a) Al_2O_3 and (b) AlN Substrate after 500 TST Cycles.

In Figure 3, propagated delamination was observed on the ceramic to copper interfaces for both Al_2O_3 and AlN substrate after 500 TST cycles. These findings suggest that, while Al_2O_3 may perform well in shorter periods of thermal stress, both substrates demonstrate similar delamination behavior over a more extended period of stress. However, it is important to note that the AlN substrate experienced more severe delamination than the Al_2O_3 substrate. This finding highlights the potential limitations of AlN as a substrate material in applications that require extended periods of thermal stress.

The high thermal conductivity of ceramics, such as AlN and Al_2O_3, provides them with excellent heat dissipation capabilities. However, their high thermal expansion mismatch (CTE) with copper, as illustrated in Table 1, results in significant mechanical stresses during cooling, leading to cracking and eventual failure after a few heating and cooling cycles.

Table 1. Summary of Experimental Combinations

Material	**Thermal Conductivity**	**Coefficient of Thermal Expansion (CTE)**
Copper	398 W/m*K	17 ppm/°C
Aluminum Nitride (AlN)	170 W/m*K	4.7 ppm/°C
Alumina (Al_2O_3)	24 W/m*K	6.8 ppm/°C

Despite its higher thermal conductivity compared to Al_2O_3, AlN substrate still experiences a higher coefficient of thermal expansion mismatch with copper, with 72.35% for AlN substrate and 60% for Al_2O_3 substrate.

In high-power devices, thermal cycling is a common occurrence, making managing thermal mismatch an area of extreme importance to ensure high reliability and long life in the field. Therefore, developing effective strategies to manage thermal expansion mismatch is crucial for improving the reliability of ceramic-metal bonding applications.

This investigation highlights the need for further research into novel substrate materials and thermal management techniques that can minimize thermal expansion mismatch and reduce the potential for failure in high-power devices.

2.0 REVIEW OF RELATED WORK

Refer to 1.0 Introduction.

3.0 EXPERIMENTAL SECTION

3.1 Materials

The AlN substrate utilized in this study was a high-quality commercially available substrate. The substrate had a rectangular shape and was made of AlN ceramic material. The AlN substrate was chosen due to its high thermal conductivity and low coefficient of thermal expansion (CTE), which make it suitable for high-power electronic packaging applications. The thermal conductivity of the AlN substrate was measured to be 170 W/m·K at room temperature, and its CTE was 4.7 ppm/°C. The Young's modulus of the AlN substrate was determined to be 320 GPa, which is an important mechanical property for delamination analysis. The thermal conductivity of the copper bond layers was measured to be 398 W/m·K, and the CTE was 17 ppm/°C. The Young's modulus of the copper bond layers was determined to be 130 GPa.

3.2 Theoretical Analysis and Simulation Setup

The finite element analysis was conducted using ANSYS Mechanical software (2023 R1) with a 3D model of the AlN direct bond copper substrate. The geometry of the substrate was modeled based on the actual dimensions and shapes of the substrate, including the dimensions and positions of the copper bond layers. The mesh size and type were chosen based on convergence studies to ensure accurate results.

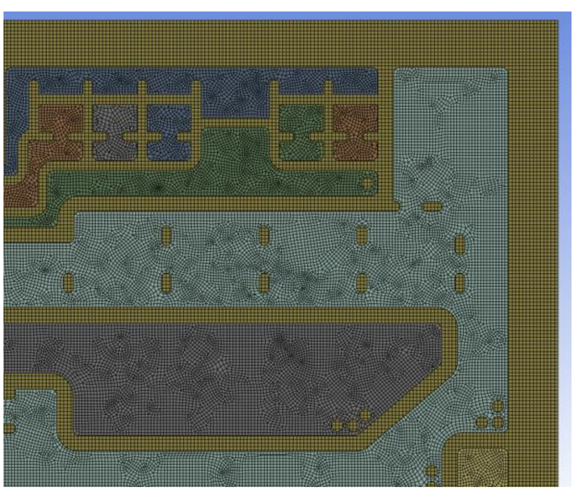

Figure 4. Mesh image extracted from the simulation setup.

The simulation employed a Static Structural analysis approach coupled with comprehensive thermal conditions. The temperature conditions applied spanned a wide range to capture the diverse thermal environments encountered in practical scenarios. The simulation encompassed temperatures ranging from 25°C to 125°C, enabling an investigation of the system's response to elevated temperatures, while also considering the impact of lower temperatures in the range of -40°C to 25°C.

By incorporating such a broad temperature range, the analysis aimed to capture the thermal expansion and contraction effects on the AlN and copper layers. These effects play a crucial role in the contact and interface behavior between the materials, as thermal fluctuations can induce stress and strain variations that may influence the initiation and propagation of delamination.

By replicating the automotive thermal conditions within the simulation, the analysis aimed to provide insights into the performance and durability of the AlN direct bond copper substrate in a real-world automotive environment. The results of the simulation, in terms of stress and strain distributions, allowed for the identification of critical delamination locations and the assessment of potential failure mechanisms that could occur under the hood.

To ensure the reliability of the simulation results, convergence studies were conducted. These studies evaluated the convergence of the numerical solution under the diverse thermal conditions encountered in the automotive setting. By verifying the convergence with respect to mesh density, element type, and other relevant modeling parameters, confidence in the accuracy and consistency of the simulation outcomes was enhanced.

The simulation aimed to investigate the effects of varying copper thickness on the behavior of the model. Three separate runs were conducted, each with a different copper thickness configuration, to assess the influence of this parameter on the performance and integrity of the system. In the first run, the model remained unchanged, and the copper thickness was set at 300 µm. Subsequently, in the second run, the copper thickness was reduced to 250 µm, while in the final run, it was increased to 400 µm.

4.0 RESULTS AND DISCUSSION

4.1 Simulation Result

By conducting these three distinct runs, it was possible to observe and analyze the response of the system under different copper thickness conditions. The simulation results from each run provided valuable insights into the behavior of the AlN direct bond copper substrate and its interface with the varying copper thicknesses. These findings are crucial for understanding the impact of copper thickness on the stability, reliability, and mechanical properties of the system.

The subsequent sections will delve into the detailed analysis of each simulation run, presenting the stress and strain distributions, critical delamination locations, and other relevant findings. By examining the results of these runs collectively, a comprehensive understanding of the influence of copper thickness on the performance of the AlN direct bond copper substrate will be established, aiding in the optimization of design parameters for enhanced system durability and reliability.

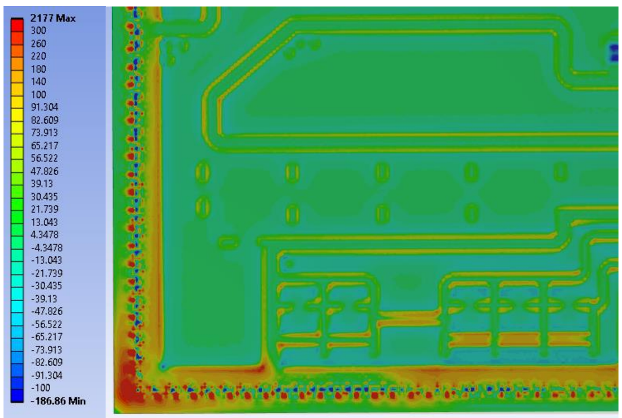

Figure 5. Showcases the simulation results obtained from the initial run, featuring a copper thickness of 300 um.

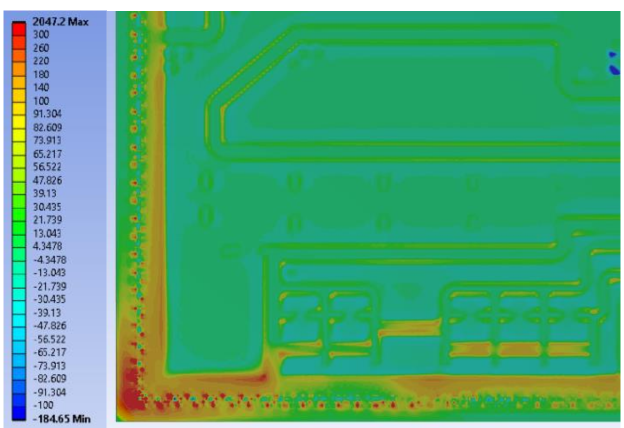

Figure 6: Simulation results for the 2nd run with a copper thickness of 250 um.

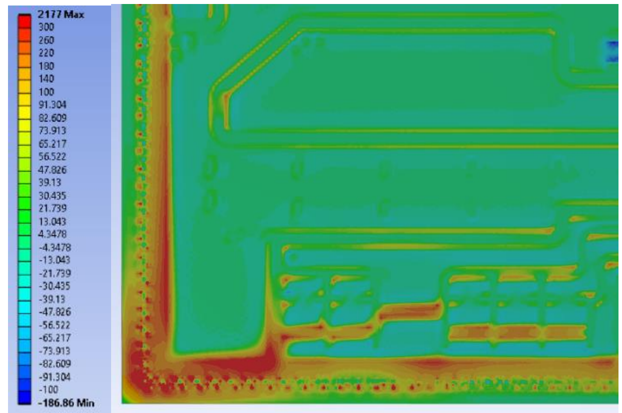

Figure 7: Simulation results for the 3rd run with an increased copper thickness of 400 um.

Upon visual observation of the stress color distribution, it is evident that the simulation results exhibit varying stress levels for the different copper thickness configurations. Notably, in Figure 6, representing the 2nd run with a copper thickness of 250 um, the stress distribution appears to be relatively lower compared to the other runs. On the other hand, in Figure 7, which corresponds to the 3rd run with an increased copper thickness of 400 um, the stress color distribution demonstrates higher stress levels compared to the other two runs.

4.2 Comparison of Simulation Result and TST Cycle

Figure 8: Simulation Stress Result and TST 50 Cycles comparison.

The simulation results obtained align with the findings from the Thermal Shock Test, providing further confirmation of the observed stress concentration behavior. In both the simulation and the Thermal Shock Test, it was noted that the stress concentration originated predominantly at the edges of the copper layer.

This consistency suggests that the copper edges play a significant role in influencing the stress distribution within the AlN direct bond copper substrate. The high stress levels observed near the edges can be attributed to the mechanical interactions and thermal gradients experienced in the system.

By observing the stress color distribution in the simulation results, it becomes apparent that the stress concentration is most pronounced at the edges, indicating a potential vulnerability and a critical area for further analysis and design considerations. These findings highlight the importance of carefully addressing the stress concentration effects near the copper edges to ensure the long-term stability and reliability of the interface between the AlN and copper layers.

Overall, the agreement between the simulation results and the observations from the Thermal Shock Test strengthens our understanding of the stress concentration phenomenon and guides the development of strategies to mitigate potential failure mechanisms originating from the copper edges. Future design optimizations should focus on minimizing stress concentrations at these regions to enhance the overall durability and performance of the AlN direct bond copper substrate.

4.3 Maximum Principal Stress at Copper Edge

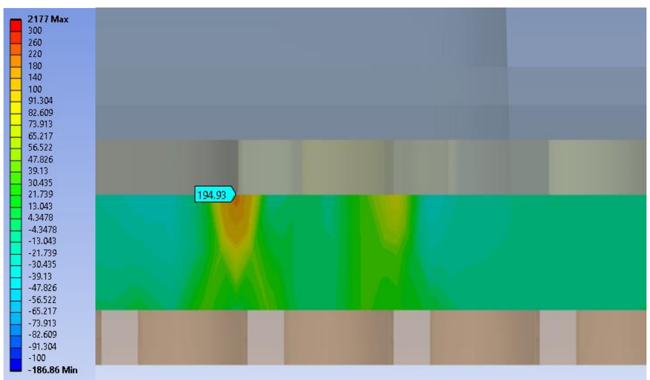

Figure 9: Maximum Principal Stress at Point B measured at 194.93 MPa during the lowest temperature condition, -40°C. Point B is located on AlN and at the copper edge. Image is from the simulation run 1 with copper thickness of 300 um.

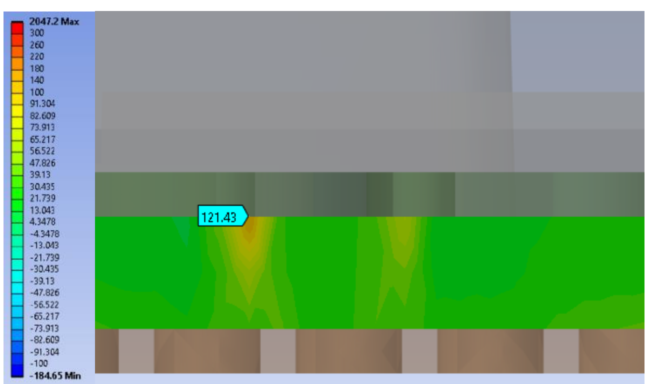

Figure 10: Maximum Principal Stress at Point B measured at 121.43 MPa during the lowest temperature condition, -40°C. Point B is located on AlN and at the copper edge. Image is from the simulation run 2 with copper thickness of 250 um.

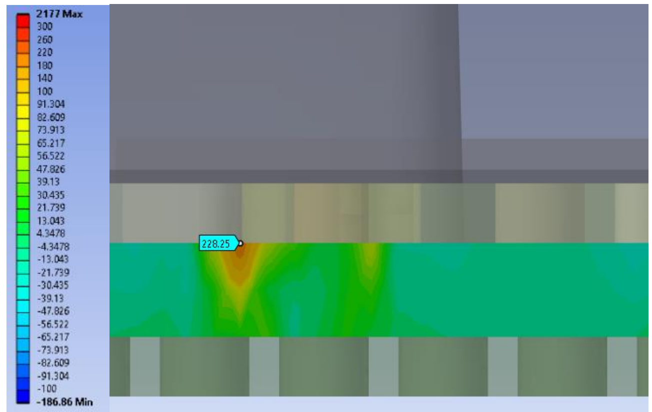

Figure 11: Maximum Principal Stress at Point B measured at 228.25 MPa during the lowest temperature condition, -40°C. Point B is located on AlN and at the copper edge. Image is from the simulation run 3 with copper thickness of 400 um.

The analysis of the simulation results revealed that the maximum principal stress occurred at the lowest temperature of -40°C, while the lowest stress levels were observed at the highest temperature of 125°C. This finding indicates a clear correlation between temperature and stress distribution within the AlN direct bond copper substrate.

At -40°C, the material experiences increased stiffness and reduced ductility, resulting in higher stress concentrations. The lower temperature causes thermal contraction, leading to higher internal stresses within the system. As a result, the maximum principal stress is observed to be at its peak at this extreme low temperature.

Conversely, at 125°C, the material exhibits higher ductility and reduced stiffness, resulting in lower stress concentrations. The higher temperature induces thermal expansion, which helps to relieve internal stresses within the system. Consequently, the lowest stress levels are observed at this elevated temperature.

This temperature-dependent variation in stress distribution highlights the significance of considering thermal effects on the performance and reliability of the AlN direct bond copper substrate. It underscores the importance of conducting analysis that account for the full temperature range of operating conditions to accurately assess the mechanical behavior and potential failure mechanisms.

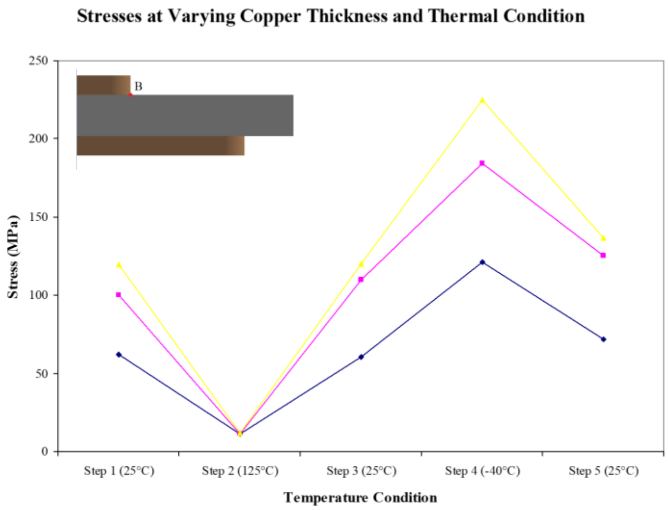

Figure 12: Variation in maximum principal stress at point B with different copper thicknesses.

5.0 CONCLUSION

In conclusion, the simulation results and analysis provide valuable insights into the behavior of the AlN direct bond copper substrate used in power modules. The comparison with the Thermal Shock Test results confirms the observed stress concentration at the copper edges, emphasizing the importance of addressing this area in design considerations.

The simulation results indicate that the maximum principal stress occurs at -40°C, while the lowest stress levels are observed at 125°C. This temperature-dependent variation in stress distribution underscores the need to consider thermal effects when assessing the mechanical behavior and potential failure mechanisms of the substrate.

Furthermore, the simulation results demonstrate that varying the copper thickness affects the stress distribution within the substrate. The stress color distribution shows higher stress levels with increased copper thickness and lower stress levels with decreased copper thickness. This finding highlights the importance of optimizing the copper thickness to minimize stress concentrations and improve the overall stability and reliability of the AlN direct bond copper substrate.

Overall, these findings contribute to the understanding of substrate delamination, thermal expansion mismatch, and stress distribution within the AlN direct bond copper substrate. They provide insights for further research and development of novel substrate materials and thermal management techniques to enhance the reliability and performance of power modules in high-power applications.

6.0 RECOMMENDATIONS

Based on the findings from the simulation and analysis of the AlN direct bond copper substrate, the following recommendations can be made to enhance the reliability and performance of power modules:

1. Design Optimization: Carefully address the stress concentration effects at the edges of the copper layer. Consider design modifications, such as rounded edges, stepped edges or stress-relief features, to minimize stress concentrations and reduce the likelihood of delamination.
2. Copper Thickness on Edges: Optimize the copper thickness on the edges to mitigate stress concentrations without compromising the electrical properties of the DBC. Conduct further investigations to determine the ideal copper thickness on the edges that provides adequate mechanical support and thermal conductivity while minimizing the potential for stress-induced failures.
3. Material Selection: Explore alternative substrate materials with lower thermal expansion mismatch and improved mechanical properties. Consider materials with higher thermal conductivity and a closer CTE match to copper, such as advanced ceramics or composite materials, to reduce stress-induced failures.
4. Comprehensive Testing: Conduct extensive testing, including thermal cycling and accelerated aging tests, to validate the performance and reliability of the AlN direct bond copper substrate under realistic operating conditions. This will provide further insights into potential failure mechanisms and guide design improvements.
5. Collaboration and Research: Foster collaborations between material scientists, engineers, and manufacturers to continue research and development of novel substrate materials, bonding techniques, and thermal management strategies. This collaborative effort will help advance the field and address the challenges associated with thermal expansion mismatch and stress concentration in power module substrates.

By implementing these recommendations, power module designers and manufacturers can improve the durability, reliability, and overall performance of power modules, ensuring their efficient operation in various high-power electronic applications.

7.0 ACKNOWLEDGMENT

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To everyone mentioned, your contributions have made a significant impact on my professional journey. We are truly honored to have had the opportunity to work with such a talented and dedicated team. We look forward to our continued collaboration and shared achievements in the future.

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