 DOI:10.30420/566414080

Comprehensive Study on the Characteristics of Large Area Transient liquid phase sintering (TLPS) Joint for SiC module

Di An[1, 2], Guiqin Chang[1, 2], Haoliang Zhang[1, 2], Haihui Luo[1, 2], Qiang Xiao[1, 2]

1 Zhuzhou CRRC Times Semiconductor Co., Ltd., Zhuzhou, Hunan, China

2 State Key Laboratory of Power Semiconductor and Integration Technology, Zhuzhou, Hunan, China

Corresponding author: Guiqin Chang, Changgq@csrzic.com

Speaker: Di An, andi@csrzic.com

Abstract

This study employs the Transient Liquid Phase Sintering (TLPS) process to achieve the connection between the substrate and the heat sink in power modules, studied the impact of printing thickness on the strength and reliability of the connection layer, and comprehensively revealed the differences in packaging performance between TLPS and traditional solder from the aspects of mechanical properties, thermal resistance, connection layer reliability, and module service life. The results show that the TLPS connection layer prepared in this paper is composed of Cu_3Sn, Cu_6Sn_5, Cu, and Ag_3Sn, and contains 15% porosity and a small amount of residual carbon. After matching the printing thickness with the warpage of the substrate, the connection layer has no obvious delamination defects, the strength reaches 60MPa and is uniform distributed, which is 30% increase compared to soldering. Under the thermal shock conditions of -65-150°C, the reliability of the TLPS joint is significantly better than that of the SnSb5 solder layer. Compared with soldering, the total thermal resistance of the power module using the TLPS process is reduced by 7%, indicating that TLPS can effectively enhance the module's heat dissipation and outflow capabilities. After undergoing 18,000 long cycle power cycle tests, the silver sintering layer on the back of the chip degrades due to the accumulation of plastic strain, and the total thermal resistance of the TLPS and soldered modules increased by 60% and 48.6% respectively, with the module service life being 6000-7000 cycles. The large-area TLPS process causes greater fluctuations in the chip's junction temperature, which has a negative impact on the service life of the module, but provides a low-cost technical solution for enhancing the heat dissipation and outflow capabilities of high power module packaging.

1 Introduction

As the operating junction temperature and power density of the module increase, the connection layer between the substrate and the baseplate has become the shortcomings for heat dissipation and reliability. Simulation results indicate that the thermal resistance of the traditional baseplate solder layer accounts for more than 20% of the total thermal resistance of the module. If a more reliable connection layer material is applied between the heat sink and AMB substrate, the connection layer can be thinned, further enhancing the heat dissipation capability of the power module. This can increase the junction temperature to 175°C or higher without additional cooling costs, fully leveraging the application potential of the device[1, 2].

In recent years, Transient Liquid Phase Sintering (TLPS) has shown great potential as an alternative to lead-free soldering in high-temperature packaging applications [3]. The TLPS process involves incorporating a low-melting-point metal into a high-melting-point metal, where the low and high melting-point components fully inter-diffuse, forming intermetallic compounds (IMCs) with a medium melting point. By controlling the composition and diffusion path, the TLPS process can generate a high-melting-point connection layer (>400°C) at a lower process temperature and in a shorter time, enhancing the creep resistance of the joint under high-temperature conditions [4,5]. Cu-Sn system TLPS interconnection materials are widely used in electronic product interconnections, where Cu and Sn react quickly to form Cu_3Sn with a melting point of 676°C and Cu_6Sn_5 with a melting point of 415°C in the connection layer.

This paper applies the TLPS process to the packaging of SiC power modules, replacing traditional Sn-based solders, and optimizes the printing thickness of the TLPS paste to successfully complete the ultra-large area connection between the AMB substrate and the heat sink of 50*60mm^2. Through shear testing, C-SAM, microstructure analysis, and thermal shock, the connection quality, bonding strength, and reliability of the soldering and TLPS layers are characterized and compared. Meanwhile, a systematic study of the impact of different connection layers on the interface thermal resistance and power cycle life of the power module is conducted, and the degradation pattern of the power module under severe power cycle test conditions is explored.

ISBN 978-3-8007-6414-3

DOI:10.30420/566414080

2 Experimental Methods

2.1 Preparation of Large-Area TLPS Power Module

The main components of the TLPS raw materials are Cu, Sn, Ag, and flux. The TLPS interconnection process is carried out using a "printing - drying - mounting - pressure sintering" process. The SiC chips-substrate interconnection uses a silver sintering process, with the raw material being a preformed silver film, and the DTS (Die Top system) technology is used to achieve the interconnection of the copper wires on the front side of the chip[6]. To compare the strength, thermal resistance, and packaging reliability, SnSb5 solder pieces are used to replace the TLPS solder paste to complete the connection between the AMB substrate and heat sink. The photo of the encapsulated module is shown in Figure 1. Figure 2 shows the structure and composition of the TLPS connection layer, with a core-shell structure of 1-3 microns uniformly distributed inside the connection layer. The core is copper nanoparticles or microparticles, which play a role in toughening the joint, and the shell is a mixed stable phase of Cu_3Sn/Cu_6Sn_5. Some cores have completely reacted with Sn but still maintain a roughly spherical shape. Around the core-shell structure, there are bright white products of varying sizes, which are Ag_3Sn. The interface is well combined, mainly with Cu_3Sn and Cu. In addition, there are 15% of pores distributed in the connection layer, partly due to the volume change during the phase change process, and partly due to the residual flux during the sintering process.

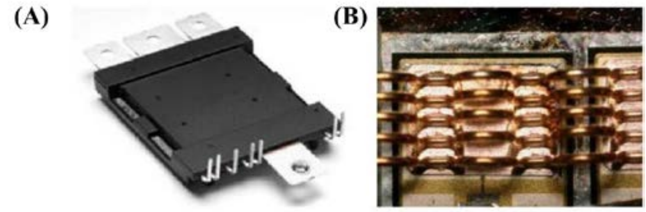

Fig. 1. The photo of the encapsulated module

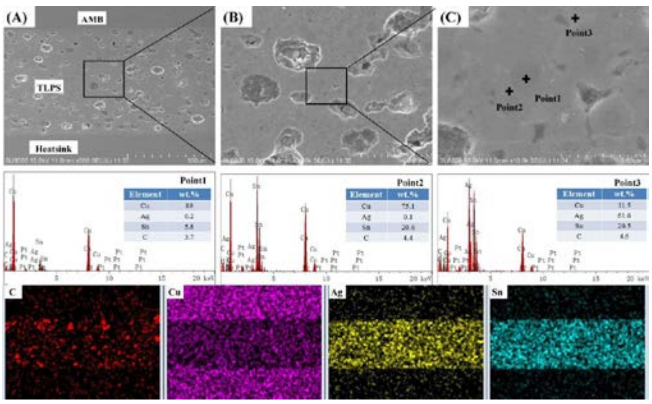

Fig. 2. Structure and composition of TLPS connection Layer

2.2 Performance testing

The shear strength of the joint is tested using a thrust machine to characterize the mechanical properties of the TLPS connection layer and the interconnection layer of soldering. C-SAM is used to analyze the quality of the connection layer, observing the existence of cracks, delamination, and other defects. The cross-section and fracture surface of the connection layer are observed using SEM and the porosity of the cross-sectional structure is calculated. Thermal shock tests are used to assess the degradation of the connection layer, with a temperature loading range of -65°C to 150°C, and the degradation area of the AMB substrate/heat sink connection layer is statistically analyzed after 1000 cycles. The thermal resistance of the power module is tested using a thermal resistance tester to evaluate the impact of the connection layer on the heat dissipation capability of the module. The impact of changes in AMB/heat sink connection layer on the reliability of power modules was evaluated using PCmin test. The experimental conditions are as follows: maximum junction temperature Tjmax = 175°C, junction temperature difference ΔTj = 150°C, on-time 30s, off-time 15s, and the experiment only tests a single channel within the module.

3 Results and Discussion

3.1 The Impact of Printing Thickness on Strength and Reliability

Figure 3 shows the bonding strength and C-SAM images of the large-area TLPS connection layer under different printing thicknesses (80μm, 100μm, 200μm, 300μm). When the printing thickness is less than 100μm, the final thickness of the connection layer is less than 25μm (Figure 4(a)), which cannot fully cover the warpage of the AMB substrate (The warpage of the substrate is 0.15μm). There is a large area of delamination between the edge area of the AMB substrate and the TLPS connection layer, and the position where defects exist is a weak point of shear strength (about 10MPa). The average strength of the sample is only 30-40MPa. When the printing thickness is increased to 200μm (the actual connection layer thickness is about 90μm), the average strength of the connection layer is increased to 61MPa, and the uniformity of the strength distribution is significantly improved. Thickening the connection layer not only reduces the stress concentration during testing but also fully compensates for the warpage of the substrate, thereby further improving the connection quality. The C-SAM shows no obvious defects and delamination, and the strength distribution does not exhibit the common pattern of low in the middle and high at the edges in large-area connection processes. When the printing thickness is increased to 300μm (the actual connection layer thickness is 120μm), the average strength of the connection layer is 60MPa. Increasing the printing thickness did not further increase the strength of the connection layer. The TLPS solder paste contains 20% organic material, and as the printing thickness increases, the organic content in the connection layer increases. During the process, organic materials are difficult to fully decompose and burn off, and residual organic matter hinders material diffusion, thereby having a negative impact on the strength of the connection layer. The shear strength of the SnSb5 solder layer is only 40MPa, indicating that the TLPS process can increase the strength of the connecting layer by 50%. Figure 4(b) shows the fracture surface of the TLPS connection layer. The fracture location of the connection layer is cohesive failure, indicating good interface bonding. However, no obvious particle deformation was found in the fracture structure of the TLPS, and the fracture occurred inside the IMC, showing an intergranular brittle fracture mode, indicating that the strength of the TLPS material is lower than the TLPS interconnection interface, which may be related to the presence of porosity defects in the TLPS.

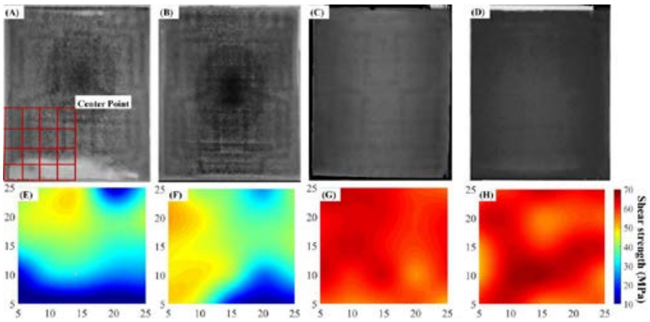

Fig. 3. C-SAM images and strength distribution of the connection layer under different printing thicknesses: (A, E) 80μm, (B, F) 100μm, (C, G) 200μm, (D, H)

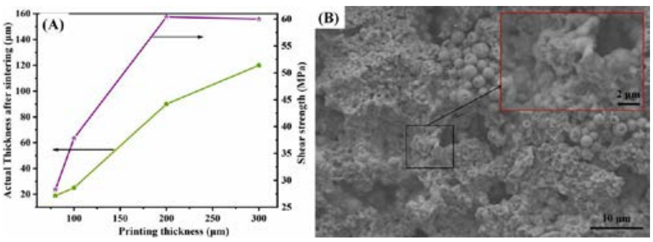

Fig. 4. (a) Actual thickness and strength of the connection layer after sintering under different TLPS printing thicknesses, (b) Fracture surface of TLPS

Figure 5 shows the degradation of the connection layer with different thicknesses during the thermal shock test. As the printing thickness increases, the reliability of the connection layer is greatly improved. When the printing thickness is 80 and 100μm, the degradation area of the connection layer is 13.3% and 4%, respectively. During the thermal shock, the connection layer undergoes fatigue degradation due to the mismatch of the thermal expansion coefficients between AMB substrate and heat sink. Since the stress and strain accumulation are the greatest at the edge, and the shear strength is lower, the degradation all occurs at the edge position [7]. For samples with a printing thickness of 200 and 300μm, there is almost no change in the thermal shock test (the degradation area of the 200μm sample is less than 1%, and the 300μm sample is 0%). Increasing the printing thickness not only improves the bonding strength of the connection layer but also helps to reduce internal stress and residual stress strain. Figure 5(e) shows the degradation of the SnSb5 connection layer after thermal shock. After 1000 cycles, the SnSb5 solder layer degrades by about 15%. Figures 5(f and g) compare the degradation mechanism of the connecting layer under thermal shock conditions. Compared with before the thermal shock, the structure and composition of the aged TLPS hardly changed, while the SnSb5 solder layer severely degenerated, forming obvious cracks near the IMC. The TLPS connection layer with higher bonding strength has better reliability than the SnSb5 solder layer, and it indicates that a printing thickness of 200μm can meet the reliability requirements of the module.

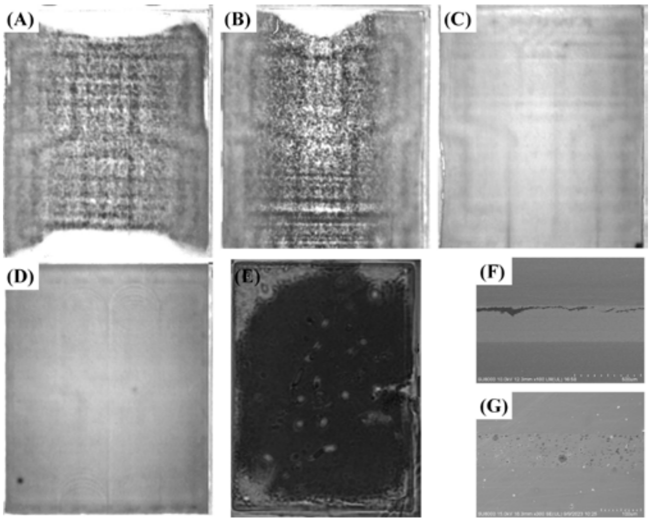

Fig. 5. Degradation of the connection layer under different TLPS printing thicknesses after thermal shock: (A) 80μm; (B) 100μm; (C) 200μm; (D) 300μm; (E) SnSb5 solder layer; (F) Structure of SnSb5 solder layer after thermal shock; (G) Structure of TLPS connection layer after thermal shock

3.2 Power Module Thermal Resistance Comparison

To explore the impact of the AMB substrate/heat sink connection layer on the heat dissipation capability of SiC power modules, this study tested the thermal resistance of power modules packaged with two types of connection layers using the T3Ster thermal resistance tester. As shown in Figure 6, the thermal resistance of power modules using TLPS and soldering as the AMB substrate/heat sink connection materials are 71.3K/W and 76.8K/W, respectively. Compared with traditional soldering, using a TLPS connection layer can reduce the thermal resistance of the power module by 7.2%. The reason is as follows: Although the thermal conductivity of the IMC components such as $Cu_3Sn/Cu_6Sn_5/Ag_3Sn$ in the TLPS connection layer is comparable to that of the solder [8], due to its interface bonding strength and reliability being much higher than that of the SnSb5 solder layer, the connection layer can be thinned to 1/2-1/3 of the solder layer, which is conducive to enhancing the module's heat dissipation capability. By changing the parameters of the thermal resistance tester, the difference in heating current when the chip junction temperature reaches 175°C was quantified. As shown in Figure 6, when the chip junction temperature reaches 175°C, the heating current required for the TLPS module is 390A, which is an 8% increase compared to the soldered module(360A). The above results indicate that using TLPS technology in power module packaging is beneficial for enhancing the heat dissipation capability of the power module, reducing the chip junction temperature, and improving the outflow capability.

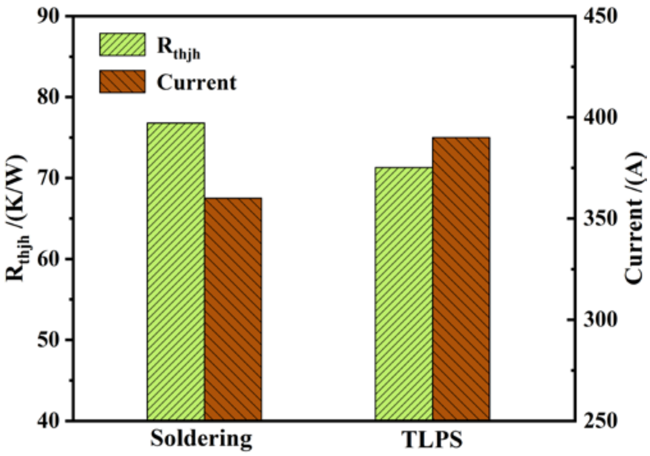

Fig. 6. Comparison of thermal resistance and outflow between soldered and TLPS modules

3.3 Power Module Power Cycling Life

In order to further explore the impact of the AMB substrate/heat sink connection layer on the service life of the power module, long-cycle power cycle tests were conducted on power modules packaged with two types of connection materials. The degradation of the connection layer in the power module was evaluated by monitoring the change in module thermal resistance. As shown in Figure 7(c), when the power cycle reaches 18,000 cycles, the thermal resistance of the TLPS and soldered modules increased by 60% and 48.6%, respectively, indicating that the connection layer underwent more significant degradation during the test, and the interface degradation in the TLPS module was more severe. By comparing the test cycle numbers when the module thermal resistance increased by 20%, the TLPS module's thermal resistance degrades by 20% at about 6,000 cycles, while the soldered module's life is about 7,000 cycles, and the life of the module using the TLPS process is reduced by 14%. Although the previous results show that TLPS has higher interface bonding strength and the reliability of the TLPS connection layer itself is better than the solder layer. However, from the perspective of power module packaging, using TLPS as the connection layer between the AMB substrate and the heat sink does not have an advantage in improving the service life of the power module. Figures 7(a-b) show the change in the integral thermal resistance curve of the two modules during the power cycle process. After the power cycle, the thermal resistance curve length contributed by the sintered layer on the back of the chip in the soldered and TLPS modules increased significantly. Combined with the curve shape and the impact of defects on thermal resistance, it is known that the sintered layer on the back of the chip underwent significant degradation during the power cycle.

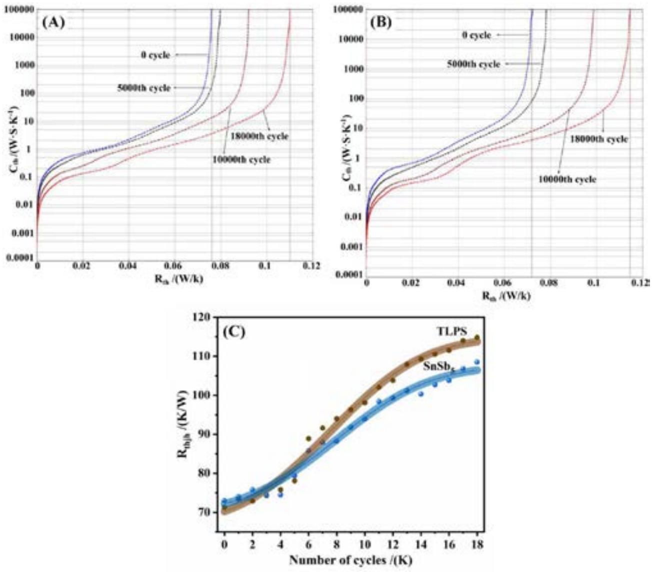

Fig. 7. Changes in the integral thermal resistance curve morphology and the overall thermal resistance change trend during the power cycle process(A) Soldered module; (B) Large-area TLPS module; (C) The trend of thermal resistance change during power cycling for both modules

Figure 8 shows the C-SAM images of the AMB substrate/heat sink connection layer and the chip/AMB substrate connection layer after the power cycling test. From images (c, d), it can be seen that the sintered layer on the back of the chip for both TLPS and soldered modules has degraded severely, which is consistent with the trend of thermal resistance change during the power cycling test, indicating that the degradation of the sintered layer on the back of the chip is the main reason for the increase in module thermal

 DOI:10.30420/566414080

resistance during the test. It is also found that the solder layer and TLPS layer in the AMB substrate/heat sink connection layer have not degraded significantly, indicating that different test methods provide different test environments that will affect the evaluation results of the connection layer's reliability.

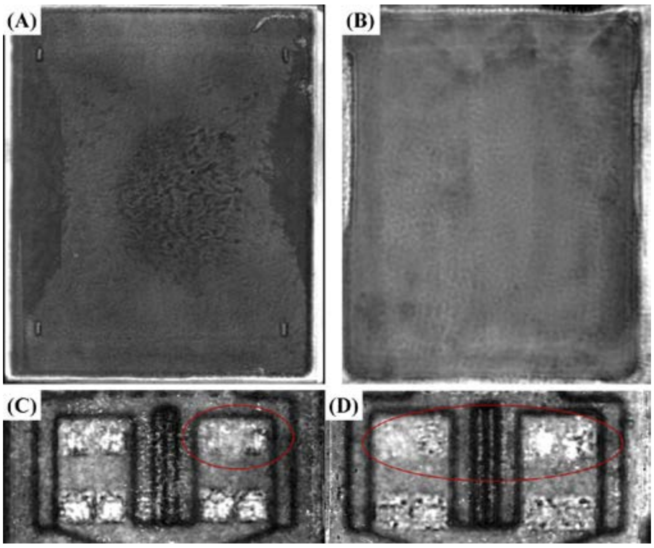

Fig. 8. C-SAM images of the AMB substrate/heat sink connection layer and the SiC chip/AMB substrate connection layer after the power cycling test: (a) Soldered; (b) TLPS; (d) Sintered layer on the back of the chip for the soldered module; (e) Sintered layer on the back of the chip for the TLPS module

Figure 9 shows the microstructure of the sintered layer on the back of the chip for both modules after the power cycling test. The degree of degradation of the sintered layer is in the order of TLPS module > soldered module, which is consistent with the thermal resistance monitoring data. For the soldered module, transverse cracking and interface delamination of the sintered silver layer can be observed. During the power cycling process, the mismatch of the thermal expansion coefficients between the SiC chip and the sintered silver causes nucleation of defects at the interface, leading to cracking at the interface and horizontal cracks in the silver layer. The interface degradation of the TLPS module is more severe, with almost complete delamination of the sintered interface below the chip, hence the most significant thermal resistance change observed during the power cycling test (Figure 7 (c)).

For the TLPS module, a lower thermal resistance implies that the module's output capacity can be increased under the maximum allowable junction temperature, while its maximum junction temperature and temperature fluctuations will also increase, resulting in a shorter service life compared to the soldered module. To meet the multiple demands of the application, the module design needs to comprehensively consider the current-carrying capacity and reliability. While adopting the large-area TLPS process to reduce the module's thermal resistance, measures should also be taken to further enhance its power cycle reliability[10].

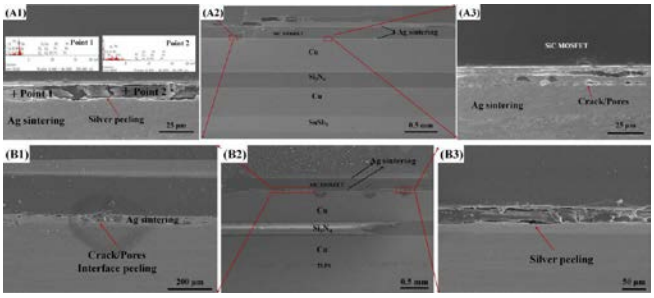

Fig. 9. Degradation of silver sintered layer on the back of the chip after power cycle test: (A1-A3)Soldering Module; (B1-B3)TLPS Module

4 Conclusion

This paper has achieved the connection between the 50*60mm^2 AMB substrate and the heat sink using the TLPS process, investigated the impact of printing thickness on the strength and reliability of the connection layer, and focused on studying the influence of the substrate/heat sink connection layer on the thermal, outflow, and power cycle reliability of the power module. The experimental results show that the strength and reliability of the connection layer need to consider the matching relationship between the printing thickness and the substrate warpage. When the substrate warpage is 0.15mm, the printing thickness of the TLPS solder paste needs to cover the substrate warpage to meet the mechanical and reliability requirements. With a printing thickness of 200μm, the final connection layer thickness after sintering is about 90μm, and the TLPS shear strength reaches 60MPa, with a relatively uniform two-dimensional distribution of shear strength. The joint of the AMB substrate interconnected with the heat sink based on TLPS degrades by only about 1% after thermal shock test, showing more excellent reliability of the material. Compared with power modules using different connection layers, the total thermal resistance of the power module using TLPS is reduced by 7.2% compared to soldering. Reducing the connection layer thickness helps to enhance the heat dissipation capability of the power module. After undergoing 18,000 long cycle power cycle tests, the sintered layer on the back of the chip degrades significantly the total thermal resistance of both TLPS and soldered modules increased by 60% and 48.6%, respectively, with the module life being between 6,000 and 7,000 cycles. Changing the substrate solder layer will improve heat dissipation capacity and affect the temperature fluctuations of SiC chips, causing a decrease in module reliability. In summary, using the TLPS process to inter-

ISBN 978-3-8007-6414-3

 DOI:10.30420/566414080

connect the AMB substrate and the heat sink is a low-cost method to enhance the heat dissipation and out-flow capability of the module, and it has application prospects in high-power device packaging.

References

[1] Lamichhane R R , Ericsson N , Frank S , et al, “A wide bandgap silicon carbide (SiC) gate driver for high-temperature and high-voltage applications”, IEEE International Symposium on Power Semiconductor Devices & Ics 2014, pp.414-417.

[2] Y. Gao, L. Song and J. Zhang, "A study of large area bonding technologies and their application in electronic industry," 23rd International Conference on Electronic Packaging Technology (ICEPT) 2022, pp. 1-6.

[3] Kang H, Sharma A, Jung J P, “Recent progress in transient liquid phase and wire bonding technologies for power electronics”, Metals, 2020, Volume 10, issue7, pp. 934.

[4] Sun L, Chen M, Zhang L, “Microstructure evolution and grain orientation of IMC in Cu-Sn TLP bonding solder joints”, J Alloy Compd, 2019, Volume 786, pp. 677-687.

[5] Billa L R, Wang Y, Grant T, et al, “Transient Liquid Phase Bond Reliability Evaluation of Die-attach for Power Module Packaging”, 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe) 2022, pp. 1-7.

[6] Fabian B, Thomas S, Kalajica M, et al, “Simulation and verification of a lifetime model based on front side metal degradation of sintered Die Top Systems (DTS®) in Power Cycling Tests”, PCIM Europe 2020, pp. 1-5.

[7] Wangjian Feng, Xin Li, “Stress and Warping Analysis of Large Area Substrate Connection in IGBT Module Package”, Chin Quar Mech, 2020, Volume 41, issue 1, pp. 59-68.

[8] Fields R, “Physical and mechanical properties of intermetallic compounds commonly found in solder joints”, The Metal Science of Joining, Cincinnati, pp. 165-174

[9] Nakako H, Natori M, Ishikawa D, et al, “Copper Sintering Pastes for Die Bonding and Large-Area Bonding”, PCIM Europe 2023, pp. 1-5.

[10] Guiqin Chang, Haihui Luo, Chao Fang, et al, “Influence of Heat Dissipation Baseplate on Power Cycling Lifetime of IGBT Modules”, T China Electro-technical Soc, 2024, Volume 39, issue 8, pp. 2485-2495.

ISBN 978-3-8007-6414-3