Brief Review of Silver Sinter-bonding Processing for Packaging High-temperature Power Devices*

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Abstract: Silver sintering is receiving increasing attention due to its novel die-attach technique for high-temperature power electronics. Excellent thermal conductivity, high melting point/remelting temperature and low-temperature sintering behaviors of the silver sintered attachment meet the requirements of high-temperature applications for power devices, specifically SiC devices. The merits and demerits of the existing pressure-assisted sintering and pressure-less sintering techniques using nano-scale, micro-scale and micro-nano-scale hybrid silver sintered materials are separately presented. The emerging rapid sintering approaches, such as the electric-assisted approach, are briefly introduced and the technical outlook is provided. In addition, the study highlights the importance of creating a brief resource guide on using the correct sintering methods.

Keywords: Pressure-less sintering, pressure-assisted, nanosilver paste, high-temperature power module, insulated gate bipolar translators (IGBT), silicon carbide (SiC)

1 Introduction

The high-temperature operation of power modules strongly depends on the performance of power devices at high temperatures. In recent years, high-temperature power devices, such as the state-of-the-art SiC devices, have been developed as high-temperature power modules because of their excellent switching performance at high temperatures [1-2]; however, they cannot be fully applied in the existing power packaging methods [3].

These high-temperature power devices have a higher operating temperature (higher than 200 ℃) than that of the Si-based devices (lower than 150 ℃). To fully utilize the potential of these devices at high temperatures, the materials used, such as die-attach and substrate-attach, have to withstand harsh high-temperature aging for temperatures higher than 175 ℃ [4-5].

In the traditional Si-based power modules, die-attach materials, such as Pb95Sn5 and Pb92.5Sn5Ag2.5, cannot meet the reliability requirements for packaging power devices for high-temperature applications owing to the creep-fatigue concerns [6-8]. Moreover, substrate-attach materials, such as Sn96.5Ag3Cu0.5, which have a lower melting temperature than the solder used as die attachment further limit the reliability of SiC power modules for high-temperature applications [9-10].

Tab. 1 lists the difference in thermal conductivities and operating temperatures between the regular Si-based power devices and SiC ones [11-14]. New die-attach materials with high melting temperature, high thermal conductivity, good reliability, and low processing temperature, should meet the requirements for

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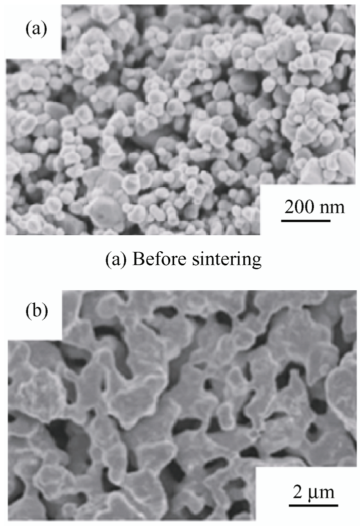
packaging power devices reliably for high-temperature applications [15].

Tab. 1 Difference in thermal conductivity, operating and processing temperature of typical solders

Material properties	Regular Si-based device	SiC device	Pb95Sn5	Sn96.5Ag3Cu0.5
Thermal conductivity/ (W/ m • K)	150	490	26	59
Operating temperature/ ℃	<125	>200	190	125
Soldering temperature/ ℃	N/A	N/A	330	250

Recently, the low temperature joining technique (LTJT) has been regarded as a promising alternative to high-lead solders for packaging high-temperature power devices. LTJT, pioneered by Schwarzbauer [16], was used to produce die-attach materials from the micro-silver flakes for packaging power electronics in the late 1980s. Initially, achieving a robust die attachment required a high sintering pressure of approximately 30-80 MPa because of the low diffusion ability among micro-silver flakes [17]. The sintered micro-silver attachment with a high melting/remelting temperature (approximately 961 ℃) may be formed at a low sintering temperature of 225 ℃, which can enhance the high-temperature reliability of the die attachment and address the remelting issues of solders [18]. The thermal conductivity (240 W/m • K) of the sintered silver was reported to be about 3 times higher than the conventional high-lead solders and met the heat-dissipating requirements of SiC power devices [19]. In addition, the shear strength of the sintered die attachment could reach a pressure of 70 MPa, which is stronger than that of most of the solders [20]. Thus, LTJT has been attracting wide attention on power packaging for high-temperature applications, specifically SiC power modules. However, the wide applicability of this high-auxiliary pressure can be limited by the production issue.

To reduce or eliminate high auxiliary pressure for LTJT, decreasing the size of silver particles/flakes to the nano-scale is an effective approach [21]. The nano-scale silver particles/flakes can effectively increase the specific surface area resulting in a large driving force for self-densification. The melting temperature could be reduced to 0.2-0.4 times that of the bulk silver [22]. In the past decade, Chen et al. [23-24] had developed several types of nanosilver paste that could be sintered without pressure or under a significantly low pressure lower than 2 MPa and at low temperatures of 190-250 ℃. Fig. 1 shows typical micrographics of the nanosilver paste before and after sintering. It is believed that a robust sintered silver die attachment with a relative density of more than 80% can be obtained using this pressure-less sintering approach at 250 ℃.



(a) Before sintering

(b) After pressure-less sintering at 250 ℃

Fig. 1 Micrographics of nanosilver paste

Owing to the rapid advancement in the synthesizing methods of silver particles, few innovative micro-scale and micro-nano hybrid particle silver pastes can achieve high-density sintered silver by low pressure-assisted or pressure-less sintering approaches [25-27]. Regardless of pressure-assisted or pressure-less sintering of the nanosilver or micro-silver used, it is critical to obtain guidelines on using these techniques separately for different applications in terms of efficiency, yield and investment [28].

Therefore, this paper mainly reviews the merits and demerits of the pressure-assisted and pressure-less sintering techniques. Suggestions are also provided on the emerging techniques such as rapid electric-assisted sintering and laser sintering. Furthermore, developing a brief resource guide on using the correct sintering methods can be helpful.

2 Pressure-assisted sintering

The sintering pressure can increase the contact surface area among silver particles to enhance the diffusion bonding as well as the driving force for densification of silver nanoparticles [29]. Hence, the pressure-assisted sintering technique can effectively decrease the required sintering temperature and improve processing efficiency [30].

A schematic diagram of the pressure-assisted sintering technique is shown in Fig. 2. Auxiliary pressure is provided by a servo-hydraulic pressure equipment with real-time feedback control. As key components for the pressure-assisted sintering technique, dynamic inserts are used to compensate for the height difference among the devices [31]. For different packaging cases, a customized sintering mold enables each device to secure an accurate bonding position. In addition, buffering materials, such as 1-3 mm silicone rubber and 50-200 μm Teflon tape, are essential in preventing damage to the device [32]. In recent times, some suppliers have developed pressure-assisted sintering equipment, and the sintering pressure and temperature range from 0.5-30 MPa and 220-270 ℃, respectively [33].

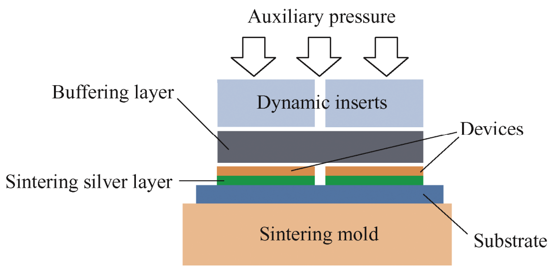


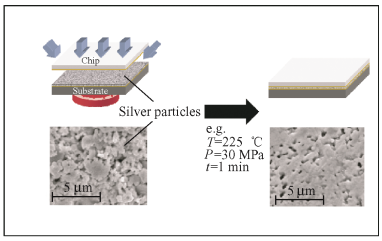
Fig. 2 Schematic diagram of the pressure-assisted sintering technique

The selection of sintering pressure, which is an important factor for sintering efficiency, yield and cost management [34-35], highly depends on the scale of the silver particle in the silver-sintering materials [36]. Tab. 2 lists the recommended pressure and cost estimation for the silver-sintering materials with scales of different particles [18, 32-33, 37-50].

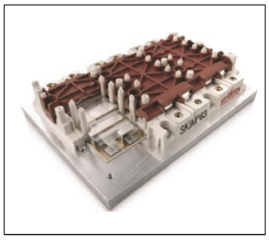
Generally, large-scale micron silver, such as 5-30 μm particles/flakes, require a high sintering pressure (higher than 15 MPa) to obtain the sintered silver attachment with low porosity [40]. Fig. 3 shows a high pressure-assisted sintering case using large-scale micron silver sintering. A dense sintered silver between the power device and the substrate can be formed under an auxiliary pressure of 30 MPa at 225 ℃ for 1 min. Based on this sintering approach, SEMICRON developed silver-sintering power modules, namely SkiM and SKiN half bridge modules [51-52].

Tab. 2 Recommended pressure and cost estimation with different silver particle scales

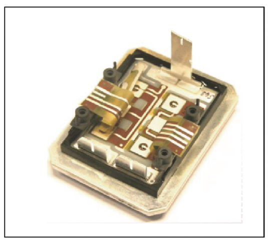
Recommended pressure	Silver particle scale /Material cost	Yield /Packaging cost
High pressure, i.e., higher than 15 MPa	Large-scale micron silver, e.g., 3-30 μm silver flakes and particles /low	Low /high
Medium pressure, i.e., 5-15 MPa	Micron silver, e.g., 1-3 μm, submicron, and micro-nano-scale /medium	Low /high
Low pressure, i.e., less than 5 MPa	Nano silver, e.g., less than 100 nm, nano/submicron and nano/micro hybrid particles /high	High /low



(a) The sintering schematic diagram under 30 MPa at 225 ℃ for 1 min



(b) SKiM module



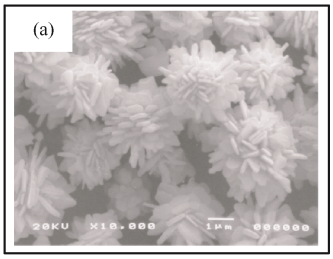
(c) SKiN half bridge module

Fig. 3 High pressure-assisted sintering case using large-scale micron silver flakes

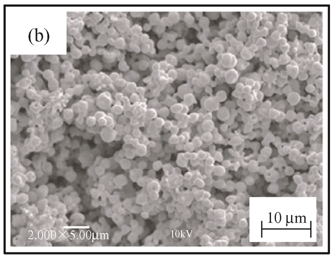
Compared to the traditional modules of soldering, the junction-to-ambient thermal resistance of the SkiM and SKiN modules using silver sintering reduces by 36% and 47%, respectively. They can work steadily at 200 ℃ and the power cycling capability improves about 70 times at $T_{j\max}$=150 ℃ [52]. The performance improvement is attributed to high thermal conductivity and high-temperature resistance of the sintered silver joints. In addition, the usage of large-scale micron silver particles/flakes can decrease the material cost [42]; however, this can result in a low sintering yield and increase the investment on equipment due to the requirement of such high auxiliary pressure. This approach may be more suitable to fabricate large-area sintered silver joints such as bonding DBC substrate, discrete heat sink or base plate.

With the development of silver sintering, few researchers reported the sintering behavior of micron, submicron, and micro-nano-scale hybrid particles under medium pressures [42, 48, 50] of 5-15 MPa. Figs. 4a and 4b show micrographics of silver paste with 3 μm silver particles before and after sintering under 10 MPa at 230 ℃ for 3 min [42, 53]. To evaluate the bonding quality of micron silver joints under the medium auxiliary pressure, 10×10 mm^2 chips and an active metal brazed substrate with silver metallization are used to fabricate the bending samples as shown in Figs. 4c and 4d. The bending test confirms the thermo-mechanical reliability of the sintered silver joints using micron-scale silver particles under the medium auxiliary pressure [53]. Although the micron silver sintering approach has medium material cost [42], the necessary medium auxiliary pressure can lead to chip damage [33], specifically in the case of hard SiC devices. It is recommended for use in the case of large-area die attachments, e.g., larger than 10×10 mm^2.

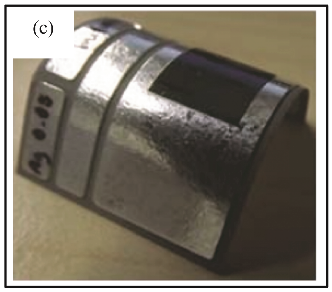
The introduction of nano-scale silver particles can reduce further auxiliary pressure during sintering. A double-sided SiC device with TO-247 packaging obtained via sintering of nano-scale silver films is depicted in Fig. 5 [54]. In this case, typical bonding wires are replaced by a clip lead frame. A 650 V IGBT (8.8×8.8 mm²) and a free-wheeling diode (8.8×5.1 mm²) are sinter-bonded with a copper tab using the silver film. The sintering pressure, temperature, and time are 3 MPa, 130 ℃, and 60 s, respectively. Meanwhile, the clip lead frame is also sintered to the emitter electrode of IGBT devices under 10 MPa auxiliary pressure at 250 ℃ for 90 s.



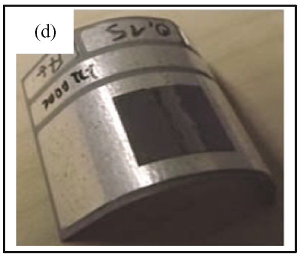
(a) Micrographic representation of silver particles before sintering



(b) Micrographic representation after sintering under 10 MPa at 230 ℃ for 3 min



(c) Bending test sample before aging



(d) Bending test sample after 2 000 cycles under the temperature swing of 40-150 ℃

Fig. 4 Medium pressure-assisted sintering case using micron-scale silver particles

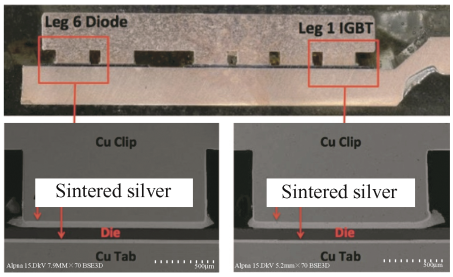
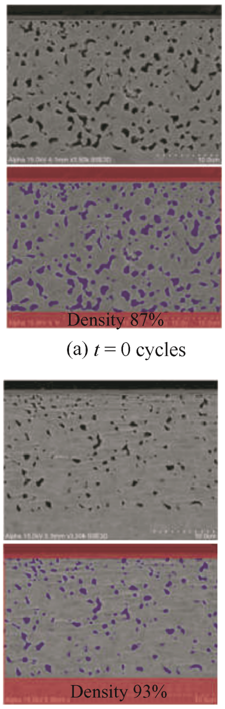


Fig. 5 Cross-sectional images of a double-sided TO 247 using the pressure-assisted sintering of silver films

In this case, the sintering of the silver film can control the bond line thickness of the die attachment effectively; however, the dry silver film cannot wet the power device, substrate, base plate, or heat sink well [54]. Consequently, auxiliary pressure during the sintering of the silver film is essential to enhance the diffusion between the silver particles in the film and the bonding surface. Note that the sintering of the silver film requires a die transfer process using a specific die bonder, which needs additional investment in equipment [55].

For the medium and low pressure-assisted sintering cases, the thermal resistance from junction-to-case could be 42% lower than that of typical solder cases. The improvement of the thermal resistance may be due to the excellent thermal conductivity of sintered silver, i.e., more than 200 W/m • K, and the ultrathin thermal conduction path, i.e., 25 μm bond line thickness. Power cycling test (PCT) shows that the silver-sintering case has no failure even after 150k cycles at ΔT_j of 85 ℃, comparing with the lift-off failure of wire bonding joints for typical packaging cases only after 12k cycles. No obvious defects could be observed when this case was aged after 150k cycles. The cross-sectional images of the sintered silver die attachment at the initial and aged stages after 150k cycles are showed in Fig. 6 [54]. Furthermore, even when the ΔT_j was elevated to 110 ℃, this case did not fail after 35k cycles.

Pressure-assisted sintering could ensure the reliability of sintered silver attachment effectively. However, compared to bonding the discrete devices, the pressure-assisted sintering would lead to lower yield for fabricating high-density power modules integrated with multiple bare devices because it is difficult to obtain a uniformly distributed auxiliary pressure for each bare devices [34, 56]. In addition, the pressure-assisted sintering requires a large investment in the sintering equipment and customized molds for different packaging cases. Considering these effects of the device dimension and the warpage of other associated packaging components, the pressure-assisted sintering may be ideal for bonding single large size device like discrete devices and components with large warpage during constraint heating, e.g., heat sink and lead frame [57]. For multiple small size SiC devices, pressure-less sintering may be suitable.



(a) t = 0 cycles

(b) t = 150k cycles

Fig. 6 Cross-sectional images using sintering silver film under PTCs

3 Pressure-less sintering

Nanosilver pastes with nano/submicron and nano/micro hybrid particles have achieved dense sintering under low auxiliary pressure, e.g., less than 1 MPa or even zero pressure [40-41]. Nanosilver paste can wet the bonding surface of power devices and substrates better [58], and pressure-less sintering of the nanosilver paste is feasible to be as simple as solder reflowing. Fig. 7 shows a typical pressure-less sintering process [58]: (1) The nanosilver paste is coated on substrates by stencil-printing or dispensing, forming an as-printed pattern similar to solders; (2) Power devices are mounted on the as-printed pattern; (3) The assembly after mounting is sintered by the pressure-less sintering according to the preset temperature profile; (4) Cooling.

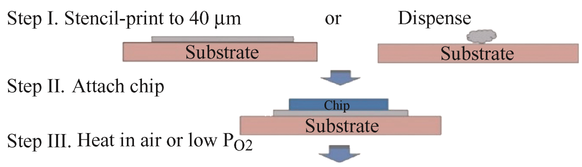
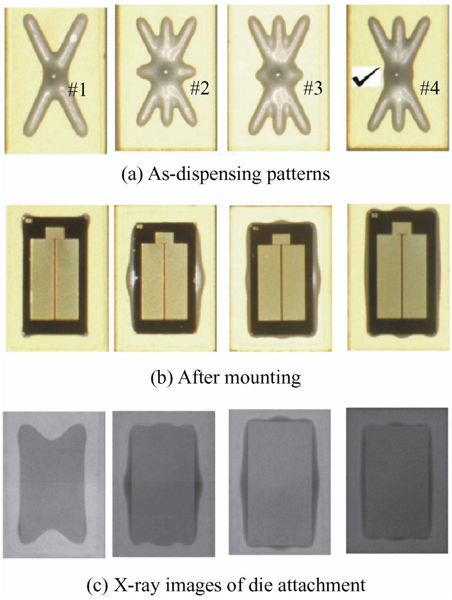


Fig. 7 A diagram of the pressure-less sintering process

Void defects are a critical concern for large-area sintered silver attachment using the pressure-less sintering [59]. Void defects must be controlled before sintering, especially during mounting devices. To minimize the void defects, some researchers designed and optimized the dispensing or stencil-print pattern of silver pastes [59-60]. Fig. 8a shows the patterns during the dispensing process [59]. The air bubbles of the as-dispensing paste during the mounting can be squeezed out. However, the pattern should be optimized to prevent the excess insufficient and overflowing of the nanosilver paste. Moreover, the mounting accurate pressure and position should be controlled strictly. The steady dispensing or stencil-print and the precise mounting process may be critical to the thickness control of the bond lines.



(a) As-dispensing patterns

(b) After mounting

(c) X-ray images of die attachment

Fig. 8 As-dispensing patterns and mounting process

Based on an optimized stencil-print pattern, the die attachment for large-area power devices (larger than 100 mm²) using pressure-less sintering has achieved a shear strength of approximately 30 MPa at a low sintering temperature of 250 ℃ [58], and small-area die attachment (4-25 mm²) could also reach approximately 45-80 MPa [50], which is significantly higher than that of solders.

Fig. 9 demonstrates a double-side cooling SiC packaging case using the pressure-less sintering [58]. These packaging cases are mainly composed of SiC MOSFETs, moly plates with silver metallization, top and bottom substrates, terminals. The back terminals of the SiC devices are sinter-bonded to the bottom substrate, and then moly plates are sinter-bonded to the front terminals without any pressure at 190 ℃. For this double-side cooling packaging, the heat-dissipating path from junction-to-case can be shortened effectively and the sintered silver with high thermal conductivity can be dissipating distribution to power devices for high-temperature applications. Therefore, those SiC modules with the pressure-less sintered nanosilver are believed to be approximately 40% better in heat-dissipating capacity than that of the traditional wire-bonding case.

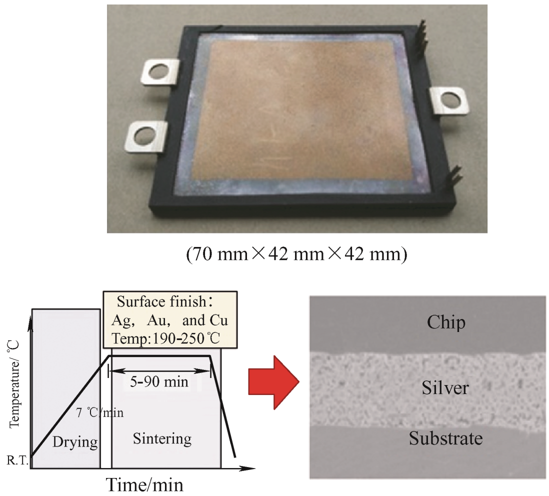


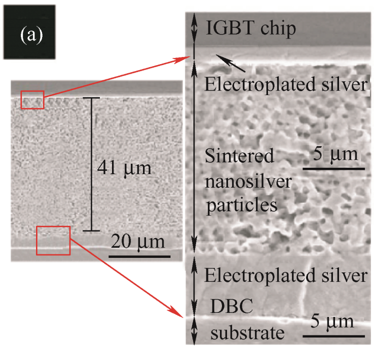
Fig. 9 Double-sided cooling SiC packaging using the pressure-less sintering

Considering that expensive SiC-based devices have higher Young's modulus than Si-based devices [15], the pressure-assisted sintering is prone to damage the power devices, resulting in a low yield for multi-chip SiC power modules [34]. Therefore, using the pressure-less sintering for bonding SiC-based power chips with the small chip size is preferred for massive production. Furthermore, the pressure-less sintering is compatible with the vacuum reflowing furnaces for solders [60]. Thus, less investment is required for specialized equipment compared to the pressure-assisted sintering.

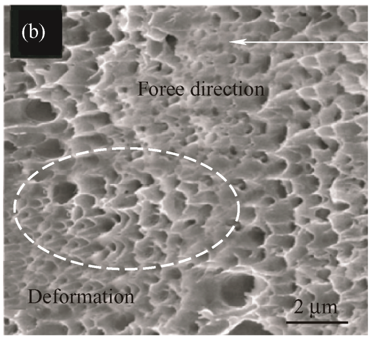
4 Other novel sintering techniques

Pressure-assisted sintering and pressure-less sintering are based on heating approaches from hot plates or atmospheres. Furthermore, there have been some novel sintering approaches, e.g., electric-current-assisted sintering (ECAS) [61], selective laser sintering [62] and microwave sintering [63], to improve the efficiency and the physical properties of sintered silver attachment.

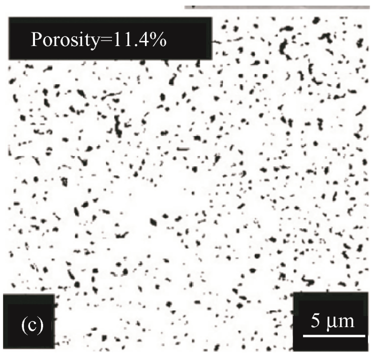
ECAS is a rapid silver sintering method, which uses a pulse current to heat the silver paste. Fig. 10 depicts an ECAS sintered silver die attachment [64]. Here, 13.5×13.5 mm^2 IGBT chips are bonded to a bare copper substrate using nanosilver paste with 20-80 nm silver particles, and the rapid sintering is finished in only 10 s under the low auxiliary pressure of approximately 1 MPa. The average shear strength with high sintered density could be higher than 25 MPa [61]. Note that ECAS may cause the interface delamination between devices and sintered silver layers owing to the rapid volatilization of organics in the nanosilver paste. Appropriate pre-heat temperature, time, and pressure are required. In addition, novel microwave sintering and selective laser sintering are utilized to sinter metals/metal matrix composites with ceramics [62-63].



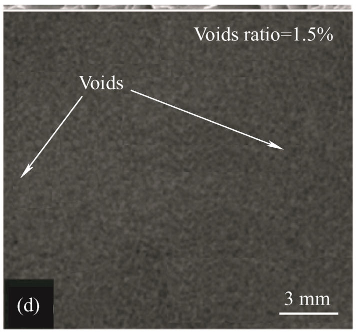
(a) Cross-sectional SEM images



(b) Fracture misconstruction



(c) Pore distribution of sintered silver



(d) Void defects

Fig. 10 ECAS case using nanosilver paste

5 Outlook

The pressure-assisted sintering is a reliable sintering approach for bonding power devices for high-temperature applications. However, the pressure-assisted sintering can cause a decrease in the yield and efficiency for bonding multiple chips, especially with complex architecture. To achieve robust sintered silver attachment efficiently under significantly low sintering pressure, new heating sources, e.g., electric-current, selective laser, microwave, etc., can be combined using pressure for low-temperature sinter-joining of silver particles in the future. The decrease in sintering pressure is essential to reduce the cost of the special sintering equipment.

The pressure-less sintering has inherent advantages itself for sinter-bonding multiple chips targeting for high-density integration of a power module. However, pre-defects should be controlled strictly for acceptable reliability. It is suggested that the defect formation mechanism of the pressure-less sintering of nanosilver should be clearly clarified to propose elimination methods. Furthermore, it is important to control precisely the warpage of substrates during the pressure-less sinter-bonding to ensure good wettability and inter-diffusion in the future.

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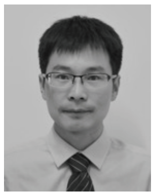

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