Development and Assessment of Power Module Using TLPS Attach

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***Abstract*—Transient liquid phase sintering (TLPS) has been demonstrated as an effective interconnect technology for electronic systems in extreme temperature conditions. TLPS joins metallic surfaces at low process temperatures and minimal pressure. Despite having low processing temperatures, TLPS has high melting temperatures post-processing, expanding its applications to extreme thermal loads, for example induced by high power densities. Wirebonds, the conventional topside interconnect technology, show limited time to failure under thermal cycling conditions. In this paper we introduce alternative topside interconnect technologies that make use of TLPS and show the potential for high temperature operation. Three different power module configurations are assessed. It is demonstrated through simulation and experiments that the design of a topside interconnect must be optimized to reduce bending and stress in the die to prevent fracture.**

Keywords—Transient Liquid Phase Sintering; Die Attach; Assessment

I. INTRODUCTION

Power electronics have many applications in a growing number of fields and increasingly needed to withstand extreme conditions. Environments that impose high thermal stresses can cause malfunctioning of power modules. For example, in the automotive industry electric cars require power electronics in under-the-hood conditions which introduces components to large amounts of thermal stress. In space applications, power electronic packages need to withstand both extreme cold and heat. Making sure that materials within power modules can withstand the conditions they will be implemented in is essential to their reliable operation.

Although silicon is mainly used as the typical semiconductor material for power electronics, application temperatures are limited to 175˚C. In order to withstand more thermal energy, wide band-gap devices are being introduces as viable replacements for silicon. These materials include silicon carbide and gallium nitride which extend constraints on operating temperatures to beyond 450˚C [1,2].

The operation of a power module generates heat. This heat will raise the temperature of the electronic device. Once the device is turned off, it no longer generates heat. The device subsequently begins to cool until it reaches a steady temperature. Continuously turning a power module on and off will cause repeated cycles of temperature rising and lowering. Internal components such as solder and wirebonds will fatigue under these repeated stresses. Repeated fatigue can eventually induce failure of a package

In order to implement power electronics under extreme thermal stresses, power modules need to not only be structured with components that can withstand drastic changes in temperature but also are not expensive to process, can form with few voids and pass established health requirements. The following conventional die attaches have qualities that make them poor candidates for high temperature applications.

- Eutectic Sn37Pb solders possess low melting points of 183˚C and show high deformation at low stress levels [4].
- Eutectic Sn3.5Ag has a low melting temperature of 221 C and Sn-Ag-Cu solders of 217˚C. Both alloys are ductile and form extensive intermetallic compounds when thermally aged [4].
- Bi-Ag solders have melting temperatures of 262˚C. They have poor wetting capabilities, ductility, and thermal conductivity. Silver can be added to reduce their brittleness but only at higher expenses. [4]
- Solders that have Pb as the main component have melting temperatures of about 290˚C. Increasing regulations on the use of Pb restrict the use of this attach for many situations. [4]

"In contrast, TLPS shows the potential for reliable operation under extreme temperature applications. This technology enables the formation of joints at low temperatures while maintaining their high melting temperature after processing. It has been shown that interconnects formed by TLPS maintain integrity at temperatures of up to 600˚C [5]."

The rate at which different materials expand or contract when undergoing a change in heat is designated by the coefficient of thermal expansion (CTE). When materials that have different CTEs are attached together and then heated, one material will expand more quickly than the other causing the conjoined materials to bend. Fig. 1 depicts this process. If a material undergoes too much thermo-mechanical stress, it may begin to fracture and crack. Because of TLPS's rigidity, fractures can sometimes occur. Properly optimizing sinter ratios and package configurations can mitigate failure in a power module.

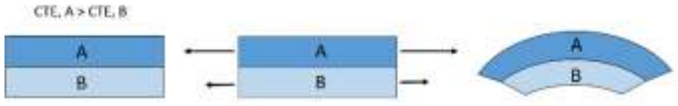

Fig. 1. CTE missmatch bending

II. TRANSIENT LIQUID PHASE SINTERING

TLPS is a potential substitute to solder in die attach applications as it can withstand more extreme thermal conditions and maintain structural integrity of die during such temperature cycling. The solders listed above pose many problems that inhibit their use in power electronics for high temperature applications.

A. *Overview of Process*

The process in which a sinter joint is formed is outlined below and depicted in Fig. 2

1. The high temperature constituent is mixed with a binder and low temperature constituent
2. The paste is stencil printed on substrate
3. Die is placed on sinter paste
4. Assembly is processed in an oven at processing temperature T_p.

This process was applied to each of the specimens recorded in this work. Fig. 2 shows what a die looks like before processing takes place, i.e. the sinter paste has not formed a solidified joint.

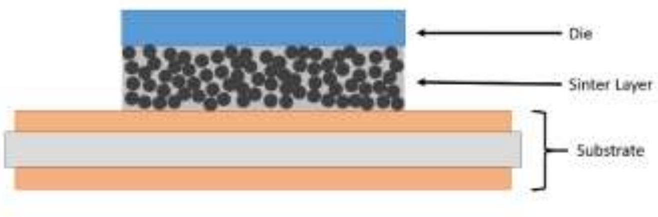

Fig. 2. Processing module set up

B. *Technology*

The TLPS used in this work is composed of a low melting point constituent A and a high melting point constituent B. This mixture is mixed with an organic binder to increase the viscosity of the low temperature constituent and ultimately improve its ability to be stencil printed.

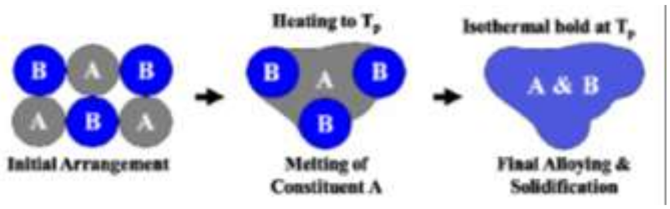

Fig. 3. Transient liquid phase sintering [5]

Processing takes place at temperature T_p which is between the melting temperatures of A and B. As shown in Fig. 3. The low melting temperature constituent A must easily be able to access B particles so that A and B can interdiffuse and form a sinter layer.

During processing, organic binder/flux first evaporates from the sinter paste. As the binder escapes the high melting temperature constituent, voids are left behind. Since processing temperature exceeds the melting temperatures of A, the solid low melting temperature constituent changes phase into a liquid. Capillary forces draw the liquid into the voids left by the binder [5]. On the interface between the low and high melting temperature constituents intermetallic compounds (IMCs) form. Enough high melting temperature constituent is needed to consume all of the low melting temperature constituent in order that the resulting compound after processing is composed of mainly high melting point constituent and IMCs [4].

C. *Ratios*

Determining which sinter materials and composition ratios to use in packages is pivotal to ensuring that interconnections can dependably be used for specific applications. In this work, since power modules are intended to endure high temperatures, the sinter material used is required to possess a high melting temperature after processing. However, a low processing temperature is also desired so that components themselves do not over heat and so that package processing is more cost effective. The processing temperature relies on the T_{melt} of the lower melting temperature constituent, since that is the material melted during processing. The low melting temperature constituent in

The sinter discussed in this paper uses a specific composition ratio to affect the permeability of the low melting temperature constituent and the generation of voids. The high melting temperature constituent experimented with in this work is composed of varying sizes: 5µm to 50µm diameter particles. Different sized particles were selected to maximize the ease at which low melting temperature constituent can flow through the sinter paste and replace the binder to circumvent voiding.

Using only large high melting temperature constituent particles causes voiding. Binder evaporated too quickly and the low melting temperature constituent did not evenly fill the voids left behind by the evaporated binder/flux as shown in Fig. 4. Often this would leave a thin coating of low melting temperature constituent (A) on the inside of an arrangement of large high melting temperature constituent (B) and a void within that coating. As in Fig. 3 Using only small particles (B), after the binder/flux evaporated, the flow of the low melting temperature constituent (A) through the sinter is restricted into flowing into the spaces left behind by rapid sintering between the thin gaps. The arrows in Fig. 5 depict how A is only partially drawn in to the spaces between the B particles. The B particles are so close together that liquid A is not able to be sucked by capillary forces into the voids. Hence, using a combination of large and small high melting temperature constituent particles is necessary to have low voiding sinter joints.

Fig. 2

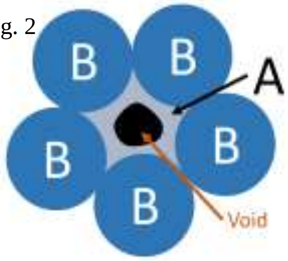

Fig. 3

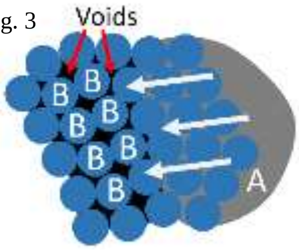

Fig. 4. Large high melting temperature constiuent particles generate voids

Fig. 5. Small high melting temperature constiuent particles generate voids

Voiding in sinter is undesired for several reasons. The presence of voids in a sinter joint reduces its thermal conductivity. This will reduce the efficiency of heat transfer from a device to a heat sink which can cause over heating of the device. The lack of continuity in a joint can also decrease its electrical conductivity, which increases the resistance and generates heat. Mechanical properties are also affected by existence of joints in a sinter interconnect. When a package undergoes mechanical stress either from vibrations or thermal expansion, cracks can be initiated from voids in a joint, and rapid crack propagation is facilitated.

Copper Nickel Tin and Nickel Tin have both been successfully demonstrated as materials for sintered joints. Nickel or copper nickel is used as the high melting temperature constituent while Tin is used as the low melting temperature constituent. Both have different properties and perform differently when undergoing equivalent conditions. Reference [6] provides a microstructural analysis of the different types of sinter pastes when implemented into a joint.

III. POWER MODULE CONFIGURATIONS

Current technology that is used in power modules can only withstand a limited range of temperature cycling before failing. Conventional power modules use wire bonds as top attaches. Wire bonds will fatigue over time due to repetitive thermal expansion and contraction. This can lead to a dislocation of the wire bond from the top of the active component. Wire bond failure is the leading failure that occurs in power electronics as a result of thermal cycling [3]. A conventional power module configuration is shown in Fig. 6.

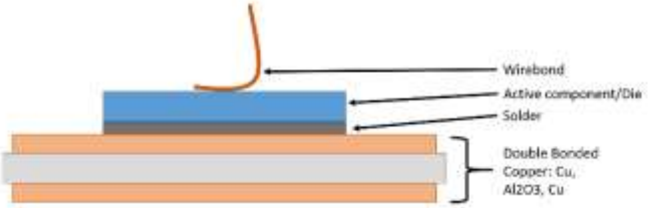

Fig. 6. Connventional power module with wirebond

To avoid wire bond fatigue, this work proposed a power module with a copper ribbon instead of a wire bond. Fig. 7 shows a power module that has a die attached to a double bonded copper (DBC) substrate and a ribbon attached to the upper side of the die. The DBC was made from a layer of Alumina with a layer of copper on either side. We labeled this configuration zero. All interconnects were formed using TLPS. A module with this configuration was processed. The resulting die had cracks initiating from its edges as shown in Fig. 14.

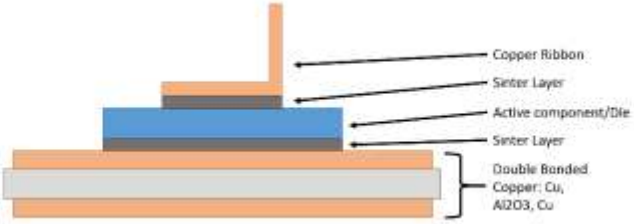

Fig. 7. Configuration 0: Copper ribbon as topside interconnect.

The die in configuration zero incurred bending on both its top and bottom. The difference in CTE of the copper and the DBC caused the die to bend more on the top then on the bottom initiating fractures.

The copper ribbon, functioning as the upper attach, and the copper interposer, separating the active component from the substrate, both have the same CTE since they are made of the same material and have the same thickness. By placing the ribbon above the die and the interposer in between the die and the substrate, the stresses on the die would be symmetrical on the top and bottom. This feature will be referred to as a type of CTE symmetry.

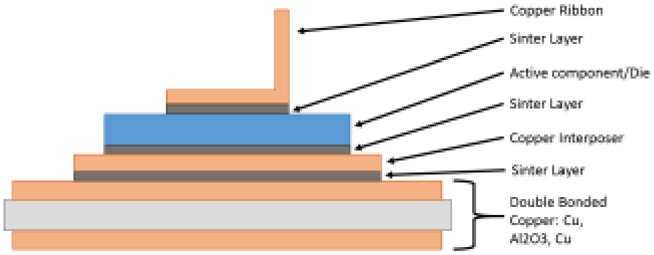

Fig. 8. Configuration 1 for CTE symmetry about die.

After implementing aforementioned criteria such as maintaining CTE symmetry about the die into a proof of concept design, the configuration in Fig. 8 was obtained. Fig. 8 illustrates that to connect each of these additional layers, extra sinter layers would be required. We labeled Fig. 8 configuration one.

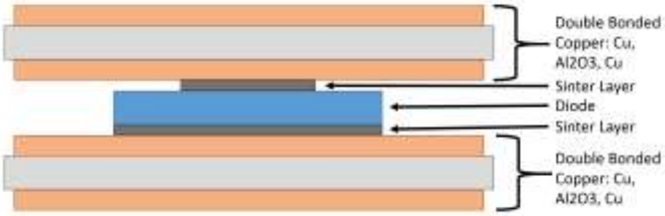

Fig. 9. Configuration 2 for CTE symmetry about die.

A second configuration requiring fewer sinter layers and more CTE symmetry was also designed. Fig. 9 shows this second assembly uses a DBC as a top attach instead of a ribbon or a wire bond. The upper sinter layer apears smaller than the sinter layer below the die because the dies used in this work all possessed a smaller mettalized area on top than on bottom. The sinter on top only wets the mettalized area and therefore only touches the die in a certain area.

IV. MODELING AND SIMULATION

CAD models of the packages were used to simulate thermal stresses from processing. This section examines the thermal and mechanical stress and strain simulations of power modules with and without a copper interposer using the first configuration shown in Fig. 4 to observe how dies can withstand fractures.

Below are strain simulations of power modules with and without interposers. These computer models simulate a geometry through a heating cycle and demonstrate that CTE mismatch can cause a package to warp when heated from 300˚C to 22˚C.

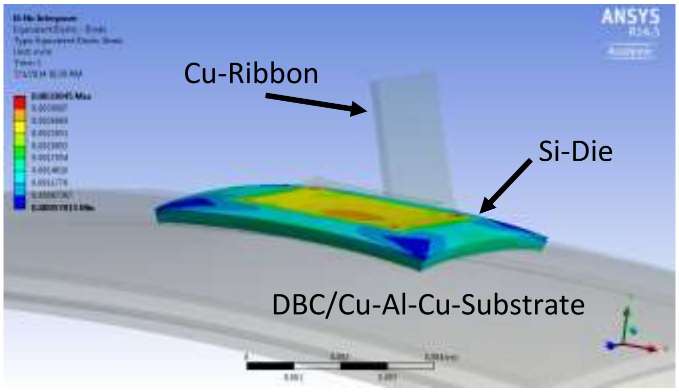

Fig. 10. Isometric view of strain on die with no interposer.

Fig. 10 and 11 show strain simulations of configuration zero. The die (colored) in Fig. 10 bends convexly because the DBC substrate decreases in surface area as it cools after processing takes place. In Fig. 11, the middle of the die is straight, while the ends are bent. The radius of curvature on the bent edges are different from on the top and bottom. The locations where the radius of curvature changes can potential initiate cracks within the diode.

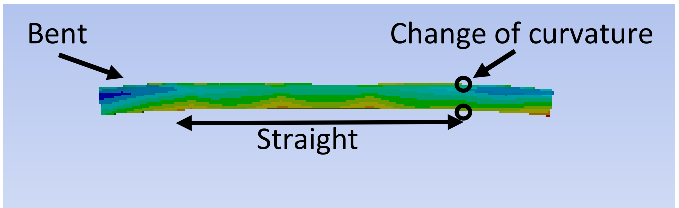

Fig. 11. Side view of strain on die with no interposer.

In Fig. 10, the die appears bent and to have significant strain. The simulation uses configuration 1 as depicted in Fig. 10. and thus possesses a 250 micrometer ribbon as a top attach and a DBC as a substrate, both of which are adjacent materials to the die (excluding the sinter). These materials have different CTEs and cause there to be CTE-mismatch about the die. Adding a Cu layer between the DBC and the die, as shown in Fig. 8 can mirror the CTE about the die and reduce strain during processing.

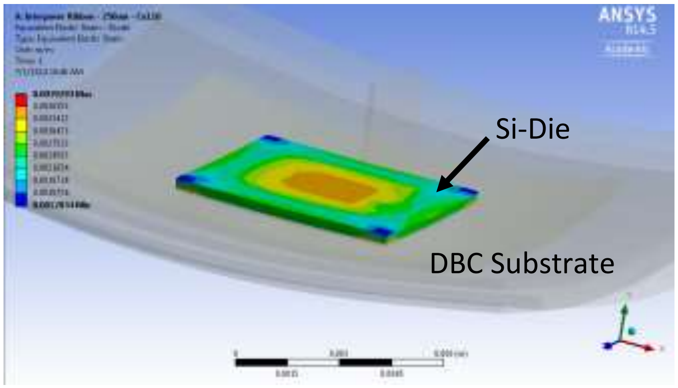

Fig. 12. Isometric view of strain on die with a 250 micrometer interposer.

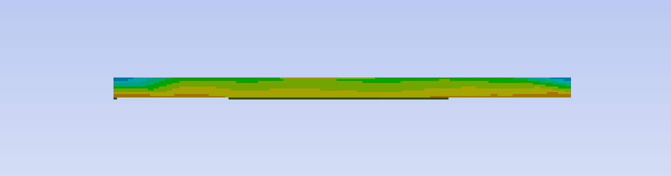

Fig. 13. Side view of strain on die with a 250 micrometer interposer.

Fig. 12 and Fig. 13 both depict strain simulations of specimens with interposers. These interposers have the same thickness and CTE as the ribbons above the die and will reduce the CTE mismatch about the die. This should ultimately reduce bending of the die. While the substrate in Fig. 12 appears to be concave from thermal expansion, the die maintains a horizontal form. Fig. 13 illustrates that after processing, the profile of the die remains unbent. The simulations indicate that using an interposer would induce symmetrical forces on the die from thermal expansion. This shows that CTE-Symmetry leads to minimized bending which should reduce the die's susceptibility to fracture.

V. ASSEMENT

This section demonstrates the assessment of the geometries described and simulated above. It also compares the results of CTE symmetry of configurations 0, 1 and 2. Using both optical microscopy and environmental scanning electron microscopy (ESEM) the quality of different

A. Optical Microscopy

Images were obtained from an optical microscope to assess the process used in sintering the aforementioned power module configurations. Fig. 14 shows a specimen using configuration 0. prepared with a die sintered in between a copper ribbon (the top attach) and a DBC substrate.

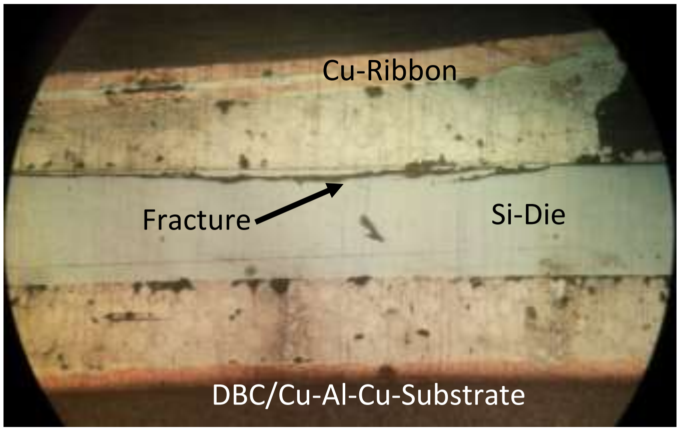

Fig. 14. Configuration 0: Fracture in die initated by thermal expansion.

The die fractured in Fig. 14. As simulations showed, the die in configuration bent during the cooling stage of processing. This bending induced enough stress and strain to the die to cause it to crack. The fracture in the die appears to have originated from the void on the right side of Fig. 14.

Although simulations predicted that adding an interposer, as in configuration one, would reduce strain on the die, implementing the interposer caused specimens with this configuration to fracture. Fig. 15 depicts a power module made with configuration 1.

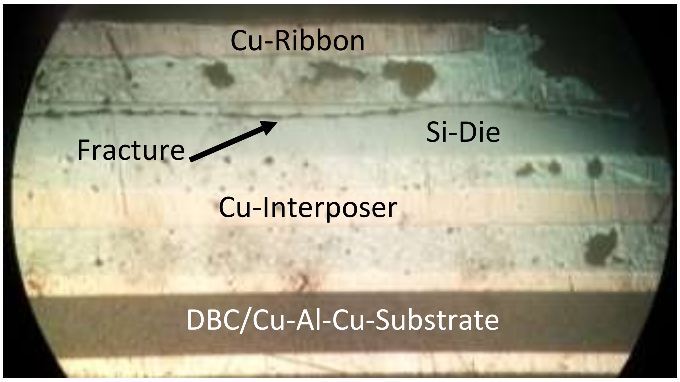

Fig. 15. Configuration one: copper ribbon symmetry about die.

The fracture was initiated from one of the edges of the specimen which implies that CTE-mismatch was a factor. Although the die remained flat, as shown in simulations Fig. 12 and 13, stresses on the die were enough to fracture the die. This configuration proved to be an ineffective way to reduce fracturing since the die still incurred stress.

Configuration two provided more promising results. Fig. 16 illustrates a configuration 2 module with an intact die post processing. This behavior was expected since the model has perfect symmetry.

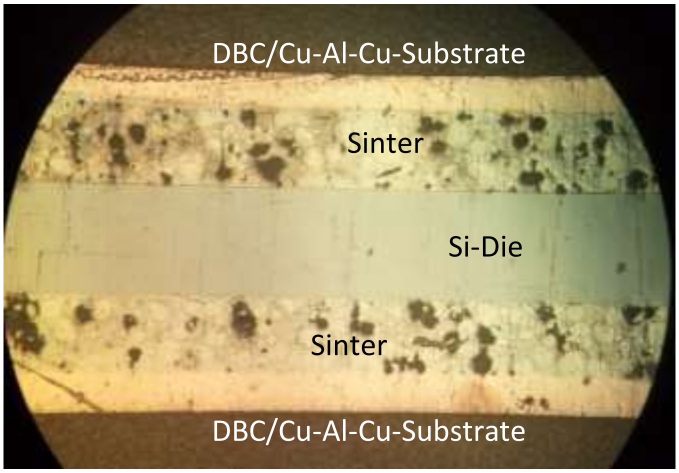

Fig. 16. Configuration two: DBC symmetry about die.

Voids seemed to be prevalent in this work's second configuration specimens, yet it did not fracture.

B. *Environmental SEM*

ESEM was used to observe cross sections of our specimens. In this work, ESEM was used to distinguish different parts of interconnects to analyze joint quality by observing IMC generation, presence of low and high melting temperature constituents, and voiding. Most of the specimens used for ESEM possessed a configuration made solely from a die attached to a DBC with a sinter interconnect, which was part of process optimization studies.

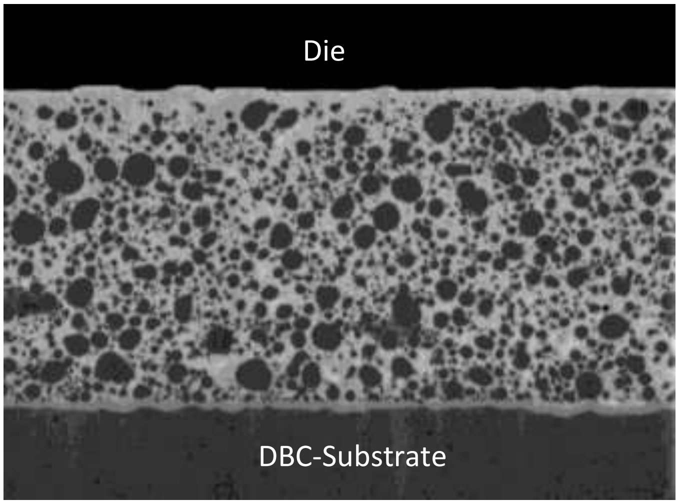

Fig. 17. High quality joint (500x).

Fig. 17 shows a specimen possessing a well processed joint with no voiding. Dark gray spots are High melting temperature constituent particles (in this sample they were made from nickel) and lighter grey surrounding them are IMCs generated during processing. No low melting temperature constituent (made from tin) is present since it has completely been consumed in the formation of IMCs with nickel. The small gray layer between the DBC and the sinter joint is made up of an IMC from copper and tin.

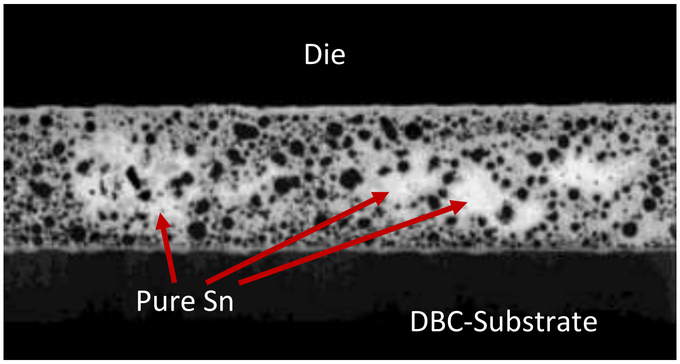

Fig. 18. Excess low melting temperature constituent in joint (250x).

Fig. 18 illustrates a different location of the same joint as in Fig. 17. Here the excess low melting temperature constituent is present (shown in the very light gray) and has not fully formed IMCs. This produces joints of lower quality and reduced mechanical integrity. Fractures may initiate at high temperatures from joints where there are large portions of excess low melting temperature constituents since it becomes softer and deforms plastically.

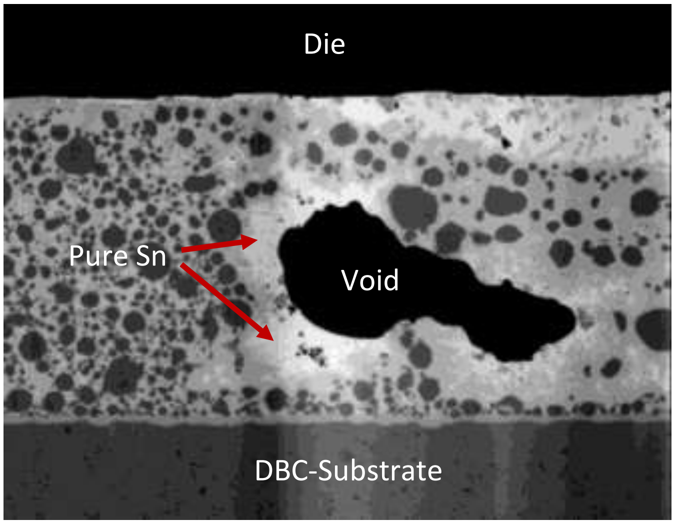

Fig. 19. Void generated by lack of Sn (500x).

Fig 19. depicts the same joint as in Fig. 17 and 18 except shows a view near the edge of the specimen. Fig. 19 depicts a joint made of TLPS with too little low melting temperature constituent. As binder evaporates, not enough low melting temperature constituent can fill the gap left behind. Localized spots of high melting temperature constituent can also lead to areas of void concentration due to particle rearrangement. This generates voids as seen above.

These voids can also generate cracks in a sinter joint. As a module flexes when it is heated, a joint that has voids can bend more easily since the interconnect has less material in various places. Shown in Fig. 20, a crack initiates from a void and fractures the adjacent IMCs. A crack like this can potentially cause a die to undergo stress that can cause it to fracture.

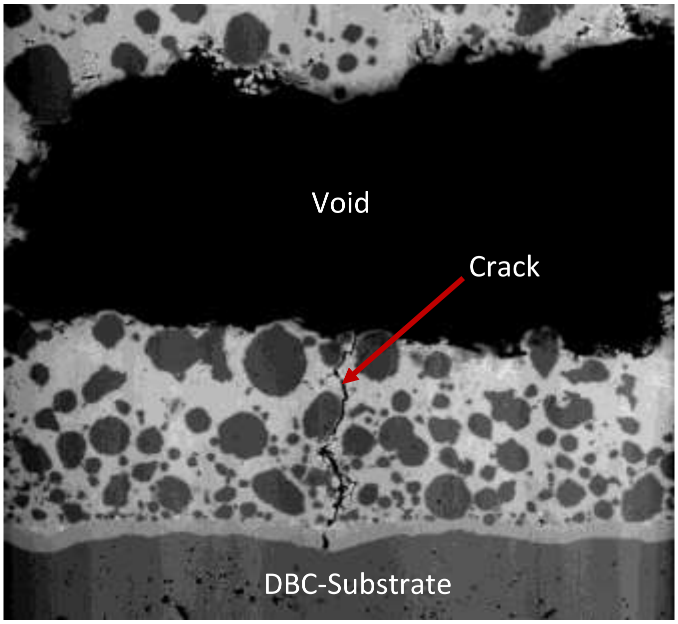

Fig. 20. Crack generated by void (1000x).

An ESEM image was also obtained for a specimen with configuration one shown in Fig. 21. The image depicts a die that has a copper ribbon on top and an interposer in between the die and the substrate. This configuration is designed to minimize stress on the die by reducing bending.

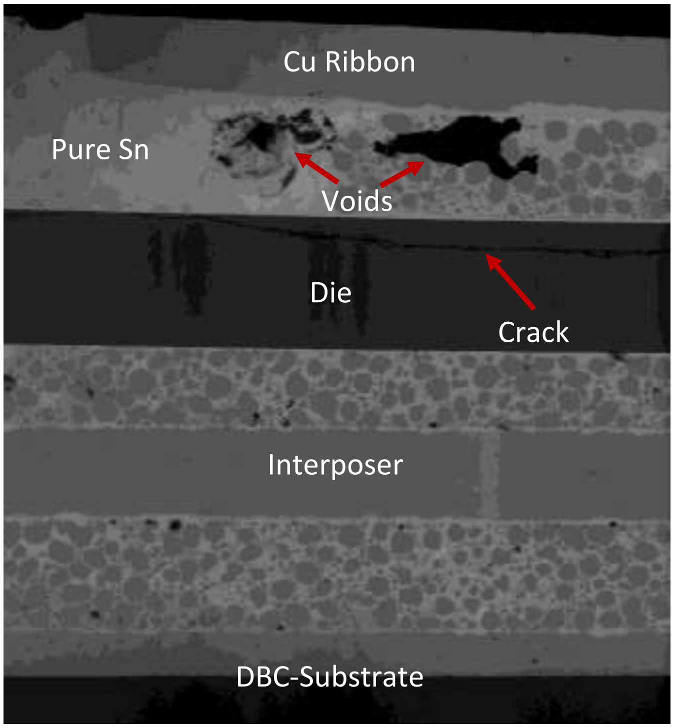

Fig. 21. Crack generated by abundance of Sn (1000x).

The joints between the DBC, the interposer, and the die appear to be high quality joints. Between the upper ribbon and the die, however, a void formed. Within the same interconnect layer there is an abundance of low melting temperature constituent. As simulations in Fig. 12 and 13 show, the die did not bend in this module but still incurred enough stress to form a crack in the die. A combination of the presence of a void, an excessive amount of low melting temperature constituent and stresses induced by CTE mismatch caused the module to have reduced integrity and the die to crack.

CONCLUSION

After thorough simulation and analysis, dies in this project that underwent high thermal stresses during processing were found to have decreased strain and fractures when they possessed configurations that minimized CTE mismatch. Specimens of configuration 1 repeatedly had cracked dies. Although simulations confirmed that an interposer would improve CTE symmetry and the dies would resist fractures, cracks nonetheless were generated. Configuration 2, having better CTE symmetry about the die, proved to be a reliable novel configuration for a power module. Voiding is still an issue with specimens that undergo thermal cycling.

FUTURE WORK

Future work for the advancement of TLPS will include altering sinter compositions, processing temperature patterns, and methods of extruding sinter paste onto a substrate. Sinter paste compositions can be improved by altering the large to small high melting temperature constituent particle ratio so that small particles can fill the voids between large particles. Adjusting the amount of flux may also improve the quality of a joint. Processing temperature can have altered ramp rates which can more quickly or more slowly change the rate at which binder/flux evaporates and low melting temperature constituent liquefies. Stencil printing quality joints can influence the presence of voids in a specimen.

Future work also includes the generation of a proof of concept model of an entire power electronic system. The electric aspect of this system would also need to function properly.

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REFERENCES

[1] T. Funaki, J.C. Balda, J. Hunghans, A. S. Kashyap, H.A. Mantooth, F. Barlow, T. Kimoto, T. Hikihara, “Power conversion with SiC devices at extremely high ambient temperatures”, *IEEE Transactions on Power Electronics, vol. 22, no. 4*, 2007.

[2] J. Casady and J. R. U. Dillard, "A hybrid 6H-SiC temperature sensor operational from 25˚C to 500˚C," *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part A, vol. 19, no. 3, pp. 416 - 422*, 1996.

[3] P. McCluskey, “Reliability of power electronics under thermal loading,” CIPS 2012, pp. 1-8.

[4] A. Moeini, H. Greve, P.McCluskey, “Strength and reliability of high temperature transient liquid phase sintered joints,” International Conference on High Temperature Electronics, 2014.

[5] H. Greve, L. Chen, I. Fox, P. McCluskey, “Transient liquid phase sintered attach for power electronics,” 63rd IEEE Electronic Components and Technology Conference (ECTC), 2013

[6] H. Greve, P. McCluskey, “Reliability of Sn based LT-TLPS joints for high temperature electronic systems,” in Integrated Power Systems (CIPS), 2014 8th International Conference on. Nuremberg, Germany: VDE, 2014, pp. 1-6.