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Influence of Material Properties on Ruggedness Evaluation of Package Architectures for SiC Power Devices

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Abstract. Button shear tests at different temperatures between different mold compounds and Cu-leadframes have been performed in order to evaluate the adhesion of mold compounds to the inner surfaces of SiC-power devices. The results at different temperatures show the behavior of different material and layer stack combination under storage at room temperatures as well as under operating conditions with elevated temperatures, where adhesion and thus the hermeticity of the device against moisture is significantly lowered. It has been shown that different thermomechanical properties of the mold compounds as well as the usage of different adhesion promoter materials have a significant effect on the adhesion properties of the mold compound to the leadframe surface of the SiC power devices, which have direct impact on the ruggedness and lifetime stability. Furthermore, these results have been correlated to thermomechanical simulations of the package architecture of SiC power devices under stress. Different wire bond architectures have been evaluated in simulations with and without die top delamination taken into account, showing that EMC delamination may play a major role in the lifetime stability of SiC power devices under thermomechanical stress like simulated in TCT- , IOL- and PTC-testing.

Introduction

The recent advancements in power electronics are mostly derived from the development of new generation wide bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN). These devices provide higher power density and operate at higher frequencies. For instance, SiC device at high voltage of 900V or more may only occupy relative small areas of just tens of square millimeters.

With their generally accepted superior electrical performance, SiC power devices and modules – especially transfer-mold module devices - are adopting widely the field of high power applications [1,2]. In this context, high reliability and ruggedness is essential to unlock the full potential of SiC in demanding high-power applications. Therefore, package and module reliability play an important role to safeguard the devices under harsh environments. Package architectures have to be carefully chosen, especially as the thermomechanical properties of the package and module material stack are different due to the special properties of SiC compared to conventional Si-power devices.

In order to safeguard the package architecture against humidity and thermomechanical stress, it is necessary to optimize the chip design, geometry and thickness as well as the adhesion of the package encapsulation mold compound (EMC) to the leadframe and die surface under all circumstances of operation. Delamination – when occurring - would have a severe impact on hermeticity against moisture on the one hand as well as on stress and strain conditions on die surface, die attach and wire bond interfaces on the other, thus affecting interconnect stability for typical wire bonding (Al wire wedge-wedge bonding) as well as for typical die attach technologies such as soft soldering, sintering etc. [3]. This paper focuses on transfer mold package architectures, for soft Si-gel encapsulation package and module architectures, the interaction of materials is completely different and the differences to Si-device behavior is not that significant [4]

Experimentals

To evaluate the adhesion properties of different mold compound types and different kinds of adhesion promoters to leadframe and die surface, standardized material button shear tests have been performed at different temperatures between 25°C and 260°C (please see Fig.1 for description). This was done to access the material adhesion under different conditions during device processing as well as device operation during application (shown in Fig. 2-5), and to correlate it to different material properties of the material stacks used which show different coefficients of thermal expansion (CTE) and glass temperatures Tg for the encapsulated mold compounds (EMC) used (please refer to table 1 for the experimental set-up). The button shear force can be taken as a direct measure to evaluate the adhesion strength of the mold material to the underlying surface. The different temperatures show the adhesion strength correlation of the mold material under different conditions.

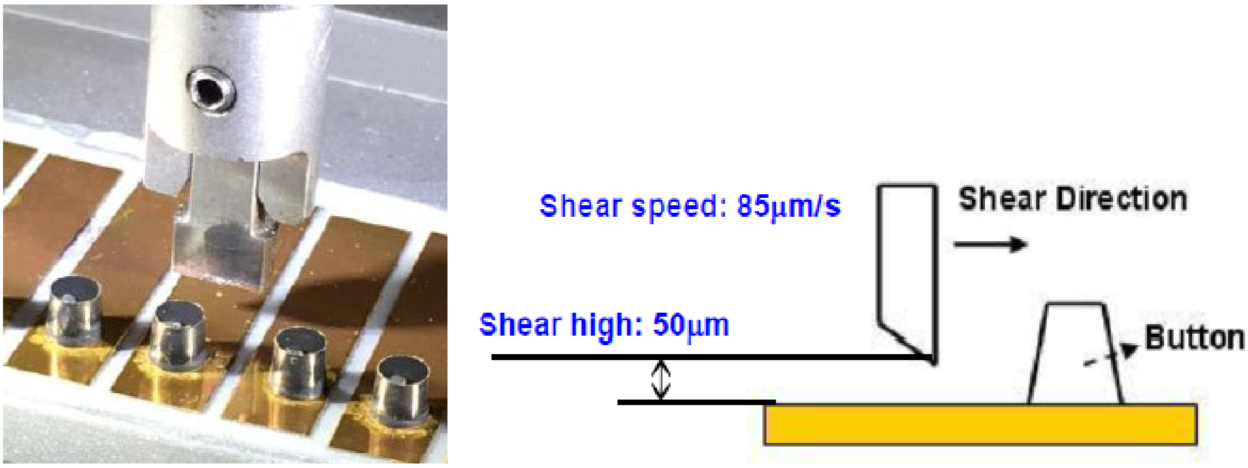


Fig. 1. Test set-up of button shear test performed for the test specimen

Table 1. Material and test selection of different mold compounds and experimental conditions for button shear tests

		Screening		Detailed investigation after material selection					
mold compounds	glass temperature Tg	T1	T4	T2	T3	T1	T2	T3	T4
EMC1	low	25°C	260°C	90°C	150°C	25°C	90°C	150°C	260°C
EMC2	very low	25°C	260°C						
EMC3	medium	25°C	260°C	90°C	150°C	25°C	90°C	150°C	260°C
EMC4	high	25°C	260°C						
EMC5	medium	25°C	260°C						
		before MSL				after MSL			

While the values at room temperature 25°C gives an insight of the adhesion of the mold and thus the hermeticity of the device during normal storage condition, measurements at elevated temperatures like 90°C and 150°C gives a flavor about the behavior and hermeticity of the device under typical and maximum operating conditions of power devices, and measurements at 260°C gives an impression about the behavior of the adhesion under typical surface-mounting-technology (SMT) conditions of devices on printed-circuit-boards. One can see in Fig. 4 that the button shear force and therefore also the hermeticity of the device is substantially decreased, given by the fact that the mold remain on the leadframe is substantially decreased at elevated temperatures. This decrease of the adhesion during elevated temperatures is important to bear in mind when judging the behavior of power devices under harsh conditions, e.g. in typical reliability tests such as TCT, IOL, PTC and HVH3TRB-testing, where temperature elevation clearly leads to a lack of device hermeticity against moisture.

It can clearly be seen from the graphs that EMC1 shows a superior performance in terms of adhesion strengths under all measurement conditions, including a preconditioning of the device due to a so-called moisture-sensitivity level test MSL (MSL condition: 168h soaking at 85°C/85%RH + 3 x reflow), which simulates moisture ingression during transport, storage and mounting of the device in final application.

This superior behavior of one EMC material over other material choices can be explained by the careful alignment of the thermal expansion coefficients CTE between the mold material and the underlying leadframe material. For the final SiC power device, also the CTE of the SiC device itself has to be taken into account and as to be balanced to the thermomechanical properties of the other materials to come to a stable layer stack. The CTE for EMC1 is the lowest one – with a value around 9ppm/K - and thus the nearest to the CTE of SiC, which is around 4 ppm/K.

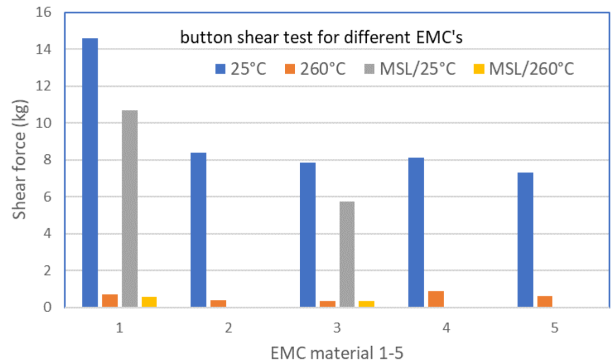


Fig. 2. Button shear tests for different EMC's on Cu-leadframes for different temperatures before and after MSL testing

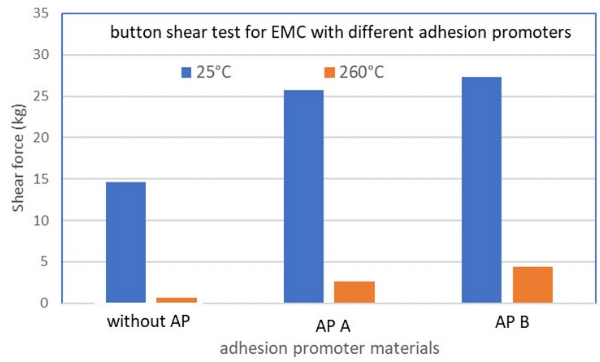


Fig. 3. Button shear tests for one EMC (EMC1) on Cu-leadframes for different temperatures and adhesion promoters

The adhesion depends strongly on the material properties as well as on the temperatures, showing that adhesion is high at 25°C and decreases significantly at higher temperatures in ranges of typical applications. For different material stacks used, the temperature dependence has been evaluated in detail showing the full trend over the full temperature range, showing that in the temperature range of operation below 150°C, special material combinations lead to a superior behavior of adhesion and therefore to higher device ruggedness in application, even after reasonable MSL stress.

As visible in Fig.3, also the use of special adhesion promoter agents between the mold compound and the underlying leadframe material can improve the button shear strength and thus the adhesion properties of the layer stack significantly. The type of adhesion promoter must be carefully balanced between the special properties of EMC, the underlying material surface – in this case Cu-leadframe, but also the special properties of SiC-chip surfaces have to be taken into account such as metal layers and polyimide coating. Please refer to table 2 for the experimental setup.

Table 2. Material and test selection of different mold compounds and experimental conditions for button shear tests with different adhesion promoter materials

		none		AP-A		AP-B	
mold compounds	**glass temperature Tg**	**T1**	**T4**	**T2**	**T4**	**T1**	**T4**
EMC1	**low**	25°C	260°C	25°C	260°C	25°C	260°C
EMC3	**medium**	25°C	260°C	25°C	260°C	25°C	260°C

To evaluate the impact of adhesion promoter coating on the adhesion strength of EMC to LF, button shear testing of EMC on pure Cu LF and PI-based adhesion promoter on Cu LF is conducted. In this study, two adhesion promoter materials are evaluated: AP A, and AP B. These two adhesion promoter materials are spray-coated onto the Cu LF, and the thickness of the PI coating is 10 µm. The button shear tests are carried out at two temperatures: 25°C and 260°C, and the results are shown in Fig.2. This result indicates that the bond stability of EMC on adhesion promoter coated LF is higher than that on pure Cu LF. The AP coating not only reduces the stress force but also improves the bonding force.

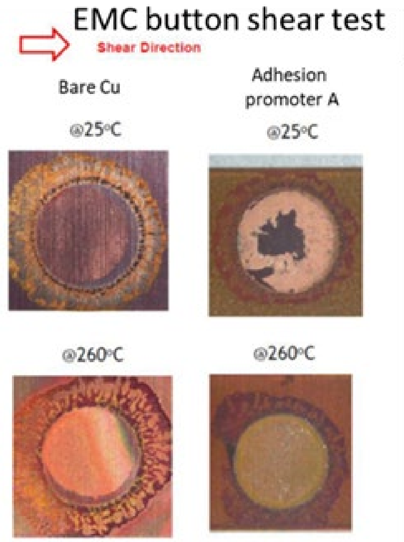


Fig. 4 Button shear tests results with adhesion promoter for one EMC on Cu-leadframes for different temperatures

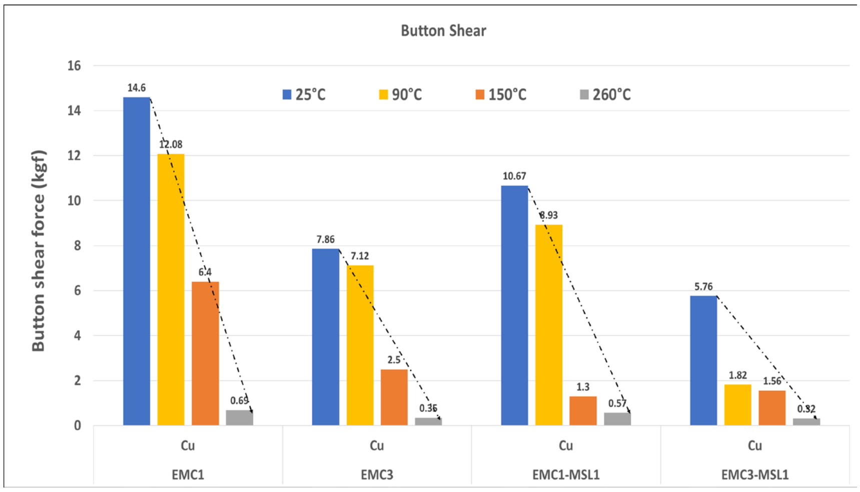
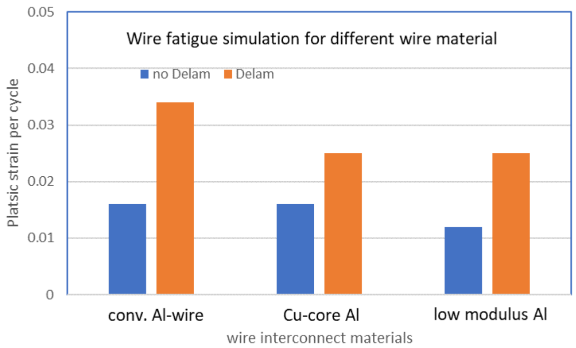


Fig. 5. Button shear tests results for two EMCs on Cu-leadframes before and after MSL for different temperatures between 25°C and 260°C

The effect of different temperatures on button shear test results can be seen in Fig 5, where two prominent mold compounds (EMC1 and EMC3) have been selected for an in-depth analysis of the mold adhesion under different temperatures before and after MSL-treatment. One can clearly see that the button shear force and the mold adhesion decreases with increasing temperature. Before MSL treatment, button shear force decreases moderately from 25°C to 90°C, while a significant drop is visible for higher temperatures up to 150°C – the typical maximum operating conditions of power devices – and especially when coming into the range of typical SMT mounting conditions like 260°C, where a dramatic decrease of the button shear force is visible. Shear forces for the two mold compounds at 260°C are almost comparable, pointing to a similar behavior during SMT mounting conditions. For this reason, it is important to control the environmental conditions during SMT mounting to avoid excessive moisture ingression during that processing time. The situation changes significantly after MSL treatment of the specimen and the subsequent similar button shear test. In this case the two mold compounds behave differently in that sense that for EMC3 the decrease at 90°C – the typical operating temperature condition of power devices - is already significant in contrast to EMC1, for which the button shear results between 25°C and 90°C are almost constant and thus a safe-operation area of the mold compound in terms of adhesion and hermeticity can be sketched. This different behavior can be correlated to different moisture absorption levels for the two mold compounds during MSL treatment. This correlation shows clearly, that a good choice of the material combination is critical to allow a stable and rugged behavior of SiC power devices especially in typical operating temperature ranges between 25°C and 90-150°C. Additionally, special attention have to be paid when MSL-treatment conditions have to be taken into account, which means the special requirements may differ from device to device layout.

These measurements can be correlated to thermomechanical simulations of the package architectures with different material stacks under delamination and non-delamination conditions (shown in Fig. 6-8), showing the significant impact of good material adhesion versus delamination on their effect in plastic strain on chip surface and interconnect interfaces as well as the creep strain on the die attach interface to the leadframe [2]. The effect of different chip surface-interconnect wire materials as well as the use of different adhesion promoter materials is presented, showing that by changes in the wire and adhesion promoter material, the balance between plastic surface strain and creep strain in die attach can be reduced significantly (see Fig. 8 and 9), thus leading to a more balanced package architecture under different circumstances of package geometries as well as different application schemes of SiC power devices [5,6].



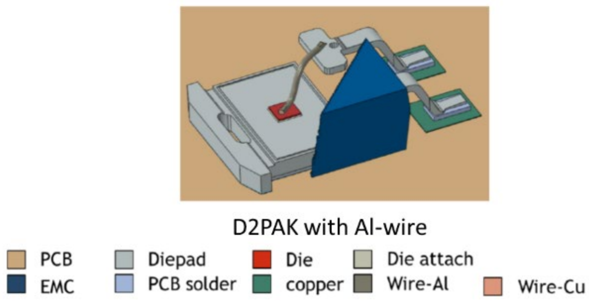


Fig. 6. Simulation model for SiC power device with Al-wire interconnection

Fig. 7. Simulation sceme of plastic strain for SiC power device with different wire material with and without die top delamination

Normally for wedge bonded wires even at zero hour, gaps can already be observed at the edges of the wedge bond. For instance, during the wedge bonding of wire to bond pad using ultrasonic power, the heel and the tail/toe part of the wire normally forms initial cracks which serves as initiation sites for the gap/crack to propagate further. For instance, during thermal cycling, the coefficient of thermal expansion (CTE) mismatch between the packaging materials particularly on adjacent materials such as the wire, die and epoxy molding compound caused the accumulation of plastic strains on the wedge [7,8]. These accumulated plastic strain causes the crack to propagate further inside the wedge bonded areas and effects on lifetime stability can be observed e.g. in TCT-tests, respectively.

Three types of thick bonding wires: type A-99.99% 4N conventional Al , type B-99% 2N purity fine-grain low-modulus Al, and type C- Al-coated Cu wires were used for thermomechanical device simulation and subsequently also for mechanical robustness evaluation [9]. Tests and simulation were performed with SiC-based device built on TO (transistor outline) package platform using 380um thick wires (3 wire types) and subjected to temperature cycling conditions of TC1 (-65°C/150°C) or TC2(-65°C/175°C).

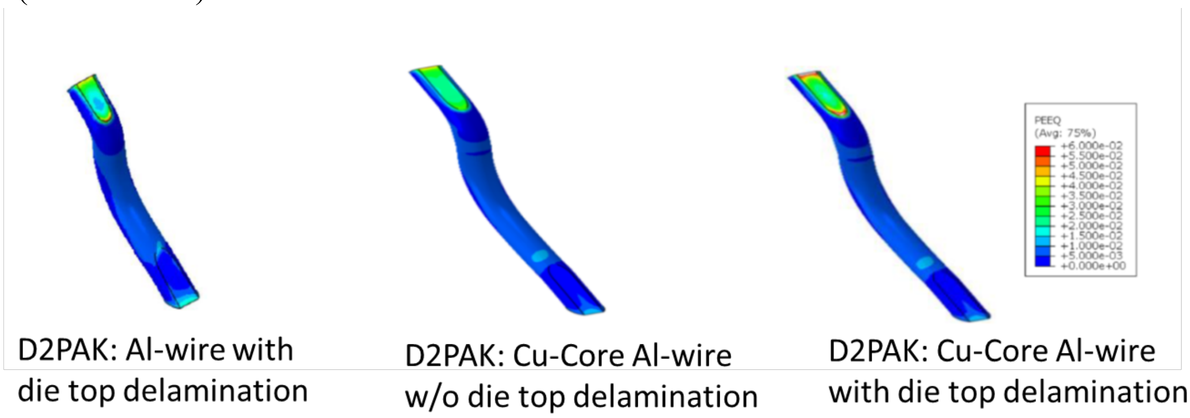


Fig. 8. Simulation of plastic strain to wedge interface for SiC power device with different wire material with and without die top delamination

Shown in Fig. 8 are the simulation results on the equivalent plastic strain at the wedge area after thermal cycle loading of -65°C to 150°C (TC1 conditions). Here, it was assumed that all interfaces have good bonding, except for delamination on the die top which was also included into the simulations.

During cyclic temperature change, crack initiation and propagation have an important impact on the bonding wire performance. For bonded wire, the CTE mismatch between the wire and SiC chip induced stress in the bonded area and at thermal cycling conditions, the wire bond connection/interface accumulates thermomechanical damage. The initial wire properties such as the yield strength, CTE, and modulus are important parameters to predict and control the wire bond performance. Thus, at higher yield strength and CTE closer to the SiC die will increase the wire's fatigue resistance when subjected to repetitive stress. Although plastic strain can be reduced by higher yield stress or lower CTE of the wire, delamination was also found to be a key factor on the induced plastic strain as shown in the simulation results in Fig. 8. The use of Al-coated Cu wire resulted to the reduction of plastic strain by as much as 26% due to the lower CTE and high yield strength of the Cu wire.

Conclusions

In summary, button shear tests at different temperatures have been performed to monitor the adhesion of different mold compounds and adhesion promoters to Cu leadframe materials of SiC power devices before and after MSL treatment. Button shear tests at different temperatures was shown as suitable method to preliminary screening EMCs with good adhesion to the leadframe. In addition, button shear tests after MSL1 treatment of molded test coupons resulted in reduced adhesion and can be used as additional selection It has been shown that different thermomechanical properties of the mold compounds as well as the usage of different adhesion promoter materials have a significant effect on the adhesion properties of the mold compound to the leadframe surface of the SiC power devices, which have direct impact on the ruggedness and lifetime stability of the devices. Additionally, the investigated adhesion promoters have shown to significantly increase the interface adhesion, especially at higher temperatures (90 - 260°C) a remarkable increase is visible. This can enable to use higher TG EMCs which have less adhesion to surfaces for high application temperatures (Tj > 175°C). It would be very interesting to extend this investigation to other inner surfaces of the device architecture such as the different materials of the chip surface, in order to get a full picture of the MC adhesion to all surfaces.

Furthermore, these results have been correlated to thermomechanical simulations of the package architecture of SiC power devices under stress (see Fig. 9). Different wire bond architectures have been evaluated in simulations with and without die top delamination taken into account, showing that EMC delamination may play a major role in the lifetime stability of SiC power devices under thermomechanical stress like simulated in TCT- , IOL- and PTC-testing. Within these Thermo-Mechanical Simulations, the negative impact of EMC delamination on strain to wedge and die attach was shown. Alternative Al wire materials can reduce the strain at wedge interface connection, but main impact is delamination, which is a clear confirmation to work on delamination reduction when improving the ruggedness of SiC power devices. These results can be used for further input on more advanced simulation models such as finite element simulations for mission profile related design for reliability for power electronics [10].

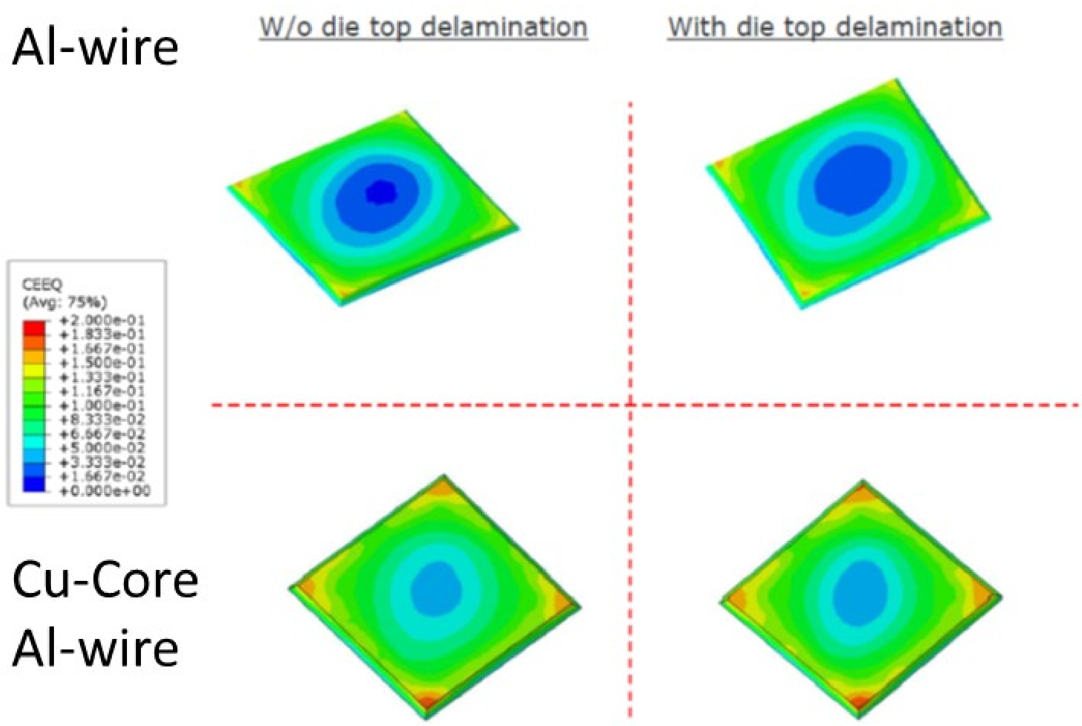


Fig. 9. Simulation of creep strain in Pb-solder die attach for SiC power device with different wire material with and without die top delamination

Button shear tests have been performed with help of the Hongkong University, Center of Engineering Materials and Reliability

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