

# Electrical Reliability of Au-In Transient Liquid Phase Bonding for SiC Power Semiconductor Devices

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**Abstract**—Transient Liquid Phase (TLP) bonding is a promising technique for SiC and other wide-bandgap power semiconductor device die-attach and high temperature packaging. TLP bonding advances modern solder technology by raising the solder melting point to over 500 °C with a low 200 °C processing temperature that creates much greater mechanical reliability and rigidity while the thermal conductivity of the die-attach is increased by 67% and the thermal resistance reduced by an order of magnitude over the traditional Sn-Pb solders. It is also shown here that Au-In TLP bonds exude excellent electrical reliability with thermal cycling degradation if designed correctly as experimentally confirmed.

## I. INTRODUCTION

As SiC power semiconductor devices gain increasing acceptance in the marketplace it is worthwhile to develop packaging technologies that allow for their full operational temperature range for utilization in extreme environments and to reduce the size, weight, and complexity of power electronic cooling systems which further reduces operating costs as well as up-front system cooling costs. Current die-attach materials limit the temperature operation range and reliability of SiC and other power devices. Traditional SnPb37 solder has a melting point of only 183° C and is incapable of supporting high the temperature operation of SiC MOSFETs that have been demonstrated to operate up to 500° C for extended periods [1].

The most desirable wide-bandgap die attach and packaging materials have a high temperature range, high thermal conductivity to dissipate device power loss efficiently, low stresses as well as high tensile and yield strength [2]. Transient liquid phase (TLP) bonding is a novel die attach method for power devices capable of providing these qualities. Several papers, primarily of proof-of-concept studies, have looked into the TLP bonding technique, but have not investigated its electrical reliability or attempted to characterize multiple bond structures [3]. This work expands the prior work in the field and is intended to measure resistivity degradation along with its material diffusion causes along with possible surface morphological changes in response to thermal cycling.

## II. TRANSIENT LIQUID PHASE BONDING

A TLP bond is composed primarily of two metals, the base layer which has a high melting point and the interlayer which has a very low melting point and a high diffusion rate into the base layer. To utilize TLP bonding as a die-attach method, the base material is typically deposited on the substrate or the die and the interlayer is deposited on the adjoining piece. The two are then put in contact with applied pressure at a temperature above the interlayer melting point causing it to quickly melt and diffuse into the base layer. The bond becomes stable by holding at the melting temperature until the interlayer is completely consumed into the base; this is known as isothermal solidification [4].

The advantage of this technique is that the resulting compound of the base and interlayer materials then becomes one solid TLP bond with a melting temperature above the original interlayer material but is joined at a much lower temperature. This results in lowering peak mechanical stresses at the high maximum operation temperature and at room temperature which lowers the total stress applied to the die-attach and device throughout operation increasing mechanical reliability, the greatest concern for die-attach. This is a large improvement over alternative high temperature brazes.

## III. FABRICATION

For this experiment, in order to measure the resistivity of the different TLP bond structures isolated from semiconductor device parameters the TLP material pair, along with a barrier layer stack, is deposited upon the surface of glass substrates opposed to forming an actual bond of a substrate and device. The material stack is shown in Fig. 1.

A base layer of gold with a high 1064° C melting point along with an indium interlayer that melts at 156° C is used as this has been shown to be a workable material pair for TLP bonding [5-7].

As an expansion of our analysis over prior TLP work, we investigate three different Au-In TLP bonds having three different compositions featuring different atomic percentages

TABLE I. TLP SAMPLE PARAMETERS

Bond	$t_{In}$ ( $\mu m$ )	$t_{Au}$ ( $\mu m$ )	Wt. % In	At. % In
A	1.261	1.0	0.323	0.45
B	3.087	1.0	0.538	0.67
C	3.087	0.223	0.84	0.90

of indium (At. % In). Bond TLP-A has a relatively high concentration of Au in the joint with an At. % In of 0.45 while bond TLP-B is proportioned to form a  $AuIn_2$  compound throughout the bond opposed to forming multiple Au-In material phases, this occurs at  $At. \% In = 0.67$ . TLP- C is a high In bond with an At. % In of 0.90 in which it is not likely that all of the In will react with the Au to form Au-In compounds possibly leaving pure In remaining after all available Au has been reacted with, this may cause instability in the bond. The three designs are summarized in Table 1 and identified on the Au-In phase diagram in Fig. 2 [8].

Each composition is sandwiched within a barrier layer stack-up of tungsten for adhesion, titanium as the primary diffusion barrier, and platinum to prevent undesirable Au-Ti intermetallics [9], [10]. All barrier layers are added to both the glass substrate along with the exposed face of the TLP bond to completely emulate the entire material stack that is present when utilizing TLP as a bond.

All samples are fabricated by first using a Denton Infinity 22 electron beam system by depositing 47 nm of W followed by 150 nm of Ti then 30 nm Pt. The TLP-A samples are then deposited with 1.261  $\mu m$  In while the B and C substrates receive 3.087  $\mu m$  In. All samples are then e-beamed with 50 nm Au as a temporary oxidation barrier before transferring the samples out of the e-beam system and immediately into a Denton Discovery 550 Sputtering System. A and B substrates are then sputtered with 777 nm Au before the C samples were placed into the chamber, all samples are then completed by sputtering an additional 173 nm of Au followed by the barrier

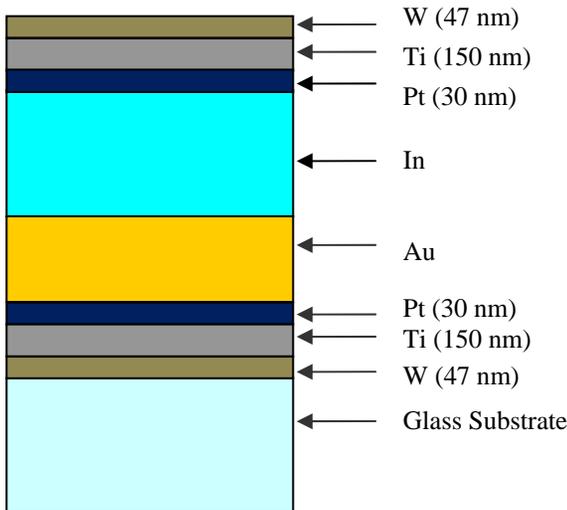
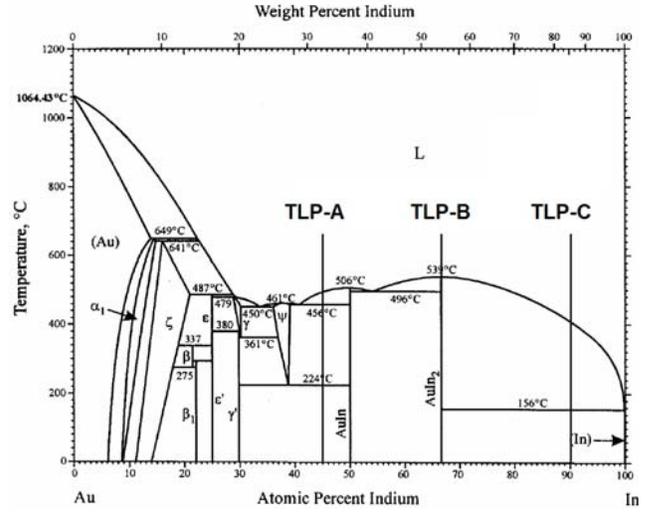


Figure 1. Material Stack of TLP samples. Au and In thicknesses vary by sample to create different material ratios seen in Table 1.



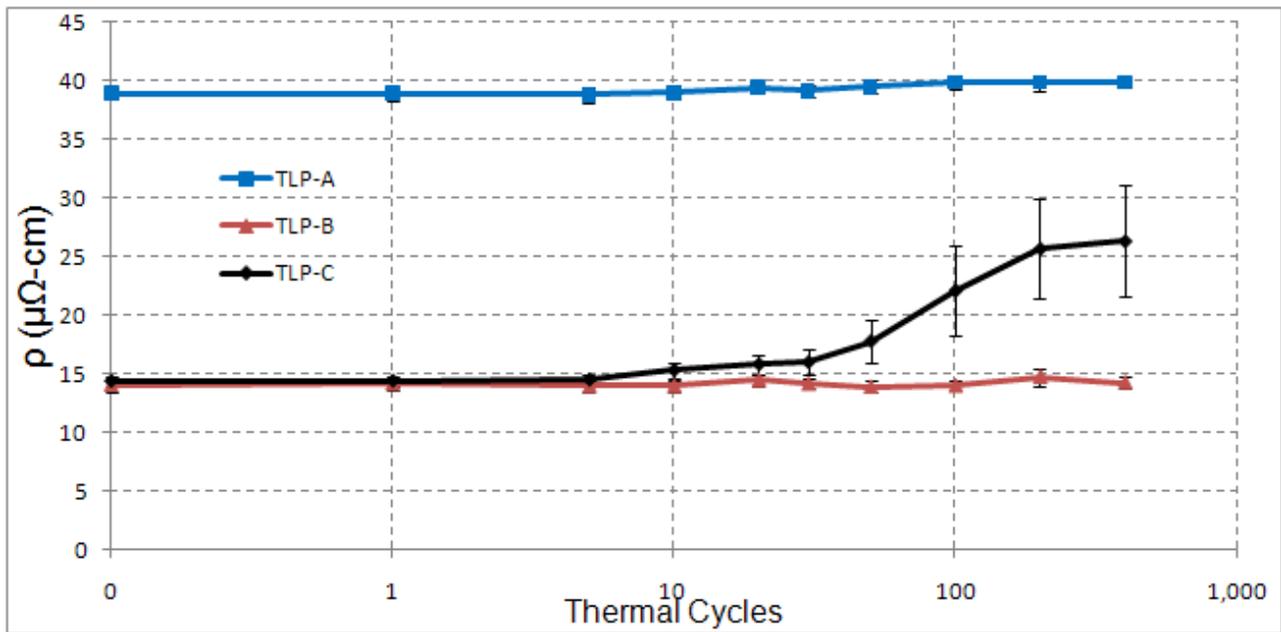


Figure 3. Logarithmic graph of resistivity measurements of samples TLP-A, B, and C versus thermal cycling degradation showing excellent reliability in higher Au concentration samples A and B while the high In sample, C, exhibited poor reliability with increasing resistivity.

greatly to the resistivity rise in which  $\rho \cong 40 \mu\Omega \cdot cm$  while most of the area remains lower at  $\rho \cong 20 \mu\Omega \cdot cm$ , although still about a ~40% increase. This disparity is the cause for the increased average resistivity value and standard deviation. Over the same period of 800 cycles TLP-A has risen only 2.43% and TLP-B has increased just 1.38% indicating little change within the TLP bond.

There is also a highly visible change in the color of the TLP-C surface in response to the thermal cycling which, as seen in Fig. 4, has gone from the original brown color created primarily by the exterior W layer to a gray color more similar to In. Whereas the color of the TLP-A and TLP-B samples remain brown and only slightly increase in darkness with cycling with TLP-B changing the least which also shows the most reliable resistivity results.

#### B. Surface Microscopy and Diffusion

Physically there is growth of small hillocks on TLP-C visible to the naked eye at a density of approximately one per  $10 \text{ mm}^2$ , largely concentrated in one region of the surface. This is likely due to a coefficient of thermal expansion (CTE) difference of the TLP-C film structure and the glass slide as well as the degradation of the adhesive W layer directly on the glass. However, SEM inspection of the samples reveals no morphological changes in the fine structure surface of the samples as a result of thermal cycling on all three samples, thus appearing identical to their un-degraded counterparts, as seen in Fig. 5. This is an indicator of isothermal solidification during the sample preparation as this unchanged morphology

may not occur if a layer of pure In were in existence within the bond and were melting with each thermal cycle, and is therefore an indicator of adverse In diffusion out of the TLP bond.

Energy-dispersive X-ray spectroscopy (EDX) analysis of the samples confirms this belief and reveals diffusion within the bonds which may also explain the change in resistivities. The TLP-A and B samples showing relative resistivity stability report a small increase in the In concentration near the surface which is expected with continued homogenization of the TLP bond during cycling. Whereas, the In concentration near the TLP-C surface has increased higher than expected and has affected the TLP barrier layers due to indium's high diffusivity showing high volatility in the sample and the cause of the increased measured resistivity.

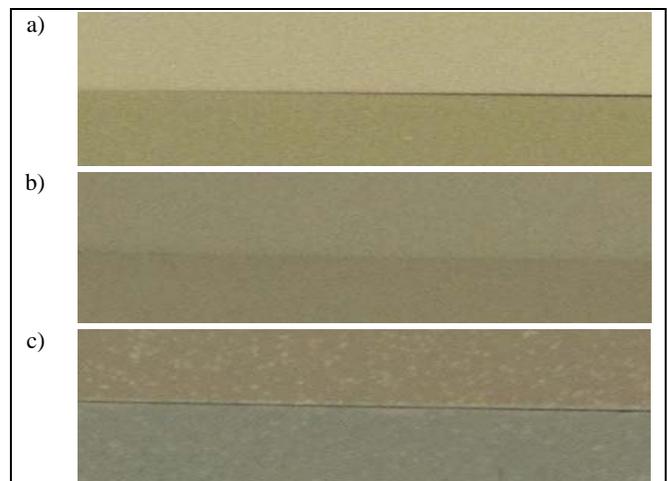


Figure 4. Color change of TLP samples after thermal cycling.

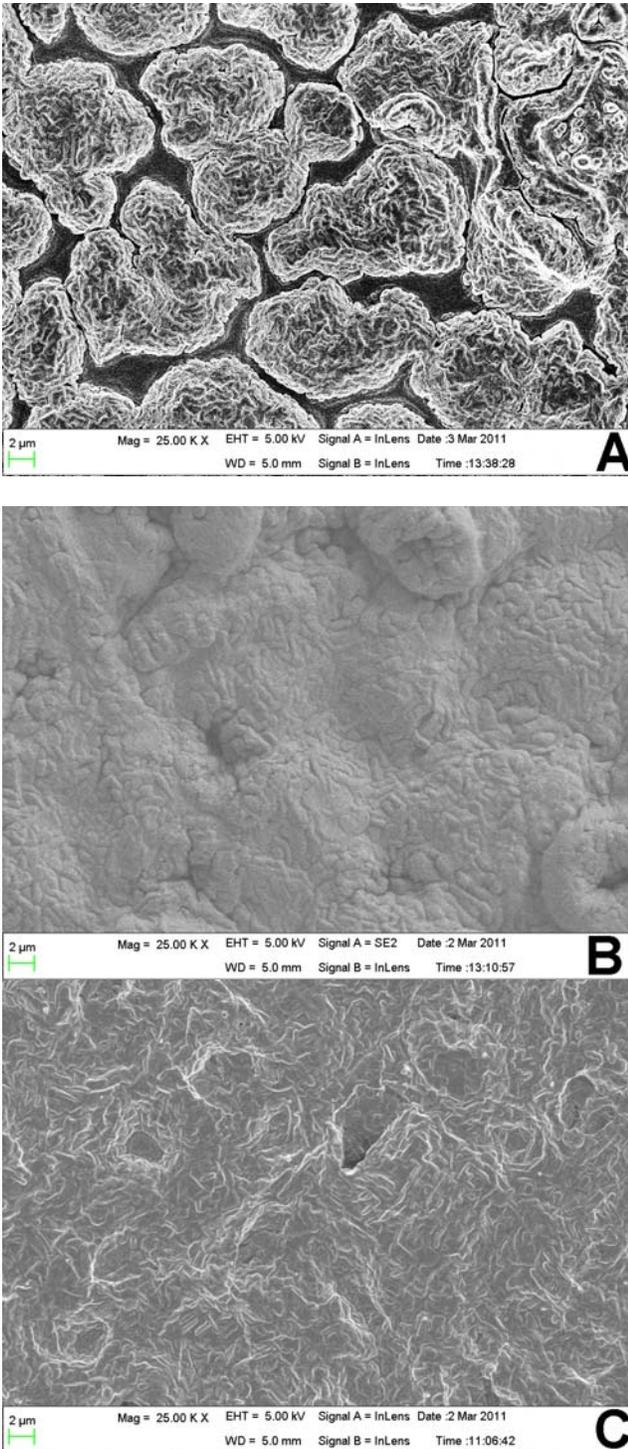


Figure 5. SEM Microscopy of surface morphologies of degraded samples at X25k. Appearance of un-degraded samples identical (not pictured).

## V. CONCLUSION

It has been demonstrated that TLP bonding is a viable high temperature die-attach method for SiC and other wide-

bandgap power semiconductors in terms of its electrical reliability. Samples TLP-A and B containing adequate proportions of the Au base and In interlayer materials have shown a negligible rise in resistivity in response to thermal cycling while also maintaining a stable surface morphology and predictable material diffusion within the TLP bond. Alternatively, sample TLP-C, containing elevated In levels exceeding what is necessary for proper Au-In bonding has demonstrated unreliable behavior. For this reason, we feel that Au-In TLP bonds below an At % In < 0.67 remain a very promising die-attach method for SiC devices. It is then worthwhile to continue electrical reliability testing of the TLP bonds that have shown the promising results in this work while also expanding to perform a robust mechanical reliability study as well.

## ACKNOWLEDGEMENTS

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