Comparison of Au-In Transient Liquid Phase Bonding Designs for SiC Power Semiconductor Device Packaging

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Abstract

Transient liquid phase (TLP) bonding is an advanced die-attach technique for wide-bandgap power semiconductor and high-temperature packaging. TLP bonding advances current soldering techniques by raising the melting point to over 500 °C without detrimental high-lead materials. The bond also has greater reliability and rigidity due in part to a bonding temperature of 200 °C that drastically lowers the peak bond stresses. Furthermore, the thermal conductivity is increased 67 % while the bond thickness is substantially reduced, lowering the thermal resistance by an order of magnitude. This work provides an in-depth examination of the TLP fabrication methodology utilizing mechanical and thermal experimental characterization data along with thermal reliability results.

Key Words: Transient Liquid Phase (TLP) Bonding, Packaging, High-Temperature, Wide Bandgap

I. Introduction

As SiC and other wide bandgap power semiconductor devices become more viable, it is necessary to expand high-temperature packaging technologies for higher operating temperatures and extreme environment applications. Traditional lead-based die-attach solders have a melting temperature below 200°C and are incapable of supporting the high-temperature operation of SiC MOSFETs that have been demonstrated to operate up to 500 °C for extended periods [1].

Ideal wide-bandgap die-attach materials need a high melting temperature, high thermal conductivity, high tensile and yield strength, and low mechanical stress [2]. Transient liquid phase (TLP) bonding is capable of providing all of these qualities for power device die-attach. While several papers have looked into the TLP bonding technique, we have uniquely characterized multiple bond structures mechanically and thermally. This work expands the prior work in the field of TLP bonding by characterizing multiple gold-indium TLP bond compositions and investigating the bond die-attach quality and their thermal characteristics.

II. Transient Liquid Phase Bonding Overview

A TLP bond is composed primarily of two materials, a base layer which has a high melting point and an interlayer which has a much lower melting point and a high diffusion rate into the base layer, in this work the base material is gold and the interlayer is indium. To utilize TLP bonding as a die-attach method, the base material is deposited on a substrate or a semiconductor die while 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 melt and quickly diffuse into the base layer. The bond becomes stable by being held at the bonding temperature until the interlayer is completely consumed into the base; this is known as isothermal solidification [3]. This process is portrayed in Fig. 1 while one of our TLP bonding samples is shown in Fig. 2 where a SiC Schottky rectifier die is TLP bonded to a silicon nitride DBC substrate.

The advantage of this technique is that the resulting compound of the base and interlayer materials become one solid TLP bond with a melting temperature significantly higher than that of the original interlayer material but is joined at a much lower temperature. This reduces the total mechanical stresses on the die-attach and device during operation over a wide temperature range and increases reliability.

III. Experiment

This work specifically investigates the mechanical and thermal effects on a TLP bond from adjusting the TLP bonding properties indium thickness, atomic percentage of indium in the bond , and the applied bonding pressure. It is a continuation of our previous examination of the electrical

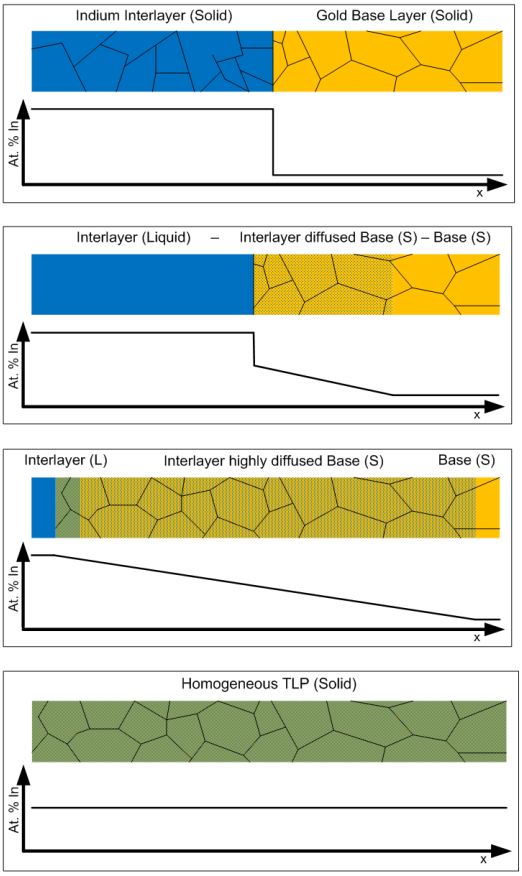

Figure 1. The general TLP reaction process featuring two materials isothermally solidifying at a fixed temperature.

reliability of TLP bonding. The primary goal is to compare the property differences between the samples and judge their effects on the success of the completed samples. The chosen properties are believed to have the greatest affect on the quality of the bond.

The indium thickness (t_{In}) is examined because it is a fundamental TLP property and possible to highly affect bonding because there is a minimum indium thickness necessary for TLP bonding to occur yet excess indium can also be detrimental [4]. Because indium begins to diffuse with gold instantaneously, even within the deposition chamber, if it is too thin the indium may be entirely consumed before creating a TLP bond, this is also possible if material barrier layers around the TLP bond structure are ineffective at containing the indium. Also, the indium must be sufficiently thick to allow for a temporary gold oxidation barrier to break apart into the molten indium during bonding so that the liquid in can contact the gold to be bonded. Conversely, if the indium is excessive it may leak out of the bonding interface with high bonding pressure thus changing the bond design or causing a short circuit of the device being attached.

The atomic percentage of indium in the TLP bond (At. % In) is also of interest for its effect on the bond quality. Our prior work found that there was electrical reliability and indium stability dependence on the At. % In. In that, within the Au-In TLP system it is necessary for the At. % In to remain below 0.667 or pure indium will remain in the TLP bond and cause reliability problems [5]. These results allowed us to focus the range of interest to $At.\,\%\,In \leq 0.667$ but the effects At. % In variation has on bond quality and thermal performance remains unknown, if existent.

Bonding pressure (ρ_{bond}) is important as well. The pressure needs to be adequately high to induce a quality bond however if ρ_{bond} is too high then indium seepage from the bond will occur – also an indium thickness problem – or worse, die cracking may also occur. Therefore, the optimal indium thickness, At. % In, and bonding pressure is examined.

During this examination, there were multiple sample structure designs and fabrications. Adjustments were made in response to initial feedback from each batch of completed samples throughout fabrication in order to obtain the most pertinent results. 25 TLP samples have been created in groups where t_{In} ranges from 1.26 µm to 4.5 µm, At. % In varies between 0.45 and 0.667, and ρ_{bond} is adjusted between 0.8 MPa and 5.56 MPa. There are enough samples to study how variations in each property affect the bond quality and the thermal behavior of the samples. Together there are six TLP structures, summarized in Table 1, and denoted in the Au-In binary phase diagram, Fig. 3. Each At. % In also corresponds to its own particular melting point, the differences between them are negligible, each being above 460 °C, which is sufficiently high.

The TLP sample structure diagram is seen in Fig. 4. Each sample consists of a 4.0 mm × 8.0 mm SiC Cree JBS diode TLP bonded to a 10 mm × 13 mm silicon nitride substrate with 7.0 mm × 10 mm of copper plating. Silicon nitride is an excellent substrate

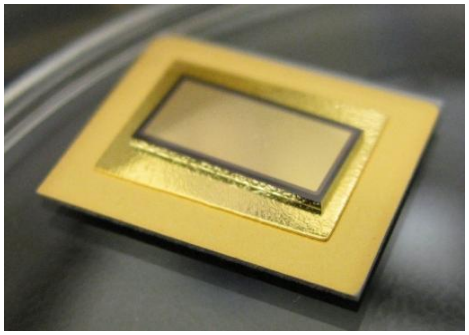

Figure 2. TLP Sample device featuring a SiC Schottky rectifier TLP bonded to a silicon nitride DBC substrate with copper metallization.

TABLE I. TLP SAMPLE PARAMETERS

Sample Batch	t_{In} (µm)	t_{Au} (µm)	At. % In (%)	ρ_{bond} (MPa)
2	3.0	1.07	0.65	0.80
3-A	1.261	1.0	0.45	0.80
3-B	3.087	1.0	0.67	0.80
3-C	3.087	0.223	0.90	0.80
4-A	4.5	2.36	0.55	1.455, 3.02, 5.76
4-B	4.5	1.458	0.67	1.455, 3.02, 5.76

material that is typically considered cost prohibitive in standard power packaging, however for specialty use environments in which WBG devices and TLP bonding are good candidates, it is an excellent choice due to its higher strength and thermal conductivity than common alumina and aluminum nitride DBC substrate. Also, silicon nitride has shown excellent adhesion to its copper plating, rivaling the high standards set by the alumina and copper through a unique active metal brazing process [6]. The use of silicon nitride will also ease the transition to full TLP modules due to the ability to pattern power vias through the substrate. This will also allow for higher voltage isolation necessary for SiC power devices [7].

Each TLP stack contains material diffusion barrier layers to contain the gold and indium materials through processing and over its lifetime. Each of the Au-In TLP bonds are sandwiched within a stack of barrier layers of tungsten for adhesion, titanium as the primary diffusion barrier, and platinum to prevent undesirable Au-Ti intermetallics [8], [9]. These barrier layers also ensure the ratio of indium to gold remains constant. The thicknesses of the indium and gold within the barriers vary depending on the TLP structure for that sample while the barrier layers remain constant.

Each sample also contains a 50 nm gold capping layer upon the indium necessary to prevent oxidation when the samples are removed from the deposition chamber but before the TLP bonding occurs due to rapid oxidation of indium in air. During the bonding process it will break apart into the liquid indium and allow it to interact with the gold base layer and bond together [10], [11]. This gold is accounted for in the At. % In calculations.

IV. FABRICATION

Samples are fabricated by first electron beam evaporating the barrier layer stack of 47 nm of tungsten followed by 150 nm of titanium and 30 nm of platinum on to the SiC devices. The samples are then deposited with 1.261, 3.0, 3.087, or 4.5 µm of indium depending on their intended At. % In and t_{In}. Each SiC device is then e-beam evaporated with 50 nm of gold before removing the samples out of the e-beam system. The silicon nitride substrates are sputter deposited with the same barrier layer stack followed by 0.173, 0.95, 1.0, 1.408, or 2.31 µm of gold. The resultant At. % In of the fabricated samples includes 0.45, 0.553, 0.645, 0.667, and 0.9.

The substrates and SiC devices are then loaded individually into a stainless steel TLP pressure mount that applies a fixed pressure on the two elements together through the use of four identical springs calculated to apply the desirable pressure. Most samples are bonded at 0.80 MPa however additional samples were bonded at 1.45, 3.02, and 5.76 MPa for comparison. The fully loaded and

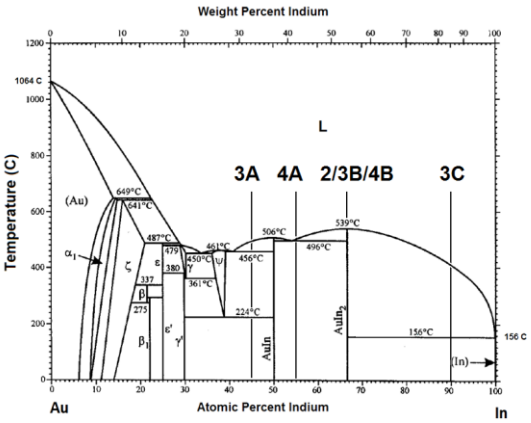

Figure 3. Binary phase diagram of the Au-In system with six TLP test sample concentrations denoted at *At. % In = 0.45, 0.55, 0.67,* and *0.90*.

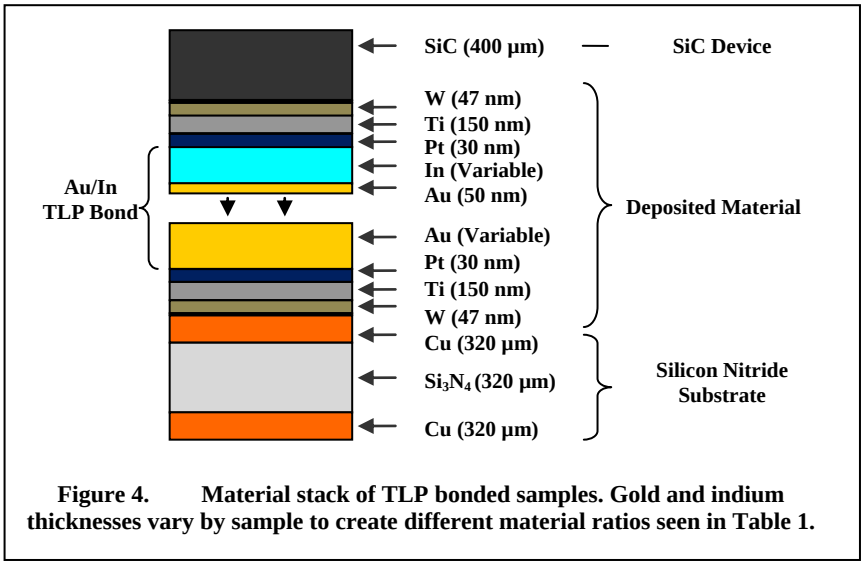

Figure 4. Material stack of TLP bonded samples. Gold and indium thicknesses vary by sample to create different material ratios seen in Table 1.

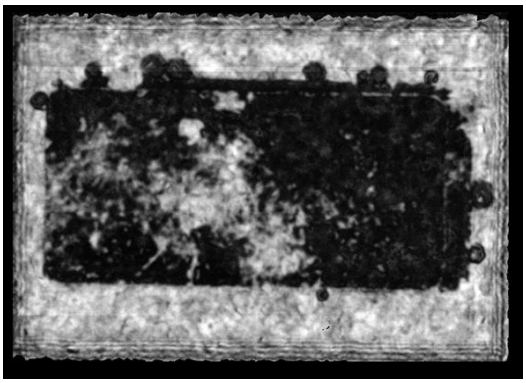

Figure 5. Scanning acoustic microscope image of TLP sample 3B-6 featuring good die attach with slight indium seepage from interface.

pressure calibrated TLP mount is then loaded into a 200 °C oven and immediately purged with nitrogen and vacuum pumped to 1.44 kPa for 15 min which far exceeds the thermal time constant of the pressure mount and the TLP samples in addition to the diffusion time constant for each of the samples, therefore ample time is allotted for TLP diffusion to complete before unloading and allowed to air cool.

The bonded samples are characterized mechanically through the use of scanning acoustic microscopy to measure the die attach percentage (DA%) , as seen in Fig. 5, and thermally by measuring the dynamic thermal impedance (Z_{th}) of each sample at 60 W of power using the NIST Transient temperature sensitive property measurement system [12]. Additionally some samples were thermally cycled between 25 °C and 200 °C and re-characterized for their thermal response to test reliability.

V. Mechanical Characterization

Most of the samples were bonded at 0.8 MPa of bonding pressure which produced low die attach areas of $\overline{DA\%}(0.80\ MPa) = 23\ \%$. This is due in part to lowering of the effective spring constant in the pressure mount at the elevated heating temperature. The spring constant varies linearly with the shear modulus of the spring material by

$$k = \frac{G(T)d^4}{8D^3n}$$

where *k* is the spring constant, *d* is the spring wire diameter, *D* is the average spring diameter, T_m is the spring steel melting temperature in Kelvin, *n* is the number of coils, and *G(T)* is the temperature dependant shear modulus which is expressed by

$$G(T) = G_0\left(1 - \frac{T}{T_m}\exp\left(\frac{T}{T_m}\left(1 - \frac{T_m}{T}\right)\right)\right)$$

Using this equation, the bonding pressure is effectively lowered to $\rho^*_{bond} = 0.712\ MPa$ which is much lower than most bonding pressures previously reported when not using forming gas to decrease oxidation further, which is not a sustainable bonding technique [4], [10], [13-16]. This result is unacceptable for usage of the bonded devices for normal operation; however these samples are extremely valuable for the purpose of this work in analyzing the dependence of bond quality on ρ_{bond}, t_{In}, and At. % In because the measured DA% still varies with respect to these properties thus many conclusions can still be made.

TABLE II. TLP Results Summary

t_{In} (µm)	ρ_{bond} (MPa)	Avg. DA% (%)	Avg. Z_{th}, 10 ms (°C/W)	Avg. Z_{th}, 50 ms (°C/W)	Avg. Z_{th}, 100 ms (°C/W)
1.261	0.80	19	0.073	0.214	0.310
3.0	0.80	24.06	0.078	0.233	0.328
4.5	1.455	42.9	0.083	0.241	0.353
4.5	3.02	63	0.086	0.231	0.284
4.5	5.575	63.2	0.108	0.304	0.427

It is observed that the bonding pressure, as assumed, has the greatest effect on the DA% while the t_{In} does as well to a lesser degree, both with a positive correlation to the DA% while attempts to independently relate the At. % In to the DA% is irregular and no correlation is found. The results are summarized in Table 2.

A. Bonding Pressure

DA% shows the greatest dependence on the bonding pressure for good results as anticipated due to the fundamental importance of good contact between the two items being TLP bonded. Fig. 6 shows the correlation of the DA% to ρ_{bond}. As noted, at the lowest pressure, in which the most samples were constructed, $DA\%(0.8\ MPa) = 22.6\ \%$, from there the DA increases at a rate of $17.2\ \frac{\%}{MPa}$ until 3 MPa and $7.25\ \frac{\%}{MPa}$ overall across all samples. When the samples are separated by t_{In} it is seen that the $\rho_{bond} = 0.8\ MPa$ samples are adversely affected by the thinner t_{In} than the higher pressure samples and thus it is estimated that $DA\%(0.8\ MPa)|_{t_{In}=4.5\mu m} \cong 34.5\ \%$. It is noteworthy, that the bonding pressure must meet a threshold in order to break the gold capping layer used during fabrication and achieve solid bonding; this effect may explain the threshold in DA% for $3.02 > \rho_{bond} > 5.75\ MPa$ in addition to other possible causes of imperfect bonding.

B. Indium Thickness

Indium thickness is also shown to be a factor in achieving high DA%, with a positive correlation between the two. Fig. 7 shows the increasing DA%

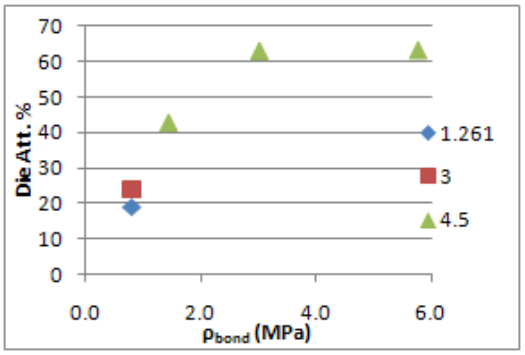

Figure 6. Results of DA% vs. ρ_{bond} differentiated by t_{In} indicating strong dependence on ρ_{bond} for quality results.

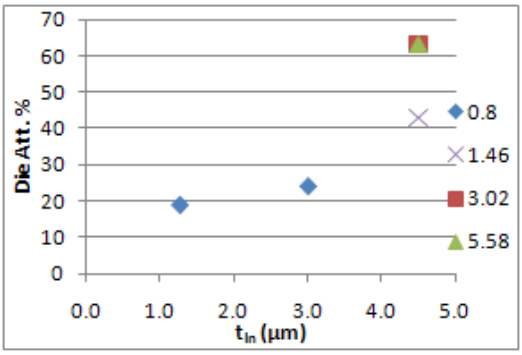

Figure 7. Results of DA% vs. t_{In} differentiated by ρ_{bond} showing reliance on t_{In} for DA%.

with increasing t_{In} at a rate of $9.47\ \frac{\%}{\mu m}$ amongst all samples. When the analysis is limited to a fixed pressure an increased t_{In} is still associated with increasing DA% however at a lower rate of $2.91\ \frac{\%}{\mu m}$ which occurs between 0.8 MPa and 1.46 MPa. When t_{In} is increased to our peak thickness of 4.5 µm with only 3.02 MPa of applied pressure the DA% increases to *63.2 %*, this is a *280 %* increase in DA% over initial samples featuring only 0.8 MPa of pressure and $t_{In} \leq 3.0\ \mu m$, thus $t_{In} > 3.0 \mu m$ is suggested for most TLP bonding applications.

C. Atomic Percentace of Indium

The results show that there is no consistency of the effect At. % In has on the DA% of the TLP bond for $At.\%\ In \leq 0.667$, established prior [5]. When the property is isolated from all other TLP properties its variation causes both increasing and decreasing DA%, this aberrance can be seen in Fig. 8. Thus, the At. % In is not believed to contribute to the quality of the TLP joint.

VI. Thermal Characterization

Thermal impedance (Z_{th}) measurement of each sample allows for an understanding of the effects the TLP properties have on their thermal behavior. It is necessary to associate the DA% results to Z_{th} since the DA% is not only a result of the bonding but a property of each sample's unique physical structure which determines Z_{th}. The same is true of t_{In} which affects the thermal impedance since it is a quality of a sample's physical structure and the higher resistivity of indium dominates the gold resistance in the bond where $\rho_{In} = 8.4\ \mu\Omega - cm$ and $\rho_{Au} = 2.2\ \mu\Omega - cm$, thus samples with thicker indium should have increased thermal resistance. When $Z_{th}(100\ ms)\ vs.\ DA\%$ is plotted for all samples in Fig. 9 the thermal impedance appears almost static with variable DA% because it requires a thicker indium layer to produce the high DA%. This is shown by $\frac{\partial Z_{th}(100ms)}{\partial DA} = -0.0006$ for a 100 ms heating pulse. However, when this relationship is investigated for each unique indium thickness, as in Fig. 10, the natural high correlation of $Z_{th}\ vs.\ DA\%$ is apparent with increasing Z_{th} for lower DA%. The correlation is stronger, expressed as $\frac{\partial Z_{th}}{\partial DA}\Big|_{t_{In}=1.26} = -0.5$, $\frac{\partial Z_{th}}{\partial DA}\Big|_{t_{In}=3.0} = -0.32$, and $\frac{\partial Z_{th}}{\partial DA}\Big|_{t_{In}=4.5} = -0.14$ for $Z_{th}(100ms)$ vs. DA%.

This strong relationship is less apparent in shorter time pulses due to the increased dependence on the effective thermal capacitance, $cp*$, of each material by

$$\Delta T(t) = \frac{qL}{k * A(DA\%)}\left(1 - e^{-\frac{t}{\tau(c_p*)}}\right)$$

which is less dependent on DA%, but as the power pulse length increases DA% dominates the $Zth(DA\%)$ relationship.

Lastly, At. % In does not show any discernable correlation to Z_{th} even with respect to DA% for each sample. Therefore, the thermal impedance of the intermetallic phases of Au-In are approximately equal given equal thickness of the TLP bond. The results also show, predictably, that the bond pressure does not influence the thermal behavior of

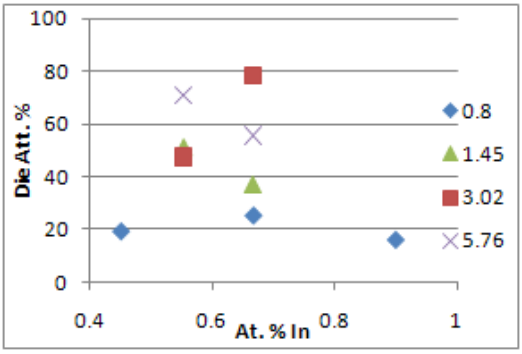

Figure 8. DA% vs. At. % In graph showing no correlation of the At. % In to DA% in the TLP bonds.

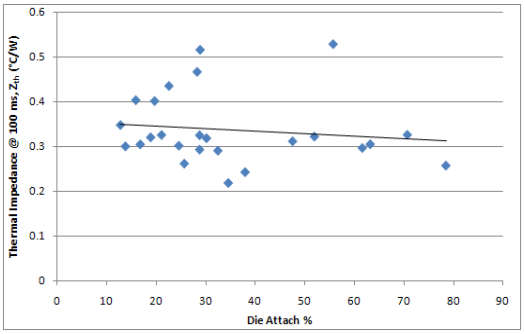

Figure 9. Thermal impedance scatter plot (Z_{th}*(100 ms) vs DA%*) of each sample's reading with unexpectedly low correlation of the two properties.

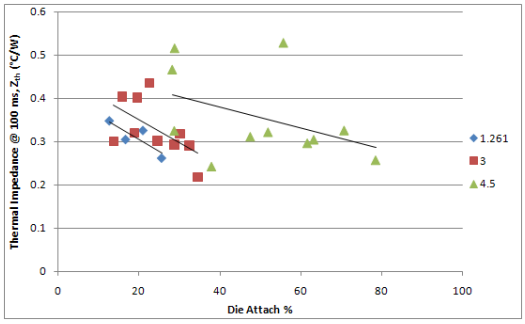

Figure 10. Thermal impedance scatter plot (Z_{th}*(100 ms) vs DA%*) differentiated by t_{In} of each sample showing strong dependence of Z_{th} on DA% and t_{In}.

the TLP bond aside from its role after establishing the DA% since it is not a structural property of the completed bond as DA% and $t_{In,}$ which do affect the bond impedance.

VII. Thermal Reliability

The sample's reliability show promising results in a preliminary investigation of their thermal performance. Three samples having properties $t_{In} = 3.0\ \mu m$, $At.\%\ In = 0.65$, and $\rho_{bond} = 0.8\ MPa$; were thermally cycled 700 cycles. Two of the three samples show signs of increasing and then decreasing Z_{th} over the course of the cycling when measured using power pulse lengths of 50 ms and 100 ms. At these time lengths, R_{th} dominates Z_{th}, suggesting an increased DA% possibly due to continued diffusion of the indium interlayer, which is possible with the initial low DA%. The third sample does not show this behavior but still maintains low, but steadily increasing, Z_{th} in response to cycling for all pulse lengths.

After 700 cycles, the samples exhibit an average decrease in Z_{th} of 1.3 % for a 10 ms pulse, with only a 5.96 % increase for $t_{pulse} = 50\ ms$, and 5.13% for $t_{pulse} = 100\ ms$. These result portray stability and reliability in the bond, particularly with consideration of the low average die attach for these reliability samples of only $\overline{DA\%} = 25.9\%$. This property would typically lead to poor reliability of the bond which would manifest itself in thermal runaway in response to thermal stressing; however these TLP bonded samples show no signs of that occurring and are more reliable than anticipated.

VIII. Conclusion

The effects of various TLP properties on the resulting TLP bonds are presented. In order to achieve quality bonding with a sufficiently high DA% the bonding pressure, indium thickness, and At. % In need to be strongly considered. It is shown that to achieve high bonding attachment the pressure should

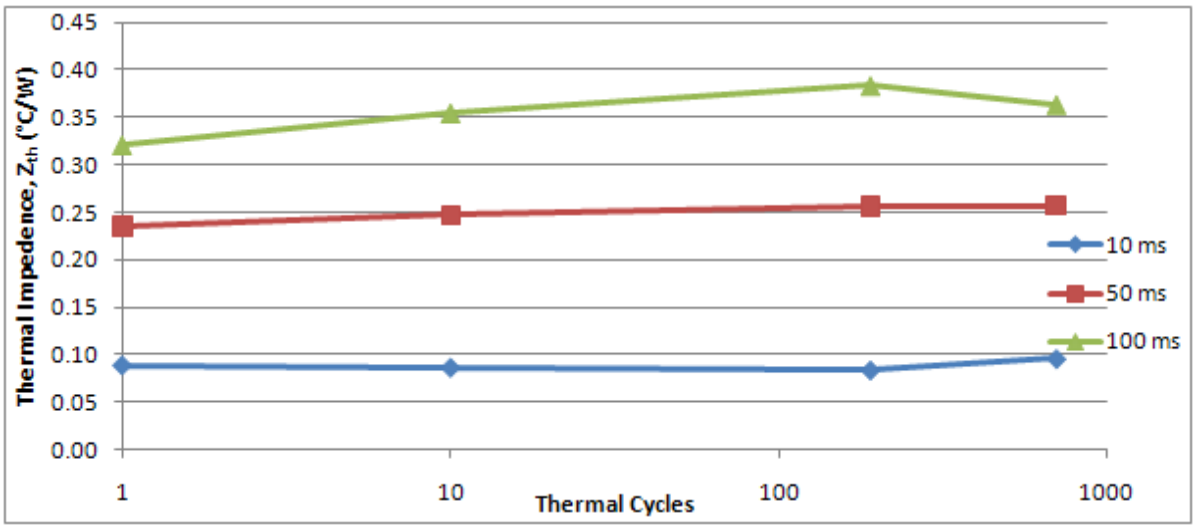

Figure 11. Reliability results of a test sample showing rising and slightly falling Z_{th} over repeated cycling demonstrating generally high reliability with no thermal runaway.

generally exceed $\rho_{bond} > 3.0\ MPa$ while typically $t_{In} > 3.0\ \mu m$, with the most preferable At. % In being 0.667 for Au-In TLP bonding. The work of refining and evaluating the TLP bonding process will continue with additional work analyzing the process of consistently producing high quality bonds along with investigating their reliability. Results continues to suggest that TLP bonding for wide bandgap power devices along with silicon nitride substrates are an attractive option for high-voltage, high-temperature, and extreme environment power electronics.

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