Optimization of Structurally Enhanced Solder Transient Liquid Phase Bonding

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***Abstract*— High temperature packaging technologies are a necessity for high temperature capable devices. SAC305 solder has an operational limit of 174℃ imposed by creep effects which aligns well with current junction temperature limits of 175℃. Wide band gap semiconductor materials have the potential to reach junction temperatures of up to 800℃ that are not currently attainable with significant reliability. Capitalizing on this potential will requires substrates and attachments that can operate well beyond the current 175℃ standard. Silver sintering pastes have received widespread interest as a high temperature attachment alternative. However, the process requires high pressure bonding in an inert environment to achieve acceptable bond quality. Transient liquid phase (TLP) sintering is capable of good bond quality without pressure requirements but suffers from low thermal conductivity and only slightly reduced cost compared to silver sintering. SAC305 solder contains the same constituent materials for TLP as available copper-tin TLP sintering paste. By introducing engineered surface structures into the bond, intermetallic formation can be accelerated producing a bond similar to TLP sintering but in an ambient environment and for reduced cost. While this process has been demonstrated, it has not yet been optimized. Currently bonds are formed using a 75 µm stencil on substrate surface structures 24 µm tall, covering 19% of the bonding area. The process takes about 4 hours not including the formation of surface structures. This study will center on the effects of stencil thickness and coating methods. Samples will be analyzed by scanning acoustic microscopy, die shear testing and cross sectional scanning acoustic microscopy.**

Keywords— die attach, high temperature, TLP

I. INTRODUCTION

Temperature accounts for 55% of failures in electronics packaging [1]. This is for two reasons, mismatching coefficients of thermal expansion and high homologous temperatures. Mismatching coefficients of thermal expansion (CTEs) exert force due to the bonding of disparate interfaces. CTE describes the temperature rate of length change. As a material cools, one material will natively shrink more which leads to a tensile stress in that material and a compressive stress in the mated material. This stress is proportional to the difference in CTE between them ($\Delta\alpha$), the stiffness of the materials (E12), and the difference in temperature at which they were joined (ΔT). Homologous temperature (Th)is the ratio of the temperature in a solid to the melting point on the kelvin scale. At Th > 0.8 creep is exaggerated and failure accelerated [2]. Modern power packages are operating with junction temperatures of 150-175℃ resulting in SAC305 solder attachments with Th of up to 0.85. Diffusion bonding technologies are designed to enhance reliability by lowering the homologous temperature of the joint minimizing the additional ΔT. This requires bonding at temperatures below the melting point of the joint being formed. Likely the most popular diffusion bonding technology is silver sintering. This method shows good thermal cycling performance compared to solder [2], but degrades with thermal aging and when bonded to copper-molly, which is commonly used in double sided packages [3]. Transient liquid phase (TLP) bonding is the process of forming high temperature intermetallics using a solid-liquid diffusion couple. As described by Fick's law bonding time in such systems is exponentially related to diffusion length [4]. This requires implementations to have thin bond lines, increasing the stress of the joint for a given CTE related displacement. Additionally, the thermal and electrical conductivities of the intermetallics are much lower than their constituent materials. TLP sintering (TLPS) is a variation that attempts to address these drawbacks. By suspending metallic particles in a flux medium, diffusion lengths can be reduced to roughly the radius of the melting constituent particles. At the same time the system can be adjusted to include excess high conductivity material or additional elements that improve the final properties of the joint [4]. TLPS is similar to silver sintering time and temperature and both require an inert environment reflow.

It has been established that engineered surfaces can shorten the effective bond length in a SAC 305 solder joint, accelerating Cu6Sn5 TLP bond completion [5]. This work begins to optimize the non-topological parameters of that process. Coatings and stencil thickness are analyzed with scanning acoustic microscopy, die shear testing and cross-sectional scanning electron microscopy. The stability of the joints is also assessed using high temperature storage.

II. THEORY AND METHOD

For copper-tin TLP, equation 1 can be taken from work by Greve [4]. Therein t is time in seconds, l_n is the bonding length or intermetallic growth required, R is the ideal gas constant, and T is temperature in kelvin. It describes the relationship between time and diffusion length. In an effort to shorten the effective diffusion length within a SAC 305 solder joint the substrate is patterned with compliant, 24µm tall copper structures over 19% of the attachment area. This decreases the diffusion length by distributing copper within the joint and allowing the process to

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occur in a more parallel than series fashion. TLP joints were produced using SAC 305 solder, deposited using a 75µm stencil onto the patterned substrates. Samples were then reflowed according to the profile of SAC 305 and subsequently stored at 260℃ to complete the formation of a Cu6Sn5 bond [5]. In that work bond height averaged 38µm, bond completion occurred between 3 and 4 hours, and the shear strength of successful joints averaged 16.18 MPa [5].

$$t = \frac{{l_\eta}^2}{(8.85E{-}13)e^{-19.72/RT}} \quad (1)$$

Voiding was identified as a point for improvement by the authors of that work. Voids can be the result of trapped gasses, substrate impurities, contraction, or a diffusion imbalance [6-8]. In copper-tin TLP Kirkendall voiding often occurs in the secondary Cu3Sn (ε-phase) intermetallic during its formation. Nickel can suppress the formation of the ε-phase avoiding the formation of a porous intermediary between the TLP joint and the bonding surfaces [4]. In this work both electroplating and autocatalytic plating were used to deposit trace thicknesses of nickel. Electroplating was done with a minimum achievable current density to accommodate the high aspect ratios in the engineered surfaces. This was done by increasing current control settings by 1 mA until electricity began to flow. Additionally, the substrate pattern used here exhibits perfect wetting on the macro scale [5]. Therefore, excess patterned area may result in voids similar to those caused by contraction. Wicking into excess patterns presents a dry-out risk. In such a scenario all solder is drawn away from the gap between the engineered surface structures and the die metallization leaving no material for TLP bond formation. Stencil thickness plays a role in each of the previous optimization solutions by determining the total available tin for the system. In the same way, stencil thickness controls the free distance between the die metal and the surface structures as well as required bonding time. The effect of reduced wire area is studied herein by removing structures with a razorblade from areas not involved in bonding.

The best results from those studies are used to produce samples for storage tests. Because TLP joints are a chemical rather than a physical bond, they should exhibit excellent thermal stability, exhibiting minimal change during storage below 277.4℃. This corresponds to a homologous temperature of 0.8 for the primary copper-tin intermetallic, Cu_6Sn_5 (η-phase). However, secondary Cu_3Sn (ε-phase) will grow during this storage period. In this study, samples were stored at 175℃ and 300℃ for up to 72 hours. Shear testing with a Dage Bond Tester and a DS100 Cartridge was then used for evaluation of performance.

III. Results and Discussion

While energy dispersive x-ray shows the autocatalytic was a success, the resulting surface prohibited the growth of intermetallic compounds. It is believed that this was due to phosphorus impurities from the plating bath that are common for autocatalytic techniques. Figure 1 shows the interaction of the solder with the plated structures as opposed to unplated ones.

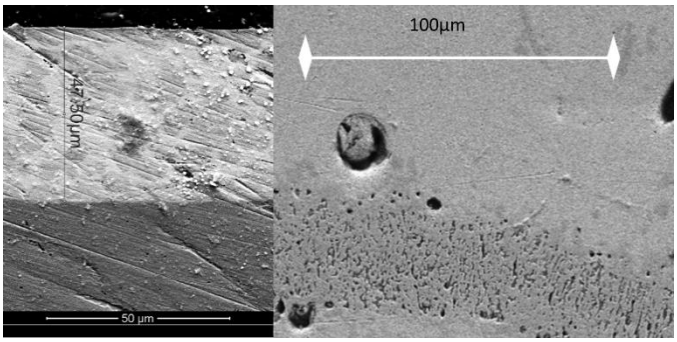

Fig. 1: Cross sections of solder joints after 1 hour at 260℃ with engineered substrate surfaces that have (right) and have not (left) been nickel plated

A comparison of joints formed on a field of structures as opposed to a limited area is shown in figure 2. The sample with reduced area of structures displayed fewer voids and greater TLP bonding acceleration. However it is notable that this result is not a direct comparison. The reduced area sample shown does not use a copper clad silicon die like the full area. Instead, a copper die was used. This likely accounts for the additional acceleration but not for the reduction in voiding. With the copper plated silicon there is much less copper available on the die side and the system quickly becomes a single sided diffusion scenario. To have sufficient copper in the system for un impeded TLP there must be 1.32 times the thickness of tin available in copper. This value is obtained through a stoichiometric balance assuming equal top down area available. Excess copper will not harm a TLP bonding system and will remain as copper once the tin supply has been consumed [4].

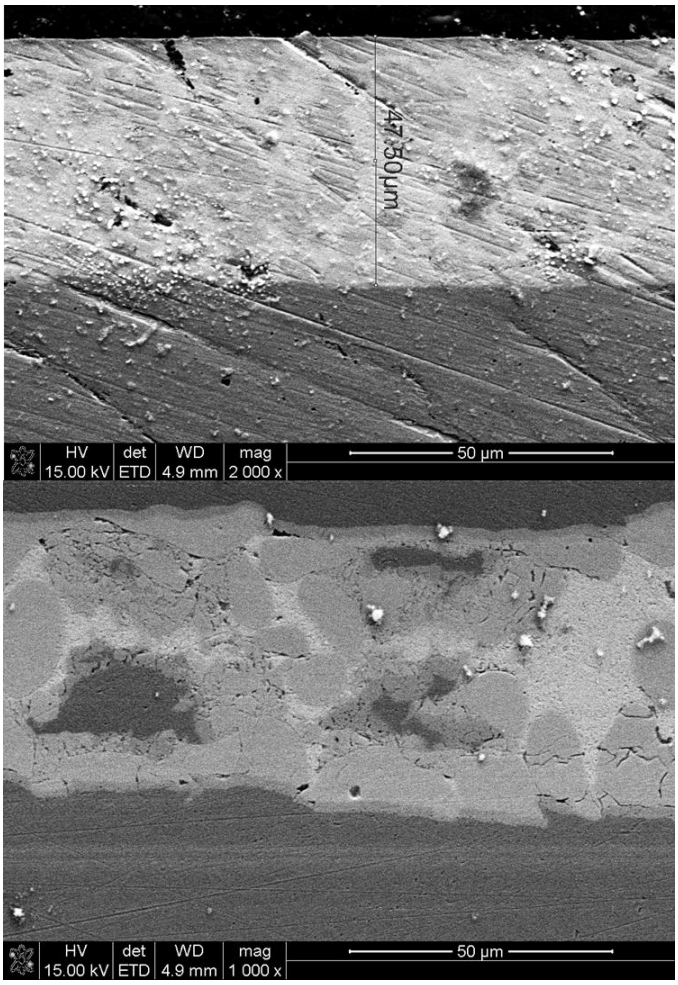

Fig. 2: Cross sections of joints made with (top) and without (bottom) excess patterned area using a 50µm stencil thickness

Samples were created for cross sectioning using 50 and 25 µm stencils. Samples were stored at 260℃ in air for 1, 1.33, and 1.66 hours. Sample yields for the 25 µm stencil samples were less than 10%, but theses samples did complete bonding faster than their 50 or 75µm counterparts. At 1 hour 20 minutes the 25µm sample is complete while the 50µm sample requires an additional 20 minutes. This is shown in figure 3.

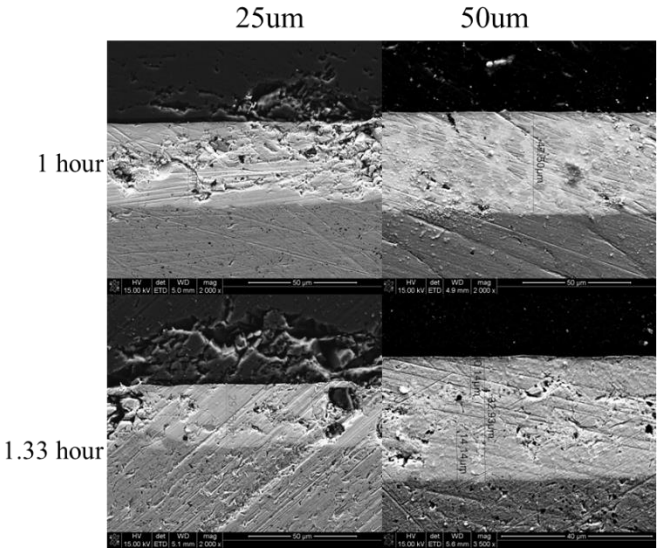

Fig. 3: cross sections comparing intermetallic growth between samples created with 25 and 50µm stencils

The die metallization is important for this process. Initial silicon and copper samples performed well, but samples acquired from another supplier failed upon completion of the TLP bonding process. This occurred due to the complete consumption of the copper layer and the underlying adhesion layer. Figure 4 shows the die after failure. The green and tan colored areas are exposed silicon where the metallization was entirely consumed. Likewise, the reflective areas are remnants of the adhesion layer and the brown is leftover copper oxide. According to literature titanium, tantalum, and chromium are the best adhesion layers that double as diffusion barriers for copper [9-10]. However, tantalum is reportedly prone to oxygen inclusion, often resulting in reduced uniformity in the copper layer [11].

Fig. 4: Optical microscope image of die surface after failure by mal-adhesion

With this knowledge, mechanical die were fabricated out of copper going forward. A pressure study was conducted to identify the optimal value for TLP bonding reduced structure area samples. A 50µm thick stencil was used with 7x7 mm punched copper die for this test. Pressures of 102, 104, 510.2 and 1020.5 Pa were used and results after 1 hour of storage are shown in figure 5. Samples with added pressure consistently showed lower bond line thickness and greater intermetallic formation as a result. This effect has diminishing returns and 204 Pa was chosen for storage testing due to reduced prevalence of voids in the cross sectional analysis. The bond line thickness of that samples was 67.8 µm

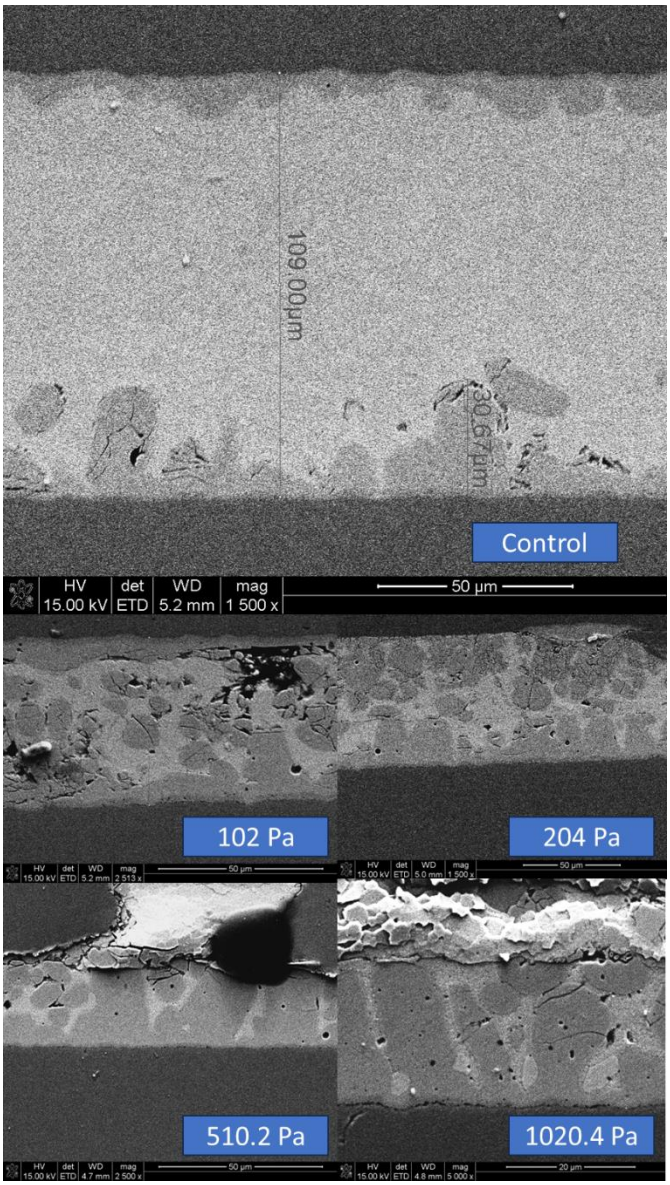

Fig. 5: Cross-sectional SEM images of pressure study results.

Samples for high temperature storage were produced in the same manner as those from the pressure study. Samples were stored at 175 and 300℃ for 24, 48, and 72 hours. As bonded samples, meaning those reflowed and stored for 2 hours, averaged 10.0 MPa. Shear strength data for samples stored at 175℃ shows an initial drop at 24 hours but subsequently rises to 10.8 and 15.1 MPa for 48 and 72 hour storage times respectively. This data is shown in figure 6. This data is in good agreement the 16.18MPa found during previous work on these engineered surfaces [5]. The failed bonds, shown in figure 7 are non-uniform displaying a pattern of ridges. This indicates that the material strength is greater than that of the bond strength and further process refinement is needed.

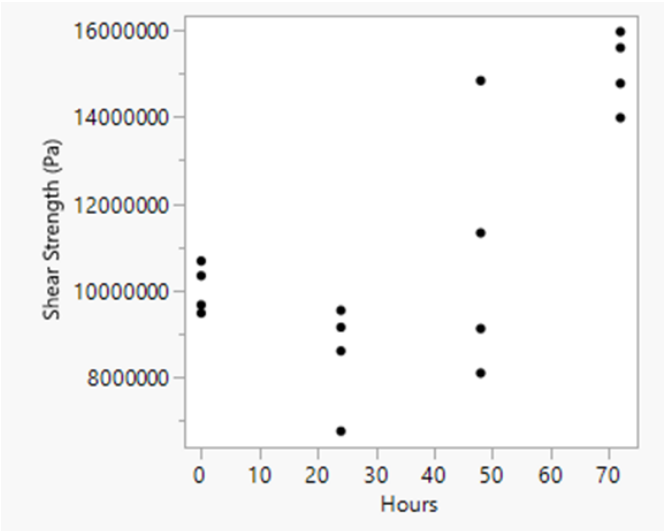

Fig. 6: Shear strength of SAC305 structurally enhanced TLP bonds stored at 175℃ under a total pressure of 224.5 Pa.

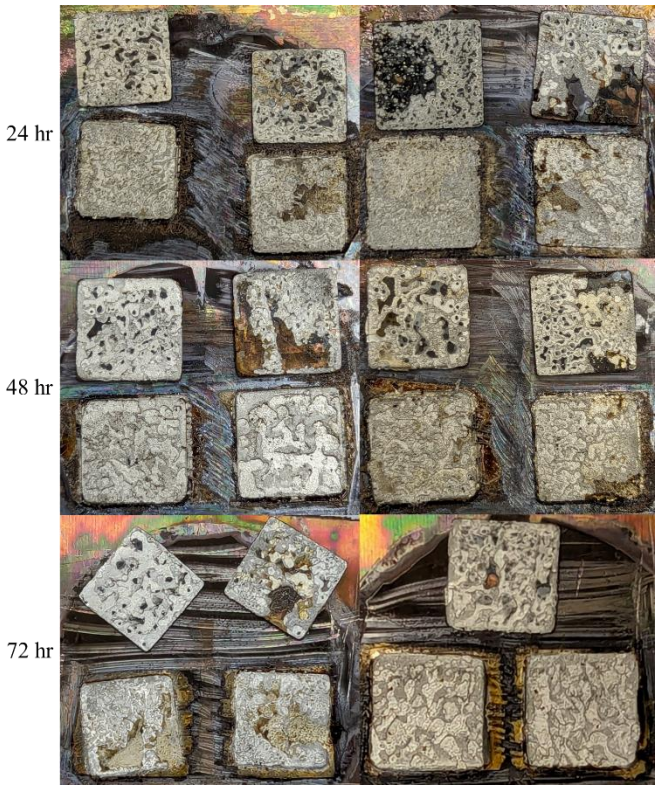

Fig. 7: Post shear die and substrate optical images of high temperature storage samples.

Samples stored at 300℃ possessed insufficient strength for data acquisition (shear force of < 60 N). This condition corresponds to a homologous temperature of 0.82 for η-phase. That combined with the rapid oxidation behavior of copper can account for the failure of these samples. Innert environment storage is required to confirm oxidation as the source of this failure.

IV. Conclusions

In this work several methods of improving structurally enhanced TLP bonding were explored. It was found that while nickel is known to be beneficial to η-phase copper-tin intermetallic bonding, its addition by means of autocatalytic plating results in a total prevention of intermetallic growth. Nickel may still prove to be effective in these bonds if deposited by physical vapor deposition or inclusion as a particulate within the solder paste. It was also shown that the elimination of unused engineered structures can lead to a reduction in contraction type voids in the final TLP bond. Reduction of bonding time was achieved by stencil thickness reduction, but at the cost of yield. 1μm proved an insufficient amount of free distance. Failures due to a lack of adhesion indicate the necessity of a Ti or TiN adhesion and barrier layer in cases where having a thick source of copper is not possible on the die side of the joint.

Storage tests at 175 ℃ showed an overall positive relationship between shear strength and storage time raising from 10 MPa to 15 MPa over 72 hours. This indicates the thermal stability of these joints at the thermal limit of current semiconductors. However, samples are not stable at 300℃ in an ambient environment. It is believed that this is the result of rapid oxidation of copper at this temperature.

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