Solid-Liquid InterDiffusion (SLID) Bonding, for Thermally Challenging Applications

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Abstract—**Solid-Liquid InterDiffusion (SLID) bonding is particularly suited for high-temperature applications, since SLID bonds can tolerate higher temperatures than the bonding temperature. SLID uses a layered binary metal structure, which reacts to high-temperature stable intermetallics at normal solder temperatures. Hence, high-temperature stability is achievable for a process at moderate bonding temperatures. Alternatively, low-temperature SLID bonding (bonding down to ~100 °C) allows bonding of temperature-sensitive components and materials, without restricting the application temperature range.**

Cu–Sn is the most mature SLID system. We show optimized Cu–Sn SLID bonding for vacuum encapsulation of MEMS devices. Au–Sn SLID has superior oxidation resistance, and we demonstrate that Au–Sn SLID has excellent reliability when bonding thermally mismatched chips and substrates. We demonstrate Ni–Sn SLID bonding, as well as the low-temperature alternatives Au–In and Au–In–Bi.

For Cu–Sn, Au–Sn and Au–In SLID, we show experimental evidence for the high-temperature stability predicted from phase diagrams.

Keywords-Microelectronics/ microsystem assembly, harsh environments, transient liquid phase.

I. INTRODUCTION

Solid-Liquid InterDiffusion (SLID) bonding has the distinct property that the bondline remelts at higher temperatures than the bonding temperature. It is therefore very suitable for high-temperature applications, also at temperatures where regular solder bonds would melt [1-4]. It is a versatile technique that can be used for interconnects, die attach or sealing, and flux-free bonding is achievable [1]. SLID bonding will survive high-temperature processes such as getter activation, hence it is also well suited for vacuum sealing. SLID bonding can eliminate the need for a hierarchy of solder alloys with different melting temperatures for bonding of stacks or for bonding at different levels of integration, hence simplifying manufacturing processes. Using appropriate metal systems, low-temperature SLID bonding can be used for temperature-sensitive materials such as polymers or poled piezoelectrics, where the resulting bond can still be reliable at somewhat elevated temperatures [5].

SLID bonds have a well-defined metallurgy and typical bondline thickness in the micrometer range. It is also very well suited for fine-pitch bonding [2, 6, 7]. SLID bonding is compatible with wafer-level, as well as chip-level, bonding.

SLID bonding technology typically uses a thin-layered metal system, with one high-temperature stable metal (such as Cu, Ni or Au) and one low-temperature melting metal (such as Sn or In). When bonding at normal soldering temperatures, all the low-temperature melting metal is consumed in reactions, isothermally solidifying to intermetallic compounds (IMCs) with high melting temperatures. The desired bondline (obtained by designing a dedicated thickness ratio of the two metal layers) is usually one that is in a thermal equilibrium state, implying that no further reactions will occur during the lifetime of the device. This enhances the reliability of the bond, particularly for high-temperature applications, since there will be no further growth of IMC layers (this being a typical failure mechanism for solder joints). The technique is also known as Transient Liquid Phase (TLP) bonding [8-10].

Cu–Sn is the most mature SLID system, using metals and processing temperatures comparable to that of conventional soldering [2]. Significant research has also been done in Au–Sn SLID [11, 12], which is a system excellently suited for harsh enviroments, but any combination of a high-temperature melting metal and a low-temperature melting metal with high-temperature stable IMCs are candidates for SLID bonding. The process temperature will then be determined by the low-temperature melting metal, and the high-temperature survivability by the resulting IMC and the high-temperature metal.

This paper presents the extensive work on various SLID systems in our group [13]. We have optimized flux-free Cu–Sn SLID bonding for wafer-level hermetic encapsulation of MEMS devices, being ready for industrial implementation [14-17]. We have verified the high reliability of Au–Sn SLID even for thermally mismatched bonding pairs, and we have identified the resulting phases in Au–Sn SLID bonds. We have also used Au–Sn SLID bonding as proof-of-concept for ultrasound transducer manufacturing, where the property of thin-layered metallurgy is more important than the high-temperature stability. Furthermore we have explored newer SLID systems: Ni–Sn, that has potential for higher thermal stability than Cu–Sn and Au–Sn; Au–In SLID (allowing lower bonding temperatures); Au–In–Bi SLID (allowing sub-100 °C

bonding temperatures). We have verified experimentally the high-temperature stability of three of the SLID systems: Cu–Sn, Au–Sn and Au–In, quantifying the bond strength at temperatures well above the melting temperatures of Sn and In.

II. EXPERIMENTAL

A. *Wafers, substrates and chips for SLID bonding*

Our most commonly used test vehicles are silicon dies or wafers. Si test vehicles were the relevant choice for our work on Cu–Sn SLID for wafer-level vacuum encapsulation of MEMS devices, and they are versatile test structures for demonstration of bonding, with a range of manufacturing processes readily adapted for Si substrates. Note that whereas SLID provides very strong bonds, IMCs tend to be brittle. Hence, care must be taken for SLID bonds to tolerate thermomechanical stress. In the case of Si-to-Si bonding, the thermal match of the bonding partners minimizes this thermomechanical stress. Our Au–Sn SLID bonding was performed on thermally mismatched bonding pairs, to represent die attach of power devices to realistic substrates: SiC dies to Cu clad Si_3N_4 substrates, in order to investigate the ability of Au–Sn SLID to withstand thermomechanical stress. For Au–Sn SLID as well as Au–In–Bi SLID, relevant substrates for ultrasound transducer manufacturing were bonded: Piezoelectric PZT (Lead Zirconate Titanate) to a Resonant Backing Layer (acoustically hard material), allowing acoustic testing of the assembly.

B. *Metallization*

Cu, Sn, Au and Ni layers for SLID bonding were deposited by electroplating, on top of sputtered adhesion/ seed layers, with electroplated layer thicknesses ranging from 1 µm to 10 µm. Electroplating is compatible with large-scale manufacturing, performed at wafer-level. It allows patterning for interconnects or seal rings in an additive process. For Au–In SLID bonding, Au layers were sputtered (0.2 µm and 0.8 µm) and In layers evaporated (1.3 µm). For Au–Sn and Au–In–Bi SLID, eutectic preforms were used as the low-temperature melting metal: $Au_{80}Sn_{20}$ (melting point 278 °C) and $In_{66}Bi_{34}$ (melting point 73 °C), the ratios here given as wt%. Preforms are versatile for fundamental characterization of the SLID bond, and they represent available manufacturing processes for die attach and for lamination (as in ultrasound transducer fabrication). However, preforms are not compatible with patterning for interconnects or wafer-level seal rings. For such applications, the preferred metallization is electroplating, sputtering or evaporation. We have also demonstrated Au–In–Bi SLID bonding, using evaporated eutectic In–Bi. For the different SLID systems, the layer thicknesses are designed in order to achieve the desired phases after bonding. The different metallization schemes for the different SLID process are summarized in Table I, in chapter VIII.

C. *Bonding*

Cu–Sn and Au–In SLID bonding is performed at wafer-level, whereas the other SLID systems are bonded at chip level, in both cases with an applied, moderate bonding force to ensure good wetting of the bonding partners while the liquid phase is present. Bonding profiles (two examples are shown in Figure 2 below) includes heating to a bonding temperature above the melting point of the low-melting metal, where the temperature is kept constant for a holding time long enough to convert the metal system to the desired phase composition (normally being a thermal equilibrium state), before the temperature is lowered to room temperature. The holding time ranges from 6 minutes for Au–Sn SLID bonded at 300-350 °C, to hours for the low-temperature (~100 °C) bonded Au–In–Bi. Note that the moderate bonding force is needed only in the initial part of the bonding, and long bonding times may be executed as annealing in a batch process. Usually, a short holding time is introduced in the bonding profile, at a temperature before the melting temperature of the low-melting metal is reached. This ensures initial formation of a uniform layer of IMC by solid-state diffusion, which is a key factor for obtaining uniform growth of IMC layers during isothermal solidification, crucial for minimizing void formation in the bondline [18]. All our SLID bonding is flux-free, eliminating the need for post-bond cleaning and allowing SLID bonds to be used for vacuum encapsulation without risking residual flux jeopardizing vacuum levels.

D. *Characterization*

SLID bond strength is characterized by shear testing, both conventional room temperature testing as well as shear testing while the bonded sample is heated to defined temperatures. The bondline morphology and microstructure is characterized by cross-section microscopy (optical and SEM) and EDX (Energy-Dispersive X-ray spectroscopy), as well as XRD (X-Ray Diffraction) and EBSD (Electron BackScatter Diffraction). The SLID systems used for ultrasound transducer prototyping (Au–Sn and Au–In–Bi) have been characterized by electrical impedance spectroscopy, for evaluating the acoustic integrity of the assembly.

III. CU–SN

A. *Cu–Sn SLID process*

Cu–Sn is by far the SLID system that has got most attention in research and industry, and the fundamentals of the SLID system is well understood. Cu and Sn are low-cost materials well known in industry, hence Cu–Sn is the SLID system most easily adapted for mass production. The desired bond is a layered structure of Cu / Cu_3Sn / Cu. According to the Cu–Sn phase diagram (Figure 1), such a bond will remain solid up to ~700 °C, and the bond is in thermal equilibrium for temperatures below ~350 °C [19].

The initial electroplated Cu and Sn layers are designed with a thickness ratio

$$\frac{t_{Cu}}{t_{Sn}} > \frac{3M_{Cu}\rho_{Sn}}{M_{Sn}\rho_{Cu}} = 1.3 \,, \qquad (1)$$

in order to ensure complete conversion to Cu_3Sn. Typically, a significantly larger thickness ratio is selected, in order to have

well-defined layers of remaining Cu on both sides of the central Cu_3Sn layer. This will give a margin to ensure that all Sn is consumed to form Cu_3Sn, and a continuous Cu layer will avoid unwanted reactions between residual Sn and the adhesion layers. Cu layers will also give ductility to the bond, compared with the hard and brittle Cu_3Sn.
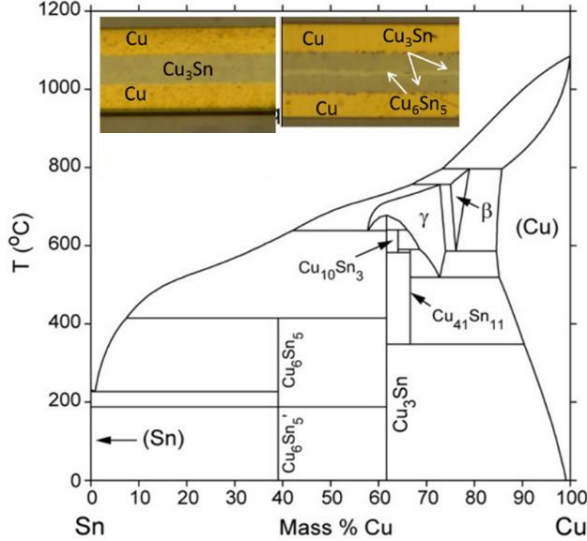

Figure 1: Cu–Sn phase diagram. The insets show cross-section of SLID bonds: Complete conversion to Cu_3Sn (left), and incomplete conversion with remaining Cu_6Sn_5 layer (right).

In our Cu–Sn SLID bonds, we typically use 5 µm Cu thickness, and 1-2 µm Sn thickness. The same layer structure is used for both bonding partners, which is ideal for a wafer-bonding process: An optimized bonding profile (heating rate and bonding force vs time) allows breaking of the thin tin oxide layer to ensure good wetting during bonding, which results in strong bonds with a minimum of voids. For chip-level bonding, Sn would be plated only on the chip side, to avoid Cu–Sn interdiffusion on the heated substrate side prior to bonding.

Bonding is performed at temperatures above the melting point of Sn (232 °C), typically at 250-300 °C. The first IMC to solidify is Cu_6Sn_5, which further reacts with Cu to form Cu_3Sn in the final bond.

B. Cu–Sn SLID wafer-level process optimization

In order to optimize the wafer-level bonding process for industrial implementation, we developed a simulation model to predict the thickness of the different layers (Cu_3Sn, Cu_6Sn_5 and remaining Sn) as function of time during the actual bonding profile [20]. We obtained the input data for the temperature-dependent kinetics of diffusion and reactions from Cu–Sn bi-layer experiments, through annealing at different times and temperatures, cross-section microscopy and EDX spectroscopy. Figure 2 shows the simulation results for two different bond profiles: One with 10 minutes holding time, where a remaining, sub-micron layer of Cu_6Sn_5 is predicted, and another with 30 minutes holding time, were full conversion to Cu_3Sn is predicted. The cross-section micrographs show that these predictions correspond well to the experimental results. Note that the simulation model takes into account diffusion and reactions in all parts of the bond profiles: the heat-up, the holding time at the bonding temperature, as well as the cool-down.

Two outputs of this simulation model are particularly important for industrial process optimization: The times t_1 and t_2, where all pure Sn, respectively all Cu_6Sn_5, has been consumed. Thus, t_1 signifies the time when the entire bondline is solid at the bonding temperature, and the assembly can be removed from the bonder for the remaining part of the bond profile to be carried out as a batch anealling process. t_2 signifies the time when the desired Cu / Cu_3Sn / Cu structure has been obtained, and the bond is in thermal equilibrium. This is therefore the minimum total time (adding the time in the bonder and the annealing time) needed to obtain the final bond, for a chosen layer thickness and bonding temperature/ bonding profile.
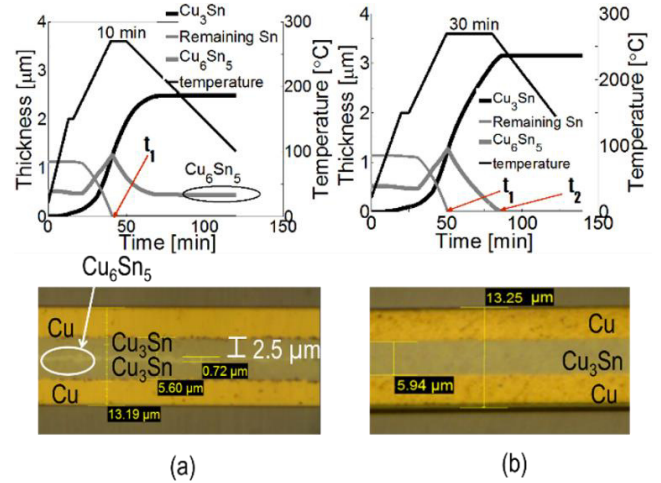

Figure 2: Different bond profiles for Cu–Sn SLID wafer-level bonding, and corresponding cross-section optical micrographs [20].

IV.   Au–Sn

A. Au–Sn SLID process

Au–Sn is a particularly interesting SLID system for applications where the excellent oxidation resistance or the ductility of Au justifies the higher cost. The Au–Sn system is more complex and exhibits more IMCs than its Cu–Sn counterpart [21] (see Figure 3). The desired bond is a layered structure where one of the Au–rich phases (β or ζ) is sandwiched between two Au layers. Such a bond will be solid for temperatures up to 522-532 °C, and a bond with β as the IMC will be in thermal equilibrium. Our work has shown that the IMC formed in a Au–Sn SLID bond is the ζ phase, and the conversion to the thermal equilibrium state will only take place after long-term annealing [22].

The Au–Sn system has a eutectic point at 29 at% Sn (20 wt% Sn), with eutectic melting point 278 °C. A SLID process with initial layer structure Au / Au–Sn eutectic / Au will have a direct reaction to the the SLID bond structure outlined above. If we use pure Sn as the low-melting metal,

there will be intermediate reactions to several IMCs, one of which has a fairly high melting point of 419 °C. It is therefore advantageous to use the eutectic composition as the low-melting metal in the initial layer structure. The corresponding bonding temperature must be above 278 °C.
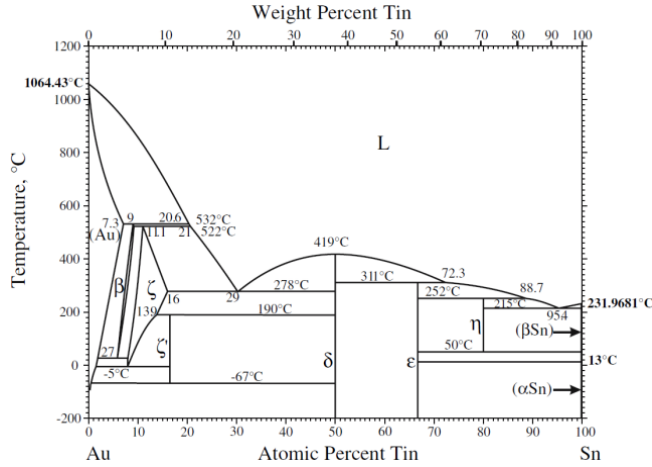

Figure 3: Au–Sn phase diagram, reprinted by permission from Springer Nature [21].

We have used eutectic Au–Sn preforms as the initial material in our Au–Sn SLID bonding, placed between electroplated Au layers on each of the bonding partners. This is a versatile bonding technique, relevant for die attach and for lamination of materials. The layer thickness used depends on the eutectic preform available: For a 7.5 µm thick preform, we have used 10 µm thick Au on both sides, in order to ensure remaining Au on both sides of the IMC. We typically use bonding temperature in the range 300-350 °C.

B. Au–Sn SLID die attach of power device

We bonded SiC dies to Cu clad Si_3N_4 substrates, as demonstrator for die attach of power devices to realistic substrates [22]. The chips and substrates are thermally mismatched: SiC and Si_3N_4 have similar CTE of 4.2 ppm/K while the thick (150 µm) Cu layers have a CTE of 17 ppm/K. It is crucial to test the reliability during thermal cycling for such an assembly, since the thermomechanical stress will be significant. The layers of ductile Au can absorb thermomechanical stress, whereas the brittle Au–Sn IMCs are susceptible of fracture if the stress is too high. The bond shear strength was tested for virgin samples, and for samples after reliability testing: high-temperature storage (HTS) at 250 °C up to 6 months, as well as thermal cycling (1000 cycles, 0 to 200 °C).

Figure 4 shows the measured bond shear strength. The as-bonded samples are extremely strong, with a shear strength of the order of 140 MPa. The reliability testing of combined high temperature storage and thermal cycling reduces the bond strength, but it is still at a very high level, around 70 MPa. Hence, we conclude that Au–Sn SLID is well suited for handling thermomechanical stress when bonding thermally mismatched dies and substrates.
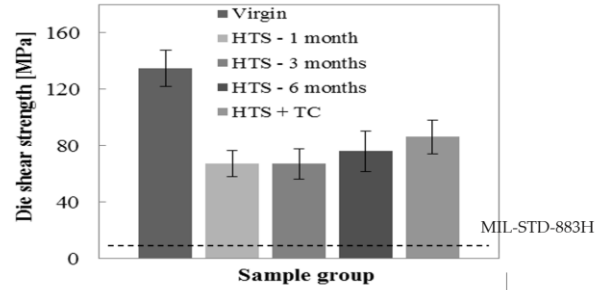

Figure 4: Die shear strength for virgin Au–Sn SLID samples, for high temperature stored (HTS) samples (250 °C for 1, 3 and 6 months), and samples exposed for 3 months HTS + 1000 thermal cycles (TC) between 0 and 200 °C. Reprinted by permission from Springer Nature [22].

C. Au–Sn SLID, lamination for transducers

To demonstrate the ability to use Au–Sn SLID for lamination of materials, we bonded substrates of the piezoelectric material PZT (Lead Zirconate Titantate) to a RBL (Resonant Backing Layer) substrate, as a demonstrator for an ultrasound transducer [23]. This particular bonding requires thin, uniform bondlines of well-defined metallurgy, hence the suitability of SLID. Figure 5 shows a cross-section of a successfully bonded assembly, demonstrating that Au–Sn SLID is suitable also for bonding rough substrates (roughness > 1 µm) over a large area (5 x 5 mm²). The bondline shows certain, but limited, voiding. The amount of voiding can be controlled by careful optimization of the bonding parameters. We have shown by electrical impedance spectroscopy that the voids obtained do not jeopardize the acoustic properties of the assembly [23].
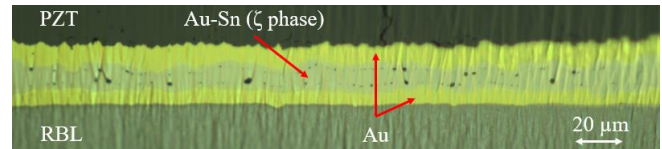

Figure 5: Cross-section optical micrograph of Au–Sn SLID bonded/ laminated acoustic materials, demonstrating the suitability of Au–Sn SLID for large-area lamination for transducers, also for substrates with rough surfaces.

V. Ni–Sn

The Ni–Sn SLID system is much less explored than its Cu–Sn and Au–Sn counterparts. The Ni–Sn phase diagram shows three IMCs: Ni_3Sn_4, Ni_3Sn_2, and Ni_3Sn, which are solid to very high temperatures (798 °C, 1280 °C and 1189 °C, respectively) [24]. According to the phase diagram [25], a thermal equilibrium SLID bond would consist of a layered Ni / Ni_3Sn / Ni structure, that would be solid for temperatures up to 1139 °C (where there is a eutectic point between Ni and Ni_3Sn), and be in thermal equilibrium for temperatures up to 948 °C (where Ni_3Sn undergoes a solid-state phase transition). Hence, Ni–Sn SLID has potential for applications for extreme temperatures, well above the temperatures where Cu–Sn SLID would be applicable. Ni and Sn are low-cost materials well known to industry. However, Ni–Sn shows a much

slower kinetics than Cu–Sn [26], bringing challenging in optimization of manufacturing processes.

We have demonstrated Ni–Sn SLID bonds, and verified the slow kinetics reported by previous workers [27]. Although the thermal equilibrium data in the phase diagrams suggest similar bonding temperatures to be used for Ni–Sn as for Cu–Sn (250-300 °C), this will call for extensive bonding times. Figure 6 shows a cross-section micrograph of a Ni–Sn SLID bond performed at 360 °C for 20 minutes. The Ni_3Sn layers have only grown to thickness of 0.8 µm, the dominating IMC in the bondline being Ni_3Sn_2.

The bondline shows significant voiding, and the level of voiding varies greatly for different positions along the bondline. This can partly be explained by the high volume contraction when Ni and Sn reacts to IMCs (15-17% for reaction to Ni_3Sn), compared to the somewhat lower values for the Cu–Sn and Au–Sn systems (~10% and ~4%, respectively). Note, however, that optimization of the bonding parameters for Ni–Sn SLID bonding is challenging due to the slow kinetics. We expect such an optimization to result in lower voiding levels, as has been our experience in our more extensive research in Cu–Sn and Au–Sn SLID bonding.
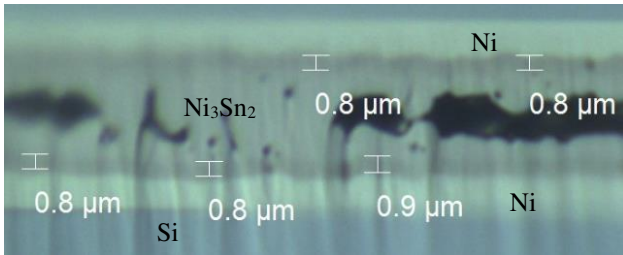

Figure 6: Cross-section optical micrograph of Ni–Sn SLID bonded at 360 °C for 20 minutes. The dark gray phase with thickness measurements, is the Ni_3Sn phase. The black regions are voids [27]. © 2016 IEEE

We obtain high strength of our Ni–Sn SLID bonds, in the order of 40 MPa. Also the more severely voided joints show high strength. When normalizing to the actual bonded area, we have achieved effective shear strengths as high as 230 MPa.

VI. AU–IN

In has a low melting point of 156 °C, whereas the numerous Au–In IMCs all have melting temperatures of 450 °C or higher [28]. Au–In SLID bonding is therefore an excellent candidate for low-temperature bonding that still has a good thermal stability. Low-temperature bonding is important for temperature-sensitive materials, as well as for minimizing thermomechanical stress induced in the manufacturing process. This can also be achieved by traditional low-temperature solders, but only allowing a temperature range during the lifetime of the device well below the melting point of the solder. Au–In SLID will not have this limitation.

Au and In show high interdiffusion already at room temperature, and a thin-layer Au–In structure can react to IMCs within the timescale of hours [29, 30]. In a realistic process where metallization takes place days or weeks before

bonding, a layered Au / In structure must be designed with significant In surplus to ensure a fresh In surface to be bonded. This implies thin Au layers, and the resulting SLID bond will not be the typical SLID bond that is a thermal equilibrium layered Au / IMC / Au structure. Since a low-temperature SLID process is not expected to be used for applications going to extreme temperatures, it is acceptable to deviate from the thermal equilibrium requirement that usually defines SLID.

We demonstrate successful wafer-level Au–In bonding, bonded at 180 °C [31]. Figure 7 shows a cross-section micrograph of a resulting bond, with two Au–In IMCs. The shear strength of the bonds is good, in the order of 30 MPa. Testing the die shear strength for higher temperatures, up to 300 °C (see Figure 9), we prove that the bonds are indeed strong well above the melting temperature of In. The strength at 300 °C is even higher than at room temperature, explained by a solid-state phase transformation between different IMCs [31].
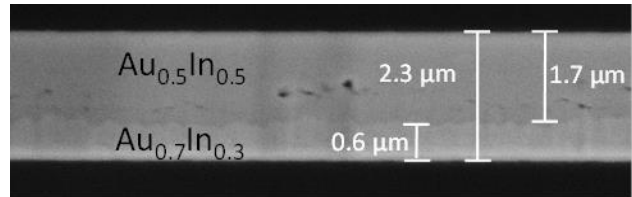

Figure 7: Cross-section SEM micrograph of Au–In bonded sample. Two Au–In intermetallic compounds (IMCs) are present in the final bond-line. Reprinted by permission from Springer Nature [31].

VII. AU–IN–BI

Several materials and applications will need even lower bond temperatures than what can be achieved by Au–In SLID bonding. Examples are polymers, poled piezoelectric and ferromagnetic materials. By using binary alloys as the low-temperature metal in SLID bonds, the bonding temperature may be pushed to even lower values.

In–Bi has a melting point of 73 °C for the eutectic point (79 at% In), and a variety of In–Bi IMCs melting in the range 89-110 °C [32]. The pure metals melt at 156 °C (In) and 271 °C (Bi). The Au–Bi phase diagram shows that these two metals are not miscible, neither do they react to IMCs that are stable at room temperatures [19]. The lowest melting point in the Au–Bi system is at 241 °C. Hence, for a low-temperature SLID bonding using Au as the high-temperature metal and In–Bi eutectic as the low-temperature metal, the expected reactions to IMCs are the Au–In IMCs described in the previous chapter. No Au–Bi reactions are expected.

We demonstrate Au–In–Bi SLID bonding, using a eutectic In–Bi preform sandwiched between electroplated Au layers, with bonding temperatures as low as 90 °C [33]. However, the resulting bond is a multi-phase bond, including $BiIn_2$ that has a melting point of 89 °C. This implies that a higher remelting temperature cannot be expected. To avoid the presence of low-melting In–Bi IMCs, a bonding temperature higher than 110 °C should be selected. Figure 8 shows a cross-section micrograph of a Au–In–Bi SLID bond performed at 115 °C, showing a Au / Au–In IMCs / Au layered structure. Inspection

along the length of the bondline reveals inclusions of elemental Bi, but no In–Bi or Au–Bi IMCs. This finding is as expected from analysis of the phase diagrams, and predicts a thermal stability up to 271 °C, where the Bi inclusions would melt. Considering that these inclusions do not form a continuous path through the bondline, we would actually expect the bond to remain solid for temperatures up to the melting point of Au–In IMCs (~450 °C).

A particular case where low-temperature bonding is required, is for lamination of ultrasound transducers where the piezoelectric material is poled prior to assembly. Polarization will be lost if the material is exposed to temperatures above the Curie temperature, typically around 150 °C for PZT. We have demonstrated Au–In–Bi bonding of PZT to RBL [5]. Electrical impedance spectroscopy verifies that the polarization of PZT is intact after bonding, and that the voiding level is acceptable for the acoustic properties of the assembly.

Bonding at low temperatures with relatively thick preforms results in extensive bonding times, in the order of hours. We have demonstrated that shorter bond times can be achieved by thermal evaporation of thin films of eutectic In–Bi on gold layers for SLID bonding [5]. The integrity of these bonds has also been verified by electrical impedance spectroscopy.
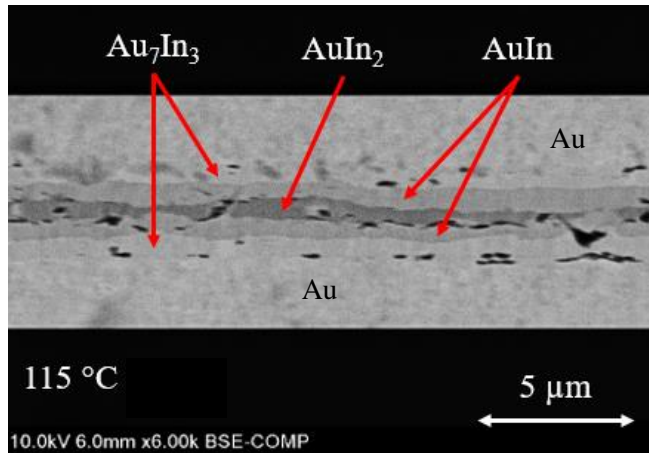

Figure 8: Cross-section SEM micrograph of Au–In–Bi SLID bonded Si dies, bonded at 115 °C. The Au layers are bonded by Au–In IMC, and Bi appears as inclusions of elemental Bi at several positions along the bondline (not in the particular part of the bondline shown here).

VIII. COMPARING THE SLID SYTEMS

A. *Properties of different SLID systems, as bonded by USN*

Table I summarizes the different SLID systems discussed in this paper, justifying the different research directions we have undertaken for the different systems, and comparing the main results. All our SLID systems show bond strength comparable with or higher than what is typically obtained with Sn-based solder (30-40 MPa [34, 35]). The highest bond strength is obtained for Au–Sn SLID. This is partially explained by the oxidation resistance of Au and eutectic Au–Sn, ensuring a bond process with excellent wetting.

B. *Shear strength vs temperature*

We have tested experimentally the high-temperature stability of SLID for three systems: Cu–Sn, Au–Sn and Au–In. The bond shear strength is measured while heating the assembly to a specified temperature, up to 300 °C [36]. Figure 9 shows this shear strength vs temperature, demonstrating that all three bonds remain solid to temperatures well above the melting points of Sn and In. For Au–Sn SLID, we have shown that the bond is solid at 400°C, but without quantifying the bond strength [37].
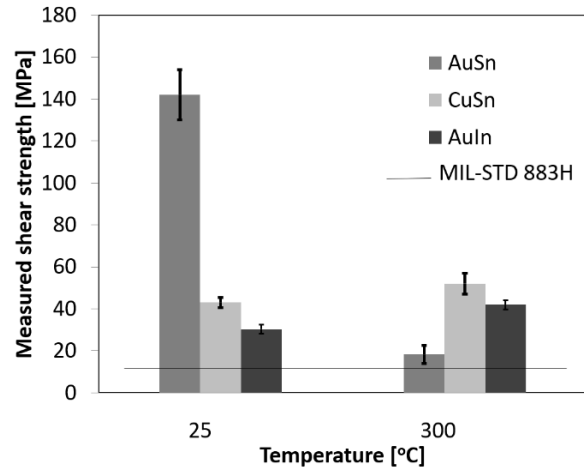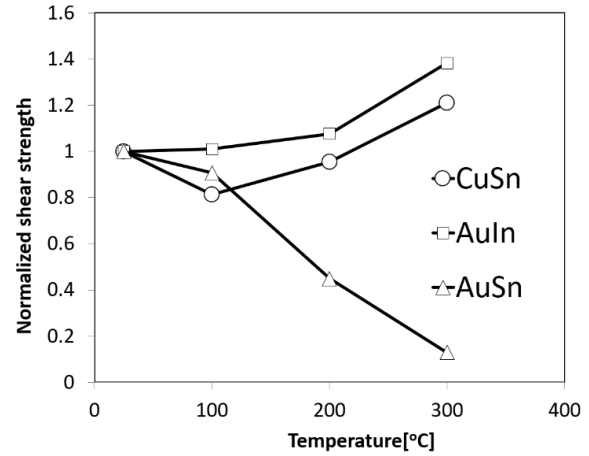

Figure 9: Normalized shear strength vs. die shear temperature and actual shear strength at RT and 300°C [36]. © 2014 IEEE

The different strength vs temperature behaviour of the three SLID systems can be explained from the phase diagrams. A Cu/ Cu_3Sn system is stable up to 350 °C, with no phase transitions, consistent with the moderate variations of Cu–Sn SLID strength with temperature. Au–In SLID shows a remarkable increase in strength between 200 °C and 300 °C. At the lower temperatures, the Au–In bond fracture typically occurs in the original bond interface, indicating that wetting of the bonding partners was the limiting factor for bond strength. Our Au–In bonds consist of AuIn and Au_7In_3 layers, which undergoes a solid-state phase transformation to the Ψ phase above 224 °C [31]. For the layer thickness design of our Au–In SLID bonds, this involves Au–In interdiffusion across

the original bond interface, strengthening the bond. The strong bonds at 300 °C show cohesive fractures, no longer following the original bond interface. For Au–Sn SLID, the strength decreases significantly at the higher temperatures, but the strength at 300 °C (20 MPa) is still much higher than what is required by Mil-Std 883H, and comparable with room-temperature strength of Sn-based solders. The decrease in strength is explained by the composition-dependent melting point of the non-stochiometric ζ phase (see Figure 3). We expect that an annealed Au–Sn SLID bond consisting of a Au / β / Au structure, would show a more constant strength vs temperature.

A related technique where we also show stability at higher temperatures than the process temperature, is off-eutectic Au–Ge bonding [38], where we measure the bond remelt temperature to 460 °C, to be compared with the eutectic melting temperature of 361 °C. In this process the high-temperature stability is not based on IMCs, but rather on a microstructure ensuring that molten eutecticum is present in isolated pockets that do not form a continuous path throughout the bondline.

TABLE I.   SUMMARY OF SLID SYSTEMS

	Cu–Sn	Au–Sn	Ni–Sn	Au–In	Au–In–Bi
USN contributions	Flux-free, wafer-level bonding for hermetic sealing Simulation model for IMC kinetics Industrial implementation Strength vs temperature	Composition determined Excellent reliability (HTS & TC, also with CTE mismatch) Strength vs temperature	Bond demonstrated and characterized	Wafer-level bonding demonstrated and characterized Strength vs temperature	Bond demonstrated and characterized (mechanically and acoustically)
Process temperature	> 232 °C	> 278 °C	> 232 °C	> 156 °C	> 73 °C (>110 °C for high-temperature stability)
Obtained bond strength	70 MPa	140 MPa	>40 MPa (nominally) > 200 MPa in the actually bonded areas	30 MPa (breaking at bond interface) 40 MPa at 300 °C	50 MPa
Metallization used in USN research	Electroplated Cu and Sn	Electroplated Au, Au–Sn eutectic preform	Electroplated Ni and Sn	Sputtered Au, evaporated In	Electroplated Au, In–Bi eutectic preform Demonstration: evaporated In–Bi eutecticum
Application demonstrator	Wafer-level vacuum encapsulation of MEMS	Die attach of power devices Lamination of transducers	Bond demonstration	Wafer-level bond demonstration	Lamination of transducers
Special attributes	Low-cost, mature process	Chemical inertness Absorbs thermomechanical stress	Extreme high-temperature stability	Low-temperature bonding	Extreme low-temperature bonding

IX. Conclusion/ Outlook

SLID bonding is a versatile technique that gives high-temperature stability of bonded joints. It can be used for high-temperature / harsh environments applications, for products that must tolerate high-temperature manufacturing processes, for low-temperature bonding that do not impose severe temperature restrictions on the final product, as well as to eliminate a hierarchy of solder alloys with different melting temperatures. It can also be used for fine-pitch interconnects, although that has not been the research direction of our group.

We have shown Cu–Sn SLID bonding for wafer-level vacuum encapsulation of MEMS devices, Au–Sn SLID bonding for harsh environment applications, and demonstrated Ni–Sn, Au–In and Au–In–Bi SLID bonding, experimentally verifying the high-temperature stability of Cu–Sn, Au–Sn and Au–In SLID.

Our future SLID work will further optimize bonding processes for the metal systems described in this paper, we will explore novel metal systems for SLID, and we will apply our SLID bonding expertise for new, relevant applications.

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