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Macroscopic Manifestations of Intermetallic Compound Transformations during Thermal Treatment and Reflow

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Abstract— *Intermetallic compounds (IMC) formation and growth are critical factors in evaluating the integrity of the base metal-solder interface, which are strongly affected by thermal treatment such as aging and reflow condition. These thermal treatments are essential in the assembly manufacturing of semiconductor and electronic devices. Herein, we demonstrate the effect of thermal treatment and reflow on the formation and integrity of IMCs in NiAu/Sn-3.0Ag-0.5Cu/NiAu sandwich systems. The deterioration and partial recovery in the macroscopic behavior manifested as shear strength as a function of thermal treatment and reflow are explained by the transformations in the IMCs: grain growth, grain boundary reduction, embrittlement, and IMC dispersion.*

Keywords— *Intermetallics, reflow, fracture, shear, failure.*

I. Introduction

Surface mount technology (SMT) has become one of the most utilized manufacturing processes in the semiconductor and electronic devices assembly. This technology provides a cost-effective high-volume solution for high density portable electronics. However, challenges imposed by the aggressive miniaturization of devices, and environmental regulations have increased the mechanical and thermomechanical stresses on the interface. These interfaces are composed of a base metal and a solder system acting as an interconnection between two materials. In the context of electronic device assembly, typical elements of interest are Sn (from the solder), and Cu and Ni (as common base materials). The solder, however, contains several other elements depending on the mission profile of the device. Also, while Cu and Ni are the most common base materials, carriers and PCBs often include other plating layers such as Pd and Au, or some organic soldering preservatives (OSP). Therefore, by using a near-eutectic lead-free solder such as SnAgCu on an electroless Ni(P)/Au base material, the interface contains six elements, thereby increasing the complexity of the interfacial chemistry [1-3].

Due to the increasing complexity of the interfacial layers, the design for reliability becomes a major field. The growth of the intermetallic compounds (IMC) between and within these layers make the solder interconnect layers more vulnerable to mechanical stresses. This is especially significant in portable consumer electronics where mechanical shock loading are experienced once dropped. In addition, the magnitude and distribution of these stresses are anisotropic at the interface and within the solder layer. A solid fundamental understanding of the material behavior and interfacial chemistry is of significant importance.

Analyses of the thermodynamics, kinetics and microstructural evolution along the interface and within the solder bulk provide fundamental understanding of the material behavior under stress. Information about the driving forces for chemical reactions and for diffusion processes occurring in the solder interconnections or thin film structures during processing, testing and in long-term use of electronic devices are provided by thermodynamics studies. Kinetics studies afford predictions on the timeframe of the processes, both chemical reactions and diffusion processes. Microstructural studies are often the source of data for both thermodynamics and kinetics studies for the transformation of materials at the areas of concern.

Herein, we explore the origin of the observed macroscopic behavior of the NiAu/Sn-3.0Ag-0.5Cu/NiAu sandwich systems in response to the thermal treatment and reflow. Moreover, new insights into the interfacial behavior and transformations in the IMCs in terms of grain growth, grain boundary reduction, embrittlement, and IMC dispersion are provided in detail.

II. Experimental Details

The sandwiched solder systems consist of NiAu pads (interposer and substrate) and SAC305 (Sn-3.0Ag-0.5Cu) solder alloy subjected to consecutive thermal treatments; T1, T2 and T3. T1 is a standard reflow process with peak temperature of 245°C. T2 consists of a 30 min ramp from RT to 180 °C, isothermal for 1 h, ramp to 200°C, isothermal for 1 h, and cooling to RT for 30 min. T3 is another reflow with peak temperature of 260°C. T1, T2, T3 are temperature profiles experienced by the metal-solder system during assembly. S1 and S2 indicate two different materials under evaluation. Samples for analysis were micro-sectioned using a standard mechanical polisher. Additional polishing prior analysis was done using JEOL IB-09020CP Ar ion polisher. Field Emission Scanning Electron Microscope (FESEM) – Energy Dispersive X-ray Spectroscopy (EDS) was performed using FEI Dual Beam Helios Nanolab 600i

III. Results and Discussion

The sandwiched solder system consisting of SAC305 solder alloy connecting the NiAu pad of an interposer material and another NiAu pad of the substrate was evaluated during

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assembly after each process step. These process steps are reflow 1 (T1), component attach and bake (T2) and reflow 2 (T3). The in-process control parameters are the shear strength and break mode.

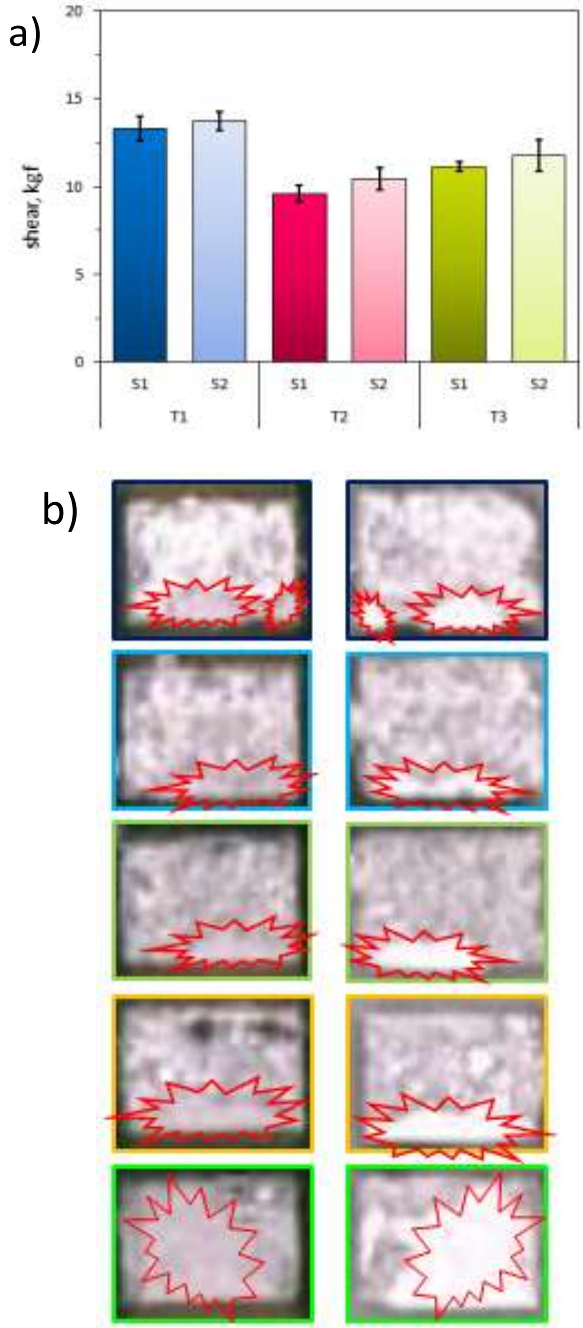

Fig. 1. a) Shear strength of soldered system subjected to three thermal treatments. b) Sheared surfaces showing significant interfacial fractures (enclosed).

Fig. 1a shows the shear strength after each thermal treatment, indicating the deterioration after prolonged heating (T2), and the partial recovery after the reflow (T3). Two materials are under evaluation namely, S1 and S2. Both materials do not exhibit significant difference in their shear strength after each thermal treatment. The break mode is mostly cohesive *i.e.*, along the solder layer. This break mode is preferred because it indicates the strength of the interfacial layer. However, the sheared surfaces also show the propensity of fractures along the interfaces as illustrated in Fig. 1b. These interfacial fractures indicate weakness in the solder-to-metal interface. The occurrence of these interfacial fractures has prompted the evaluation of the effect of the device's thermal budget during assembly to its solder joint reliability. Investigation of the interfacial structure via micro-sections coupled with elemental analysis were designed to understand the material evolution as a function of temperature.

Fig. 2 summarizes the SEM-EDS results showing the components and plating layers. Clearly, Ag is dispersed in the solder phase, and no stratification on the interface was observed, suggesting that Ag will not affect the interfacial behavior of the substrate-solder system [3,4]. Elemental analysis identifies Ag_3Sn in certain regions around the bulk Ag in the solder phase. The IMC formation is thermodynamically and kinetically favored even at room temperature and is expected to grow through time [5]. However, interdiffusion towards the metal-solder interface is highly unlikely.

Cu and Ni show distinct layers with minimal diffusion of Cu into Ni, indicating high barrier efficiency of the Ni layer [6]. After T1, a thin IMC layer forms with a mixture of $(Cu,Ni)_3Sn_4$ and $AuSn_4$. Prolonged heat treatment (T2) promotes Ni diffusion resulting in the conversion of $(Cu,Ni)_3Sn_4$ to $(Cu, Ni)_6Sn_5$, and grain growth. $(Cu,Ni)_6Sn_5$ is the thermodynamic product of the Ni and Sn interfacial reaction in the presence of Cu [7-8]. Redeposition of $AuSn_4$ along the interface is also evident after T2. The extensive ternary solubilities and co-existence at local equilibrium of $AuSn_4$ and $(Cu,Ni)_3Sn_4$ explain the redeposition of dispersed $AuSn_4$ in the solder phase on the $(Cu,Ni)_6Sn_5$ layer [3, 8-9]. In the case of T3, redeposition was not observed. Instead, distinct elongated microstructures were formed on the solder phase, suggesting interfacial embrittlement is expected to dominate. Interestingly, the reflow process resulted in the presence of dispersed Ni IMC on the solder phase. It is possible that these IMC islands break off from the interfacial layer during the molten state of the solder and were trapped in the solder phase during solidification. Another possibility is the formation of $(Au_{1-x}Ni_x)Sn_4$ IMC previously observed in the solder phase [9-12].

The growth of the IMC layer as a function of the thermal treatments are shown in Fig. 3. The initial treatment afforded a thin layer of IMC (0.30 ± 0.05 μm) in the form of $(Cu,Ni)_3Sn_4$ and $AuSn_4$. The layer thickness is homogeneous along the interfacial plane. The prolonged heat treatment resulted in faster growth and IMC conversion to $(Cu,Ni)_6Sn_5$ resulting in an IMC thickness of 1.03 ± 0.10 μm. The additional reflow step resulted in an IMC thickness of 1.70 ± 0.24 μm. The growth of the columnar IMCs, a characteristic geometry of $(Cu,Ni)_6Sn_5$ [3] appears favored orthogonal to the interfacial layer. Grain fusion affords the growth of larger grains.

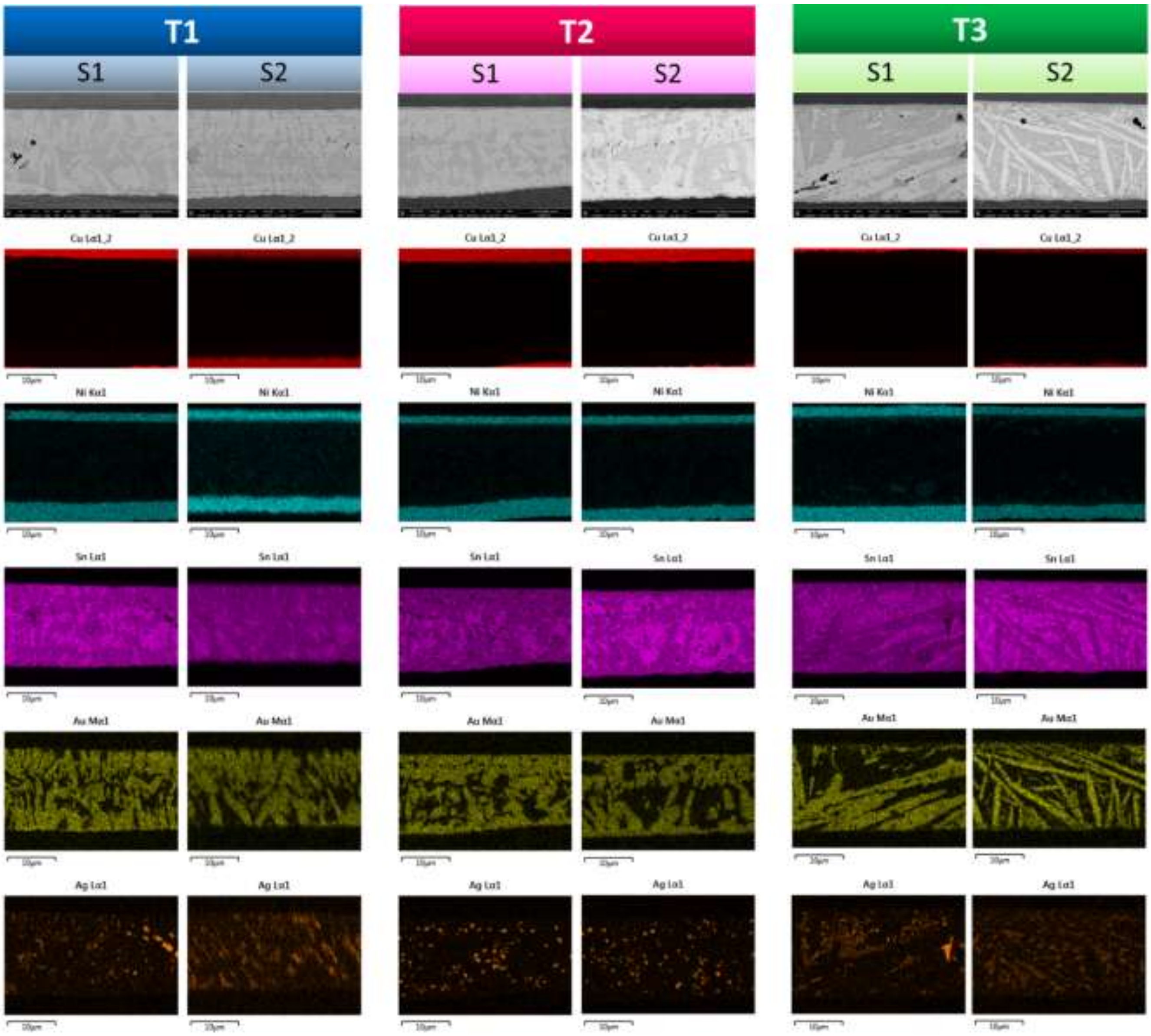

Fig. 2. SEM images and EDS maps of the sandwiched solder cross-sectioned surfaces. Cu - red, Ni - blue green, Sn - violet, Au - yellow, and Ag - orange.

High magnification SEM images (Fig. 4) reveal the grain structure of the IMCs after each treatment. Clearly, T1 has induced the formation of a thin IMC layer. T2 promoted Ni diffusion resulting in the IMC growth, with thickness about 3.0 - 3.5 times larger than the initial layer thickness. Moreover, the grain size also increases. The observed deterioration could be attributed to the increase in the grain boundaries, which are the fracture points during thermo-mechanical stresses [13-15]. The additional reflow (T3) afforded partial recovery by reducing the weak points during fracture propagation. The grain size is significantly larger leading to fewer grain boundaries. In addition, the dispersed IMCs cause embrittlement of the solder layer triggering a shift of the break mode from interfacial to cohesive fracture. The interplay of the IMC transformations involving grain growth, grain boundary reduction, embrittlement, and IMC dispersion could explain the observed macroscopic manifestations of the effects of thermal treatment and reflow in this sandwiched solder system.

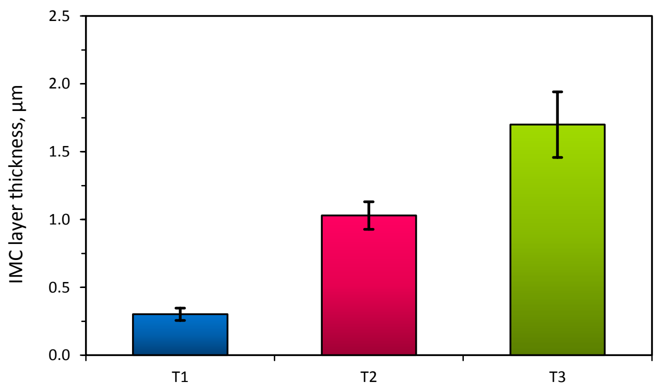

Fig. 3. IMC layer thickness after the thermal treatments; a) T1, b) T2, and c) T3.

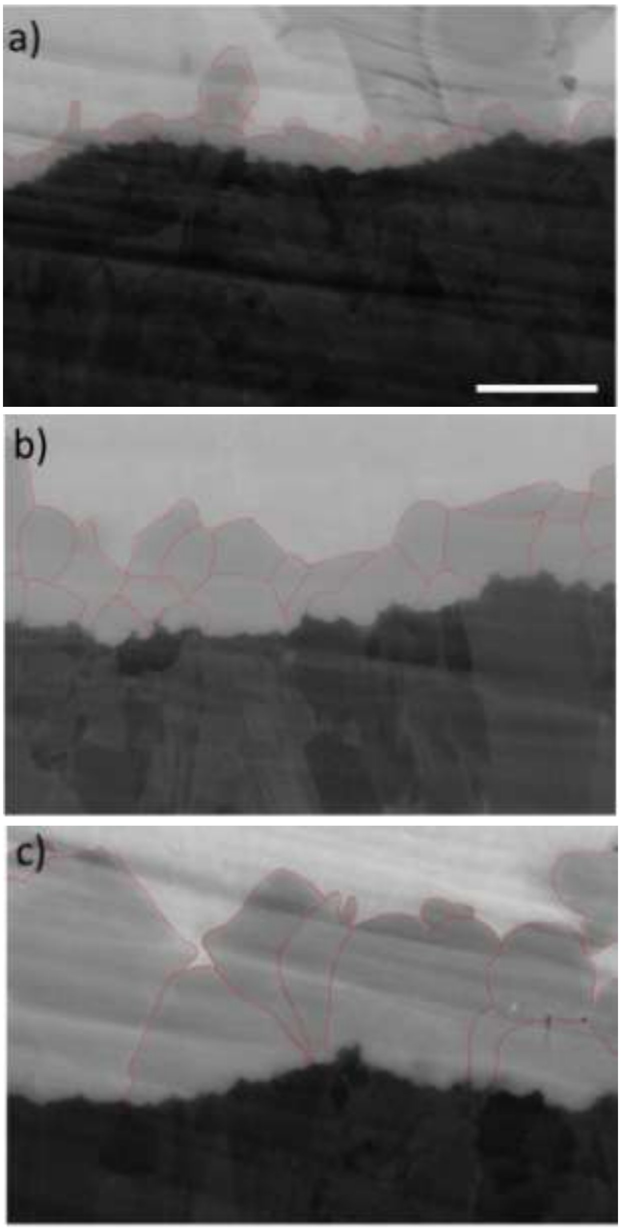

Fig. 4. IMC growth after the thermal treatments; a) T1, b) T2, and c) T3.

IV. CONCLUSION

The behavior of metal-solder systems under thermal and reflow conditions are revisited in the context of fractography and IMC growth dynamics. The observed macroscopic signature of the deterioration and recovery of shear strength, and the observed shift from cohesive to interfacial fractures were explained via the evolution of the IMC layer as a function of thermal treatment. Initial reflow produced a thin $(Cu,Ni)_3Sn_4$ and $AuSn_4$ IMC layer. Prolonged thermal treatment induced grain growth leading to a thicker IMC layer, with increased grain boundaries. Reflow at a peak temperature of 260 °C resulted in grain fusion and growth, effectively reducing fracture points and reduced occurrence of interfacial fractures.

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