

# Lead-free Solder Interconnect by Variable Frequency Microwave (VFM)

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## Abstract

A novel lead-free interconnect technique using a variable frequency microwave (VFM) was investigated. Melting the Sn-3.5Ag, Sn-3.8Ag-0.7Cu and Sn46Pb solder pastes and their wetting on the metal pads were achieved by heating the organic flux vehicle through a radio frequency microwave. The lead-free solder interconnection between the component chips and the metal pads through VFM was first demonstrated.

The microstructures of the lead-free solders/Cu and Sn surface joints formed by a conventional thermal reflow process and VFM were analyzed.

From the intermetallic compound (IMC) formation study, it was found that more heat energy could be employed into the solder paste by the VFM heating process than by the thermal reflow process at the peak temperatures used in this study, because VFM provided more uniform heat than the reflow oven that may lead a temperature gradient in the test boards. It is believed that by VFM the soldering process at a lower peak temperature could be feasible than by a conventional reflow process.

## Introduction

Lead-free solder interconnect technology has been of great importance, as a result of more aggressive legislative pressure against the use of lead containing solder in electronics industry. Many research efforts have been performed on the metallurgical behavior of the lead-free solder joints after the reflow process or under aging in the harsh environmental conditions. In particular, the IMC formation between the lead-free solders and metal pads, and the grain size of the IMC have been intensively investigated [1]. They have been identified as critical parameters to the reliability of the solder joints. The excessive IMC such as Cu-Sn that forms between the Sn-based alloys and the Cu pad will weaken the solder joint strength and eventually cause the fatigue failure, due to the brittle nature of the IMCs and the thermal mismatch with the solder and the printed circuit board. In addition, a fine grain size of IMCs is desirable in solder joint for the reliability due to the improved fatigue resistance and possible superplastic behavior. The IMC layer at the joints and the grain size of the IMC can be affected by the peak temperature, the holding time at the temperature of above melting point of the solder and aging under the harsh environment. A faster heating and a shorter holding time at the peak temperature in the reflow can minimize the excessive growth of the IMC layer and its grain size.

Recently, due to the faster heating capability than a conventional thermal oven, VFM has been used in microelectronics area for curing thermoset polymers and to evaporate solvents from solvent-based polymers. The

microwave power vibrates polar groups in the polymers and the polar molecules can be thermally agitated and heated. The absorbed energy in a target material is proportional to the dielectric loss of the target material and the applied power of microwave. The dielectric loss of the material increases with the polarity, impurity, etc.

The solder paste is a mixture of prealloyed solder powders, and the flux-vehicle that has a creamy, peanut butter-like consistency. The flux-vehicle portion of the paste is made with rosin or resin, activators, viscosity control additives, flux chemicals, stabilizers and solvents. Since these constituents in the flux vehicle possess the polarity, the flux vehicle can be heated by VFM. This heat can be transferred to the prealloyed solder powders and then the solder powder can melt at the melting point, where the heat reaches to the metal powder through the flux vehicle rather than by direct heating as in a thermal reflow machine. We could successfully make the interconnection between the lead-free solders and 1206 resistors by VFM. This VFM heating technique provides a faster and selective heating on the polar flux vehicle.

In this paper, the soldering behaviors of the Sn-3.5Ag and Sn-3.8Ag-0.7Cu joints on a copper and a tin surface formed by VFM are first reported. The peak temperatures in the reflow and VFM oven were varied, while the preheat temperature, the ramping rate and the whole reflow process time were fixed. The solder joints formed by a conventional reflow process were compared with those soldered in the VFM oven, and their morphologies and the IMC formation were discussed.

## Experimental

Sn3.8Ag0.7Cu and Sn3.5Ag pastes were used as lead-free solders. Eutectic Sn46Pb was used as a reference. Hereafter, they are simply called SnAgCu, SnAg and SnPb, respectively. Commercial 1206 resistors were used as the interconnecting components and the commercial Cu/organic solderable preservative (OSP) and Sn surfaces on FR-4 boards were employed as the substrates.

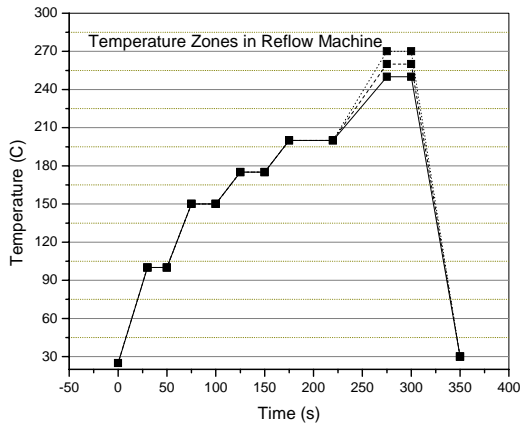
The solder pastes were printed on the substrates by a stencil mask and solder joints were formed by means of a standard infrared reflow and a microwave oven. For microwave heating, variable frequency microwave (VFM, MicroCure 2100, Lamda Technologies Co.) was used. The center frequency of the microwave, the bandwidth and the sweeping time were 6.425 GHz, 1.15 GHz and 0.1 sec., respectively. For metallographic observation, specimens were ground down to 4000 grit on a silicon carbide paper under water cooling. Polishing was performed using 1 um and 0.1 um Al<sub>2</sub>O<sub>3</sub> suspension. The specimens were then etched in a 10% HNO<sub>3</sub> solution for about 10 sec. This process provides the contrast between the intermetallic compound and the solder matrix boundary.

Optical microscopy and scanning electron microscopy (SEM) were used to study the morphology of IMCs. Energy dispersive x-ray analysis (EDX) was also used to characterize the composition of the IMCs.

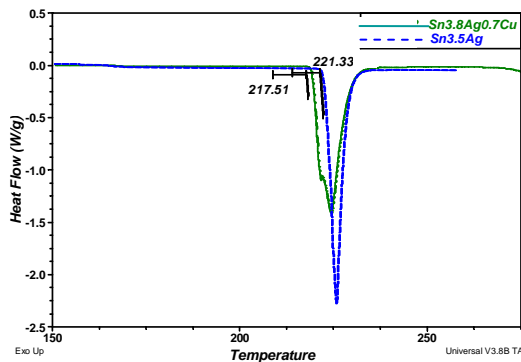
## Results & Discussion

*Thermal profiles of the SnAgCu and SnAg Pastes in the Reflow and the Microwave Ovens and Their Optical Microscopy Observation.*

Figure 1 shows the reflow profile for the SnAgCu and SnAg solder paste in the thermal reflow oven. The preheat temperature and time were kept constant and the peak temperatures were varied by 250 °C, 260 °C and 270 °C. The peak temperatures were rather higher than the melting point of the solders used, because there is a temperature difference between the test boards on the convey belt inside the reflow oven and the specific zone temperatures in the oven. The melting points of the solders used were shown in Figure 2. The onset points for the melting point of the SnAgCu and SnAg solder paste were 217 °C and 221 °C, respectively.



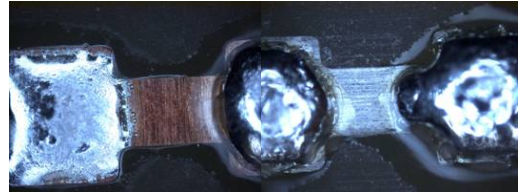
**Figure 1. Reflow profiles used in a reflow machine.**



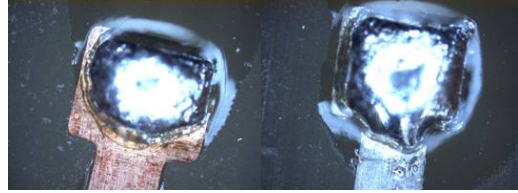
**Figure 2. DSC profile of the Sn3.8Ag0.7Cu and Sn3.5Ag pastes used.**

After the thermal reflow process with the different temperatures, the shape of the solders was observed by optical microscopy. The peak temperature of 270 °C was high enough for the lead-free solders used to melt and wet on the Cu and Sn substrates. Figure 3 and Figure 4 show the top view of the SnAgCu and SnAg solders after the reflow process at 270 °C, respectively. The photos in the left and right hand indicate the Cu and Sn surfaces, respectively. It was obvious that the solders formed a single bulk material

from the paste. For 260 °C, the shape of the SnAgCu and SnAg solders were same as that of 270 °C (this is not shown here).



**Figure 3 SnAgCu alloys on Cu and Sn formed at 270 °C in the thermal reflow.**



**Figure 4. SnAg alloys on Cu and Sn formed at 270 °C in the thermal reflow.**

However, the peak temperature of 250 °C seemed rather low for the solders to completely melt and wet. Figure 5 and Figure 6 show the top view of the SnAgCu and SnAg solders after the reflow process at 250 °C. The left hand pictures in these figures show the solders on the Cu surfaces and the photos on the right side are on the Sn surfaces. For the SnAgCu solder paste, some region was melt and wet but some part was not melt at all remaining as the particles. For the SnAg solder paste, all the pastes were still remaining as the particulates. The peak temperature of 250 °C in the reflow oven might be very close to a boundary temperature at which the SnAgCu and SnAg paste start to melt and wet on the Cu and Sn surfaces. Note that there is a difference in temperature between the test boards and the zone temperature of the reflow machine.

In fact, the SnAgCu alloy has a lower melting point than the SnAg alloy as shown in Figure 1 and the SnAgCu paste could be melt at a slightly lower temperature than the SnAg paste. In addition, it has been known that adding the Cu element in the SnAg composition can catalyze the formation of the nuclei and form a required bond in a shorter reflow time [4]. That's why some of the SnAgCu paste wet on the metal surfaces and some did not at 250 °C and SnAg did not form a molten shape at all at the temperature.

Non uniform melting of the SnAgCu solder paste at 250 °C also indicates that there is a large temperature gradient in the reflow machine.



**Figure 5. SnAgCu alloys on Cu and Sn formed at 250 °C in the thermal reflow.**



**Figure 6. SnAg alloys on Cu and Sn formed at 250 °C in the thermal reflow.**

Figure 7 shows the temperature response of the FR-4 test boards in the VFM oven. As same in the reflow oven, the preheating temperature (140 °C) and time (10s) were constant and only the peak temperatures were varied. The ramping rate above the preheat temperature was set to 0.5 °C/s that makes the total reflow duration time by VFM similar to that by the reflow oven. It took 5 min to reach the peak temperature and the temperature was held for 10 sec and microwave power was then turned off. The specimens were cooled down without any specific ramping control.

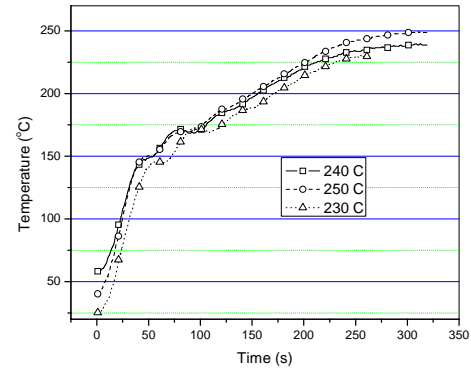
To monitor the temperature of the test samples and to control the microwave power in the VFM oven, a built-in infrared (IR) sensor was used rather than a built-in thermocouple, because the IR sensor has very fast feedback capability which enables to control the microwave power quickly. The IR light of the sensor was faced to the FR-4 board near the solder/pad joint and the sensor read the temperature on the surface of the FR-4 board. It was assumed that the distance between the IR sensor spot on the board and the solder joint location was short enough to neglect the temperature difference between them.

The sensor could not be faced to the solder paste directly, because the emissivity value of the solder paste could not be varied in-real time on the IR controller. In order to read an accurate temperature of the target materials with the IR sensor, the emissivity of a target material should be set to a certain value corresponding to the material. The organic flux vehicle in the solder paste that mainly absorbs the microwave energy starts to evaporate at 150~160 °C and then the material composition of the solder paste surface becomes changing with the increase of the temperature, because the solder alloy particles become exposed to outside and the IR light faces to the alloy particles.

Thus, in order for the IR controller to monitor accurate temperatures of the targets, the emissivity value in the IR controller should be varied along with the composition change of the target material, i.e. from the emissivity of the organic flux material to that of the metal solder particles. Although the value can be set manually, it is experimentally hard to decide the accurate emissivity of the solder pastes at a certain temperature. Therefore, the emissivity was set to 0.95 that is commonly used for plastic materials and the IR sensor was faced to the FR-4 board.

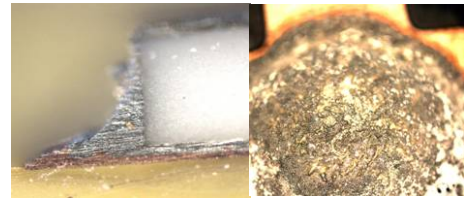
We also found that the heat profile of the materials by microwave heating was affected by many parameters such as the type of the material, volume of the material, uniformity of

the components and so on. In particular, the heat response to the microwave power was mainly dependent upon the type of the material. Additionally, where the IR sensor is facing to was another critical factor to affect the temperature response. Thus, it was found that consistency of the location of the IR spot is important for a consistent heat profile of the specimens.



**Figure 7. Temperature response of the solders and the test board in the VFM oven.**

Figure 8 shows the eutectic SnPb solder/Cu joint formed at 200 °C by VFM. The 1206 resistor (SnPb terminated) could be interconnected by VFM at 200 °C as shown in the left hand. However, the solder particles that were not completely melt were found on the surface of the solder droplet and the surface had rather a coarse structure. The photo in the right hand shows the top view of a solder droplet on the Cu pad. Some particles were found on the surface of the solder fillet in the left hand picture as well. 200 °C in VFM was not high enough to lead the SnPb solder paste to completely melt.



**Figure 8. SnPb formed at 200 °C by VFM.**

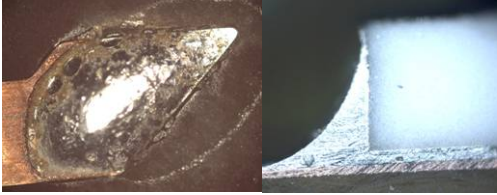
230 °C was applied to the SnPb solder/Cu joint in VFM and the finer structure of the solder surface could be obtained as shown in Figure 9. No alloy particles were remaining on the solder surface after the VFM process. The eutectic SnPb paste was successfully soldered at 230 °C.



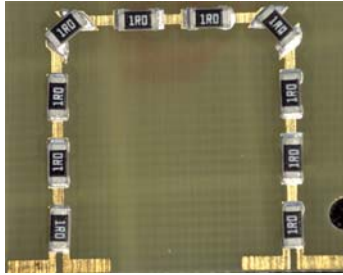
**Figure 9. SnPb formed at 230 °C by VFM**

VFM was used to form the SnAgCu paste/Cu joint at 250 °C and a solder melt and the fillet formed in the 1206 resistor joint are shown in Figure 10. The SnAg paste also showed good interconnect joints by VFM. The 1206 resistors were

interconnected on the Cu pads with the SnAgCu paste at 250 °C by using VFM and this is shown in Figure 11. It was demonstrated that VFM could be utilized for making interconnect joints with either SnPb or lead-free solder on metal pads.



**Figure 10. SnAgCu alloy formed at 250 °C by VFM**



**Figure 11. 1206 resistors/SnAgCu/Cu joints on the FR-4 board.**

*SEM Observation of the SnAgCu and SnAg Joints on Cu and Sn pads Formed by Thermal Reflow.*

The microstructures of the lead-free solder joints on the Cu and Sn surfaces were observed. In particular, the IMC formation at their interfaces and in the bulk solder was compared. Figure 12 shows the interface IMC of the SnAgCu/Cu joint formed at 260 °C and 270 °C by a conventional reflow process. A scallop-like layer of the  $\text{Cu}_6\text{Sn}_5$  IMC located at the solder-Cu interface was identified by EDX analysis. The IMC formed at a higher reflow peak temperature (270 °C) was thicker than formed at a lower temperature (260 °C). This was also applied to the SnAgCu/Sn, SnAg/Cu and SnAg/Sn joints as shown in Figures 13, 14 and 15.

The IMC thickness is a function of the peak temperature in the reflow process and the holding time at above the melting points of the solder alloys and the thickness increases by increasing the peak temperatures.

The fundamental framework for most of the investigations to predict the IMC layer growth in solid joints is either based on the one-dimensional Fick's law or a power law. It was reported that the growth of the IMCs for SnAgCu and SnAg on Cu deviates the Fick's law at the early stage of the growth process and the approaches the parabolic law. In fact, the IMC formation at early stage is mainly reaction-controlled and afterward mainly the diffusion-controlled [4].

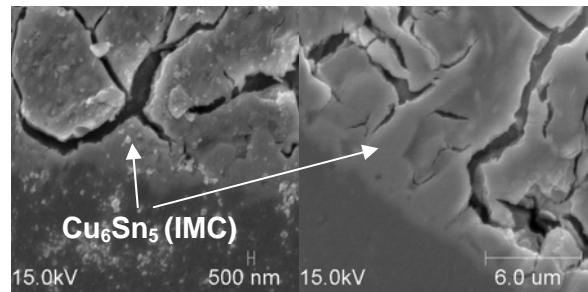
In particular, the growth kinetics of IMC layers at the lead-free solder/Cu surface has been reported intensively. If the layer growth obeys the diffusion of one element in a solid-state system and the reaction layer consists of one phase, the layer growth can be expressed by a simple equation expressing the time-constant exponent  $n \sim 0.5$  [5]:

$$L = L_0 + At^n \left( -\frac{Q}{RT} \right) \quad (1)$$

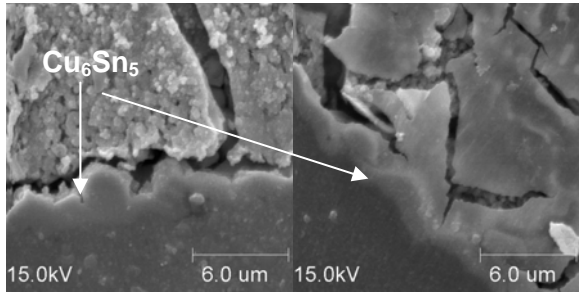
where  $L$  is the thickness of the reaction layer at time  $t$  at temperature  $T$ , and  $L_0$  is the initial thickness, at which temperature reaches  $T$ .  $Q$  and  $A$  are an activation energy for diffusion and a material constant, respectively.  $R$  is a universal constant. In most Sn alloys/Cu systems, Eq. (1) is valid because the diffusion of Sn plays a key role in the formation of reaction layers, even though the layers consist of two phases [2, 3]. However, in some cases there is deviation such as in the  $n$  value.

In the present study, the IMC grow kinetics is not discussed in detail. However, it was observed that the IMC thickness of the SnAg alloys formed at 260 °C was thinner than that of the SnAgCu alloy systems formed at the same temperature. Cu addition in SnAg alloys can catalyze the formation of the nuclei and form a required bond in a shorter time. The IMC grain growth of the SnAgCu alloy was found faster than that of the SnAg system. The faster growing of the IMC grains for the SnAgCu alloys at the early stage of the reflow process is the reason why the IMC layer of the SnAgCu alloy system is thicker than that of the SnAg alloy.

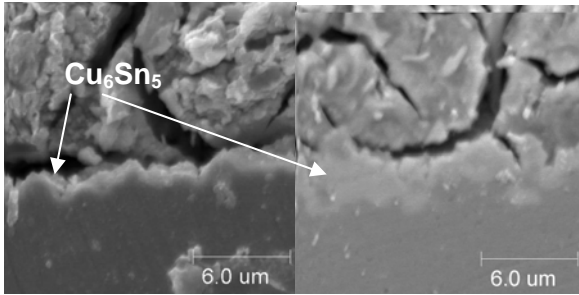
In addition, it can be seen that the IMC growth behavior of the SnAgCu/Sn and SnAg/Sn joints was similar to those of the Cu joints. It was also found that the IMCs of all the SnAgCu/SnAg/Cu/Sn joints formed by the reflow process were only the CuSn compound at the solder/pad interfaces. In general, large Ag rich IMCs ( $\text{Ag}_3\text{Cu}$ ) are observed for high Ag content solder joints (over 3.5% of Ag), regardless of the type of the substrates used. As the present study, the large Ag rich phases were not observed in the solder joints formed by the reflow process. This may be because the actual temperature of the test board in the reflow oven was not high enough or the holding time at the peak temperature was not long enough for large  $\text{Ag}_3\text{Sn}$  IMC to form. In fact, the formation of the  $\text{Ag}_3\text{Sn}$  IMC is not desirable with respect to the solder joint reliability.



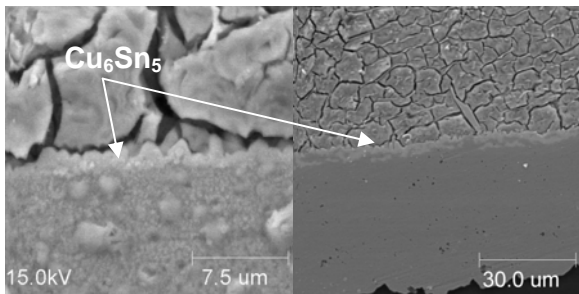
**Figure 12. The SnAgCu/Cu joint at 260 °C and 270 °C (thermal reflow).**



**Figure 13. The SnAgCu/Sn joint at 260 °C and 270 °C (thermal reflow).**



**Figure 14. The SnAg/Cu joint at 260 °C and 270 °C (thermal reflow).**



**Figure 15. The SnAg/Sn joint at 260 °C and 270 °C (thermal reflow).**

*SEM Observation of the SnAgCu and SnAg joints on Cu and Sn pads by VFM.*

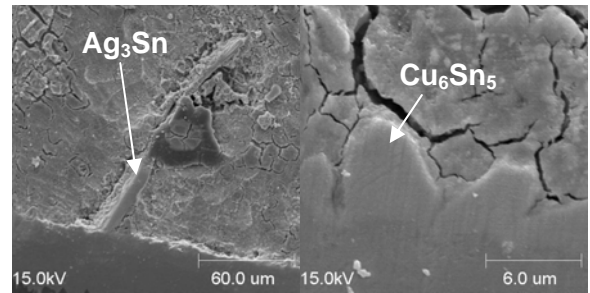
**a) SnAgCu/Cu joints at 230 °C, 240 °C and 250 °C.**

Figures 17, 18 and 19 show the SnAgCu/Cu joints formed at 230 °C, 240 °C and 250 °C by VFM, respectively. The scallop-like IMC was found at the solder/pad interface and the thickness slightly increased with increasing the peak temperature. This is as same as found in the solder joints formed by the thermal reflow process.

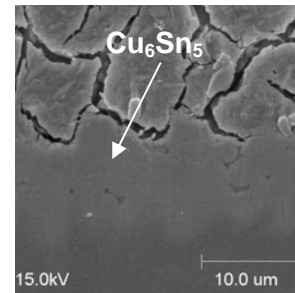
Compared with the reflow process, the IMC formed by VFM had a larger and coarser structure. In particular, much larger scallop-like structure can be found in the solder joint formed by VFM. As mentioned earlier, for the reflow process, there is a 20~30 °C difference between the actual test board temperature on the convey belt and the temperature of each zone in the reflow oven. Thus, if the peak temperature of a zone in the reflow oven was set to 270 °C, the board temperature may be 240 °C ~ 250 °C. Therefore, the set temperature of 230 °C in VFM may be lower than that of 270

°C in the reflow oven. Nonetheless, the larger IMC size and the bigger scallop-like structures were found by VFM than those by the thermal reflow process. Therefore, it is thought that in the VFM soldering more uniform and more amount of thermal energy may be applied to the solder paste body than in the reflow process. For the reflow process there could be a temperature gradient in the whole test board. It is believed that VFM could provide the solder body with more uniform energy than the reflow oven resulting in forming larger IMCs.

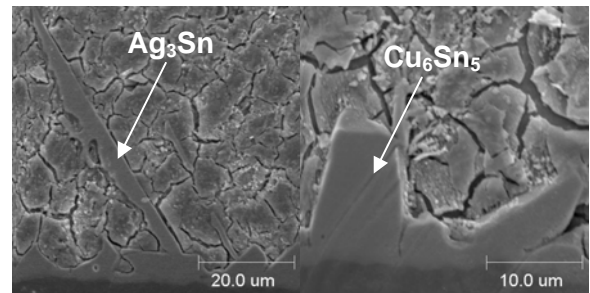
In addition, long needle-like structured  $Ag_3Sn$  IMCs were found at the solder joint formed by VFM, which was grown from the interface IMCs.



**Figure 16. SnAgCu/Cu joint at 230 °C (VFM)**



**Figure 17. SnAgCu/Cu joint at 240 °C (VFM)**



**Figure 18. SnAgCu/Cu joint at 250 °C (VFM)**

**b) SnAgCu/Sn joints at 230 °C, 240 °C and 250 °C.**

For the SnAgCu/Sn system, the CuSn IMC layer growth by increasing the peak temperature was also found as shown in Figures 20, 21 and 22. The size of the scallop-like IMCs was increasing with increasing the peak temperature. More  $Ag_3Sn$  IMCs were observed in the SnAgCu/Sn joint than that in the SnAgCu/Cu joint. It is believed that this is because the Sn surface provides Sn elements to the IMCs at the early stage resulting in occurring Sn diffusion and forming the  $Ag_3Sn$  IMCs with Ag elements diffused out of the matrix solder. It is known that the large  $Ag_3Sn$  platelets formed in the bulk alloys are brittle in nature and cause tensile failures

at the solder joints, which is not found in this study [5]. However, there is no report about the negative effect of the needle-like structured  $Ag_3Sn$  IMC on the mechanical performance of the solder joints.

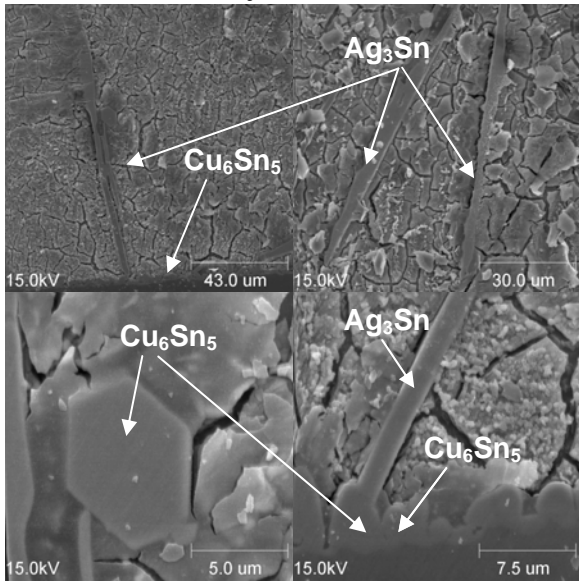


Figure 19. The SnAgCu/Sn joint at 230 °C (VFM)

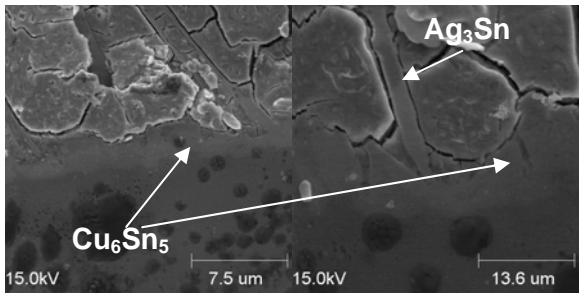


Figure 20. The SnAgCu/Sn joint at 240 °C (VFM)

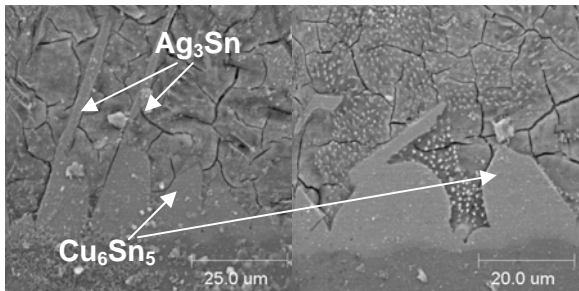


Figure 21. The SnAgCu/Sn joint at 250 °C (VFM)

**c) SnAg/Cu joints at 230C, 240C and 250C.**

Figures 23, 24 and 25 show the SnAg/Cu joints formed by VFM at 230 °C, 240 °C and 250 °C, respectively. For the SnAg joints formed at 230 °C the  $Ag_3Sn$  IMC was not observed, while at 240 °C and 250 °C the  $Ag_3Sn$  IMC was found at the joints. Note that the  $Ag_3Sn$  IMC was seen at the SnAgCu/Cu and SnAgCu/Sn joints even at 230 °C. As mentioned earlier, this is because the IMC formation rate of the SnAg alloy is slower than that of the SnAgCu alloy. Thus, 230 °C in VFM was not high enough for the  $Ag_3Sn$  IMC to form in the SnAg/Cu joint. For the peak temperatures of 240

°C and 250 °C, the  $Ag_3Sn$  IMC was observed. Therefore, the formation of the  $Ag_3Sn$  IMC needs more time and higher temperatures than the CuSn IMCs.

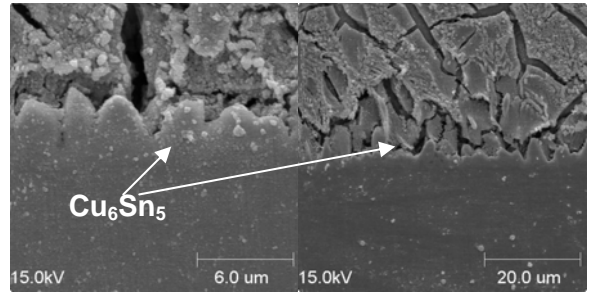


Figure 22. The SnAg/Cu joint at 230 °C (VFM)

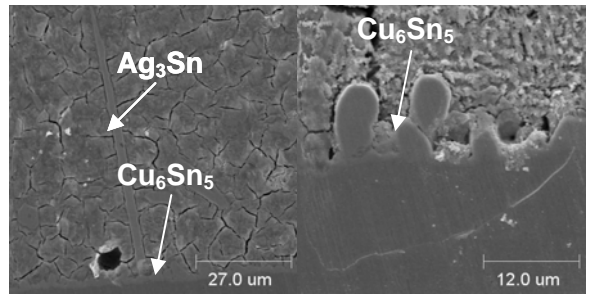


Figure 23. The SnAg/Cu joint at 240 °C (VFM)

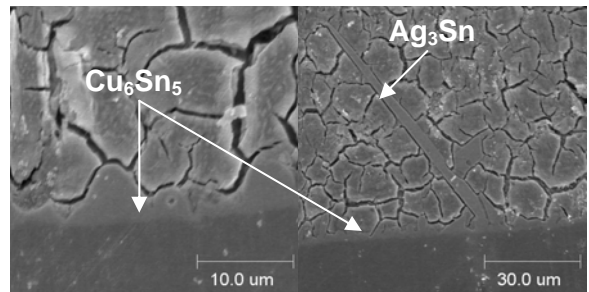


Figure 24. The SnAg/Cu joint at 250 °C (VFM)

**d) SnAg/Sn joints at 230C, 240C and 250C.**

Figures 26, 27 and 28 show the SnAg/Sn joints formed by VFM at 230 °C, 240 °C and 250 °C, respectively. As same as in the SnAg/Cu joints for the peak temperature of 230 °C, no needle-like  $Ag_3Sn$  IMC was found, while the  $Ag_3Sn$  IMC was observed in the joints formed at 240 °C and 250 °C.

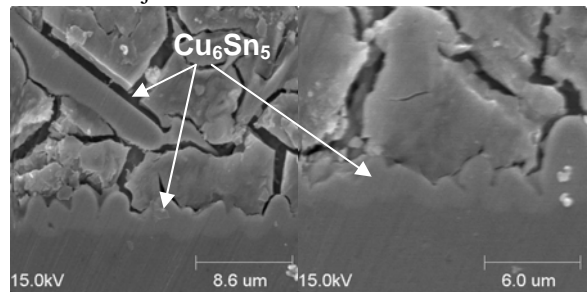
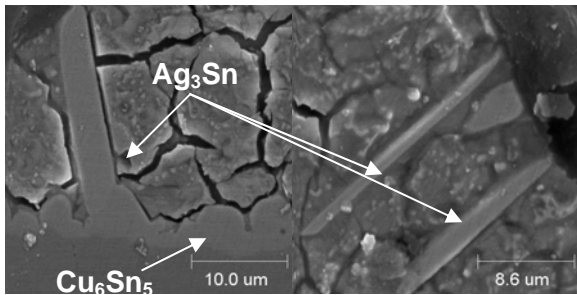
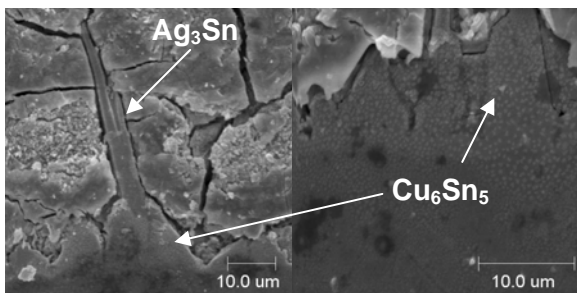


Figure 25. The SnAg/Sn joint 230 °C (VFM)



**Figure 26. The SnAg/Sn joint at 240 °C (VFM)**



**Figure 27. The SnAg/Sn joint at 250 °C (VFM)**

### Conclusions

A variable frequency microwave (VFM) was used as a novel lead-free interconnect technique. Melting the Sn-3.5Ag, Sn-3.8Ag-0.7Cu and Sn46Pb solder pastes and their wetting on the metal pads were achieved by heating the organic flux vehicle through a radio frequency microwave. The lead-free solder interconnection between the component chips and the metal pads through VFM was first demonstrated.

The microstructures of the Sn-3.5Ag/Cu, Sn-3.5Ag/Sn, Sn-3.8Ag-0.7Cu/Cu, and Sn-3.8Ag-0.7Cu/Sn joints formed by a conventional thermal reflow process and VFM were investigated by SEM-EDX.

For the solder joints formed by the conventional reflow process (peak temperatures; 260 °C and 270 °C), the CuSn IMC was found at the solder-pad interface, while the peak temperature of 250 °C was too low to lead the solders to melt and wet on the metal pad. This is because there was a difference in temperature of the test board surface and the heating zones. Also it was found that there was a temperature gradient of the test boards in the thermal reflow machine. Thus, the actual board temperature could be 220 °C~240 °C.

The solder joints formed by VFM also showed the CuSn IMC at the solder-pad interface. The Ag<sub>3</sub>Sn IMC was observed regardless of the surface finish of the pad. However, it was found that the peak temperature and the type of the solder paste affected the Ag<sub>3</sub>Sn IMC formation. The SnAg/Cu and SnAg/Sn joints formed at 230 °C did not show the Ag<sub>3</sub>Sn IMC and the Ag<sub>3</sub>Sn IMC was found in these joints formed at 240 °C and 250 °C, while the SnAgCu alloys formed the needle-like Ag<sub>3</sub>Sn IMC even at 230 °C. This is because the SnAg alloy is slightly less reactive than the SnAgCu alloy.

The CuSn IMC formed by VFM was larger and coarser than that formed by the reflow process.

Consequently, it was found that the IMC formation in the lead-free solder joints by VFM at similar peak temperatures to that of the thermal reflow process occurred more actively and the IMC thickness of the solder joint formed by VFM was thicker. In general, the thick IMC (e.g. CuSn) affects the reliability of the solder joint adversely due to its brittle nature. However, the IMC growth kinetics is controlled by peak temperature and the holding time at above the melting point of the solder alloys. This means that more heat energy was employed into the solder paste by VFM heating process than by the reflow process at similar peak temperatures, because VFM provided more uniform heating than the reflow process that may possess a temperature gradient in the test boards. Therefore, the peak temperature can be reduced by VFM.

To reduce the cost for lead-free solder process, a lower peak temperature and faster heating will be desirable. Thus, study on reducing the peak temperature and faster ramping rates is on progress.

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