INFLUENCE OF THE VOLUME-CONTACT AREA RATIO ON THE GROWTH BEHAVIOR OF THE Cu-Sn INTERMETALLIC PHASE

BY

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ABSTRACT

Effect of IMC growth rate behavior with variation in the ratio of

volume of the solder to substrate/Solder contact area in the

Sn based solder Joint

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Solder Joints play a very important role in electronic packaging industry by serving as mechanical support and provides integrity to the device. The increasing demand for high performance, environmental and economic feasibility and miniaturization led to the development of high density interconnects. With the reduction in the size/standoff height of the solder reliability issues in the surface mount assemblies and packaging structures under various rigorous environments are becoming significant.

One of the most important impact factors that affect the solder joint reliability is the growth rate IMC formed between the solder and substrate with reduction in joint size. IMC formation is required to ensure good bonding and connectivity of the device in packaging. However excess IMC growth rate is detrimental to the device from mechanical aspects due to its brittle nature. Thus there is a need to study effect the IMC growth rate behavior with the solder joint size/standoff height.

In this present study, two solder joints of different standoff heights and same composition (pure Sn solder) are used subjected to reflow process at 270°C for 1-7 min to study solid liquid interfacial reaction on joint size and the same experiment is repeated with SAC alloy of composition (96.5% Sn, 3.0% Ag, 0.5% Cu) to investigate the effect of joint size and initial copper concentration on IMC growth rate. The IMC thickness of the Sn 15µm solder joint at 1 min and 7 min is found to be 1.52µm and 2.86µm respectively while that of Sn 150µm solder joint is 1.31µm and 3.16 µm. The thickness is high in low standoff height sample at the early stage of reaction with decrease in IMC growth rate as the time of reflow increases. In case of 25µm SAC alloy solder joint the IMC thickness from 1 and 7 min is found to be 2.1µm and 3.5µm while that of 250µm SAC alloy solder joint its 1.43µm and3.235µm. Similar trend is observed but the IMC thickness is more in SAC alloy compared to Pure Sn due to initial Cu concentration effect. The CGC model is applied for growth kinetics of IMC formation and is in well agreement with the experimental results. It is found that the low standoff height solder joint follow $t^{1/3}$ law and high standoff height solder joint deviates from the $t^{1/3}$ due to unsaturation.

The pure Sn solder of two different standoff heights is also subjected to isothermal aging tests at 120°C for 0-600 hours to investigate the effect of IMC growth rate on solder joint size in solid state diffusion. It has been found that low solder joint height is having high growth rate compared to high standoff height joint and it is found to obey parabolic law and follow reaction diffusion control mechanism.

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Chapter 1

Introduction and Background

With the increase in customer demand for pocket size devices, the dimension of the device and consequently the packaging is shrinking day by day. The high density interconnect packaging replaces the conventional solder joint to Microbump with shrinkage. This reduced solder joint in addition to the lead free solders challenges the reliability of the device. Thus study of size effects on microstructure and properties of lead free solders bear a most significant role. The study of kinetic behavior of IMC formation with size effect in lead free solders is carried out as the IMC formation rate is crucial for solder joint performance. In this study pure Sn tin and SAC305 alloy are studied.

1.1 Need for Miniaturization

Customer demands for faster devices with improved performance and integrity by reducing the power budget and utilizing minimum energy and materials in manufacturing led to the evolution of miniaturization. This demand for smaller, faster and low cost electronics has lead the industry move to higher density interconnects. Thus electronics miniaturization challenges board assembly materials, processing conditions and reliability. There are many challenges with high density packaging such as thermal management and stress due to coefficient of thermal expansion mismatch, warpage inducing stress on micro bump. The technological key drivers cost form factor and performance are responsible for packaging evaluation. Package cost, device performance and overall size determines the choice of packaging options. Surface mount technology, package-on-package, wire bonding, flip chip and 3D ICs have evolved with decreasing size.

1.2 Solder Joint Reliability

Solder joints are simply electrically interconnections. Due to advancement in technology electrical component size is decreased and the number of input/output interconnections increased; making the solder joint function more critical. There are many benefits of shrinking the solder joint dimensions, for instance increase in the speed and the performance of the device, high interconnect density, but concerns about solder joint reliability have also increased. Solder joint reliability is critical in the devices used for controlling operational and safety functions in automotive and aerospace applications.

To improve the reliability it is important to understand the thermodynamic and chemical relationship between the solders and different metallic substrates. This relationship is explained as follows- in the soldering process, solders act by wetting the base metal surfaces forming the joint; flow between the surfaces to fill the space between them and metallurgical bonding to the surfaces when solidified (Steller et al. 2010). This metallurgical bonding is called IMC layer.

The formation of intermetallic layer by the reaction of the solder with the substrate occurs during the wetting process. Presence of IMC signifies good metallic bonding but it's also the weakest part of the joint as it is brittle. Thick IMC layer will weaken the joint making it vulnerable to thermal cycling and operating strains imposed on the joint during its lifetime. Furthermore, the solder joint also gets depleted of the elemental constituents used to form the IMC which in turn changes the mechanical properties of the joint. IMC formation and parameters affecting IMC growth rate behavior.

1.3 IMC formation and parameters affecting IMC growth rate behavior

During the soldering process the molten solder comes into contact and reacts with the substrate material. During this reaction in most of the cases the formation of IMC at the solder substrate interface is observed as well as in the bulk of the solder. IMC formation signifies the good bond formation between the substrate and the solder. The IMC is brittle nature due the lattice configurations of the different elements and constraints in the lattice structure. Thus excessive IMC formation is to be avoided to maintain the joint to be fatigue resistant. The interaction between the solder constituents with the substrate and the alloy compositions can govern the nature of the IMC compounds formed. Other governing factors are the soldering parameters such as the time, Soldering temperature, time, pressure and cooling rate etc. These can alter the type and amount of the IMC formed. IMC morphology and composition differs with the constituents present in the solder. [12] With variation in the volume, the concentration of dissolved substrate in the solder differs which affects the interfacial reaction. Thus IMC formation is affected by the volume of the solder. In case of micro bump, as the volume of the solder is very less, the IMC formed is comparable to the joint size and with time the joint may be totally converted to IMC which makes the joint prone to failure. Thus the study of IMC growth rate with volume variation is required to solve the reliability issue of the micro bump.

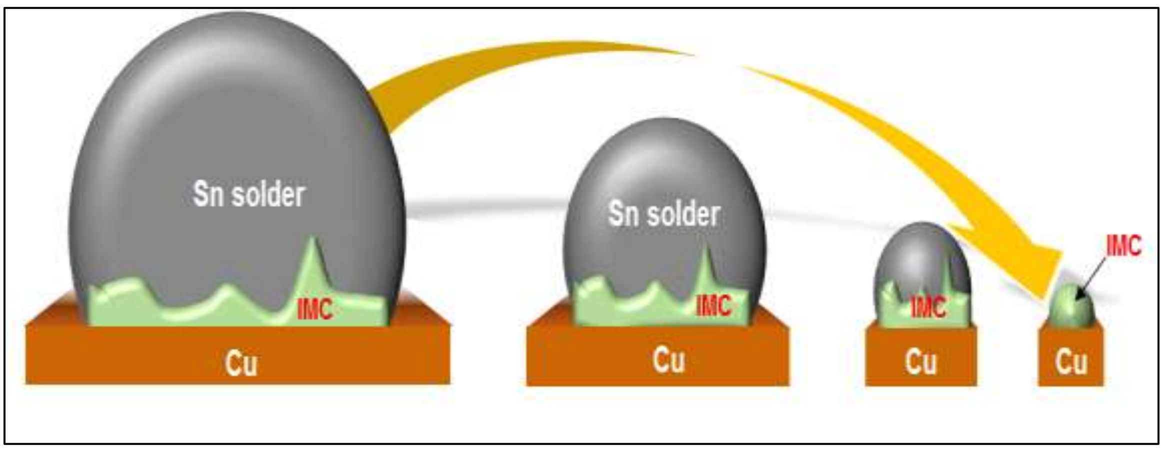


Figure 1 *IMC formation variation from conventional solder joint to micro bump*

1.4 Scope of Research Study

1.4.1 *Problem statement*

As the demand for smaller and miniature handheld and pocket electronic consumer products such as laptops, continuous, the drive towards further miniaturization of the devices and the solder joints will also continue. The reliability of solder joints is depended on the microstructures and IMC layers as IMCs have higher resistivity than the base metal.

Furthermore, with the elimination of toxic Pb from the conventional solders, other metallic additives were incorporated in the solder alloys to tailor their properties to meet the requirements for certain applications. These additives added to the solder are reactive with Sn and the elements present at the metallization. These elements diffusion is also fast in Sn based joints even at room temperature. They can alter the behavior at solder or metal interface in miniaturize joints. This may degrade the properties of joints compromising the reliability. Sn-Ag-Cu alloy systems are best alternatives for Sn-Pb solder alloy and there is wide agreement that the existing empirical kinetic relationships developed for Sn-Pb alloys cannot be extrapolated for Sn-Ag-Cu lead free alloy systems.

Thus there is an urgent need to study the formation of IMCs in lead free solders with volume variation during reflow process since there is no established data. This will provide better understanding of their effect on long term reliability of solder joints. From various studies on reflow soldering process there are different conclusions on the impact of IMC growth rate behavior with volume variation during reflow process. Therefore, determining the optimal reflow settings for lead free solder volumes and the factor that influences the process were investigated. This will help in improving the solder joint performance when the experience, vibration and thermomechanical loading due to coefficient of thermal expansion mismatch (Mingyi et al 2004).

1.4.2 *Research Objectives*

The objective of the research work is as follows-

- The study of effect of change in volume to area of contact ratio on IMC layer formation and growth for lead free solder joints under reflow conditions.
- The application of CGC model on the growth kinetics of IMC formation.
- The study of initial copper concentration on IMC growth rate using SAC 305 alloy.

1.4.1 Research Objectives

To study the effect of volume of the solder joint on IMC growth rate the following conditions and approach is set.

- The solder joint with 2 different noticeable stand off heights are prepared using Pure Sn and SAC 305 alloy solder.
- They are reflowed at 270°C with time variation and IMC formation is analyzed with time using mechanical polishing and SEM.
- Kinetical behavior of the IMC formed with time is studied

Chapter 2

Background and Experimental Setup

2.1. Lead free solder joints solder alloys in electronic packaging

Sn – Pb solders are intensively used in electronic industry due to their unique and advantages properties of low cost, low melting point eutectic composition, provides maximum stiffness to the joint. However due to environmental concerns there are legal enactments to eliminate the use of lead. So the research is focused mainly on the search of lead free solders. To date although there are number of lead free solders available in the industry but there is no best alternative to Sn-Pb. The lead free solders not only should meet the performance and reliability requirements they should also be in compatible with the existing soldering properties. The following table summarizes some of the properties of the solders that are important to consider for long term reliability of the devices.

However up to date there is no apt replacement for the conventional solder and most of the developed ate application specific. In this development they are focused in the identification of potential substitutes for lead (Pb): Silver (Ag), antimony (Sb), Zinc (Zn), copper (Cu), gold (Au) Bismuth (Bi) etc.

Eutectic composition is preferable because of their single and low melting point. The table shows the eutectic temperatures of the binary lead free solders systems in relation to eutectic Sn-Pb (Zeng and Tu, 2002)

Table 1 Important properties of solder alloys (Zeng and Tu, 2002)

Properties significant to the performance	Properties for industrial manufacturing
Electrical conductivity	Wettability to copper
Thermal conductivity	Accessibility
Creep resistance	Ability of paste formation
Tensile properties	Ability of making into balls
Corrosion and oxidation resistance	Cost
Coefficient of thermal expansion	Compatibility with current process
Fatigue properties	Melting temperature
Intermetallic formation	Recyclable

Table 2 Eutectic temperatures and composition of Binary Alloys [25]

System	Eutectic temperature	Eutectic composition (substitute composition)
Sn-Pb	183	38.1
Sn-Cu	227	0.7
Sn-Ag	221	3.5
Sn-In	120	51
Sn-Zn	198.5	0.9
Sn –Au	217	10
Sn-Ag	221	3.5

The low melting point is preferable because increase in melting temperature in turn increases the reflow temperature that causes the increase in the rate of dissolution and solubility of Cu in molten solder as well as the increase in the IMC growth rate. To meet the requirements of the ideal solder ternary systems are also introduced. Among the most promising lead free solders SAC (Sn- Ag- Cu) alloys appears to be the most popular.

Thus introduction of lead free solders increased the demand to study and understand the material properties and behavioral aspects of these lead free solders especially on the IMC formation and interfacial reaction.

The trend of increasing importance and complexity on consumer electronic products is the driving force for carrying out research on the development of reliable and cost effective electronic packages meeting the requirement of high interconnect density while shrinking in the interconnect size. Solder joints serve as electrical interconnections between the components and the board providing the mechanical support to the board higher density in interconnect size may create reliability concerns as the solder joint size decreases. One of the most important factors dominating with decrease in solder joint standoff height on reliability of the device is the IMC growth rate.

Intermetallic formation plays a most significant role on the strength and other mechanical properties of the solder joint. IMC formation is required for good bond formation between the solder and substrate. However the formation of more IMC layer can proved to be disastrous due to its brittle nature making the joint more prone to fracture during mechanical loading. The decrease in solder joint size can impact the IMC formation. Thus the study on the growth kinetics of the IMC formation based on the volume of solder joint is needed for preventing the reliability issues with the miniaturization of devices especially in electronic packaging.

2.2 Surface mount technology

The SMT process involves deposition of solder paste onto the pads on the surface of PCB and placing of electronic components onto the PCB. Then the PCB along with the components is reflowed to form surface mount solder joints.

SMT components are typically smaller in size than through hole technology (THT) components and can be mounted on both sides of the PCB. Thus SMT assemblies can achieve higher density interconnections. The SMT provides design related benefits of cost and weight reduction and also decrease in electrical noise thus providing improved performance of devices with high shock and vibration resistance [7]. The use of SMT methods in area array packages like Ball Grid Array (BGA) and Chip Scale Package (CSP). These lead free packages can accommodate higher I/O density. However the need of miniaturization completely eliminated the minimum IC chip packaging and the cost effective Flip chip technology is emerged. This involves attachment of chips directly onto the substrate PCB board. Fig1.1 shows Area Array packages

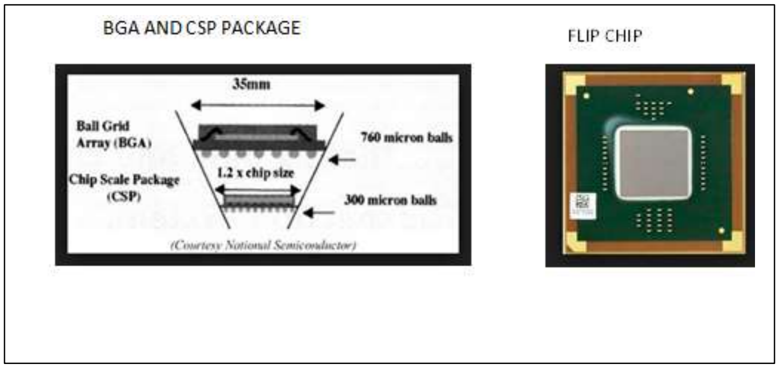


Figure 2. *Examples of Area Array of SMT packages*

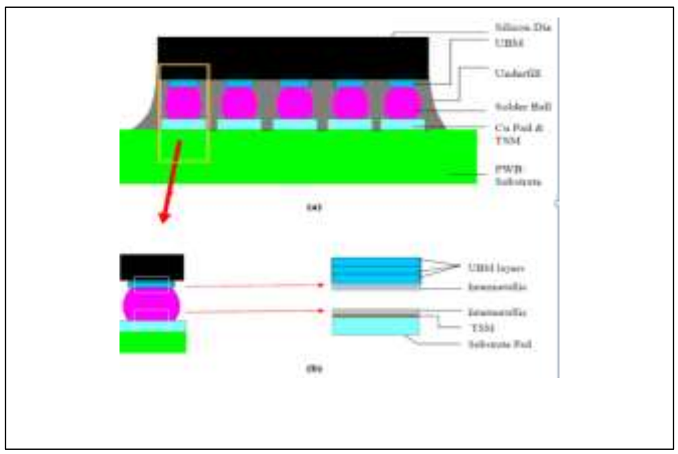


Figure 3 *Example of flip chip on board a) cross section b) enlarged view of die*

The components of SMT chip for example in flip-chip on board consists of four functional areas Under-bump metallization (UBM); Underfill; solder ball and substrate pad. UBM provides adhesion and acts as barrier between solder and conduction chip such as Au. This entire interconnection is shown in figure 1.2

2.3 Flip chip technology

In the development of increasing the packaging concept of flip-chip packaging is evolved where the semiconductor chip is oriented phase down onto the circuit board and assembled with the solder joint directly on the semiconductor chip minimizing the area. It decreases the number of connections as there is only one level of connection between the chip and the board.

2.3.1 Flip Chip Process

The common feature of the flip chip joint is that the chip is lying phase down to the substrate and the connections between the chip and the substrate are made with the help of electrically conducting bumps (solder). Cross-sections of flip chip without and with underfill material is shown in the figure. In flip chip soldering process, solder bump chip are attached on the circuit board. Usually by depositing on the substrate pad areas. For good adhesion of the solder flux is applied and these bumps are reflowed in an oven. The underfill material is applied by dispensing along one side of the chip where the low viscosity epoxy is filled into the space between the chip and substrate through capillary forces. Finally underfill is cured by heat. Thus the steps involved are die and substrate preparation, reflow soldering, and underfill dispensing and curing.

Thus this flip chip technology has decreased the gap between the PCB to the electrical devices making the device performance to be faster.

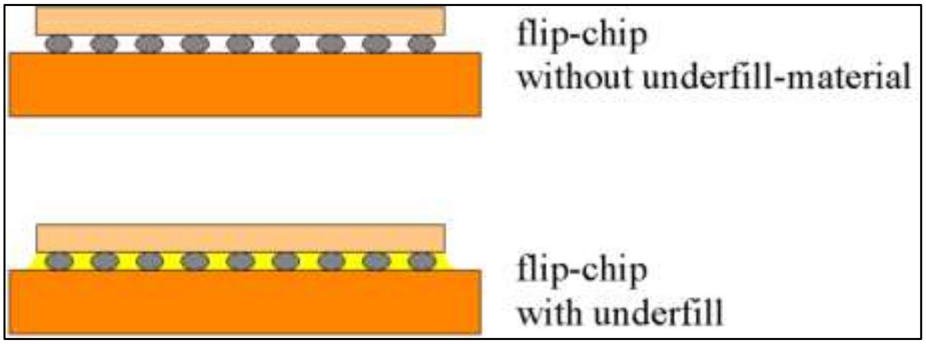


Figure 4 *Flip Chip joint with and without under fill.*

2.3.2 3D ICs

To further improve the form factor 3D IC technology has been evolved. Its main advantage is that it significantly enhances interconnect resources by integrated solution involving the stacking of chips to reduce system size. The following table shows the summary of different 3D interconnect approaches. The main approach of interest is micro bump technology in 3D IC. It involves the use of solder or gold bumps on the surface of the die to make connections with the pitch value of 50-500µm or even less. This technology involved embedding of fabricated die into a set of carrier wafers with a fixed size assembling them in the form of a tight cube. A layer of micro bumps bond on each die carrier tied to an epoxy rooting tire brings the signals to the edges of the cube. Then laminations of the tires into a single stack with metallization to the sides is done to connect the rooting tires. This approach offers a much greater vertical density than wire bonded approach but it faces reliability issues like thermal mismatch, fracture. As the micro bump size is small, the amount of stress is effective on the bump making it prone to failure. This can be attributed due to the formation of IMC which is comparable to the size of the micro bump making it more brittle.

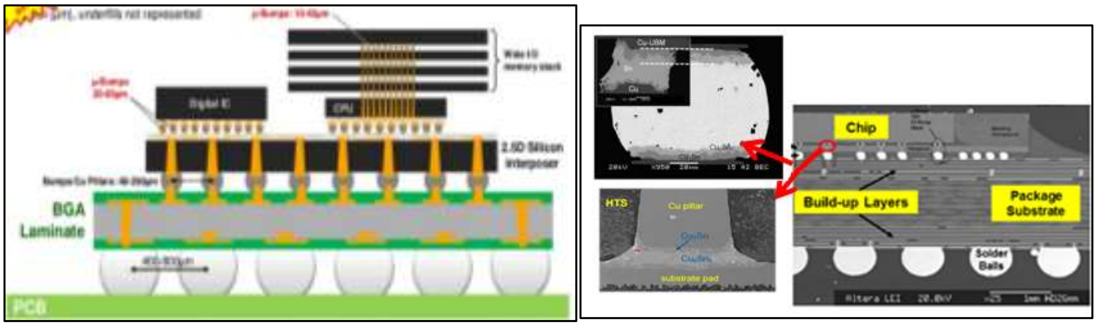


Figure 5 *3D IC vertical stacking with micro bumps and IMC of the micro bumps.*

2.4 Size Effects on solder joint reliability

Miniaturization is driving the dimensions and sizes of the electronic devices to be smaller. High interconnect density is in demand for increasing the speed and accuracy in the performance of the device. The solder joint size is to be decreased for attaining high interconnects density. The mechanical effects come into picture when the size reaches the critical size. Thus the properties and behavior gets affected when scaling factor arises in the scenario. Thus significant changes in the properties may take place as some of the factors depend upon the scaling factor and these can be predicted using macroscopic evaluation. These effects are generally called size effects and are classified into four areas: microstructural effects, gradient effect, interfacial effect and grain statistics effect.

2.4.1 Microstructural Effects

There is effect of the dimensions of the phases and particles in the microstructure on the overall performance of the material. Thus the size variation in the microstructure results in the change in the properties and performance of the device .These microstructural effect influence on the material overall behavior can be analyzed from detailed underlying microstructure e.g. grain size, distribution , orientation of the phase. Variety of models are studied to understand the behavior through the incorporation if the microstructural effects. Hall petch model is a grain boundary strengthening relationship. It relates the yield strength of the material with the grain size. Its states that with the decrease in the grain size yield stress increases [1] .After some point the model breaks down where the strengthening effect reversible. Other model, Freidal model applies the precipitation based strengthening approach on hindering the motion of dislocations and the loops.

2.4.2 Gradient Effects:

It is one the widely discussed size effects that provides the possible explanation for the strengthening behavior exhibited by metals at small length. With no change in geometrical dimensions if the component is downscaled then it finishes in the increase of the gradients of strain. Due to the geometrical constraint posed by the lattice structure the only way to relax the strain gradient is by the introduction of extra dislocations in the lattice usually known as geometrically necessary dislocations (GNDs). [1] [17].Thus the material strengthens as more stresses are needed to introduce the GNDS into the lattice structure.

Interfacial and grain statistics affects also helps in understanding the mechanical properties, deformation ad response mechanisms of small scale components.

2.5 Preparation of Solder Joints with aspect ratio

The aim of the work is to observe the effect of IMC growth rate with variation in the aspect ratio of the solder joint during Reflow technique and aging conditions. The reliability of the interconnect device and other electronic packaging devices is major critical issue as they are subjected different environmental conditions during manufacturing and storage. Thus it's important to study the influence of the parameters on solder joint property especially under different temperature conditions. Thus aging test is critical for solder joint reliability study. Due to miniaturization of the devices the solder joint size is getting reduced significantly. Thus the effect of solder volume changes under aging and reflow conditions is critical for reliability concern. The solder joint samples with two different aspect ratios are prepared for the study. The low aspect ratio sample solder joint height is around 150~300 µm. The high aspect ratio sample joint height ranges from 20~50 µm.

The experimental procedure involves: Patterning the PCB board – used as Top substrate; Solder deposition on the top substrate [22]; The Cu plate bottom substrate; Solder joint formation between the top and the bottom substrate.

During the solder joint formation the height variation is controlled by varying the load and height of contact between the substrates

2.5.1 Patterning Of PCB Board:

Commercial PCB board is patterned using the photolithography technique for 3 min followed by developing and etching of the board using copper etchant. The process is depicted in the following figure 3.1.

2.5.2 Preparation of Bottom Cu substrate:

The Cu plate of purity 95.9% is used for the bottom substrate. The substrate is polished for smooth surface. It's sonicated using Acetone, Ethanol and distilled water

2.5.3 *Solder deposition on the top substrate*:

The Tin and SAC alloy solders are deposited on the respective samples of study. Tin is the main solder of the study. To compare the Tin behavior SAC alloy is studied in reflow process as a comparison.

The Tin shots and SAC alloy shots are rolled and plated on the copper plate with required volume (less amount of solder on high aspect ratio joint and more amount of solder plated on low aspect ratio sample) using liquid flux as activator and The solder alloys are plated at 270°C using hot plate. The top substrate is immediately removed after the plating and sonicated using acetone, ethanol and water for removal of residual flux.

2.5.4 Solder Joint Formation:

Using liquid flux the Top substrate is adhered to the bottom Cu plate and then the sample is heated or reflowed at 270°C resulting in the formation of solder joint.

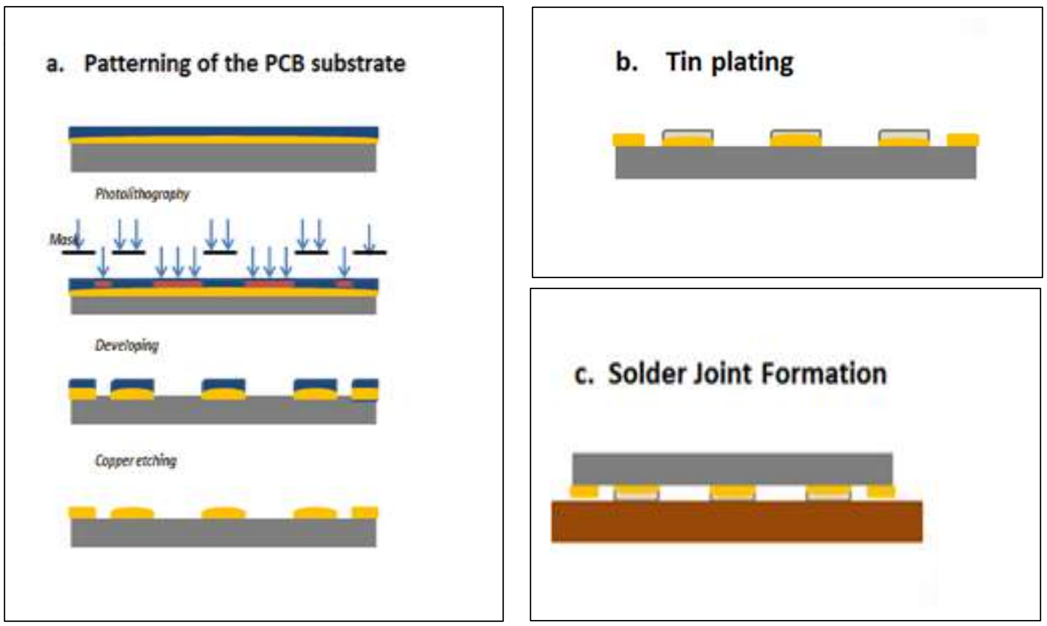


Figure 6 *Steps involved in the preparation of solder joint*

2.5.1 Strategy for achieving aspect ratio difference in solder joints

Low Aspect Ratio Sample:

Samples with low aspect ratio are achieved using 5 layers of solder masking on the edge Cu support or using the Cu thin film on the edge of the support and removing it immediately after joint formation.

Solder Masking procedure: Samples are masked with solder resist film and underwent photolithography using the solder mask. Then the sample is developed using sodium carbonate solution after storing it in dark for 1 hour. The same process is repeated for 4 other times and then sample is cured for 30 min. Thus samples with joint height around 150~200 µm are formed using solder masking technique.

High Aspect Ratio Sample:

The joint is formed without having any height insertion on the top substrate at the copper edge support. During the heating or reflow immediately at the onset of the melting of solder little for is applied on the joint for few seconds. Thus solder joint height around 20~40 µm is achieved.

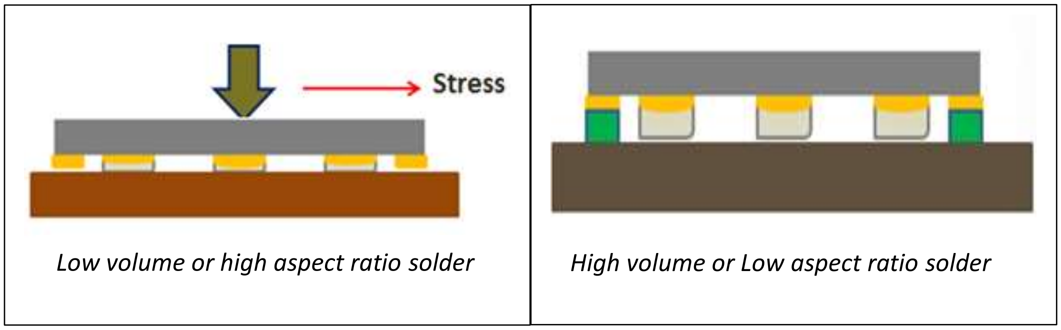


Figure 7 *Different aspect ratios of the solder joint.*

2.6 Experimental Tests on the Solder Joint Sample

The IMC growth rate behavior is studied under 2 experimental conditions.

a) Reflow process

b) Isothermal aging test

2.6.1 Reflow Technique

Samples are subjected at the temp above the melting temperature of Tin and SAC solder for short duration of time respectively. The IMC growth behavior is investigated by varying the time of reflow at constant temperature. The IMC formation is the result of interface reaction between the solid substrate and molten solder. In this process the Tin and SAC Alloy solder joint samples are reflowed at 270°C for the following duration.

TABLE 3 *Reflow conditions used during the preparation of sample*

Aspect Ratio	Reflow Time (min) at temp. 270^0C			
High Aspect Ratio	1	3	5	7
Low Aspect Ratio	1	3	5	7

2.6.2. Isothermal Aging

Samples are subjected at the temp below the melting temperature of pure Tin solder for long duration of time respectively. The IMC growth behavior is investigated by varying the aging time at constant temperature. The IMC formation is the result of interface reaction between the solid substrate and solid solder being controlled by solid state diffusion mechanism

2.7 Characterization Techniques

2.7.1 Scanning Electron Microscope:

A SEM is essentially a high magnification microscope, which uses a focused scanned electron beam to produce images of the sample. Primary electrons generate low energy secondary electrons that help in giving the topographic nature of the specimen. Primary electrons can be backscattered which produces images with a high degree of atomic number (Z) contrast.

Ionized atoms can relax by electron shell-to-shell transitions, which lead to either X-ray emission or Auger electron ejection. The X-rays emitted are characteristic of the elements in the top few μm of the sample and are measured by the EDX detector. The SEM consists of 3 main components: electron gun, lens system and imaging system. Electron energy used for SEM ranges from 5KV to 40KV. The higher electron energy results in high the spatial resolution. However, higher energy electron will produce damage to samples. Lens system consists of 3 main lenses: condenser, objective, and scan lens. The condenser lens is used to focus electron beam into a bundle, the objective lens focuses it to target size and x-y scan lens raster electron beam on top of sample. The resulting interaction between electron beam and sample produces emission of electrons from sample surface. The first and most well utilized is the secondary electron. The image formed by the secondary electron is called SEI [10] and it is typically referred as SEM image. Secondary electron emission is extremely sensitive to surface topology, making it significant for surface image formation. The second type of image is backscattered electron image. Backscattering of electrons is a result of elastic scattering of electrons, and it is sensitive to atomic weight of elements in the sample. Therefore, BEI imaging helps in getting composition sensitive image. In TOPO mode, backscattered electron intensity is mapped based on the height difference in the sample surface.

There are many factors affecting resolution:

1) Higher electron energy makes the contrast to be stronger and thus resolution higher.

2) Larger spot size (beam current) makes the contrast to be stronger but resolution to be poorer

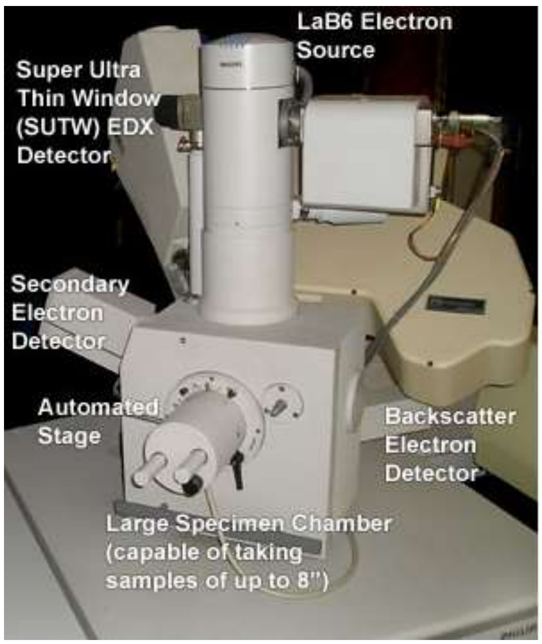


Figure 8 *SEM Instrumentation components*

Chapter 3

Size Effect on IMC Growth Rate at the Copper/ Tin Interface During Reflow process

3.1 Method of analysis

The reflow process is the process of heating the solder joint sample at a temperature above the melting point of solder. The solder joint undergoes multiple reflows during manufacturing. The time and temperature during reflow affects the IMC growth rate. Thus studying the IMC growth kinetics under reflow conditions is needed for dealing the reliability issues of the devices.

As the solder joint size decreases the effect of reflow conditions may vary the IMC growth rate kinetics of the IMC formation compared to the conventional solder joint size. Thus the size effect on the growth rate kinetics during reflow with varying time parameter is studied.

As discussed above in the experimental section the high and low volume solder joints are reflowed at 270°C for 1, 3, 5 and 7 min during the bonding of both substrates with the solder. Then these samples are mounted and the cross sectional view of the solder joint obtained through mechanical polishing is examined under SEM to observe the IMC formation between the substrates.

The average thickness of the IMC is calculated by cropping the SEM images using adobe Photoshop and Picasa viewer and applying MATLAB code to find the area of the IMC occupied. Thus the thickness of the IMC is obtained by dividing the total area of IMC by the length of the IMC.

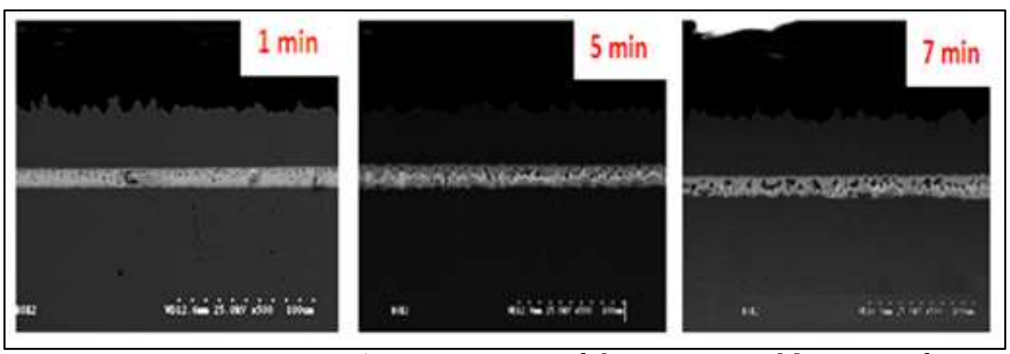
Thus the obtained IMC thickness is plotted against the time of reflow to see the rate of the IMC growth and CGC model is applied to validate the experimental results.

3.2 IMC growth rate behavior in pure Sn solder joint sample with different aspect ratio or stand of heights

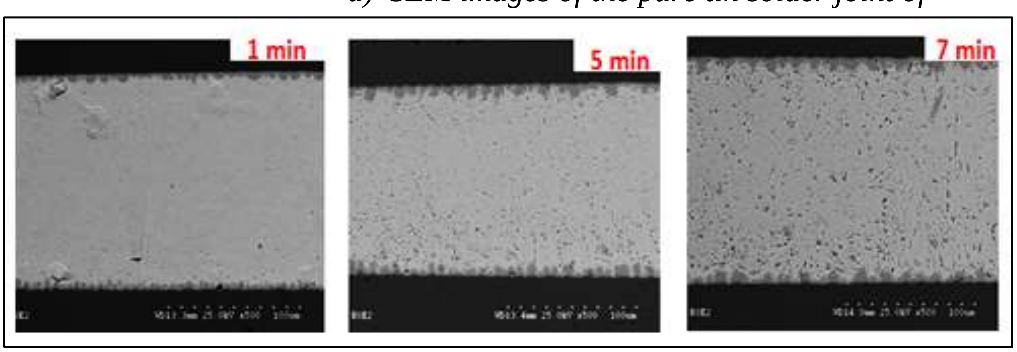
The Sn solder reacts with the copper substrates to form IMC compound. There are 2 Sn-Cu IMC compounds that can form η- Cu_6Sn_5 and ε-Cu_3Sn. In reflow process majorly η- Cu_6Sn_5 IMC is formed with a little ε-Cu_3Sn.

The following SEM images in figure shows the consistency in the height of solder joint prepared for different aspect ratios.

The IMC thickness variation with time is compared between the two solder joints withhstandoff height 15µm and 150µm respectively.



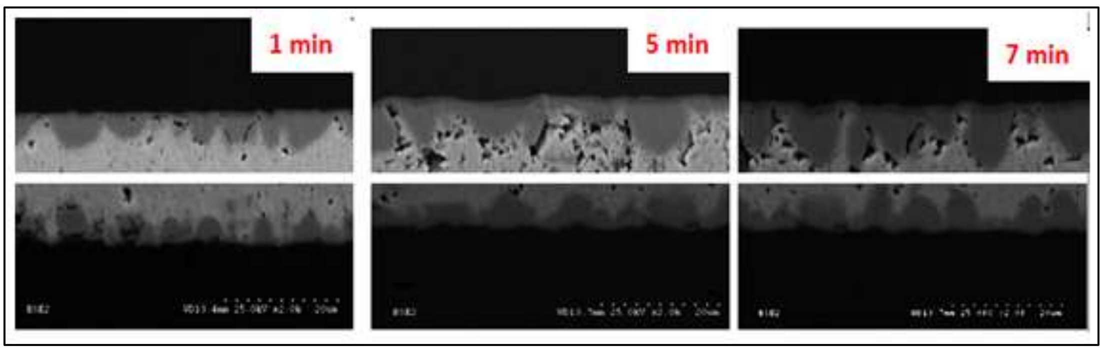
a) SEM images of the pure tin solder joint of



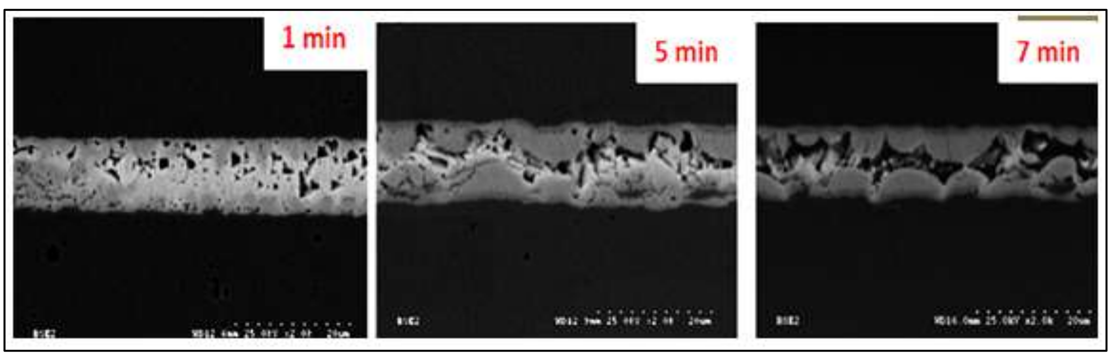
b) SEM images of the pure tin solder joint of thickness ~ 150µm

Figure 9: *SEM images showing the consistency in the solder joint standoff*

From figure SEM images, we can observe η- Cu_6Sn_5 with scallop morphology. The IMC thickness variation can be observed. The IMC thickness increases with reflow time. The IMC thickness is high in low standoff height sample in early stage of reflow then the growth rate increases in high standoff height sample compared to low standoff height sample.



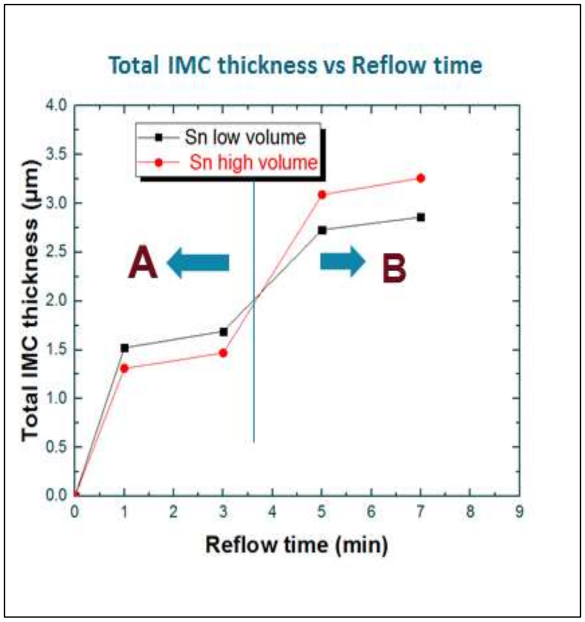
a) SEM images with solder joint standoff height ~ 150µm



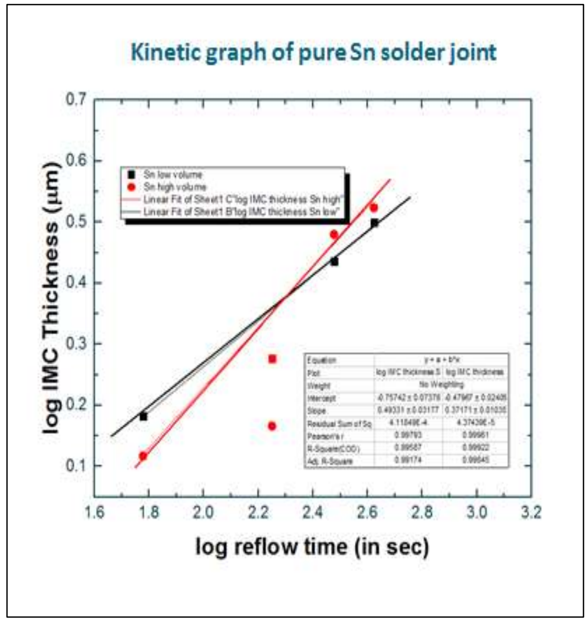
b) SEM images of the solder joint with standoff height ~ 15µm

Figure 10 *The IMC thickness variation between the high volume and low volume solder joint.*

The IMC thickness calculated is plotted against time to observe the growth rate behavior. The cross over point is observed in growth rate between high volume and low volume solder.



Graph 1 *The IMC Growth rate with reflow time in pure Sn solder joint*



Graph 2 *The kinetical IMC Growth rate with reflow time in Pure Sn solder joint*

From graph1 we observe cross over after critical point around 5 min resulting in 2 regions A and B with low volume solder joint possessing thicker IMC in the A region and high volume with thicker IMC in the B region.

A region: The IMC thickness of low volume solder joint is higher than high volume solder joint. The determining factor for the growth of IMC thickness with solder volume variation at early reflow process is the difference in the rate of saturation.

B region: The IMC thickness of high volume solder is more than low volume. The determining factor in this case based on the combined effect of relative amount of remaining solder and already grown IMC thickness.

The growth rate of the solder joints increases in the early reaction stage. With prolonged reflow time the rate of IMC growth decreases. The above behavior is depicted for both solder joints.

The log graph is fitted with linear fitting and slope is determined and is equal to 0.38083 in low volume Sn solder from graph 2 which shows the IMC growth follows $(t)^{1/3}$ kinetics. The reflow technique follows $(t)^{1/3}$ kinetics.

$$D = (kt)^{n}$$

$$\text{Log } D = n \log t + \log k$$

Here n = 0.3806. Thus low standoff height joint follows the $(t)^{1/3}$ showing high growth rate.

The log graph is fitted with linear fitting and slope is determined and is equal to 0.53 in case of high volume solder joint from graph 3 which shows the IMC growth follows $(t)^{1/2}$ kinetics. The reflow technique follows $(t)^{1/2}$ kinetics and diffusion controlled mechanism.

$$D = (kt)^{n}$$

$$\text{Log } D = n \log t + \log k$$

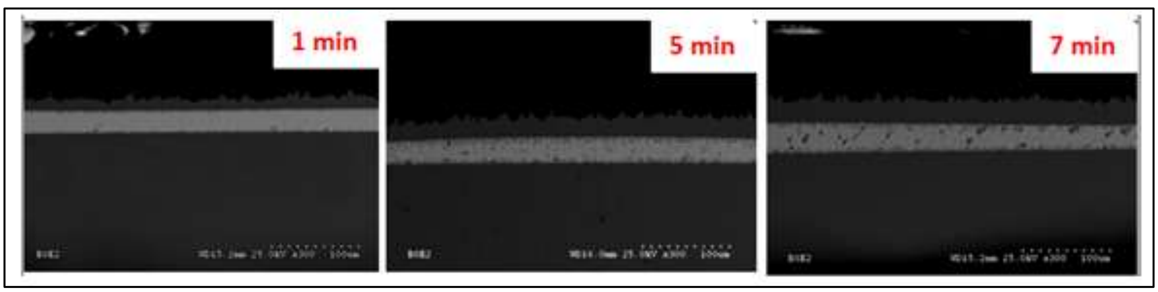
Here n = 0.53. Thus high standoff height joint follows the $(t)^{1/2}$ showing deviation from the $(t)^{1/3}$ behavior. Thus show low growth rate compared to low standoff height.

The effect of copper concentration gradient is validated using SAC 305 alloy. As SAC alloy has initial copper concentration, the IMC growth rate behavior should show a deviation from pure tin. According to CGC model, the IMC growth rate of SAC alloy is higher than that of pure tin at early stage of reaction.

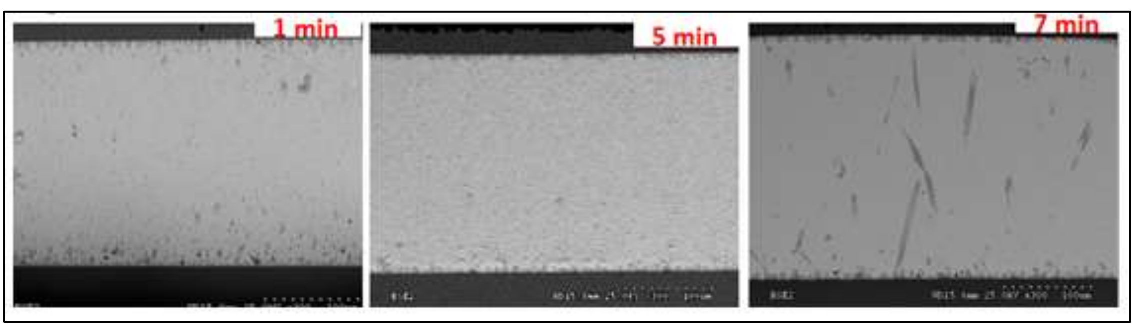
3.3 IMC growth rate behavior in pure SAC305 solder joint sample with different aspect ratio or stand of heights

The SAC alloy samples are reflowed under same conditions as Sn solder samples to analyze the effect of initial copper concentration in the solder.

The IMC thickness variation with time is compared between the two solder joints with standoff height 15µm and 150µm respectively.



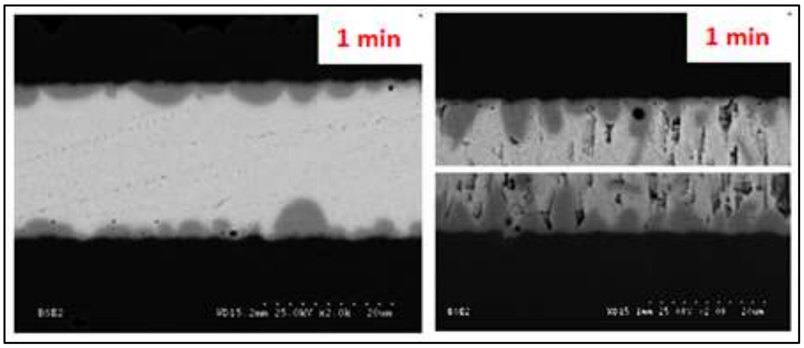
a) SEM images with SAC 305 solder joint standoff height ~ 25µm at 270^{0}C



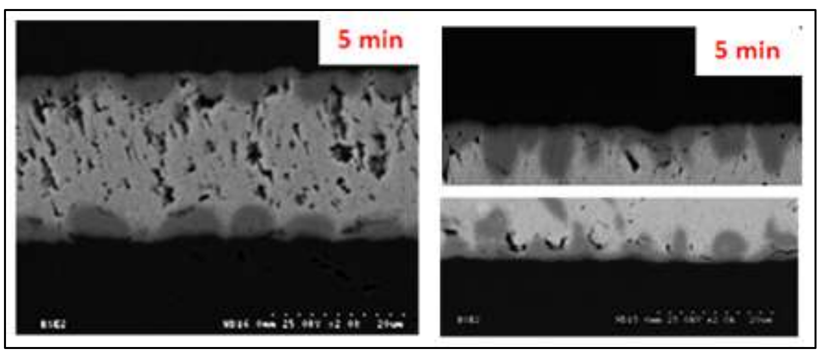
b) SEM images with SAC 305 solder joint standoff height ~ 25µm

Figure 11 *SEM images showing the consistency in the solder joint standoff height*

From the figure 16 SEM images, we can observe η- Cu_6Sn_5 with scallop morphology. The IMC thickness variation can be observed. The IMC thickness increases with reflow time. The IMC thickness is high in low standoff height sample and growth rate is abruptly high during early reaction time later on with prolonged time it decreases due to the consumption of solder.



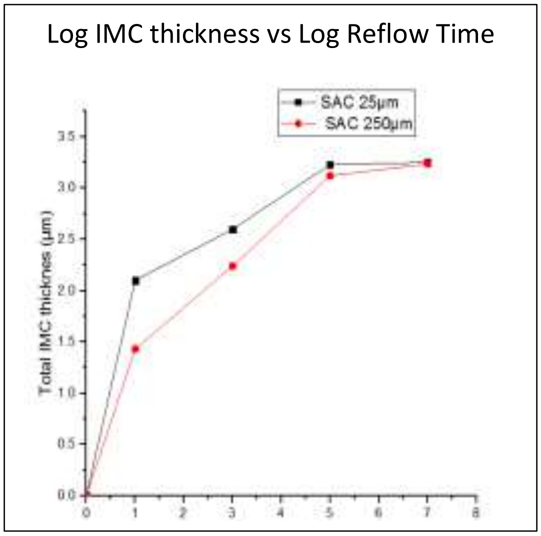
a) *SEM images with solder joint standoff height ~ 25µm*



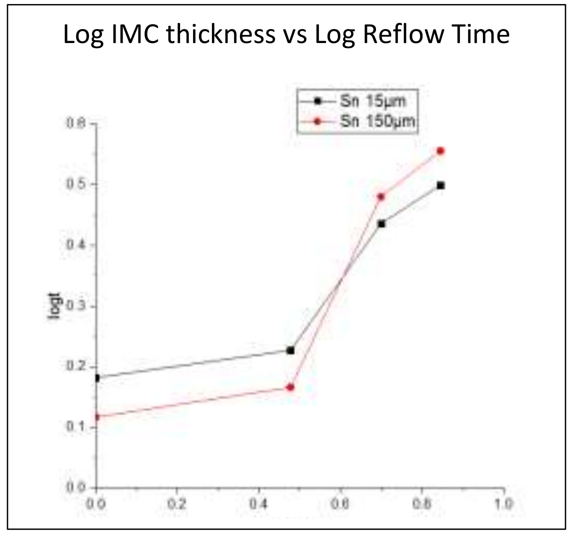
b) *SEM images with solder joint standoff height ~ 250µm*

Figure 12 *SEM images showing IMC thickness for different conditions*

From the graph 5 and 6 we can see that 25µm solder joint has thicker IMC compared to 150µm solder joint. The growth rate of the low standoff solder joints increases in the early reaction stage. With prolonged reflow time the rate of IMC growth decreases due to consumption of Solder. The high solder joint growth rate increases steadily upto critical reflow time them decreases.



Graph 3 *The IMC Growth rate with reflow time in SAC 305 solder joint*



Graph 4 *the kinetical IMC Growth rate with reflow time in SAC 305 solder joint*

The growth rate of the low standoff solder joints increases in the early reaction stage. With prolonged reflow time the rate of IMC growth decreases due to consumption of Solder. The high solder joint growth rate increases steadily upto critical reflow time them decreases.

3.4 Effect of Cu concentration in the solder on IMC growth rate

The IMC growth rate of pure Sn and SAC solder joint is compared to see the effect of initial Cu concentration.

From the above SEM images, we can observe ɳ- Cu_6Sn_5 with scallop morphology. The IMC thickness variation can be observed. The IMC thickness increases with reflow time. The IMC thickness is high in SAC solder joint compared to tin solder joint.

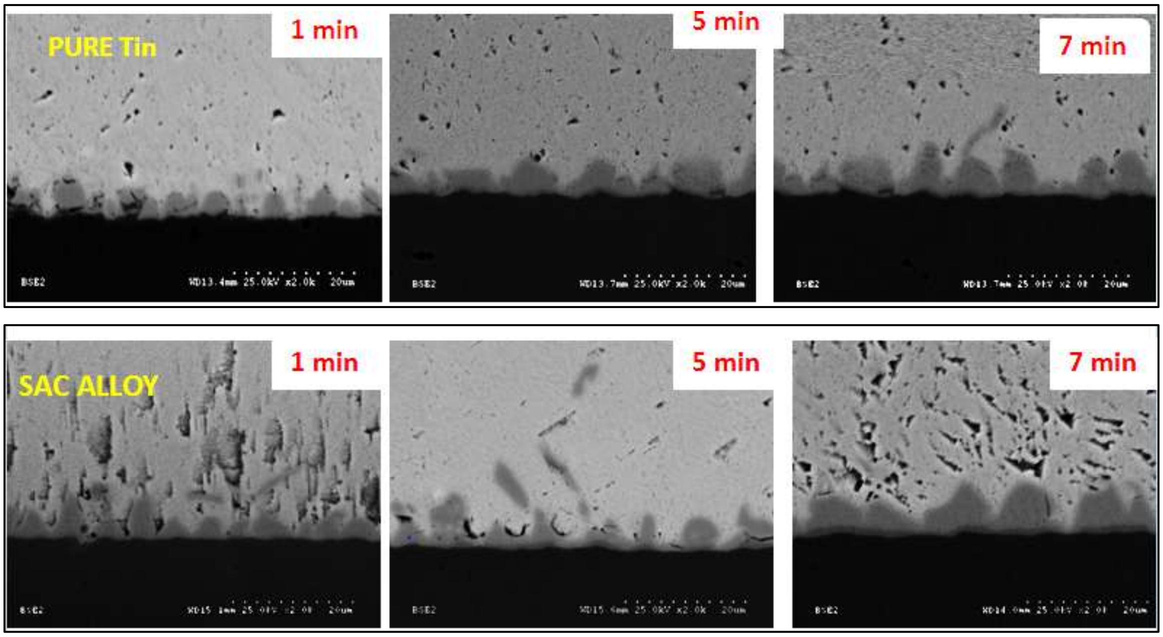


Figure 13: *SEM images related to high volume solder joint of pure Sn & SAC alloy*

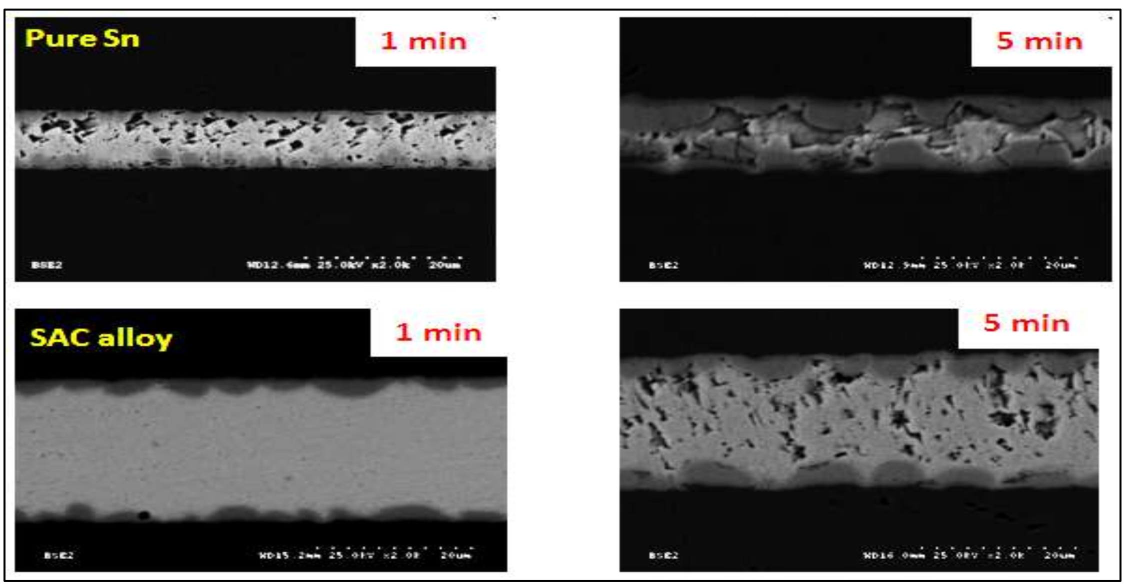
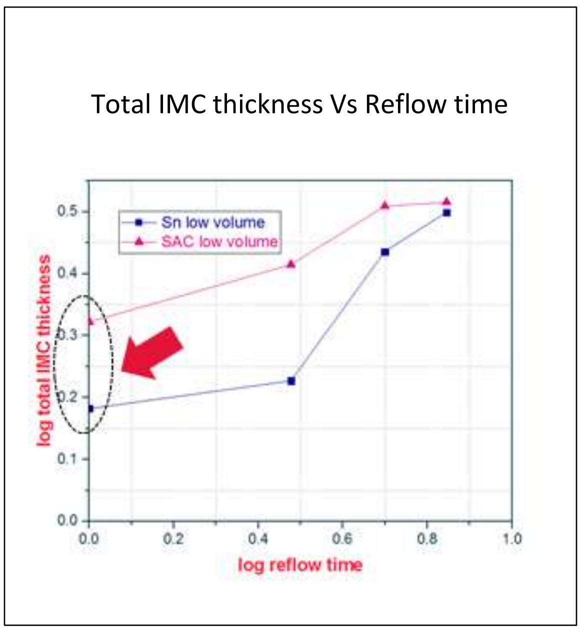


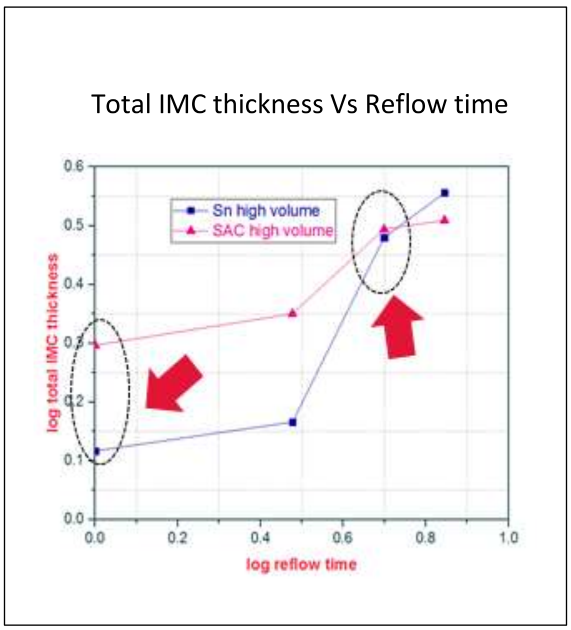
Figure 14 *SEM images related to high volume solder joint of pure Sn & SAC alloy respectively*

From the above SEM images, we can observe η- Cu_6Sn_5 with scallop morphology. The IMC thickness increases with reflow time both solder joints. The IMC thickness is high in SAC solder joint compared to tin solder joint.

The cross sectional SEM images of the solder joints figure shows the common scallop-type Cu_6Sn_5 grains formed at the Cu/Sn interfaces during wetting reaction. The size of the grains decreases as the volume of solder joint increases as during reflow process the Cu saturation time is less in low volume solder joint compared to high volume solder resulting in the rapid formation of scallop-type Cu_6Sn_5 with more grain size.



Graph 5 *The IMC Growth rate with reflow time in SAC 305 and Sn low volume solder joint*



Graph 6 *The IMC Growth rate with reflow time in SAC 305 and Sn high volume solder joint*

From the graph 7, we can see that low volume SAC solder joint has thicker IMC compared to that of Sn solder joint. The growth rate between the low volume SAC and Sn joints bear no significant difference. With prolonged reflow time the rate of IMC growth decreases due to consumption of Solder. The SAC solder joint has higher IMC growth rate.

From the graph 8 we can see that high volume SAC solder joint has thicker IMC compared to that Sn solder joint. The growth rate of the high volume Sn joints increases more than that of SAC solder with time upto critical reflow time.

Chapter 4

Discussion

To explain the above IMC growth rate phenomenon with Size effect and initial copper concentration effect, Concentration gradient controlled kinetics model (CGC) proposed by M.L. Huang et.al. is applied.

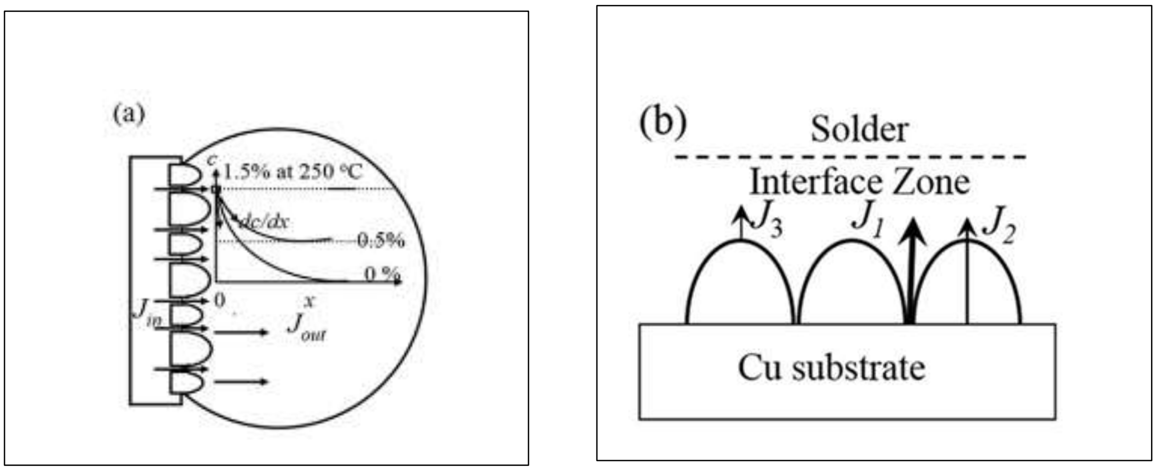
4.1 Concentration Gradient Control Kinetics Model (CGC)

This model proposes that the IMC growth at the interface is the net result of Cu flux availability at the interface and in the bulk solder. It assumes that the Cu influx into molten solder is driven by concentration gradient and the dominant diffusive path is channels between IMC scallops and is considered as grain boundaries.

Based on the model the IMC growth is resulted from the Cu_{in} (J_{in}) and Cu_{out} (J_{out}) as shown in fig. (a). Cu influx (J_{in}) represents the flux of Cu atoms into the Cu_6Sn_5/ solder interfacial zone and Cu outflux (J_{out}) represents the flux of Cu atoms from Cu_6Sn_5/ solder interfacial zone into the molten solder.

Cu influx (J_{in}) is contributed by three influxes J_1, J_2, J_3 as shown in the figure (b). J_1 represents the Cu flux diffusing along Cu_6Sn_5 grain boundary channels from Cu substrate into the Cu_6Sn_5/solder interface zone. J_2 represents the Cu flux diffusing from Cu substrate into the Cu_6Sn_5/solder interface zone through IMC grains via bulk diffusion and J_3 represents dissolution of Cu_6Sn_5 grains into molten solder at the Cu_6Sn_5/solder interface zone. [6]

This model suggests that the concentration gradient at the interface is main determining factor for dissolution of Cu in the molten solder which affects the IMC formation.



a)Cross-section view of the solder joints and Cu fluxes at the interface b)three Cu influxes of Cu into the solder.[6] [14]

Figure 15 *Schematic diagrams of interfacial Cu fluxes between Cu6Sn5 grains*

Cu influx (J_{in}) is contributed by three influxes J_1, J_2, J_3 as shown in the figure (b). J_1 represents the Cu flux diffusing along Cu_6Sn_5 grain boundary channels from Cu substrate into the Cu_6Sn_5/solder interface zone. J_2 represents the Cu flux diffusing from Cu substrate into the Cu_6Sn_5/solder interface zone through IMC grains via bulk diffusion and J_3 represents dissolution of Cu_6Sn_5 grains into molten solder at the Cu_6Sn_5/solder interface zone. J_1 is considered to be dominant as the kinetics follows $t^{1/3}$ law and the diffusion via the boundary channels assumed as grain boundary is the controlling mechanism during the reflow process. Therefore it is assumed that J_{in} is contributed by J_1.

Thus the IMC growth is contributed by the difference between J_{in} and J_{out}. Thus this model is established based on the mass fluxes.

The existence of thin Cu_6Sn_5 is layer is ignored as it has little effect on Cu diffusion and the deposition of the Cu atoms on the IMC during cooling is neglected in the model.

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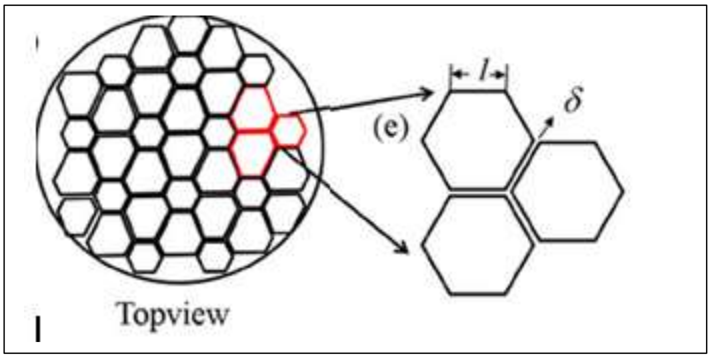

Figure 16 *Top view of Cu6Sn5 grains with a side length l and a grain boundary channel width δ*

The Cu_6Sn_5 is assumed to have scallop morphology with hexagonal pillar structure from the figure we can see the grain having an average length l and channel width δ. We can relate the average IMC thickness of the interfacial layer to be l.

Thus mass influx of Cu atoms can be given as

$$J_{in} = D\ S_{GB}\frac{C_b - C_e}{l} \quad [6]$$

Where D is diffusivity of Cu atoms at the channel, S_{GB} is ratio of channel area to the whole area, C_b is equilibrium concentration of Cu in solder at planar interface of Cu_6Sn_5 and molten solder and C_e is the equilibrium concentration of Cu in solder at interface of substrate and molten solder at the bottom of the channel. Thus J_{in} depends on the thickness of IMC layer as the other ones are constant. As the thickness of IMC increases the inflow of Cu flux decreases which decreases the growth rate.

From Fick`s first law, the mass flux of Cu atoms is expressed as

$$J_{out} = -D \frac{dc}{dx}$$

Where dc/dx is the concentration gradient at the solder / Cu_6Sn_5 interface in the direction normal to the interface.

As the Cu concentration gradient increases the outflux increases the growth rate decreases. Thus growth rate is given as

$$\frac{dl}{dt} = (\rho_{solder} (J_{in} - J_{out}))/\omega\, \rho_{IMC}$$

The growth rate increases when the influx of Cu atoms is more than outflux of Cu atoms. As the influx increases more Cu atoms diffuse into the solder which can be used at the interface of solder for the IMC growth or dissolved in the molten solder which depends on J_{out}. As the J_{out} decreases more Cu atoms are present at the interface which saturates the solder and contributes to the growth of IMC. As the J_{out} increases more Cu atoms diffuses into the bulk solder making it unsaturated and decreases the growth of IMC layer.

4.1.1 Illustration Of The Effect Of Jin And Jout On The Imc Growth Rate At Early Stage Of Reaction

Low standoff height sample:

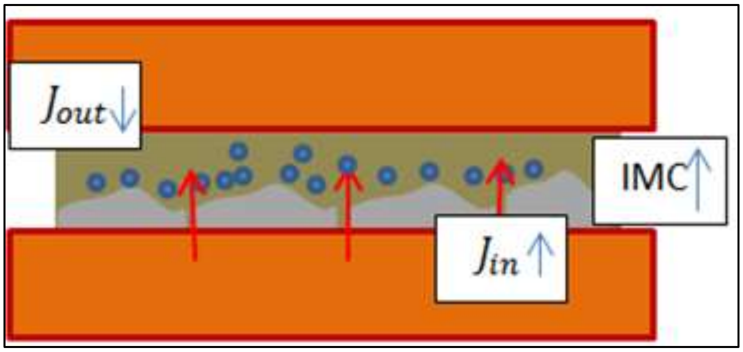

Figure 17 *The mass flux of Cu atoms in low volume solder joint height sample. (For simplicity the top IMC is not presented)*

In low standoff height solder joint sample the average concentration of the Cu atoms is high, even less amount of Cu is dissolved, due to the volume constraint. This decreases the Cu concentration gradient across the solder joint decreasing the J_{out} which is proportional to concentration gradient making the influx of the Cu atoms close to interface. The influx Cu react with the solder and contribute to the IMC growth. Thus IMC growth rate increases resulting in thicker IMC. At early stage of reaction the IMC thickness is low which helps in facilitating the inflow of Cu atoms into the molten solder increasing J_{in} which is inversely proportional to the thickness of the IMC. Due to large net difference in mass fluxes IMC growth rate increases resulting in thicker IMC formation. Even the low volume solder joint reaches the saturation so rapidly that $J_{out} = 0$ and then entire Cu influx is supplied for IMC growth rate. Thus after the saturation point the IMC growth rate is determined by the $J_{in.}$ Thus IMC growth is based on grain boundary controlling mechanism as the Cu influx is dependent on availability of grain boundary/liquid channels.

High standoff height sample:

In high standoff height solder joint the average concentration of the Cu atoms is less due to high volume which increases Cu concentration gradient making J_{out} to be high resulting in more influx of the Cu atoms into bulk solder rather close to interface. Thus IMC growth rate decreases resulting in low IMC thickness than that of low volume solder

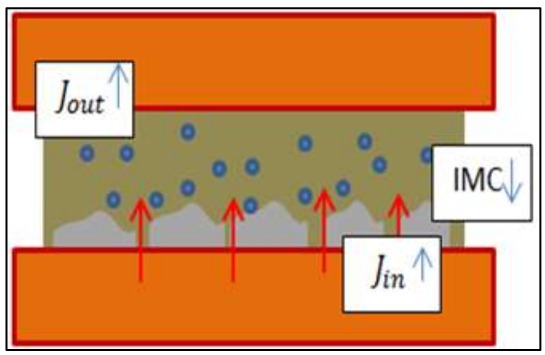

Figure 18 *The mass flux of Cu in high volume solder joint sample. (for simplicity the top IMC is not presented)*

. At early stage of reaction the IMC thickness is low which helps in facilitating the inflow of Cu atoms into the molten solder making J_{in}, inversely proportional to the thickness of the IMC, high. Thus IMC growth rate decreases compared to the low volume solder joint sample resulting in reduced IMC thickness than low standoff height sample due to low net difference in mass fluxes. As J_{in} is high at early stage the IMC growth is based on Jout, dependent on concentration gradient, controlled by diffusion of Cu into molten solder

4.1.2 Illustration Of The Effect Of Jin And Jout On The Imc Growth Rate As The Reflow Time Increases

As the reflow time increases the thickness of IMC layer increases making J_{in} to decrease as the channel area decreases making it difficult for the Cu atoms to diffuse. As the reflow time increases the thickness of IMC layer increases making J_{in} to decrease as the channel area decreases making it difficult for the Cu atoms to diffuse. As the Cu concentration in molten solder increases with time the Cu concentration gradient decreases resulting in decreased J_{out}. Thus growth rate decreases after some critical time due to the thicker IMC formation which inhibits the Cu influx into the solder. Shown in fig 13.

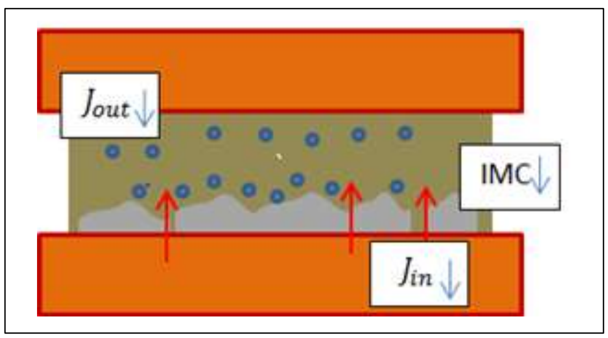

Figure 19 *The mass flux of Cu in solder joint sample after prolonged reflow process*

As the Cu concentration is initially present in the solder the average Cu concentration is more compared to zero initial Cu concentration. Thus the concentration gradient decreases in the joint having initial Cu concentration thus Jout decreases in the sample making the IMC growth rate high. Thus the solder joint with initial Cu concentration has thicker IMC.

The cross sectional SEM images of the solder joints figure shows the common scallop-type Cu_6Sn_5 grains formed at the Cu/Sn interfaces during wetting reaction. The

Cu diffusion behavior in liquid Sn-0.3Ag-0.5cu and Sn-Cu solder is assumed to obey Fick`s second law. The low volume solder is almost saturated with Cu while the high volume solder is far from saturation due to the fact that low standoff height solder joints dissolve less amount of Cu than high standoff height joint since the amount of solder is less. Although the amount of copper dissolved is more in high volume solder joint the average concentration of Cu in those joints is still small compared to that in low volume solder.

As the average concentration of Cu in the high volume solder is less compared to low volume solder at the early stage of reaction, the absolute Cu concentration gradient is dc/dx at the interface is higher in high solder volume joint. This Cu concentration gradient is considered to be the driving force of the dissolution of Cu. The dissolution kinetics of Cu substrate is dependent on the size of interfacial Cu_6Sn_5 as the liquid channel diffusion is considered to be the controlling mechanism in the reflow process for diffusion of Cu through the IMC layer.

In case of high volume solder joints the small size of interfacial grains provides the large liquid channel area for rapid diffusion of Cu into molten solder. Integrated with high concentration gradient the dissolution of Cu is more in molten solder with rapid diffusion of Cu through channels.

Thus the interfacial reaction in solder joints is the result of the response from combined effects of IMC growth, dissolution of Cu substrate and composition variation at the interface.

4.2 Application of CGC Model To study IMC Growth Rate At Cu-Sn Interface

Case 1: IMC growth rate of Pure Sn solder joint

In case of Sn solder joint samples the 150 µm sample has less thickness compared to 15µm sample in early stage of reaction then the high volume sample. The 150 µm sample IMC growth crosses the IMC growth of 15µm sample at 5 min. Both samples growth rate decrease at 7 min.

$$J_{out}(low\ vloume) < J_{out}\,(high\ vloume) \quad \text{as} \quad \frac{dc}{dx}\,(\text{low}) < \frac{dc}{dx}\,(\text{high}).$$

Thus as the Concentration gradient in high volume solder joint is more compared to that of low volume joint more Cu flux is driven into molten solder for dissolution in high volume solder.

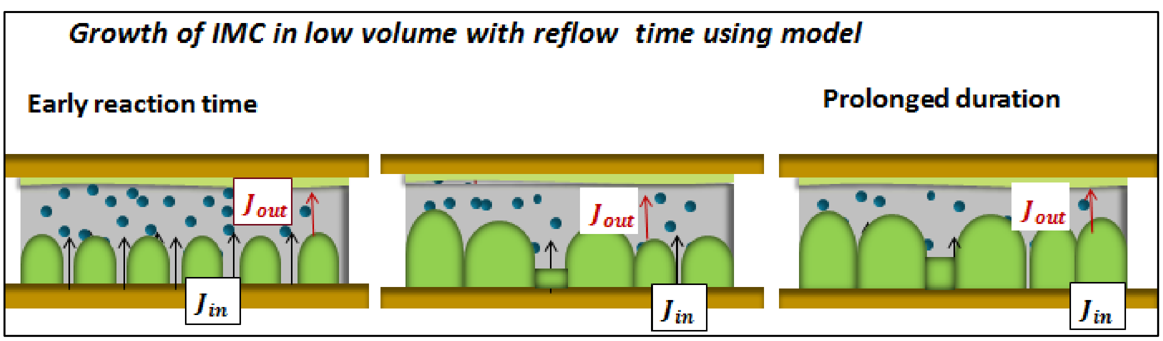

Figure 20 *IMC growth rate in low volume solder joint during reflow*

Also the low volume solder sample saturate much faster than the high volume sample making the J_{out} (low volume) = 0. Thus the entire J_{in} is supplied to the interface area resulting in thicker IMC growth as it saturates much faster that the concentration gradient effect is less experienced in the low volume sample. Thus at the early stage of reaction the low volume solder sample has thicker IMC compared to that of high volume solder joint.

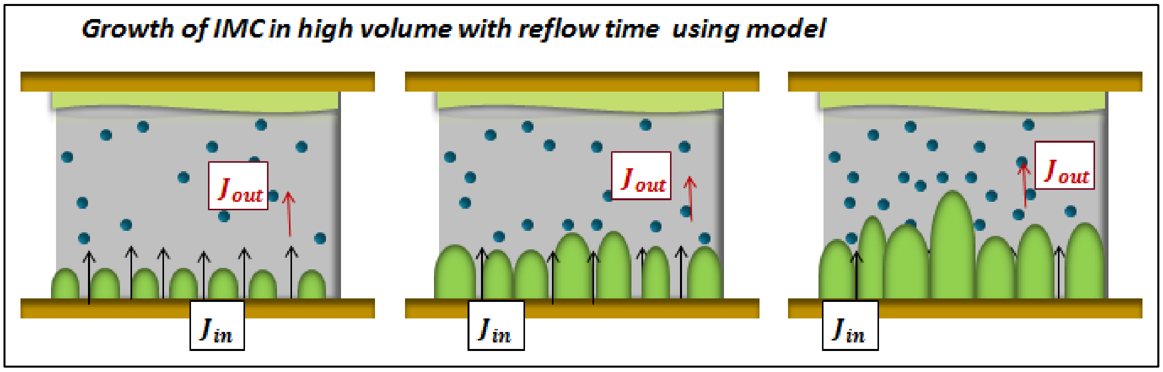

Figure 21 *IMC growth rate in high volume solder joint during reflow process with time*

At 5 min there is cross over point. As time proceeds the IMC thickness increases that restricts the Cu influx and reduces the availability of remaining solder to react. Thus the combined effect of reduction in J_{in} and limited availability of solder decreases the growth rate that high volume solder joint IMC thickness increases than that of low volume solder. In case of high volume solder joint the J_{out} decreases as the average concentration of Cu in the solder increases with time thus enhancing the growth rate upto critical time of reflow.

Case 2: IMC growth rate of SAC solder joint

In case of Sn solder joint samples the 250 µm sample has less thickness compared to 25µm sample in early stage of reaction then the high volume sample. Both samples growth rate decrease at 7 min.

$$J_{out}\ (25\ \mu m) < J_{out}\ (250\ \mu m) \quad \text{as} \quad \frac{dc}{dx}(25\ \mu m) < \frac{dc}{dx}(250\ \mu m)$$

Also the 25 µm sample saturate much faster than the 150 µm sample making the Jout (25 µm) = 0 Thus the entire Jin is supplied to the interface area resulting in high IMC thickness growth .As it saturates much faster that the concentration gradient effect is less experienced in the 25 µm sample. Thus at the early stage of reaction the 25µm sample has higher IMC thickness compared to 150µm.

As time proceeds the IMC thickness increases that it restricts the Cu influx and reduces the amount of solder to react. Thus the combined effect of reduction in J_{in} and limited availability of solder decreases the growth rate that 150 µm solder IMC thickness nearly approaches the thickness of 15 µm solder. In case of 150 µm J_{out} decreases as the average concentration of Cu in the solder increases with time thus enhancing the growth rate upto critical time of reflow.

Case 3: Comparison of IMC growth rate of Sn and SAC solder joint

The SAC305 alloy has 0.5% initial Cu concentration that reduces the concentration gradient of SAC alloy.

$$J_{out\ SAC}\ (25\ \mu m) < J_{out\ Sn}\ (15\ \mu m) \quad \text{as} \quad \frac{dc}{dx}(25\ \mu m) < \frac{dc}{dx}(15\ \mu m)$$

Thus SAC alloy has thicker IMC growth rate compared to Sn solder joint. There is no significant growth difference between the SAC and Sn solder joint growth rate in give in experimental reflow time. The SAC solder is always has thicker IMC compared to Sn low volume solder.

In Case of high standoff height sample at the early state of reaction due to the presence of Cu initial concentration in SAC solder the IMC growth rate is high compared to Pure Sn solder joint.

$J_{out\ SAC}$ (Low volume) < $J_{out\ Sn}$ (high volume) as $\frac{dc}{dx}$ (low volume) < $\frac{dc}{dx}$ (high volume)

As time proceeds further, the thicker IMC layer in SAC alloy restrict the Cu influx resulting in decreased IMC growth rate in SAC alloy. Thus Sn has near IMC layer thickness as SAC at 7 min.

$J_{in\ SAC}$ (low volume) > $J_{in\ Sn}$ (high volume) as l (low volume) > l (high volume)

Chapter 5

Conclusion

Due to miniaturization effect the reduction in solder joints has become inevitable. As the solder joint size decreases it influences the solder joint properties due to change in the microstructure. Thus study on the effect of solder joint size on its properties is demanded for reliability concern. The most significant property of the solder joint is its IMC formation. IMC formation is necessary for bonding but due to its brittle nature excess growth needs to be avoided. The IMC growth rate is studied in 2 different solder joint size samples under reflow and aging conditions. From the results it’s clear that low solder joint size samples have high growth rate at early reflow state and aging time. Thus there needs to be reliability concern for low solder joints due to their high IMC growth rate.

APPENDIX A

MATLAB CODE

```
clc;
clear all;
close all;

Time = [0,1,3,5,7];
low=[];
high=[];
low(1)=0;
high(1)=0;
%%% Reading the input images into array Img
%%% For 1 min low
Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min low\1.bmp');
Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min low\2.bmp');
Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min low\3.bmp');
Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min low\4.bmp');
Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min low\5.bmp');
Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min low\6.bmp');
I1 = rgb2gray(Img1);
I2 = rgb2gray(Img2);
I3 = rgb2gray(Img3);
I4 = rgb2gray(Img4);
I5 = rgb2gray(Img5);
```

```
I6 = rgb2gray(Img6);
thickness = [];
thickness(1) = Thick(I1);
thickness(2) = Thick(I2);
thickness(3) = Thick(I3);
thickness(4) = Thick(I4);
thickness(5) = Thick(I5);
thickness(6) = Thick(I6);

%%%% Average thickness
avg_thick = sum(thickness)/6 ;
fprintf('Average Thickness for 1 min low =%f \n',avg_thick);
low(2) = avg_thick;

%%% Reading the input images into array Img
%%% For 1 min high
Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min high\1.bmp');
Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min high\2.bmp');
Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min high\3.bmp');
Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min high\4.bmp');
Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min high\5.bmp');
Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\1 min high\6.bmp');
```

```
I1 = rgb2gray(Img1);

I2 = rgb2gray(Img2);

I3 = rgb2gray(Img3);

I4 = rgb2gray(Img4);

I5 = rgb2gray(Img5);

I6 = rgb2gray(Img6);

thickness = [];

thickness(1) = Thick(I1);

thickness(2) = Thick(I2);

thickness(3) = Thick(I3);

thickness(4) = Thick(I4);

thickness(5) = Thick(I5);

thickness(6) = Thick(I6);


%%%% Average thickness

avg_thick = sum(thickness)/6 ;

fprintf('Average Thickness for 1 min high =%f \n',avg_thick);

high(2) = avg_thick;


%%% Reading the input images into array Img

%%% For 3 min low

Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min low\1.bmp');

Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min low\2.bmp');

Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min low\3.bmp');
```

```
Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min
low\4.bmp');

Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min
low\5.bmp');

Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min
low\6.bmp');

I1 = rgb2gray(Img1);

I2 = rgb2gray(Img2);

I3 = rgb2gray(Img3);

I4 = rgb2gray(Img4);

I5 = rgb2gray(Img5);

I6 = rgb2gray(Img6);

thickness = [];

thickness(1) = Thick(I1);

thickness(2) = Thick(I2);

thickness(3) = Thick(I3);

thickness(4) = Thick(I4);

thickness(5) = Thick(I5);

thickness(6) = Thick(I6);


%%%% Average thickness

avg_thick = sum(thickness)/6 ;

fprintf('Average Thickness for 3 min low =%f \n',avg_thick);

low(3) = avg_thick;


%%% Reading the input images into array Img

%%% For 3 min high
```

```
Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min high\1.bmp');

Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min high\2.bmp');

Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min high\3.bmp');

Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min high\4.bmp');

Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min high\5.bmp');

Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\3 min high\6.bmp');

I1 = rgb2gray(Img1);

I2 = rgb2gray(Img2);

I3 = rgb2gray(Img3);

I4 = rgb2gray(Img4);

I5 = rgb2gray(Img5);

I6 = rgb2gray(Img6);

thickness = [];

thickness(1) = Thick(I1);

thickness(2) = Thick(I2);

thickness(3) = Thick(I3);

thickness(4) = Thick(I4);

thickness(5) = Thick(I5);

thickness(6) = Thick(I6);


%%%% Average thickness

avg_thick = sum(thickness)/6 ;
```

```
fprintf('Average Thickness for 3 min high =%f \n',avg_thick);

high(3) = avg_thick;


%%% Reading the input images into array Img

%%% For 5 min low

Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min low\1.bmp');

Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min low\2.bmp');

Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min low\3.bmp');

Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min low\4.bmp');

Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min low\5.bmp');

Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min low\6.bmp');

I1 = rgb2gray(Img1);

I2 = rgb2gray(Img2);

I3 = rgb2gray(Img3);

I4 = rgb2gray(Img4);

I5 = rgb2gray(Img5);

I6 = rgb2gray(Img6);

thickness = [];

thickness(1) = Thick(I1);

thickness(2) = Thick(I2);

thickness(3) = Thick(I3);

thickness(4) = Thick(I4);
```

```
thickness(5) = Thick(I5);

thickness(6) = Thick(I6);


%%%% Average thickness

avg_thick = sum(thickness)/6 ;

fprintf('Average Thickness for 5 min low =%f \n',avg_thick);

low(4) = avg_thick;


%%% Reading the input images into array Img

%%% For 5 min high

Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min high\1.bmp');

Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min high\2.bmp');

Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min high\3.bmp');

Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min high\4.bmp');

Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min high\5.bmp');

Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\5 min high\6.bmp');

I1 = rgb2gray(Img1);

I2 = rgb2gray(Img2);

I3 = rgb2gray(Img3);

I4 = rgb2gray(Img4);

I5 = rgb2gray(Img5);

I6 = rgb2gray(Img6);
```

```
thickness = [];

thickness(1) = Thick(I1);

thickness(2) = Thick(I2);

thickness(3) = Thick(I3);

thickness(4) = Thick(I4);

thickness(5) = Thick(I5);

thickness(6) = Thick(I6);


%%%% Average thickness

avg_thick = sum(thickness)/6 ;

fprintf('Average Thickness for 5 min high =%f \n',avg_thick);

high(4) = avg_thick;


%%% Reading the input images into array Img

%%% For 7 min low

Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min low\1.bmp');

Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min low\2.bmp');

Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min low\3.bmp');

Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min low\4.bmp');

Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min low\5.bmp');

Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min low\6.bmp');

I1 = rgb2gray(Img1);
```

```
I2 = rgb2gray(Img2);
I3 = rgb2gray(Img3);
I4 = rgb2gray(Img4);
I5 = rgb2gray(Img5);
I6 = rgb2gray(Img6);
thickness = [];
thickness(1) = Thick(I1);
thickness(2) = Thick(I2);
thickness(3) = Thick(I3);
thickness(4) = Thick(I4);
thickness(5) = Thick(I5);
thickness(6) = Thick(I6);

%%%% Average thickness
avg_thick = sum(thickness)/6 ;
fprintf('Average Thickness for 7 min low =%f \n',avg_thick);
low(5) = avg_thick;

%%% Reading the input images into array Img
%%% For 7 min high
Img1 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min high\1.bmp');
Img2 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min high\2.bmp');
Img3 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min high\3.bmp');
```

```
Img4 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min high\4.bmp');

Img5 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min high\5.bmp');

Img6 = imread('C:\Users\Abhilash Pavan\Documents\MATLAB\tin images\7 min high\6.bmp');

I1 = rgb2gray(Img1);

I2 = rgb2gray(Img2);

I3 = rgb2gray(Img3);

I4 = rgb2gray(Img4);

I5 = rgb2gray(Img5);

I6 = rgb2gray(Img6);

thickness = [];

thickness(1) = Thick(I1);

thickness(2) = Thick(I2);

thickness(3) = Thick(I3);

thickness(4) = Thick(I4);

thickness(5) = Thick(I5);

thickness(6) = Thick(I6);


%%%% Average thickness

avg_thick = sum(thickness)/6 ;

fprintf('Average Thickness for 7 min high =%f \n',avg_thick);

high(5) = avg_thick;
```

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BIOGRAPHICAL INFORMATION

Supraja Giddaluri was born in Hyderabad, India, in 1990. She received her Integrated Masters degree from Nizam College, India, in 2013 in the department of Chemistry, her M.S. from The Univeristy of Texas at Arlington in 2015 in the department of Material Science. Her current research interest is in the area of Semiconductors and Reliability. She is a member of Material Science societies.