Growth Behavior of Intermetallic Compounds in Various Solder Joints Induced by Electromigration

Electromigration에 의한 다양한 솔더 접합부에서의 금속간 화합물 성장거동

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Abstract

With the development of the fine pitch technology, the size of the solder bumps contacting the chip and the substrate has decreased, thereby significantly increasing the current density. As a result, intermetallic compounds (IMCs) are formed in solder bumps, and the formation/growth of Kirkendall voids is the main reason for failure, which is accelerated by electromigration. Therefore, various studies have been conducted to restrain the growth of IMCs and Kirkendall voids. This study summarizes the issues that should be considered when investigating the effects of electromigration on solder joints. The prediction and observation of the growth behavior of the IMCs is summarized for various solder bump joints. In addition, we provide an effective method for assisting the fine pitch technology.

Key Words: Electromigration, Solder bump joints, Intermetallic compounds, Kirkendall voids, Modeling

1. Introduction

There is an increasing demand for miniaturization and high performance of major products such as smart phones, 3D TVs and computers recently in the electronics industry, and technology for implementing a fine pitch for mounting many devices and terminals in a printed circuit board (PCB) substrate that connects a chip and a main board has been continuously developed in order to satisfy this demand^{1,2)}. There was a problem that the current density applied to solder bump increased rapidly as the solder bump that connects the chip and the substrate became finer along with the development of fine pitch technology. The formation and growth of secondary phases induced by electromigration (EM) and thermo-migration (TM) are observed in the solder bump due to the increase in current density and temperature induced by joule heating, and this phenomenon leads to serious problems such as open-circuit failure due to

rapid increase in electrical short and electrical resistance in the package³⁾. It has been reported that the formation and growth of Kirkendall voids and intermetallic compounds (IMC) formed between the solder and the substrate, which are the main causes of the problem, is accelerated due to electromigration (EM)^{4,5)}. Pb-Sn-based alloys are the alloys that were mainly applied to solder bumps in electronic devices, which have been actively used until 2006. However, studies on Pb-free solders were continuously conducted and solders of various alloys have been developed with the emergence of lead poisoning problems⁶⁻⁸⁾. Although studies have been mainly conducted on intermetallic compounds and Kirkendall void growth behavior in Sn-Ag alloy solder bumpers^{9,10)}, studies on the EM effect in solder bump joints of Sn-Cu-based alloys have also been conducted recently^{11,12)}.

There is a trend of increasing and miniaturization of components mounted in a package due to microminiature fine-pitch technology with the application of Package

Fig. 1 Development trend of electronic packages¹⁵⁾

on Package (PoP) and 3D System in Package (SiP) technologies as shown in Fig. 1¹³⁻¹⁵⁾. It is determined that the structure of the package needs to be changed and the solder bump material needs to be changed for an efficient method to inhibit the formation of defects since the current density applied to the solder bumps is rapidly increasing due to miniaturization. Therefore, the changes of voids and IMC in the joints according to EM effect in solder bump joints of various materials are summarized, and a study that predicts the change in IMC according to EM is introduced in this paper.

2. Experimental and Modeling of Electromigration

The growth of IMC due to EM is observed when a metal atom moves in the movement direction of electron due to an exchange of momentum when a moving electron collides with a metal atom when a current is stressed on the metal interconnect. The driving force of the movement of metal atoms due to EM includes an electron wind force and an electrostatic force. Electron wind force refers to the force that causes electrons that are accelerated by an electric field to collide with a metal atom and transfer momentum to the metal atom to move, and electrostatic force refers to the force that acts on an atom that has lost its valence electron and remains as an ion. Therefore, the effective driving force in EM is given as¹⁶⁾,

$$J = \frac{CD}{kT} Z^* e \rho j \quad (1)$$

where J is the EM flux, C is the concentration, D is the diffusivity, Z^* is the effective charge number, k is the Boltzmann constant, T is the absolute temperature, e is the quantity of electric charge, ρ is the specific resistance, and j is the current density.

Moreover, the concentration of metal atoms is actually changed according to time. The change in concentration over time is represented by Fick's second law¹⁶⁾.

Fig. 2 Schematics diagram of (a) current stressing method for the EM experiments and (b) the TM experiments¹⁷⁾

$$\frac{\partial C}{\partial t} = - \frac{\partial J}{\partial x} \quad (2)$$

The thickness of the growing IMC according to the current stressing time by calculating the EM flux at the formed IMC, the solder, and the metal atom can be predicted through Equations (1) and (2). The increase in electrical resistance and electrical short due to voids are indirectly predicted through the growth prediction modeling of IMC since the growth of IMC is related to the formation and growth of Kirkendall voids. The experimental verification is essential in order to verify that the predicted IMC thickness shows the same result when the current is actually stressed. A schematic diagram of current stressing for EM experiments is as shown in Fig. 2a and a schematic diagram of applying a temperature gradient for TM experiments is as shown in Fig. 2b. Sn-0.7Cu is the solder alloy that is used in Fig. 2, and DC source meter (IT6153) of ITECH was used as a power supply. The IMC is grown by stressing a current for a certain period of time through a power supply after constructing the EM experiment set as shown in Fig. 2a. Subsequently, an experimentally verified modeling result was produced by comparing the actual measured thickness of the IMC with the thickness of the IMC that is calculated through modeling.

3. Results & Discussion

3.1 Selection of Pb-free solder alloy

It is required to apply an eco-friendly Pb-free solder

alloy with a melting point similar to that of Sn-Pb-based solder ($\sim 183^\circ\text{C}$) and good electrical and mechanical properties as a consideration when selecting a Pb-free solder alloy. Currently, a variety of Sn-based solders that can replace Sn-Pb based solders are on the market, and Sn-Ag-Cu, Sn-Ag, Sn-Cu, Sn-Zn, and Sn-Bi-based solders are the most common Pb-free solders¹⁸⁾. Most Pb-free solder alloys consist of Sn as the main component and trace amounts of Ag, Cu, Zn, In, and Bi components¹⁹⁾.

The eutectic point of the Sn-Zn-based eutectic composition solder is 199°C , which has the advantage that the conventional processor can be applied as it is since the melting point is similar to that of the conventional Sn-Pb solder, and it has high strength, and good creep characteristics and thermal fatigue resistance. However, the commercialization is limited since it has fast reactivity with oxygen and the wettability with the substrate is poor²⁰⁾. It has been reported that the oxidation resistance can be improved by adding a trace amount of Ag and Cu since there is a disadvantage that the oxidation is accelerated although the wettability can be improved when a small amount of Bi is added to the Sn-Zn eutectic alloy²¹⁾.

The eutectic composition of Sn-Cu-based solder is Sn-0.7Cu and the eutectic point is 227°C . The solder is deformed due to fatigue properties since Sn-0.7Cu solder has lower creep strength than Sn-Ag alloy, and studies and use have been increasing recently since it has been reported that the deformation of the solder resulting from the warpage defect due to the difference in the coefficient of thermal expansion between the chip and the substrate has excellent crack resistance in electronic packages²²⁾.

The eutectic composition of Sn-Ag-based solder is Sn-3.5Ag and the eutectic point is 221°C . The increase in the applied temperature of Sn-Ag solder tends to decrease the surface tension and contact angle. Since the surface tension of Sn-Ag solder is higher than that of Sn-Pb and the contact angle is also high²³⁾ it has been reported that Sn-Ag solder has lower wettability than that of Sn-Pb solder²⁴⁾. For compensation, it has been reported that adding a trace amount of Cu to Sn-Ag can improve the wettability and fatigue properties, and adding a trace amount of Bi improves the wettability^{25,26)}.

Currently, Sn-Ag-Cu-based solder is mainly applied in soldering and it can be defect generation and propagation sites since coarse Ag_3Sn phase is formed when the content of Ag is increased. Therefore, Sn-3.0Ag-0.5Cu solder with a melting point of 217°C has been established as a representative solder that can replace Sn-Pb based solder²⁷⁾.

3.2 Causes and characteristics of EM phenomenon in solder joints

The metal atoms in the solder generally have a strong flow along the movement direction of electrons due to temperature rise when a current is stressed to a solder joint, and the IMC on the anode side grows rapidly as this flow of atoms becomes a driving force and movement of atoms in the same direction is activated. On the contrary, voids are formed by being accumulated on the cathode side, which leads to electrical short due to the growth of the voids and generation of cracks, since the diffusion rate of atoms around the vacancy is relatively reduced. This is a problem caused by the EM phenomenon and a schematic illustration of the EM phenomenon is as shown in Fig. 3²⁸⁾. In addition, the internal temperature rises to 100°C or above due to the joule heating effect in the joint and the degradation phenomenon induced by EM is accelerated due to the current crowding phenomenon which is generated by structural problems of the solder joint. Therefore, it is difficult to predict the reliability of the solder joint lifespan, and many studies are being conducted to improve the joint lifespan. The studies that covered the effect of EM phenomenon on each solder joint are summarized in Table 1. The IMC formation behavior of the joints by solder material according to EM is described from the next section.

3.2.1 Characteristics of Sn-Zn solder joints

The microstructure of the Sn-9Zn alloy is as shown in Fig. 4. The as-cast solder of Sn-9wt%Zn eutectic composition did not form intermetallic compounds (Fig. 4a), and the microstructure of this alloy has a structure in which needle-like α -Zn is finely dispersed in a matrix of β -Sn phase^{29,30)}. Moreover, oxidation resistance is significantly reduced when the Zn-rich phase is increased in Sn-Zn solder since ZnO is formed due to high reactivity with oxygen of the Zn element as shown in Fig. 4b¹⁹⁾. A method to control the formation of ZnO is required in order to improve the bonding

Fig. 3 Schematic illustration of electromigration phenomenon²⁸⁾

Table 1 Previous studies on EM for various solder joints

Solder	Surface-finished	IMC	EM properties
Sn-9Zn	Cu OSP	$\text{Cu}_5\text{Zn}_8/\text{Cu}_6\text{Sn}_5$	Anode : IMC decreased, Cathode : IMC increased (Reverse polarity) ^{33,36,37)}
Sn-0.7 Cu	Cu OSP	$\text{Cu}_3\text{Sn}/\text{Cu}_6\text{Sn}_5$	Anode : IMC increased, Cathode : IMC decreased (polarity) ¹⁷⁾
Sn-0.7 Cu	Cu OSP/ENIG	$\text{Cu}_3\text{Sn}/\text{Cu}_6\text{Sn}_5$ / $(\text{Ni,Cu})_6\text{Sn}_5$	Anode : IMC increased, Cathode : IMC decreased (polarity) ⁴²⁾
Sn-3.5Ag	Cu OSP	$\text{Cu}_3\text{Sn}/\text{Cu}_6\text{Sn}_5$	Anode : IMC increased, Cathode : IMC decreased (polarity) ⁴⁷⁾ Cathode : voids and cracks increased
Sn-3.0Ag-0.5Cu	Cu OSP/ENIG	$\text{Cu}_3\text{Sn}/\text{Cu}_6\text{Sn}_5$ / $(\text{Ni,Cu})_6\text{Sn}_5$	Anode : IMC increased, Cathode : IMC decreased (polarity) ⁴⁷⁾ Cu OSP : thick IMC formed, ENIG : thin IMC formed

Fig. 4 Microstructure of Sn-9Zn alloy²⁰⁾: (a) the shape of each phase, (b) the formation of ZnO

characteristics of Sn-Zn solder.

Xue³¹⁾ observed the growth and component behavior of IMC through energy-dispersive spectroscopy (EDS) line/spot analysis, and Guo³²⁾ analyzed the IMC behavior of the solder/Cu substrate interface by adding Ag as a method to improve the oxidation resistance of Sn-Zn solder. The components of the IMC layer between Sn-9Zn solder and Cu substrate (Sn-9Zn/Cu), and the growth behavior of IMC with increasing Ag content and aging time, respectively, are as shown in Figs. 5a and 5b. The IMC layer between Sn-9Zn solder and Cu substrate is mainly composed of CuZn_5 and Cu_5Zn_8 (Fig. 5a), and the possibility of lowering the reliability

of the solder joint is increased as the Sn component is decreased and the Zn component is increased significantly in the IMC layer through the EDS line analysis³¹⁾. Therefore, the formation of ZnO was suppressed by adding Ag which has good reactivity with Zn in order to improve the oxidation resistance of Sn-9Zn. The IMC layer that is formed at the interface between the Sn-8.5Zn solder and the Cu substrate is composed of AgZn_3 and Cu_5Zn_8 due to the addition of Ag as shown in Fig. 5b, and the IMC layer of Cu_5Zn_8 tends to be decreased as the addition amount of Ag is increased, while the IMC layer tends to be increased as the aging time is increased³²⁾.

Zhang³³⁾ observed changes in the thickness of the anode and cathode sides of the IMC over time (0, 36, 72 and 166 h) with a current density of $3.87 \times 10^3 \text{ A/cm}^2$ at 150°C , and the results are as shown in Fig. 6. The IMC layer tended to be decreased at 166 h of current stressing although the IMC layer thickness of Cu_5Zn_8 was increased at the anode side until after 72 h of current stressing depending on the aging time. The tendency to decrease after 166 h shows the opposite

Fig. 5 Growth and component behavior of IMC in the interface between Sn-Zn solder and Cu substrate: (a) component behavior³¹⁾, (b) effects of Ag content and aging temperature³²⁾

Fig. 6 SEM images of IMCs at the anode (left column) and the cathode (right column) for a current density of 3.87×10^3 A/cm² and 150 °C: (a,b) 0 h, (c,d) 36 h, (e,f) 72 h, and (g,h) 166 h³³⁾

result from the general thermal effect although the increase in the thickness of the IMC layer is induced with the aging time. Moreover, the thickness of the IMC layer was increased until after 72 h of current stressing on the cathode side similar to the anode and the IMC thickness was increased sharply to about 5.4 μm after 166 h (Fig. 6h). The thickness of the IMC layer on the anode side was reduced to about 3.2 μm (Fig. 6g). The formation of the thicker IMC layer on the cathode side is generally the opposite of the “polarity effect” and it has been reported that such a case of reverse polarity is often observed^{34,35)}. Zn affects IMC formation in Sn-Zn system. Sn atoms move to the anode due to electron wind force when current is stressed. On the contrary, it is determined that reverse polarity is observed since the back stress acts and the Zn atoms move toward the cathode.

Fig. 6 SEM images of IMCs at the anode (left column) and the cathode (right column) for a current density of 3.87×10^3 A/cm² and 150 °C: (a,b) 0 h, (c,d) 36 h, (e,f) 72 h, and (g,h) 166 h³³⁾.

Huang³⁶⁾ observed the change in the thickness of the IMC layer due to liquid-solid electromigration (L-S EM) according to the current stressing time at 250 °C with a current density of 1.2×10^4 A/cm² through in-situ images and the results are as shown in Fig. 7. First, air bubbles were slightly formed at the solder interface and the solder began to melt before the current is stressed (0 min) (Fig. 7a), and continuous IMC layers were formed at each interface of anode and cathode after 5 min of L-S EM (Fig. 7b). After 8 min, the IMC layer of the anode marked with a white dotted line was dissolved or Cu was consumed although IMC was grown at the cathode-side interface that is marked with a yellow circle. In addition, the IMC layer that is formed at the anode side interface was extremely thin although the IMC layer that is formed on the cathode side grew thicker up to the Sn-9Zn solder as the L-S EM time increased. These results show that the dissolution of Cu on the anode side is accelerated although the growth of the IMC layer is induced due to the limited consumption of Cu on the cathode side.

Kuo³⁷⁾ observed the IMC behavior that is formed at

Fig. 7 In situ observation of L-S EM of the Cu/Sn-9Zn/Cu interconnect under a current density of 1.2×10^4 A/cm² at 250 °C for (a) 0 min, (b) 5 min, (c) 8 min, (d) 9 min, (e) 10 min, (f) 12 min, (g) 13 min, (h) 15 min, and (i) 20 min, respectively³⁶⁾

Fig. 8 TEM images for anode area of Sn-Zn solder/Cu interface after current stressing at 1.0×10^3 A/cm²: (a) 100 h, (b) mechanism at 100 h, (c) 185 h, and (d) mechanism at 185 h³⁷⁾

the Sn-9Zn solder and Cu interface on the anode side through the TEM image of the specimen that is prepared with focused ion beam (FIB) after 100 and 185 h of stressing current at 130 °C with a current density of 1.0×10^3 A/cm² as shown in Fig. 8. Huang³⁶⁾ mechanically explained the accelerated dissolution and consumption of Cu on the anode side as shown in Fig. 8. The behavior and mechanism of IMC formation at the solder/Cu interface on the anode side with 100 h of current stressing are as shown in Figs 8a and 8b. A layered Cu₅Zn₈ IMC in the longitudinal direction was formed at the solder/Cu interface on the anode side and the IMC of Cu₆Sn₅ was observed at the Cu₅Zn₈ IMC/Cu interface (Fig. 8a). The Sn atoms move rapidly through the γ -Cu₅Zn₈ crystal grain boundary due to EM since the grain boundary of γ -Cu₅Zn₈ phase in the longitudinal direction is almost parallel to the movement direction of the electrons when a current is stressed. Therefore, IMC of Cu₆Sn₅ is formed through the accumulation of Sn and the interaction of Cu at the Cu₅Zn₈ IMC/Cu interface on the anode side (Fig. 8b). The consumption of Cu on the anode side is relatively severe due to the growth of the Cu₆Sn₅ IMC layer after 185 h of current stressing (Fig. 8c). Since the diffusion of Cu in Sn is more dominant than the diffusion of Sn in Cu, it is formed in the Cu layer on the anode side after forming Cu₆Sn₅ IMC at the Cu₅Zn₈ IMC/Cu interface as Sn moves to the Cu layer on the anode side through EM, thereby explaining the consumption of Cu (Fig. 8d).

3.2.2 Characteristics of Sn-Cu solder joints

The microstructure of Sn-0.7Cu alloy is composed of β -Sn and Cu₆Sn₅/ β -Sn eutectic composition, and the microstructure of this alloy is as shown in Fig. 9³⁸⁾. Hung³⁹⁾ observed the microstructure change in Sn-xCu according to the Cu content, and the β -Sn phase tended to become finer although the IMC of Cu₆Sn₅ was increased as the Cu content was increased. An appropriate addition is required since the melting point of the solder is also increased significantly depending on the Cu content although a large amount of IMC that

Fig. 9 Microstructure of Sn-0.7Cu alloy³⁸⁾: (a) the shape of each phase, (b) magnified image of the interface between β -Sn and eutectic mixture

is evenly dispersed in the matrix serves as a strengthening mechanism. In addition, Yang⁴⁰⁾ and El-Daly⁴¹⁾ conducted studies to improve the electrical/thermal conductivity and solder joint properties of the solder joint by adding Al and Ag components to the Sn-0.7Cu alloy, and observed that the fraction of various IMCs increased and the β -Sn phase became finer.

Baek¹⁷⁾ observed the effects of EM and TM that are related to the formation and growth of IMC in the solder joint of Sn-0.7Cu. The specimens were prepared for accurate implementation of current straightness and temperature gradient, and were compared with the results of IMC growth modeling. The change in IMC thickness due to EM after 0-300 h of current stressing with a constant current of 6 A and a current density of 10 kA/cm² at 120 °C is as shown in Fig. 10a. The IMC layer that is formed at the Sn-0.7Cu/Cu interface is mainly composed of Cu₆Sn₅ and Cu₃Sn, and the IMC layer became thicker as the current stressing time is increased. In particular, the growth of IMC and void showed a close correlation with the electrical short since the void fraction at the interface between the IMC layer of Cu₆Sn₅ and the Sn-0.7Cu solder was increased simultaneously after 200 h of current stressing. The change in the thickness of the IMC layer due to TM after maintaining the temperature for 0-300 h under heating and cooling conditions of 55/150 °C is as shown in Fig. 10b. The IMC formed at the solder/Cu interface due to TM is composed of Cu₆Sn₅ and Cu₃Sn as shown in Fig. 10a, and the IMC layer tends to be slightly increased as the temperature holding time is

Fig. 10 SEM image of an IMC grown by (a) EM and (b) TM¹⁷⁾

Fig. 11 Schematic diagram of (a) solder joint and (b) IMC area measurement to calculate IMC thickness⁴²⁾

Fig. 12 IMC thickness for applying the various current densities⁴²⁾: (a) 1.3×10^4 A/cm², (b) 1.9×10^4 A/cm²

increased. However, it was observed that EM has a greater influence than TM on the thickness change in the IMC layer that is formed at the solder/Cu interface. Heo⁴²⁾ observed the IMC growth behavior according to the current density and stressing time at the solder joint that connects the Cu land of the Si wafer and the electroless nickel-immersion gold (ENIG) of the substrate, and the schematic diagram of the solder joint and the method of measuring the IMC thickness are as shown in Figs 11a and 11b, respectively. The change in IMC thickness growing at the interface of the solder joint after 0-300 h of current stressing at 150 °C with current densities of 1.3×10^4 A/cm² and 1.9×10^4 A/cm² are as shown in Figs. 12a and 12b, respectively. As a result of the experiment on the change in the thickness of IMC according to the current density and stressing time, Cu₃Sn and Cu₆Sn₅ IMC were grown as the current stressing time was increased and the growth rate of Cu₆Sn₅ IMC was faster than that of Cu₃Sn. In addition, the growth rate of IMC was observed to be about 2-3 times, which is higher than the current density increase rate of 1.5 times, as the current density was increased from 1.3×10^4 A/cm² to 1.9×10^4 A/cm². Therefore, it was found that the aging and TM effects due to Joule heating effect need to be considered in addition to EM in the phenomena related to the growth of IMC when the current density is increased⁴²⁾.

3.2.3 Characteristics of Sn-Ag solder joints

Sn-3.5wt%Ag eutectic alloy is composed of almost pure β-Sn and ε-Ag₃Sn phase microstructure. The needle-

like Ag₃Sn grows along the solidification direction in Sn-matrix according to the two-stage (CR1-CR2) cooling, and nucleation is promoted if the cooling rate is increased during soldering (P1), which hinders the growth of Ag₃Sn and shows a finely dispersed structure as shown in Fig. 13⁴³⁾. It has the greatest mechanical strength in the eutectic composition of 3.5wt%Ag with the dispersion strengthening effect due to the characteristics of the finely dispersed ε-Ag₃Sn phase²⁵⁾. The IMC layer between the Sn-3.5Ag solder and the Cu substrate (Sn-3.5Ag/Cu) is mainly composed of Cu₃Sn and Cu₆Sn₅, and there is an Ag₃Sn phase dispersed in a fibrous form. The study results that are related to the effect of the Ag content and reflow temperature in the solder on the IMC behavior in Sn-Ag solder joints are as shown in Fig. 14. It has been reported that the average number of grains of Cu₆Sn₅ is increased as the concentration of Ag is increased and the grain width is decreased as the reflow temperature is decreased⁴⁴⁾.

Jung⁴⁵⁾ investigated the growth behavior of IMC and Kirkendall voids on the anode and cathode sides according to the current stressing time of the Cu/Sn-3.5Ag/Cu junction. The IMC growth behavior of the Sn-3.5Ag/Cu solder interface with time variation of 0-200 h

Table 2 Primary and secondary cooling rates at measurement position P1-P4 in continuous cooling experiment⁴³⁾

Position	P1	P2	P3	P4
CR1 (°C/s)	263.6	116	43.9	27.1
CR2 (°C/s)	113.6	42.1	30.8	21.6

Fig. 13 3D SEM morphologies of Ag₃Sn compounds at measurement positions P1-P4 in continuous cooling experiment⁴³⁾: (a) P1, (b) P2, (c) P3, and (d) P4

Fig. 14 Cross-sectional SEM images of air-cooled solder alloys to indicate Cu₆Sn₅ grains for various magnitudes of pre-cooled isothermal reflow temperature and Ag concentrations⁴⁴⁾

Fig. 15 Sn-3.5Ag/Cu solder joint aged at 150 °C without electricity flow for 0-400 h: (a) Cross-sectional SEM images, (b) thickening of IMC at the solder joint⁴⁵⁾

without current stressing at 150 °C is as shown in Fig. 15. The main IMCs, Cu₃Sn and Cu₆Sn₅ layers, were grown as the aging time was increased, and most of the Kirkendall voids were formed at the Cu₃Sn/Cu interface after 100 h of aging. The increase in aging time causes continuous nucleation and growth of voids, and voids completely cover the Cu₃Sn /Cu interface after 200 h. The position of the void formed at the Cu₃Sn /Cu interface is moved to the Cu₃Sn/Cu₆Sn₅ interface after 400 h. The reason is that Cu₃Sn is converted to Cu₆Sn₅ and new Cu₃Sn is formed at the Cu₆Sn₅/Cu interface.

The IMC growth behavior and Kirkendall void fraction of anode/cathode after 40-150 h of current stressing at

150 °C with a current density of 1×10^4 A/cm² are as shown in Fig. 16. It was found that EM had a polarity effect not only on the thickness of the IMC but also on the fraction of Kirkendall voids. The polarity effect of the IMC thickness is mainly caused by Cu₆Sn₅ since there is no significant difference in thickness of Cu₃Sn depending on the current stressing time, and the growth rate on the cathode side is reduced although the growth of IMC and void is accelerated on the anode side. The formation and growth behavior of Kirkendall voids according to the current stressing time on the anode side were almost similar to the case where there was no current stressing. However, the voids were formed at

Fig. 16 Cross-sectional SEM images of Sn-3.5Ag/Cu solder joint aged at 150 °C under the electric current density of 1×10^4 A/cm²: (a) the anode side, (b) the cathode side, (c) fraction of Kirkendall void after 40-150 h⁴⁵⁾

the Cu₃Sn /Cu interface on the cathode side, while Kirkendall voids accounted for most of the Cu₆Sn₅/Sn interface after 100 h, and the micro cracks were formed at 150 h since the Kirkendall void was saturated at the Cu₆Sn₅/Sn interface. It has been reported that the formation and growth of Kirkendall voids affect the lifespan of the solder joints³⁾.

3.2.4 Sn-Ag-Cu solder joint characteristics

Sn-3.5wt%Ag-0.7wt%Cu eutectic alloy generally has a microstructure similar to that of Sn-3.5Ag alloy. There is a crystalline phase of η -Cu₆Sn₅ in the eutectic phase of β -Sn and Sn/Ag₃Sn, and in the ϵ -Ag₃Sn phase, which are constituent structures, due to the addition of a trace amount of Cu as shown in Fig. 17⁴⁶⁾. Therefore, Sn-3.0Ag-0.5Cu alloy has been established as a representative alloy in order to prevent the formation of coarse Ag₃Sn phases in a composition with high Ag content.

The IMC layer between the Sn-3.0Ag-0.5Cu solder and the Cu substrate (SAC305/Cu) is mainly configured of Cu₃Sn and Cu₆Sn₅, and there is a eutectic phase of Sn/Ag₃Sn as shown in Fig. 18a⁴⁷⁾. SEM images and schematic diagrams of the microstructure changes at

Fig. 17 Microstructure of SAC305 joint: (a) microstructure at solder matrix, (b) EBSD image with inverse pole figure (IPF)⁴⁷⁾

the boundary of the IMC layer/matrix according to the cooling method (cooling rate) are as shown in Figs. 18b and 18c. The size and fraction of Ag₃Sn and Cu₆Sn₅ intermetallic compounds in the matrix are reduced due to the fast cooling rate, and the IMC (Cu₆Sn₅) layer in the SAC305/Cu boundary is also reported to be reduced⁴⁸⁾.

Kim⁴⁹⁾ investigated the effect of heat treatment according to the upper/lower part of the SAC305 solder joint and the behavior growth of IMC due to current stressing. Immediately after soldering, IMCs of (Cu,Ni)₆Sn₅ and Cu₆Sn₅/Cu₃Sn were formed at the joint interface in the ENIG surface finish of the upper joint and in the organic solderability preservative (OSP) surface finish of the lower joint, respectively (Fig. 19a). The IMC of

Fig. 18 Growth behavior of IMC in the interface between SAC305 solder and Cu substrate: (a) configuration of IMC layer⁴⁷⁾, (b) formation of microstructure by cooling methods⁴⁸⁾, and (c) schematic diagram of microstructure⁴⁸⁾

Fig. 19 SEM images of ENIG and OSP interfaces of cross-sectioned SAC305 solder⁴⁹⁾: (a) as-bonded, (b) annealing after 184 h at 130 °C, (c) electron downstream and (d) upstream at 5.0×10^3 A/cm² for 184 h

Cu_6Sn_5 and Cu_3Sn in OSP grew thicker than $(\text{Cu},\text{Ni})_6\text{Sn}_5$ in ENIG under the heat treatment condition of 130 °C for 184 h, (Fig. 19b) due to rapid diffusion of Cu in a high-temperature atmosphere and rapid growth of the IMC phase of Cu_6Sn_5 . IMC growth behavior according to the electron direction after 184 h of current stressing at a current density of 5.0×10^3 A/cm² at 130 °C is as shown in Figs. 19c and 19d. The thickness of the IMC tended to be increased as the current was stressed, and thick Cu_6Sn_5 was observed in OSP although thin $(\text{Cu},\text{Ni})_6\text{Sn}_5$ IMC layer was formed in ENIG regardless of the electron direction. In the case of downstream electron, the Cu_6Sn_5 IMC layer was formed thicker by about twice that of the case of upstream electrons. This is because IMC is generated due to diffusion of solder and Cu, and Cu in the solder is accumulated at the interface on the OSP side due to the electron direction in the case of downstream electrons. This IMC growth behavior is caused by the polarity effect due to EM⁵⁰⁾. It also changes the difference in the diffusion degree of the type of surface finish. In the case of the ENIG surface finish, the plated Ni layer acts as a diffusion barrier layer for Cu to suppress the diffusion of Cu. Therefore, IMC grew less than that of OSP surface finish in the case of ENIG surface finish.

There is a problem in general that the rapid formation of IMCs such as Cu_6Sn_5 and Cu_3Sn due to the rapid reactivity with the solder reduces the reliability of the junction in the junction between the Cu substrate and the SAC305⁴⁹⁾. Ni plating technology, which acts as a diffusion barrier layer, is being applied in order to improve this problem, and Electroless Nickel Immersion Gold (ENIG) and Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) plating layer are mainly

being used^{51,52)}. This surface finish affects the reliability of the package, and furthermore, it has a substantial correlation with the lifespan of the package. Therefore, ENIG and ENEPIG surface finishes are used as UBM (under bump metallization) materials in the fine pitch flip chip process recently due to their good wettability and electroless plating characteristics, and outstanding diffusion barrier characteristics.

3.3 Future trend of solder joint technology development

Since a bonding process such as soldering is performed on the PCB surface finish layer in the electronic packaging, the weldability and long-term reliability of the package itself are significantly affected by the surface finish characteristics. The surface finish method of the substrate rather than the type of solder has an important influence on EM since Sn is the main alloying element in various solder alloys. Although the representative surface finish methods include Cu OSP, hot air solder leveling (HASL), immersion tin, immersion silver, and ENIG and ENEPIG, the ENIG and ENEPIG surface finishes which are the electroless plating technologies, are mainly used rather than the surface finish in which the Cu substrate is directly exposed^{53,54)}. In particular, it has been reported that the ENEPIG surface finish layer is better than ENIG in metallurgical and mechanical reliability. The reason is that it suppresses the formation of IMC and Kirkendall voids of Ni_3Sn_4 and Ni_3P due to the Pd layer between the Au and Ni layers of the ENEPIG layer⁵⁵⁾. However, there is a problem that the gap between solders is decreased and the occurrence of defects due to the increased electrical resistance is increased in order to satisfy the accelerated fine pitch technology since the conventional

Fig. 20 Schematics of surface finishes: (a) normal- and (b) thin-ENEPIG

ENEPIG surface finish is thick with about 3-7 μm -thick Ni⁵⁶⁾. A thin surface finish technology with less than 1 μm -thick Ni is being developed (Fig. 20) and various studies are being conducted in order to solve these shortcomings^{56,57)}.

The thin ENEPIG surface finish has good applicability to fine pitch technology and can be applied not only to soldering but also to various bonding methods. In addition, it is expected to expand the scope of application for R&D as it has good thermal resistance and plating adhesion, and furthermore, reduces the process price⁵⁸⁾. Many research institutes are currently conducting studies on the properties of solder joints with ENEPIG surface finish of less than 1 μm applied, and commercialization is slow due to problems with reliability and lack of experience in the development field although advanced package manufacturers have entered the test stage for mass production applications.

In addition, the EM phenomenon at the Pb-free solder junction has the closest relationship with the nucleation and growth rates of IMC and void. The stress-migration induced by TM effect and stress, and the warpage phenomenon caused by the stacking of packages in addition to the EM phenomenon need to be considered since the TM effect of increasing the temperature due to Joule heating in the solder joint is increased remarkably as the current density is increased. It is determined that the reliability for the life of the package can be further improved by considering the above.

4. Conclusions

There are challenges that must be overcome technologically with the advent of the next-generation packaging era beyond the current packaging technology. Although the defects due to EM phenomenon among them, which have the greatest effect on solder joints, have been reported so far, they are recognized as the most practical problems due to changes in requirements resulting from miniaturization and high density of packages. In summary, the following problems and improvements are presented.

1) The studies on EM phenomena in various solder joints are being conducted as solder became Pb-free. It

is determined that the application of Pb-free solder has stronger resistance to EM phenomenon than Sn-Pb solder according to the previously reported research data⁶¹⁾. It is believed that the problem with the EM phenomenon can be solved once additional studies such as the nucleation and growth rate of IMC and void due to EM phenomenon in various Pb-free solder joints, EM rate prediction due to variables such as current density and stressing time, and the effect of Sn growth direction on EM phenomenon are conducted.

2) Various study equipment have been used to conduct these studies, and analyses that applied the latest equipment such as analysis of IMC behavior over time through in-situ images and identification of mechanisms for IMC behavior through TEM analysis have been conducted recently, and these analyses can improve the reliability of study results on solder joints.

3) A number of studies have been conducted on various joints so far, and although solder/ENEPIG is known to have the best bonding characteristics when applying ENEPIG surface treatment substrates, research to reduce the Ni layer of ENEPIG to less than 1 μm is being conducted to satisfy the accelerated micro-pitch technology. However, various research and development must be conducted since it is currently in the test phase for mass production application. Therefore, it is expected the development for solder joints will be intensively researched through the method of reducing the Ni layer of ENEPIG in the future.

4) In accordance with the era of the 4th industrial revolution, modeling studies and warpage studies that can predict the experimental results of the growth of IMC layers and Kirkendall voids due to EM and TM at the interface between ENEPIG and solder are essential.

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References

1. M. Kim, Y. Ko, J. Bang and C. Lee, The Chip Bonding Technology on Flexible Substrate by Using Micro

- Lead-free Solder Bump, *J. Microelectron. Packag. Soc.* 19(3) (2012) 15-20.
<http://dx.doi.org/10.6117/kmeps.2012.19.3.015>
2. Y. K. Ko, Y. H. Ko and C. W. Lee, Micro-bump Joining Technology for 3 Dimensional Chip Stacking, *J. Korean Soc. Precis. Eng.* 31(10) (2014) 865-871.
<http://dx.doi.org/10.7736/KSPE.2014.31.10.865>
 3. G. Kim, K. Son, G. T. Park, Y. B. Park, Effect of Current Densities on the Electromigration Failure Mechanisms of Flip-Chip Sn-Ag Solder Bump, *Korean J. Met. Mater.* 55(11) (2017) 798-805.
<https://doi.org/10.3365/KJMM.2017.55.11.798>
 4. J. M. Park, S. H. Kim, M. H. Jeong and Y. B. Park, Effect of Cu-Sn intermetallic compound reactions on the Kirkendall void growth characteristics in Cu/Sn/Cu microbumps, *Jpn. J. Appl. Phys.* 53 (2014) 1-4.
 5. G. Ross, V. Vuorinen and M. P-Krokel, Void formation and its impact on Cu-Sn intermetallic compound formation, *J. Alloy. Compd.* 677 (2016) 127-138.
<https://doi.org/10.1016/j.jallcom.2016.03.193>
 6. J. H. Lee, N. H. Kang, C. W. Lee and J. H. Kim, Necessity of Low Melting Temperature Pb-free Solder Alloy and Characteristics of Representative Alloys, *J. Koran Weld. Join. Soc.* 24(2) (2006) 17-28.
 7. S. Jin, N. Kang, K. Cho, C. Lee and W. Hong, Behavior of Vibration Fracture for Sn-Ag-Cu-X Solders by Soldering, *J. Koran Weld. Join. Soc.* 30(2) (2012) 169-173.
<http://dx.doi.org/10.5781/KWJS.2012.30.2.169>
 8. C. Y. Kang, Research Trend in Development of Pb Free Solder, *J. Koran Weld. Join. Soc.* 13(4) (1995) 1-6.
 9. W. Yang, R. W. Messler and L.E. Felton, Microstructure Evolution of Eutectic Sn-Ag Solder Joints, *J. Electron. Mater.* 23 (1994) 765-772.
<https://doi.org/10.1007/BF02651371>
 10. Y. Wang, K. H. Lu, V. Gupta, L. Stiborek, D. Shirley, S. H. Chae, J. Im and P. S. Ho, Effects of Sn grain structure on the electromigration of Sn-Ag solder joints, *J. Mater. Res.* 27(8) (2012) 1131-1141.
<https://doi.org/10.1557/jmr.2012.10>
 11. S. H. Kim, B. R. Lee, G. T. Park, J. M. Kim, S. H. Yoo and Y. B. Park, Effects of PCB surface finishes on the Mechanical and Electrical Reliabilities of Sn-0.7Cu Pb-free Solder Bump, *J. Microelectron. Packag. Soc.* 53(10) (2015) 735-744.
<https://doi.org/10.6117/kmeps.2012.19.4.057>
 12. Y. Kim, J. Kwon, D. Yoo, S. Park, D. Lee and D. Lee, Influence of Nickel Thickness and Annealing Time on the Mechanical Properties of Intermetallic Compounds Formed between Cu-Sn Solder and Substrate, *Korean J. Met. Mater.* 55(3) (2017) 165-172.
<https://doi.org/10.3365/KJMM.2017.55.3.165>
 13. S. K. Lim, Physical Design for 3D System on Package, *IEEE Design and Test of Computers.* 22(6) (2005) 532-539.
<https://doi.org/10.1109/MDT.2005.149>
 14. M. Dong, F. Santagata, R. Sokolovskij, J. Wei, C. Yuan and G. Zhang, 3D system-in-package design using stacked silicon submount technology, *Microelectron. Int.* 32(2) (2015) 63-72.
<https://doi.org/10.1108/MI.11.2014.0050>
 15. J. H. Lan, Evolution and Outlook of TSV and 3D IC/Si Integration, *2010 12th Electronics Packaging Technology Conference*, Singapore (2010)
<https://doi.org/10.1109/EPTC.2010.5702702>
 16. B. H. L. Chao, X. Zhang, S. H. Chae, P. S. Ho, Recent advances on kinetic analysis of electromigration enhanced intermetallic growth and damage formation in Pb-free solder joints, *Microelectron. Reliab.* 49(3) (2009) 253-263.
<https://doi.org/10.1016/j.microrel.2009.01.006>
 17. S. Baek, Y. Park, C. Oh, E. Chun and N. Kang, Modeling and Experimental Verification of Intermetallic Compounds Grown by Electromigration and Thermomigration for Sn-0.7Cu Solders, *J. Electron. Mater.* 48(1) (2019) 142-151.
<https://doi.org/10.1007/s11664-018-6786-4>
 18. S. Li, X. Wang, Z. Liu, Y. Jin, S. Zhang, J. Geng, X. Chen, S. Wu, P. He and W. Long, Corrosion behavior of Sn based lead free solder alloys: a review, *J. Mater. Sci.* 31 (2020) 9076-9090.
<https://doi.org/10.1007/s10854-020-03540-2>
 19. P. Zhang, S. Xue, J. Wang, P. Xue, S. Zhong and W. Long, Effect of Nanoparticles Addition on the Microstructure and Properties of Lead-Free Solders: A Review, *Appl. Sci.* 9(10) (2019) 1-20.
<https://doi.org/10.3390/app9102044>
 20. J. Lee, K. Kim and S. Huh, Development of Sn-Zn Based Low Temperature Lead-Free Solder for Improvement of Oxidation Resistance, *J. Korean Weld. Join. Soc.* 29(5) (2011) 514-521.
<http://dx.doi.org/10.5781/KWJS.2011.29.5.514>
 21. J. Lee, K. Kim, M. Inoue, J. Jiang and K. Suganuma, Effects of Ag and Cu addition on microstructural properties and oxidation resistance of Sn-Zn eutectic alloy, *J. Alloy. Compd.* 454 (2008) 310-320.
<https://doi.org/10.1016/j.jallcom.2006.12.037>
 22. R. Darveaux and K. Banerji, Constitutive Relations for Tin-Based-Solder Joints, *IEEE Trans. Compon. Hybrids. Manuf. Technol.* 15(6) (1992) 1013-1024.
<https://doi.org/10.1109/33.206925>
 23. I. Artaki, A. M. Jackson and P. T. Vianco, Evaluation of Lead-Free Solder Joints in Electronic Assemblies, *J. Electron. Mater.* 23(8) (1994) 757-764.
<https://doi.org/10.1007/BF02651370>
 24. J. Y. Park, J. P. Jung and C. S. Kang, The Analysis of the Withdrawal Force Curve of the Wetting Balance Curve, *IEEE Trans. Compon. Hybrids. Manuf. Technol.* 22(3) (1999) 372-377.
<https://doi.org/10.1109/6144.796538>

25. M. Kim, K. Shin and J. Jung, Research Trends of Sn-Ag Based Pb-Free Solders, *J. Weld. Join.* 19(1) (2001) 15-20.
26. P. T. Vianco and J. A. Rejent, Properties of Ternary Sn-Ag-Bi Solder Alloys: Part II—Wettability and Mechanical Properties Analyses, *J. Electron. Mater.* 28(10) (1999) 1138-1143.
<https://doi.org/10.1007/s11664-999-0251-3>
27. J. Lee, H. Kim, Y. Lee and Y. Choi, Interfacial Properties with Kind of Surface Finish and Sn-Ag Based Lead-free Solder, *J. Korean Weld. Join. Soc.* 27(1) (2009) 20-24.
<https://doi.org/10.5781/KWJS.2009.27.1.020>
28. K. Lee, K. Kim and K. Suganuma, Electro-migration Phenomenon in Flip-chip Packages, *J. Microelectron. Packag. Soc.* 17(4) (2010) 11-17.
29. R. A. Islam, B. Y. Wu, M. O. Alam, Y. C. Chan and W. Jillek, Investigations on microhardness of Sn-Zn based lead-free solder alloys as replacement of Sn-Pb solder, *J. Alloy. Compd.* 392 (2005) 149-158.
<https://doi.org/10.1016/j.jallcom.2004.08.079>
30. M. Date, T. Shoji, M. Fujiyoshi, K. Sato and K. N. Tu, Ductile-to-brittle transition in Sn-Zn solder joints measured by impact test, *Scr. Mater.* 51 (2004) 641-645.
<https://doi.org/10.1016/j.scriptamat.2004.06.027>
31. P. Xue, S. Xue, Y. Shen and H. Zhu, Interfacial microstructures and mechanical properties of Sn-9Zn-0.5Ga-xNd on Cu substrate with aging treatment, *Mater. Des.* 60 (2014) 1-6.
<http://dx.doi.org/10.1016/j.matdes.2014.03.052>
32. R. S. Lai, K. L. Lin and B. Salam, Suppressing Growth of the Cu₅Zn₈ Intermetallic Layer in Sn-Zn-Ag-Al-Ga/Cu Solder Joints, *J. Electron. Mater.* 38(1) (2009) 88-92.
<https://doi.org/10.1007/s11664-008-0579-0>
33. X. F. Zhang and J. D. Guo, Reverse polarity effect from effective charge disparity during electromigration in eutectic Sn-Zn solder interconnect, *J. Mater. Res.* 23(12) (2008) 3370-3378.
<https://doi.org/10.1557/JMR.2008.0413>
34. M. L. Huang, Q. Zhou, N. Zhao, X. Y. Lin and Z. J. Zhang, Reverse polarity effect and cross-solder interaction in Cu/Sn-9Zn/Ni interconnect during liquid-solid electromigration, *J. Mater. Sci.* 49 (2014) 1755-1763.
<https://doi.org/10.1007/s10853-013-7862-z>
35. M. Huang, Z. Zhang, N. Zhao and X. Feng, Reverse Polarity Effect in Cu/Sn-9Zn/Ni Interconnect under High Current Density at High Temperature, *2014 15th International Conference on Electronic Packaging Technology*, Chengdu China (2014)
<https://doi.org/10.1109/ICEPT.2014.6922690>
36. M. L. Huang, Z. J. Zhang, N. Zhao and Q. Zhou, A synchrotron radiation real-time in situ imaging study on the reverse polarity effect in Cu/Sn-9Zn/Cu interconnect during liquid-solid electromigration, *Scr. Mater.* 68 (2013) 853-856.
<http://dx.doi.org/10.1016/j.scriptamat.2013.02.007>
37. S. Kuo and K. Lin, Polarity effect of electromigration on intermetallic compound formation in a Cu/Sn-9Zn/Cu sandwich, *J. Mater. Res.* 23(4) (2008) 1087-1094.
<https://doi.org/10.1557/jmr.2008.0142>
38. M. Zhao, L. Zhang, Z. Lin, M. Xiong and L. Sun, Structure and properties of Sn-Cu lead-free solders in electronics packaging, *Sci. Technol. Adv. Mater.* 29 (2019) 421-444.
<https://doi.org/10.1080/14686996.2019.1591168>
39. F. Hung, T. Lui, L. Chen and N. He, Resonant characteristics of the microelectronic Sn-Cu solder, *J. Alloy Compd.* 457 (2008) 171-176.
<https://doi.org/10.1016/j.jallcom.2007.03.026>
40. L. Yang, Y. Zhang, J. Dai, Y. Jing, J. Ge and N. Zhang, Microstructure, interfacial IMC and mechanical properties of Sn-0.7Cu-xAl ($x = 0-0.075$) lead-free solder alloy, *Mater. Des.* 67 (2015) 209-216.
<http://dx.doi.org/10.1016/j.matdes.2014.11.036>
41. A. A. El-Daly and A. E. Hammad, Enhancement of creep resistance and thermal behavior of eutectic Sn-Cu lead-free solder alloy by Ag and In-additions, *Mater. Des.* 40 (2012) 292-298.
<http://dx.doi.org/10.1016/j.matdes.2012.04.007>
42. M. Heo, N. Kang, S. Park, J. Kim and W. S. Hong, Kinetics of Intermetallic Compounds Growth Induced by Electromigration of Sn-0.7Cu Solder, *Korean J. Met. Mater.* 54(12) (2016) 908-915.
<https://doi.org/10.3365/KJMM.2016.54.12.908>
43. H. Lee, Y. Chen, Evolution of Ag₃Sn intermetallic compounds during solidification of eutectic Sn-3.5Ag solder, *J. Alloy. Compd.* 509 (2011) 2510-2517.
<https://doi.org/10.1016/j.jallcom.2010.11.068>
44. B. Guo, A. Kunwar, N. Zhao, J. Chen, Y. Wang, H. Ma, Effect of Ag₃Sn nanoparticles and temperature on Cu₆Sn₅ IMC growth in Sn_xAg/Cu solder joints, *Mater. Res. Bull.* 99 (2018) 239-248.
<https://doi.org/10.1016/j.materresbull.2017.11.022>
45. Y. Jung and J. Yu, Electromigration induced Kirkendall void growth in Sn-3.5Ag/Cu solder joints, *J. Appl. Phys.* 115 (2014) 083708:1-9.
<https://doi.org/10.1063/1.4867115>
46. Y. Park, J. Bang, C. M. Oh, W. S. Hong and N. Kang, The Effect of Eutectic Structure on the Creep Properties of Sn-3.0Ag-0.5Cu and Sn-8.0Sb-3.0Ag Solders, *Met.* 7(12) (2017) 540:1-12.
<https://doi.org/10.3390/met7120540>
47. A. T. Tan, A. W. Tan and F. Yusof, Evolution of microstructure and mechanical properties of Cu/SAC305/Cu solder joints under the influence of low ultrasonic power, *J. Alloy. Compd.* 705 (2017) 188-197.
<http://dx.doi.org/10.1016/j.jallcom.2017.02.165>
48. M. Z. Yahaya, N. A. Salleh, S. Kheawhom, B. Illes, M. F. M. Nazeri and A. A. Mohamad, Selective etching and hardness properties of quenched SAC305 solder

- joints, *Solder. Surf. Mount Technol.* 32(4) (2020) 225-233.
<https://doi.org/10.1108/SSMT-01-2020-0001>
49. S. Kim, G. Park, B. Lee, J. Kim, S. Yoo and Y. Park, Effects of PCB Surface Finishes on in-situ Intermetallics Growth and Electromigration Characteristics of Sn-3.0Ag-0.5Cu Pb-free Solder Joints, *J. Microelectron. Packag. Soc.* 22(2) (2015) 47-53.
<http://dx.doi.org/10.6117/kmeps.2015.22.2.047>
50. J. Choi, S. Jun, H. Won, B. Jung and T. Oh, Electromigration Behavior of Flip-Chip Bonded Sn-3.5Ag-0.5Cu Solder Bumps, *J. Microelectron. Packag. Soc.* 11(4) (2004) 43-48.
51. K. Kim, W. Seo, S. Kwon, J. Kim, J. Yoon and S. Yoo, Effects of Ni-P Bath on the Brittle Fracture of Sn-Ag-Cu Solder/ENEPIG Solder Joint, *J. Weld. Join.* 35(3) (2017) 1-6.
<https://doi.org/10.5781/JWJ.2017.35.3.1>
52. S. Huh, J. Lee and S. Ham, Reliability of Sn-Ag-Cu Solder Joint on ENEPIG Surface Finish: 1. Effects of thickness and roughness of electroless Ni-P deposit, *J. Microelectron. Packag. Soc.* 21(3) (2014) 43-50.
<http://dx.doi.org/10.6117/kmeps.2014.21.3.043>
53. J. Yoon, B. Noh and S. Jung, Comparative Study of ENIG and ENEPIG as Surface Finishes for a Sn-Ag-Cu Solder Joint, *J. Electron. Mater.* 40(9) (2011) 1950-1955.
<https://doi.org/10.1007/s11664-011-1686-x>
54. J. Yoon, J. Bang, C. Lee and S. Jung, Interfacial reaction and intermetallic compound formation of Sn-1Ag/ENIG and Sn-1Ag/ENEPIG solder joints, *J. Alloy. Compd.* 627 (2015) 276-280.
<http://dx.doi.org/10.1016/j.jallcom.2014.11.208>
55. C. Ho and J. Duh, Quantifying the dependence of Ni(P) thickness in ultrathin-ENEPIG metallization on the growth of Cu-Sn intermetallic compounds in soldering reaction, *Mater. Chem. Phys.* 148 (2014) 21-27.
<http://dx.doi.org/10.1016/j.matchemphys.2014.06.072>
56. J. Back, S. Yoo, D. Han, S. Jung and J. Yoon, Interfacial Reactions and Mechanical Strength of Sn-3.0Ag-0.5Cu/0.1 μ m-Ni Thin ENEPIG Solder Joints, *J. Weld. Join.* 35(6) (2017) 51-58.
<https://doi.org/10.5781/JWJ.2017.35.6.8>
57. J. Kim, S. Jung and J. Yoon, Effect of Ni(P) thickness in Au/Pd/Ni(P) surface finish on the electrical reliability of Sn-3.0Ag-0.5Cu solder joints during current-stressing, *J. Alloy. Compd.* 850 (2021) 156729: 1-11.
<https://doi.org/10.1016/j.jallcom.2020.156729>
58. J. Back, B. Lee, S. Yoo, D. Han, S. Jung and J. Yoon, Solderability of thin ENEPIG plating Layer for Fine Pitch Package application, *J. Microelectron. Packag. Soc.* 24(1) (2017) 83-90.
<https://doi.org/10.6117/kmeps.2017.24.1.083>

Electromigration에 의한 다양한 솔더 접합부에서의 금속간 화합물 성장거동

Growth Behavior of Intermetallic Compounds in Various Solder Joints Induced by Electromigration

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1. 서 론

최근 전자산업은 스마트폰, 3D TV 및 컴퓨터 등과 같은 주요 제품의 소형화 및 고성능화에 대한 요구가 증대하고, 이러한 요구를 만족시키기 위하여 칩과 메인 보드를 연결시켜주는 PCB(Printed Circuit Board) 기판 내 많은 소자 및 단자를 실장하기 위한 미세피치 구현기술이 지속적으로 개발되고 있다^{1,2)}. 미세피치 기술개발과 함께 칩과 기판을 연결시켜주는 솔더범프가 미세화 되면서 이에 인가되는 전류밀도가 급격히 증가되는 문제가 발생되었다. 이러한 전류밀도 및 joule heating에 의한 온도 증가로 솔더범프에 electromigration (EM) 및 thermo-migration(TM)에 의한 2차상의 생성 및 성장이 발생하며, 이 현상이 패키지에서 전기적 단선 및 전기저항이 급격히 증가되어 단선(Open-Circuit Failure)되는 심각한 문제까지 야기된다³⁾. 발생한 문제점의 주원인인 솔더와 기판 사이에 형성되는 금속간 화합물 (Intermetallic Compound, IMC)과 Kirkendall voids의 형성 및 성장은 electromigration (EM)에 의하여 가속화된다고 알려져 있다^{4,5)}.

Pb-Sn계 합금은 전자기기의 솔더범프에 주로 적용되던 합금으로 2006년까지 활발히 사용되어져 왔다. 하지만 납중독 문제가 대두되면서 무연(Pb-free) 솔더에 대한 연구가 지속적으로 진행되어 다양한 합금의 솔더가 개발되어 있다⁶⁻⁸⁾. 현재까지는 Sn-Ag계 합금 솔더 범프에서의 금속간 화합물 및 Kirkendall void 성장거동과 관련된 연구가 주로 이루어져 왔으나^{9,10)}, 최근에는 Sn-Cu계 합금의 솔더범프 접합부에서의 EM 효과에 대한 연구도 진행되었다^{11,12)}.

Fig. 1은 Package on Package (PoP) 및 3D System in Package (SiP) 기술 등이 적용되면서 초 소형화된

Fig. 1 Development trend of electronic packages¹⁵⁾

미세피치 기술에 의해 패키지 내에 실장되는 부품의 증가 및 소형화 추세를 나타낸다¹³⁻¹⁵⁾. 소형화에 따라 솔더범프에 인가되는 전류밀도는 급격히 증가하고 있기 때문에 결함 발생의 효율적인 방안을 위하여 패키지의 구조적 변화 및 솔더범프 재료의 변화가 이루어져야 할 것으로 판단된다. 따라서, 본 논문에서는 다양한 재료의 솔더범프 접합부에서 EM 효과에 따른 접합부 IMC 및 voids 변화를 정리하고, EM에 따른 IMC의 변화를 예측하는 연구를 소개한다.

2. Electromigration 실험과 모델링 방법

EM에 의한 IMC의 성장은 금속 배선에 전류가 인가되었을 때 이동하는 전자가 금속 원자와 충돌하면서 생기는 운동량 교환에 의해서 전자의 이동 방향으로 금속 원자가 이동하게 되면서 발생하게 된다. 이 때 EM에 의한 금속원자 이동의 구동력으로는 전자풍력(electron wind force)과 정전기력(electrostatic force)이 있다. 전자풍력은 전기장에 의해 가속된 전자들이 금속원자와 충돌하여 금속원자에 운동량을 전달하면서 움직이게 하는 힘을 말하며, 정전기력은 가전자를 뚫고 이온으로 남아있는 원자에 작용하는 힘을 말한다. 따라서

EM에서의 유효 구동력은 아래 식 (1)과 같다¹⁶⁾.

$$J = \frac{CD}{kT} Z^* e p j \quad (1)$$

J는 EM flux, C는 농도(concentration), D는 확산계수(diffusivity), Z^* 는 유효전하수(effective charge number), k는 볼츠만 상수, T는 절대온도, e는 전하량, p는 비저항, j는 전류밀도이다.

또한 실제로 금속원자의 농도는 시간에 따라 변화한다. 시간에 따른 농도 변화는 Fick's second law에 의해 나타내어 진다¹⁶⁾.

$$\frac{\partial C}{\partial t} = - \frac{\partial J}{\partial x} \quad (2)$$

식 (1)과 (2)를 통해 금속 원자, 솔더, 그리고 형성되는 IMC에서의 EM flux를 계산하여 전류 인가 시간에 따라 성장하는 IMC의 두께를 예측할 수 있다. IMC의 성장은 Kirkendall voids의 형성 및 성장과 연관되어 있으므로, IMC의 성장 예측 모델링을 통해 voids로 인한 전기저항 증가와 전기적 단선을 간접적으로 예측한다. 예측한 IMC의 두께가 실제 전류 인가 시 동일한 결과가 나오는지 검증하기 위해서는 실험적 검증이 반드시 필요하다. Fig. 2a는 EM 실험을 위한 전류 인가 모식도를 나타내고, Fig. 2b는 TM 실험을 위한 온도 구배 적용 모식도를 나타낸다. Fig. 2에서 사용된 솔더합금은 Sn-0.7Cu이고, 전원공급장치로는 ITECH사의 DC source meter(IT6153)를 사용

하였다. Fig. 2a와 같이 EM 실험 세트를 구축한 후 전원공급장치를 통해 일정 시간동안 전류를 인가하여 IMC를 성장시킨다. 그 후 실제 측정된 IMC의 두께와 모델링을 통해 계산된 IMC의 두께를 비교하여 실험적으로 검증된 모델링 결과를 내었다.

3. 결과 및 고찰

3.1 무연 솔더 합금의 선택

무연솔더 합금 선정 시 고려사항으로 Sn-Pb계 솔더와 유사한 용점(melting point: $\sim 183^\circ\text{C}$)을 가지며, 양호한 전기적 및 기계적 특성을 가지는 친환경 무연솔더 합금의 적용이 요구된다. 현재 Sn-Pb계를 대체할 수 있는 Sn계 기반의 다양한 솔더가 시판 중이며, 가장 일반적인 무연솔더는 Sn-Ag-Cu, Sn-Ag, Sn-Cu, Sn-Zn, Sn-Bi계 등이 있다¹⁸⁾. 대부분의 무연솔더 합금은 Sn이 주성분으로 이루어지며, 미량의 Ag, Cu, Zn, In 그리고 Bi 등의 성분으로 이루어진다¹⁹⁾.

Sn-Zn계 공정조성의 솔더의 공정점은 199°C 로 용점이 종래의 Sn-Pb 솔더와 유사하여 기존의 프로세스를 그대로 적용할 수 있다는 장점을 가지며, 높은 강도와 크리프 특성 및 내열피로성이 우수하다. 하지만 산소와의 반응성(reactivity)이 빠르고 기판과의 젖음성(wettability)이 불량하므로 상용화에 제한적이다²⁰⁾. Sn-Zn 공정합금에 Bi를 소량 첨가시키면 젖음성의 향상은 가능하나 산화가 가속화되는 단점이 발생되므로 미량의 Ag와 Cu 첨가를 통하여 내산화성을 개선시킬 수 있다고 보고된다²¹⁾.

Sn-Cu계 솔더의 공정 조성은 Sn-0.7Cu이며, 공정점은 227°C 이다. Sn-0.7Cu 솔더는 Sn-Ag 합금에 비해 크립(creep)강도가 낮으므로 피로특성에 의하여 솔더의 변형이 일어나며, 전자패키지에서 칩과 기판 간의 열팽창 계수 차이에 의한 평탄도(warping) 불량에 따른 솔더의 변형이 크랙(crack) 저항성이 우수하다고 보고되어 있으므로 최근 연구 및 사용이 증가되고 있다²²⁾.

Sn-Ag계 솔더의 공정조성은 Sn-3.5Ag이며, 공정점은 221°C 이다. Sn-Ag 솔더의 적용온도 증가는 표면장력 및 접촉각을 감소시키는 경향이 있다. Sn-Ag 솔더의 표면장력이 Sn-Pb에 비해 높으며, 접촉각 또한 높은 결과를 보이므로²³⁾ Sn-Ag 솔더가 Sn-Pb 솔더에 비해 젖음 특성이 떨어진다고 보고된다²⁴⁾. 이러한 점을 보완하기 위하여 Sn-Ag에 미량의 Cu를 첨가하면 젖음 및 피로특성을 개선시킬 수 있으며, 미량의 Bi 첨가 시 젖음성이 개선되는 것으로 알려져 있다^{25,26)}.

현재 솔더링에서는 Sn-Ag-Cu계 솔더가 주로 적용

Fig. 2 Schematics diagram of (a) current stressing method for the EM experiments and (b) the TM experiments¹⁷⁾

되는데, Ag의 함유량이 증가되면 Ag_3Sn 상이 조대하게 생성되어 결합의 생성 및 전파 사이트가 될 수 있다. 그러므로 217 °C 용점의 Sn-3.0Ag-0.5Cu 솔더가 Sn-Pb계를 대체할 수 있는 대표적인 솔더로 자리 잡고 있다²⁷⁾.

3.2 솔더 접합부 내 EM 현상의 원인과 특성

일반적으로 솔더 접합부에 전류를 인가하면, 온도상승으로 인해 솔더 내의 금속원자가 전자의 이동방향을 따라 강한 흐름을 가지게 되며 이러한 원자의 흐름이 구동력이 되어 동일한 방향으로 원자의 이동이 활성화 되면서, anode 측의 IMC가 급속하게 성장된다. 이와 반대로 공공 주위의 원자는 상대적으로 확산속도가 감소하므로 cathode 측에 집적되어 void가 형성되고, 그 void의 성장 및 크랙(cracks) 생성으로 인한 단선 결합에 이른다. 이는 EM 현상으로 발생하는 문제점이며, EM 현상에 대한 개략도를 Fig. 3에 나타낸다²⁸⁾. 또한, 접합부 내의 joule heating 효과로 인하여 내부 온도가 100 °C 이상으로 상승되며, 솔더 접합부가 가지는 구조적 문제점으로 인하여 생성되는 전류과밀 현상 때문에 EM에 의한 열화 현상이 가속화된다. 그러므로 솔더 접합부의 수명에 대한 신뢰성은 예측하기 힘

Fig. 3 Schematic illustration of electromigration phenomena²⁸⁾

든 실정이며, 접합부 수명 향상을 위한 많은 연구가 진행 중이다. EM 현상이 각 솔더 접합부에 미치는 영향을 다른 연구들은 Table 1에 정리하였다. EM에 따른 솔더 재질별 접합부의 IMC 생성 거동은 다음 절부터 설명한다.

3.2.1 Sn-Zn계 솔더 접합부 특성

Fig. 4는 Sn-9Zn 합금의 미세조직을 나타낸다. Sn-9wt%Zn 공정조성의 as-cast 솔더는 금속간 화합물을 형성하지 않았고(Fig. 4a), 이 합금계의 미세조직은 침상(needle-like shape)의 α -Zn이 β -Sn 상의 기지 내에 미세하게 분산된 구조를 가진다^{29,30)}. 또한, Fig. 4b는 Sn-Zn 솔더에서 Zn-rich phase가 증가하면 Zn 원소가 산소와의 고반응성에 의해 ZnO가 생성되므로 내산화성을 크게 저하됨을 나타낸다¹⁹⁾. Sn-Zn 솔더의 접합특성을 향상시키기 위해서는 ZnO의 형성을 조절하는 방안이 필요하다.

Xue³¹⁾의 연구에서는 energy-dispersive spectroscopy (EDS) line/spot 분석을 통하여 IMC의 성장 및 성분 거동을 관찰하였고, Guo³²⁾는 Sn-Zn 솔더의 내산화성 향상을 위한 방안으로 Ag를 첨가하여 솔더/Cu 기판 계면의 IMC 거동을 분석하였다. Figs. 5a와 5b는 Sn-9Zn 솔더와 Cu 기판 (Sn-9Zn / Cu) 간의 IMC 층의 성분과 Ag 함유량 및 aging 시간 증가에 따른 IMC의 성장 거동을 각각 나타낸다. Sn-9Zn 솔더와 Cu 기판 간의 IMC 층은 주로 $CuZn_5$ 와 Cu_5Zn_8 으로 구성되며(Fig. 5a), EDS 선분석을 통하

Fig. 4 Microstructure of Sn-9Zn alloy²⁰⁾: (a) the shape of each phase, (b) the formation of ZnO

Table 1 Previous studies on EM for various solder joints

Solder	Surface-finished	IMC	EM properties
Sn-9Zn	Cu OSP	Cu_5Zn_8/Cu_6Sn_5	Anode : IMC decreased, Cathode : IMC increased (Reverse polarity) ^{33,36,37)}
Sn-0.7 Cu	Cu OSP	Cu_3Sn/Cu_6Sn_5	Anode : IMC increased, Cathode : IMC decreased (polarity) ¹⁷⁾
Sn-0.7 Cu	Cu OSP/ENIG	$Cu_3Sn/Cu_6Sn_5/(Ni,Cu)_6Sn_5$	Anode : IMC increased, Cathode : IMC decreased (polarity) ⁴²⁾
Sn-3.5Ag	Cu OSP	Cu_3Sn/Cu_6Sn_5	Anode : IMC increased, Cathode : IMC decreased (polarity) ⁴⁷⁾ Cathode : voids and cracks increased
Sn-3.0Ag-0.5Cu	Cu OSP/ENIG	$Cu_3Sn/Cu_6Sn_5/(Ni,Cu)_6Sn_5$	Anode : IMC increased, Cathode : IMC decreased (polarity) ⁴⁷⁾ Cu OSP : thick IMC formed, ENIG : thin IMC formed

여 IMC 층에서 Sn 성분은 감소하고 Zn 성분이 크게 증가하면서, 솔더 접합부의 신뢰성이 낮아질 가능성이 높아진다³¹⁾. 그러므로 Sn-9Zn의 내산화성을 향상시키기 위하여 Zn과의 반응성이 우수한 Ag를 첨가하여 ZnO의 생성을 억제하였다. Fig. 5b에서는 Sn-8.5Zn 솔더와 Cu 기판의 계면에서 형성되는 IMC 층은 Ag의 첨가로 인하여 AgZn_3 와 Cu_5Zn_8 로 구성되고, Ag의 첨가량이 증가될수록 Cu_5Zn_8 의 IMC 층이 감소하고 aging 시간이 증가될수록 IMC 층이 증가하는 경향을 보인다³²⁾.

Zhang³³⁾는 150 °C에서 $3.87 \times 10^3 \text{ A/cm}^2$ 의 전류 밀도로 시간(0, 36, 72 및 166 h)에 따른 anode와 cathode측의 IMC 두께 변화를 관찰하였으며, 그 결과를 Fig. 6에 나타낸다. Aging 시간에 따라 anode측에서는 72 h 전류인가 후까지 Cu_5Zn_8 의 IMC 층 두께가 증가되지만 166 h 전류 인가에서는 IMC 층이 감소되는 경향을 보였다. 이렇게 aging 시간에 따라

IMC 층의 두께 증가를 유발하지만 166 h 이후 감소 되는 경향은 일반적인 열적 효과와는 반대되는 결과를 보인다. 또한, cathode 측에서도 anode와 유사하게 72 h 전류인가 후까지 IMC 층의 두께가 증가되었고, 166 h 이후에는 IMC 두께가 약 $5.4 \mu\text{m}$ 로 급격하게 증가되었다 (Fig. 6h). 이때, anode측의 IMC 층 두께는 약 $3.2 \mu\text{m}$ 로 감소되었다 (Fig. 6g). Cathode측에서 발생된 더 두꺼운 IMC 층의 생성은 일반적으로 “극성 효과”와 반대되는 특성이며, 이러한 역극성 결과의 경우가 종종 발생된다고 보고되고 있다^{34,35)}. Sn-Zn계에서 IMC 형성에 영향을 주는 것은 Zn입니다. Sn 원자는 전류 인가 시 전자풍력에 의해서 anode로 이동합니다. 이와 반대로 back stress가 작용하여 Zn 원자는 cathode 쪽으로 이동하여 역극성 결과가 나타나는 것으로 판단된다.

Huang³⁶⁾은 in-situ 이미지를 통하여 250 °C에서 $1.2 \times 10^4 \text{ A/cm}^2$ 의 전류밀도로 전류인가 시간에 따

Fig. 5 Growth and component behavior of IMC in the interface between Sn-Zn solder and Cu substrate: (a) component behavior³¹⁾, (b) effects of Ag content and aging temperature³²⁾

Fig. 6 SEM images of IMCs at the anode (left column) and the cathode (right column) for a current density of $3.87 \times 10^3 \text{ A/cm}^2$ and 150 °C: (a,b) 0 h, (c,d) 36 h, (e,f) 72 h, and (g,h) 166 h³³⁾

라 liquid-solid electromigration (L-S EM)에 의한 IMC 층의 두께변화를 관찰하였으며, 그 결과를 Fig. 7에 나타낸다. 먼저 전류인가 전(0 min)에는 솔더 계면에 약간의 기포가 발생되어 솔더가 녹기 시작하였으며 (Fig. 7a), L-S EM이 5 min 진행된 이후, anode와 cathode의 각 계면에서 연속적인 IMC 층이 생성되었다 (Fig. 7b). 그리고 8 min 후에는 노란색 원으로 표시된 cathode 측 계면에서 IMC가 성장되었으나, 흰색 점선으로 표시된 anode의 IMC 층은 용해되거나 Cu가 소모되는 현상을 보인다. 또한, L-S EM 시간이 길어질수록 cathode 측에 생성된 IMC 층이 Sn-9Zn 솔더까지 두껍게 성장하지만, anode측 계면에 생성된 IMC 층은 매우 얇은 결과를 보였다. 이러한 결과는 cathode 측의 Cu의 소모는 제한되어 IMC 층의 성장을 유도하지만, anode측 Cu의 용해는 가속화되는 것을 보여준다.

Kuo³⁷⁾의 연구에서는 130 °C에서 1.0×10^3 A/cm²의 전류밀도로 100 및 185 h 동안 전류를 인가한 후, focused ion beam (FIB)로 준비된 시편의 TEM 이미지를 통하여 anode 측 Sn-9Zn솔더와 Cu 계면에 형성된 IMC 거동을 관찰한 결과를 Fig. 8에 나타낸다. Fig. 8의 결과는 Huang³⁶⁾ 연구에서 anode 측 Cu의 가속화된 용해 및 소모를 메커니즘적으로 설명하였다. Figs. 8a 및 8b은 100 h 동안 전류를 인가한 anode

측 솔더/Cu 계면의 IMC 형성 거동 및 메커니즘을 나타낸다. Anode 측 솔더/Cu 계면에서 길이방향의 층상 Cu₅Zn₈ IMC가 형성되었으며, Cu₅Zn₈ IMC/Cu 계면에서는 Cu₆Sn₅의 IMC가 관찰되었다(Fig. 8a). 전류가 인가되면 길이방향의 γ -Cu₅Zn₈ 상의 결정립계가 전자의 이동 방향에 거의 평행하기 때문에 EM에 의하여 Sn 원자가 γ -Cu₅Zn₈의 결정립계를 통하여 빠르게 이동하게 된다. 따라서 anode 측 Cu₅Zn₈ IMC/Cu 계면에서 Sn의 축적과 Cu의 상호작용을 통하여 Cu₆Sn₅의 IMC가 형성된다(Fig. 8b). 전류인가 185 h 이후에는 Cu₆Sn₅ IMC층의 성장으로 인해 anode 측 Cu의 상대적으로 심각한 소모되는 결과를 보인다(Fig. 8c). Sn 내 Cu의 확산이 Cu 내 Sn의 확산보다 더 지배적으로 이루어지기 때문에 EM을 통해 anode 측 Cu 층으로 Sn이 이동하면서 Cu₅Zn₈ IMC/Cu 계면에서 Cu₆Sn₅ IMC를 생성한 후에 anode 측 Cu층에 형성되어 Cu의 소모를 설명해 준다(Fig. 8d).

3.2.2 Sn-Cu계 솔더 접합부 특성

Sn-0.7Cu 합금의 미세조직은 β -Sn 및 Cu₆Sn₅/ β -Sn 공정조성으로 구성되며, 이 합금계의 미세조직은 Fig. 9에 나타낸³⁸⁾. Hung³⁹⁾의 연구는 Cu 함유량에 따른 Sn-xCu의 미세조직 변화를 관찰하였으며, Cu 함유량의 증가에 따라 Cu₆Sn₅의 IMC는 증가되나, β

Fig. 7 In situ observation of L-S EM of the Cu/Sn-9Zn/Cu interconnect under a current density of 1.2×10^4 A/cm² at 250 °C for (a) 0 min, (b) 5 min, (c) 8 min, (d) 9 min, (e) 10 min, (f) 12 min, (g) 13 min, (h) 15 min, and (i) 20 min, respectively³⁶⁾

Fig. 8 TEM images for anode area of Sn-Zn solder/Cu interface after current stressing at 1.0×10^3 A/cm²: (a) 100 h, (b) mechanism at 100 h, (c) 185 h, and (d) mechanism at 185 h³⁷⁾

Fig. 9 Microstructure of Sn-0.7Cu alloy³⁸⁾: (a) the shape of each phase, (b) magnified image of the interface between β -Sn and eutectic mixture

-Sn 상은 미세해지는 경향을 보였다. 기지에 고르게 분산된 다량의 IMC가 강화 메커니즘의 역할을 하나, Cu 함유량에 따라 솔더의 용융점 또한 크게 상승되므로 적절한 첨가가 필요하다. 또한 Yang⁴⁰⁾와 El-Daly⁴¹⁾는 Sn-0.7Cu 합금에 Al 및 Ag 성분을 첨가하여 솔더 접합부의 전기/열전도성 및 솔더 접합성을 향상을 위한 연구를 진행하였으며, 다양한 IMC의 분율이 증가하며, β -Sn 상은 미세해지는 결과를 보였다.

Baek¹⁷⁾의 연구에서는 Sn-0.7Cu의 솔더 접합부에서 IMC의 생성 및 성장과 관련 있는 EM과 TM의 영향을 관찰하였다. 전류의 직진성과 온도구배의 정확한 구현을 위하여 시편을 제작하였고, 이를 통하여 IMC 성장 모델링 결과와 비교하였다. Fig. 10a는 120 °C에서 6 A의 정전류 및 10 kA/cm²의 전류밀도로 0-300 h 동안 전류를 인가한 후 EM에 의한 IMC 두께 변화를 나타낸다. Sn-0.7Cu/Cu의 계면에서 생성된 IMC 층은 주로 Cu₆Sn₅ 및 Cu₃Sn으로 구성되며, 전류인가 시간이 길어질수록 IMC 층이 두꺼워지는 결과를 보였다. 특히, 전류인가 200 h 이후, Cu₆Sn₅의 IMC 층과 Sn-0.7Cu 솔더 간의 계면에 존재하는 void 분율은 동시에 증가하므로, IMC와 void의 성장은 단전 결함과 밀접한 상관관계를 보였다. Fig. 10b는 55/150 °C의 가열 및 냉각조건에서 0-300 h 동안 온도를 유지한 이후 TM에 의한 IMC 층의 두께 변화를 나타낸다. Fig. 10a와 동일하게 TM에 의해 솔더/Cu 계면에 생성된 IMC는 Cu₆Sn₅ 및 Cu₃Sn으로 구성되며, 온도 유지시간이 증가됨에 따라 IMC 층의 소

Fig. 11 Schematic diagram of (a) solder joint and (b) IMC area measurement to calculate IMC thickness⁴²⁾

폭 증가되는 경향을 보인다. 하지만 솔더/Cu 계면에 생성된 IMC 층의 두께 변화에 대하여 TM 보다는 EM의 영향력이 더 크다고 볼 수 있다.

Heo⁴²⁾의 연구에서는 Si 웨이퍼의 Cu 랜드와 기관의 도금층(electroless nickel-immersion gold, ENIG)을 연결시켜주는 솔더 접합부에서 전류밀도와 인가시간에 따른 IMC 성장거동을 관찰하였으며, 솔더 접합부의 개략도 및 IMC 두께 측정 방법을 Figs. 11a 및 11b에 각각 나타낸다. Figs. 12a와 12b는 150 °C에서 각각 1.3×10^4 A/cm²와 1.9×10^4 A/cm²의 전류밀도로 0-300 h 동안 전류를 인가한 후 솔더 접합부의 경계면에서 성장하는 IMC 두께 변화를 나타낸다. 전류밀도 및 인가 시간에 따른 IMC의 두께변화에 대한 실험 결과, 전류인가시간이 증가함에 따라 Cu₃Sn과 Cu₆Sn₅ IMC가 성장되었으며, Cu₃Sn보다 Cu₆Sn₅ IMC의 성장속도가 더 빠른 결과를 보였다. 또한 전류밀도가 1.3×10^4 A/cm²에서 1.9×10^4 A/cm²로 증가하면서, IMC의 성장은 전류밀도 증가율인 1.5배 보다

Fig. 12 IMC thickness for applying the various current densities⁴²⁾: (a) 1.3×10^4 A/cm², (b) 1.9×10^4 A/cm²

Fig. 10 SEM image of an IMC grown by (a) EM and (b) TM¹⁷⁾

높은 2-3 배 정도의 성장율이 확인되었다. 따라서, 전류밀도가 증가되면 IMC의 성장과 관련된 현상에서 EM 이외에도 Joule 열 효과에 의한 Aging 및 TM 효과 등을 고려할 필요가 있음을 밝혔다⁴²⁾.

3.2.3 Sn-Ag계 솔더 접합부의 특성

Sn-3.5wt%Ag 공정합금은 거의 순수한 β -Sn과 ϵ -Ag₃Sn 상의 미세조직으로 구성되어 있다. Fig. 13은 2단(CR1-CR2) 냉각에 따라 Sn 기지에 침상형태의 Ag₃Sn가 응고 방향을 따라 성장하고, 솔더링 중에 냉각 속도가 빠르게 되면 (P1) 핵생성이 촉진되어 Ag₃Sn의 성장이 방해되고 미세하게 분산된 조직을 나타낸다⁴³⁾. 미세하게 분산된 ϵ -Ag₃Sn 상의 특징으로 인한 분산강화효과로 기계적 강도가 공정조성인 3.5wt%Ag에서 가장 뛰어난 효과를 가진다²⁵⁾. Sn-3.5Ag 솔더와 Cu 기판 (Sn-3.5Ag/Cu) 간의 IMC 층은 주로 Cu₃Sn와 Cu₆Sn₅으로 구성되며, 섬유상 형태로 분산된 Ag₃Sn 상이 존재한다. Fig. 14는 Sn-Ag계 솔더 접합부에서 솔더 중 Ag의 함량 및 리플로 온도가 IMC 성장거동에

미치는 영향과 관련된 연구 결과를 나타낸다. Ag의 농도가 높을수록 Cu₆Sn₅의 평균 결정립 수가 증가하며, 리플로 온도가 낮을수록 결정립의 폭이 감소되는 경향을 보이는 것으로 알려져 있다⁴⁴⁾.

Jung⁴⁵⁾의 연구에서는 Cu/Sn-3.5Ag/Cu 접합부의 전류인가 시간에 따른 anode와 cathode측의 IMC 및 Kirkendall void 성장거동을 조사하였다. Fig. 15는 150 °C에서 전류인가 없이 0-200 h의 시간변화에 따른 Sn-3.5Ag/Cu 솔더 계면의 IMC 성장 거동을 나타낸다. Aging 시간의 증가에 따라 주된 IMC인 Cu₃Sn 및 Cu₆Sn₅ 층이 성장되며, aging 100 h 이후부터 대부분의 Kirkendall void가 Cu₃Sn/Cu의 계면에 생성되었다. Aging 시간의 증가는 void의 연속적인 핵생성 및 성장을 유발하며, 200 h 후에는 void가 Cu₃Sn/Cu 계면을 완전히 덮는 결과를 보인다. 400 h 후 Cu₃Sn/Cu 계면에 생성된 void의 위치가 Cu₃Sn/Cu₆Sn₅ 계면으로 이동한다. 그 원인은 Cu₃Sn이 Cu₆Sn₅로 변환되고, Cu₆Sn₅/Cu 계면에서 새로운 Cu₃Sn이 생성되었기 때문이다.

Fig. 16은 150 °C에서 1×10^4 A/cm²의 전류밀도로 40-150 h 동안 전류인가 후, anode/cathode의 IMC 성장거동 및 Kirkendall void 분율을 나타낸다. EM이 IMC의 두께뿐만 아니라 Kirkendall void의 분율에도 극성효과를 미치고 있음을 확인하였다. 전류인가 시간에 따라 Cu₃Sn의 두께는 큰 차이가 없으므로 IMC 두께의 극성효과는 주로 Cu₆Sn₅에 의해서 야

Table 2 Primary and secondary cooling rates at measurement position P1-P4 in continuous cooling experiment⁴³⁾

Position	P1	P2	P3	P4
CR1 (°C/s)	263.6	116	43.9	27.1
CR2 (°C/s)	113.6	42.1	30.8	21.6

Fig. 13 3D SEM morphologies of Ag₃Sn compounds at measurement positions P1-P4 in continuous cooling experiment⁴³⁾: (a) P1, (b) P2, (c) P3, and (d) P4

Fig. 14 Cross-sectional SEM images of air-cooled solder alloys to indicate Cu₆Sn₅ grains for various magnitudes of pre-cooled isothermal reflow temperature and Ag concentrations⁴⁴⁾

Fig. 15 Sn-3.5Ag/Cu solder joint aged at 150 °C without electricity flow for 0-400 h: (a) Cross-sectional SEM images, (b) thickening of IMC at the solder joint⁽⁴⁵⁾

Fig. 16 Cross-sectional SEM images of Sn-3.5Ag/Cu solder joint aged at 150 °C under the electric current density of 1×10^4 A/cm²: (a) the anode side, (b) the cathode side, (c) fraction of Kirkendall void after 40-150 h⁽⁴⁵⁾

기되며, anode 측에서는 IMC 및 void의 성장이 가속화되지만, cathode 측의 성장속도는 감소된 결과를 보였다. Anode 측의 전류인가 시간에 따른 Kirkendall void 생성 및 성장거동은 전류를 인가하지 않은 경우와 거의 유사하였다. 그러나 cathode 측에서는 Cu₃Sn/Cu의 계면에 void가 생성되며, 100 h 이후에는 Kirkendall void가 Cu₆Sn₅/Sn 계면의 대부분을 차지하며, 150 h에서는 Cu₆Sn₅/Sn 계면에서 Kirkendall void가 포화되어 미세 균열의 생성이 야기되는 결과를 보였다. 이러한 Kirkendall void의 생성 및 성장은 솔더 접합부의 손상거동에 대한 수명에 영향을 미치는 것으로 보고된다⁽³⁾.

3.2.4 Sn-Ag-Cu계 솔더 접합부 특성

Sn-3.5wt%Ag-0.7wt%Cu 공정합금은 일반적으로 Sn-3.5Ag 합금과 거의 유사한 미세조직을 가진다. Fig. 17은 미량의 Cu 첨가로 인하여 구성 조직인 β-Sn과 Sn/Ag₃Sn의 공정상 그리고 ε-Ag₃Sn상 중에 η-Cu₆Sn₅의 정출상이 존재하게 된다⁽⁴⁶⁾. 따라서 Ag 함량이 높은

Fig. 17 Microstructure of SAC305 joint: (a) microstructure at solder matrix, (b) EBSD image with inverse pole figure (IPF)⁽⁴⁷⁾

조성에서 생성되는 조대한 Ag₃Sn상의 형성을 방지하기 위하여 Sn-3.0Ag-0.5Cu 합금이 대표적인 합금으로 자리잡고 있다.

Fig. 18a는 Sn-3.0Ag-0.5Cu 솔더와 Cu 기판 (SAC-305/Cu) 간의 IMC 층은 주로 Cu₃Sn와 Cu₆Sn₅으로 구성되고, Sn/Ag₃Sn의 공정상이 존재함을 나타낸다⁽⁴⁷⁾. Figs. 18b와 18c는 냉각방법(냉각속도)에 따른 IMC 층/기지 조직 경계의 미세조직 변화를 SEM 이미지 및 모식도로 각각 표현한 것이다. 빠른 냉각속도에 의해서 기지의 Ag₃Sn과 Cu₆Sn₅ 금속간 화합물의 크기 및 분

Fig. 18 Growth behavior of IMC in the interface between SAC305 solder and Cu substrate: (a) configuration of IMC layer⁴⁷⁾, (b) formation of microstructure by cooling methods⁴⁸⁾, and (c) schematic diagram of microstructure⁴⁸⁾

Fig. 19 SEM images of ENIG and OSP interfaces of cross-sectioned SAC305 solder⁴⁹⁾: (a) as-bonded, (b) annealing after 184 h at 130 °C, (c) electron downstream and (d) upstream at 5.0×10^3 A/cm² for 184 h

율이 감소되며, SAC305/Cu 경계에 존재하는 IMC (Cu_6Sn_5) 층도 감소시키는 것으로 알려져 있다⁴⁸⁾.

Kim⁴⁹⁾은 SAC305 솔더 접합부의 상/하부에 따른 열처리의 영향 및 전류인가에 의한 IMC 성장 거동을 조사하였다. 솔더 접합 직후에 상부 접합부의 ENIG 표면처리에서는 $(\text{Cu},\text{Ni})_6\text{Sn}_5$, 하부 접합부의 organic solderability preservative (OSP) 표면 처리에서는 Cu_6Sn_5 , Cu_3Sn 의 IMC가 접합면에 생성되었다(Fig. 19a). 130 °C 에서 184 h 동안의 열처리 조건 하에서는 OSP에서의 Cu_6Sn_5 , Cu_3Sn 의 IMC가 ENIG에서의 $(\text{Cu},\text{Ni})_6\text{Sn}_5$ 보다 더 두껍게 성장하였으며(Fig. 19b), 그 원인은 고온 분위기에서 Cu의 확산이 급속하게 이루어져 Cu_6Sn_5 의 IMC 상이 빠르게 성장된 결과이다. Figs. 19c 및 19d는 130 °C 에서 5.0×10^3 A/cm²의 전류밀도로 184 h 동안 전류 인가 후, 전자 방향에 따른 IMC 성장거동을 나타내었다. 전류가 인가됨에 따라 IMC의 두께가 증가하는 경향을 보였으며, 전자방향과 상관없이 ENIG에서의 $(\text{Cu},\text{Ni})_6\text{Sn}_5$ IMC 층은 얇게 형성되었으나, OSP에서의 두꺼운 Cu_6Sn_5 를 관찰된

다. 전자가 아래로 흐를 경우, 위로 흐르는 경우의 보다 2배 정도 Cu_6Sn_5 IMC 층이 더 두껍게 형성되었다. 이는 전자가 아래로 흐르는 경우, 솔더와 Cu의 확산에 의한 IMC 생성 및 솔더 내부에 존재하는 Cu가 전자방향에 의해서 OSP 쪽 계면에 쌓이게 된다. 이러한 IMC 성장거동의 원인은 EM현상에 의한 극성효과(polarity effect) 때문이다⁵⁰⁾. 또한 표면처리의 종류가 확산되는 정도의 차이를 변화시킨다. ENIG 표면처리의 경우 도금된 Ni층이 Cu의 확산 방지층 역할을 하여 Cu의 확산을 억제시킨다. 따라서, ENIG 표면처리의 경우 OSP 표면처리에 비해서 IMC가 덜 성장하였다.

일반적으로 Cu 기판과 SAC305의 접합부에서는 솔더와의 빠른 반응성으로 인한 Cu_6Sn_5 및 Cu_3Sn 과 같은 IMC의 빠른 생성이 접합부 신뢰성을 저하시키는 문제가 있다⁴⁹⁾. 이 문제를 개선하기 위하여 확산방지층 역할을 하는 Ni 도금기술이 적용되고 있으며, 주로 무전해 니켈-침지금(electroless nickel immersion gold, ENIG) 및 무전해 니켈-무전해 팔라듐-침지금

(electroless nickel electroless palladium immersion gold, ENEPIG) 도금층이 사용되고 있다^{51,52}. 이러한 표면처리는 패키지의 신뢰성에 영향을 미치며, 나아가 패키지의 수명에도 실질적인 연관성이 있다. 그러므로 최근 ENIG와 ENEPIG 표면처리가 우수한 것임 및 무전해 도금특성, 그리고 뛰어난 확산방지 특성으로 인해 미세 피치 플립칩 (fine pitch flip chip) 공정 등의 UBM (under bump metallization) 재료로 사용되고 있다.

3.3 솔더 접합부 기술개발의 향후 동향

전자 패키징 내의 PCB 표면처리 층 위에서 솔더링 등의 접합공정이 이루어지므로, 표면처리 특성에 따라 접합성 및 패키지 자체의 장기적 신뢰성이 큰 영향을 받는다. 다양한 솔더합금은 Sn이 주요 합금원소이므로 솔더의 종류보다는 기판의 표면처리 방법이 EM에 중요한 영향을 미친다. 대표적인 표면처리법은 Cu OSP, HASL (hot air solder leveling), 침지 주석 (immersion tin), 침지 은 (immersion silver), ENIG 및 ENEPIG가 있으나, 직접적으로 Cu 기판이 드러나는 표면처리보다는 무전해 도금 기술인 ENIG 및 ENEPIG 표면처리가 주로 사용된다^{53,54}.

특히, ENIG 보다 ENEPIG 표면처리 층이 야금학적이거나 기계적 신뢰성이 우수하다고 보고된다. 그 원인은 ENEPIG 층의 Au 및 Ni 층 사이에 존재하는 Pd 층으로 인한 Ni_3Sn_4 와 Ni_3P 의 IMC 및 Kirkendall void의 생성을 억제하기 때문이다⁵⁵. 하지만 기존에 사용되던 ENEPIG 표면처리는 Ni의 두께가 약 3-7 μm 로 두꺼우므로 가속화되는 미세피치 기술을 만족시키려면 솔더 간의 간격 감소 및 전기저항 증가에 의한 결함발생이 증가된다는 문제점이 있다⁵⁶. 이러한 단점을 해결하기 위하여 Ni 층의 두께를 1 μm 미만으로 얇은 표면처리 기술이 개발되고 있으며 (Fig. 20), 다양한 연구가 진행 중이다^{56,57}.

얇은 ENEPIG 표면처리는 미세피치 기술에 대한 적용성이 우수하며, 솔더링 뿐만 아니라 다양한 접합방법에도 적용이 가능하다. 또한, 양호한 내열성 및 도금밀착성, 더 나아가 공정가격을 저감 시키는 장점을 가지

Fig. 20 Schematics of surface finishes: (a) normal- and (b) thin-ENEPIG

므로 연구개발에 대한 적용범위가 확대될 것으로 전망된다⁵⁸. 현재 많은 연구기관에서 1 μm 미만의 ENEPIG 표면 처리를 적용한 솔더 접합부의 특성에 대한 연구가 진행 중이며, 선진 패키지 제조업체에서 양산 적용을 위하여 가능성을 테스트 단계로 진입하였지만 신뢰성에 대한 문제와 개발분야의 경험부족의 단점으로 인하여 상용화가 더딘 실정이다.

추가적으로, 무연솔더 접합부에서 발생하는 EM 현상은 IMC 및 void의 핵생성 및 성장속도와 가장 밀접한 관계를 가진다. 전류밀도가 높아짐에 따라 솔더 접합부에서 Joule 가열에 의한 온도 증가의 TM 효과가 현저하게 증가하므로, EM 현상 이외에도 TM 효과 및 응력에 기인하는 stress-migration, 그리고 패키지의 적층에 따른 휨(warping) 현상 등을 함께 고려할 필요가 있다. 이를 고려한다면, 패키지의 수명에 대한 신뢰성을 더욱 향상시킬 수 있을 것으로 판단된다.

4. 결 론

현재의 패키징 기술을 넘어선 차세대의 패키징 시대가 도래하면서 기술적으로 극복해야 될 과제들이 존재한다. 그 중 솔더 접합부에 가장 큰 영향을 미치는 EM 현상에 의한 결함은 현재까지 보고되어진 문제점이지만, 패키지의 소형화 및 고밀도화에 따른 요구 조건의 변화로 인하여 가장 현실적인 문제로 인식되고 있다. 이를 정리하여 다음과 같은 문제점과 개선사항을 제시한다.

1) 솔더의 무연화가 이루어짐에 따라, 다양한 솔더 접합부에서의 EM 현상에 대하여 연구되고 있다. 이미 보고된 연구자료에 의하면 무연솔더의 적용이 Sn-Pb 솔더 보다 EM현상에 대한 저항성이 강한 것으로 판단된다⁶¹. 다양한 무연솔더 접합부에서 발생하는 EM 현상으로 인한 IMC와 void의 핵생성 및 성장 속도, 전류 밀도 및 인가시간 등의 변수에 의한 EM 속도 예측, Sn 성장 방향이 EM 현상에 미치는 영향 등의 연구가 추가적으로 이루어져야 EM 현상에 대한 문제점이 해결될 수 있을 것으로 판단된다.

2) 이러한 연구를 진행하기 위하여 다양한 연구 장비가 활용되어져 왔으며, 최근에는 in-situ 이미지를 통하여 시간에 따른 IMC 거동 분석, TEM 분석을 통한 IMC 거동에 대한 메커니즘 규명 등의 최신 장비를 적용한 분석이 이루어지며, 이러한 분석은 솔더 접합부에 대한 연구 결과에 대한 신뢰성을 향상시킬 수 있다.

3) 현재까지 다양한 접합부에 대한 연구가 다수 진행되어 왔으며, ENEPIG 표면처리를 한 기판의 적용한 경우에 솔더/ENEPIG의 접합 특성이 가장 우수하

다고 알려져 있으나, 가속화되는 미세피치 기술을 만족시키기 위하여 ENEPIG의 Ni 층을 $1\mu\text{m}$ 이하로 감소시키는 연구가 진행 중에 있다. 하지만 현재 양산 적용을 위한 시험 단계 이므로 많은 연구개발이 이루어져야 한다. 그러므로 앞으로의 솔더 접합부에 대한 개발 방향은 ENEPIG의 Ni 층을 감소시키는 방안을 통하여 집중적으로 연구가 진행 될 것이라 예상된다.

4) 4차산업혁명 시대에 맞추어 ENEPIG와 솔더의 계면에서 EM과 TM에 의한 IMC층과 Kirkendall void의 성장에 대한 실험결과를 예측할 수 있는 모델링 연구와 휨(warpage) 연구가 필수적이다.

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References

1. M. Kim, Y. Ko, J. Bang and C. Lee, The Chip Bonding Technology on Flexible Substrate by Using Micro Lead-free Solder Bump, *J. Microelectron. Packag. Soc.* 19(3) (2012) 15-20.
<http://dx.doi.org/10.6117/kmeps.2012.19.3.015>
2. Y. K. Ko, Y. H. Ko and C. W. Lee, Micro-bump Joining Technology for 3 Dimensional Chip Stacking, *J. Korean Soc. Precis. Eng.* 31(10) (2014) 865-871.
<http://dx.doi.org/10.7736/KSPE.2014.31.10.865>
3. G. Kim, K. Son, G. T. Park, Y. B. Park, Effect of Current Densities on the Electromigration Failure Mechanisms of Flip-Chip Sn-Ag Solder Bump, *Korean J. Met. Mater.* 55(11) (2017) 798-805.
<https://doi.org/10.3365/KJMM.2017.55.11.798>
4. J. M. Park, S. H. Kim, M. H. Jeong and Y. B. Park, Effect of Cu-Sn intermetallic compound reactions on the Kirkendall void growth characteristics in Cu/Sn/Cu microbumps, *Jpn. J. Appl. Phys.* 53 (2014) 1-4.
5. G. Ross, V. Vuorinen and M. P-Krokel, Void formation and its impact on Cu-Sn intermetallic compound formation, *J. Alloy. Compd.* 677 (2016) 127-138.
<https://doi.org/10.1016/j.jallcom.2016.03.193>
6. J. H. Lee, N. H. Kang, C. W. Lee and J. H. Kim, Necessity of Low Melting Temperature Pb-free Solder Alloy and Characteristics of Representative Alloys, *J. Koran Weld. Join. Soc.* 24(2) (2006) 17-28.
7. S. Jin, N. Kang, K. Cho, C. Lee and W. Hong, Behavior of Vibration Fracture for Sn-Ag-Cu-X Solders by Soldering, *J. Koran Weld. Join. Soc.* 30(2) (2012) 169-173.
<http://dx.doi.org/10.5781/KWJS.2012.30.2.169>
8. C. Y. Kang, Research Trend in Development of Pb Free Solder, *J. Koran Weld. Join. Soc.* 13(4) (1995) 1-6.
9. W. Yang, R. W. Messler and L.E. Felton, Microstructure Evolution of Eutectic Sn-Ag Solder Joints, *J. Electron. Mater.* 23 (1994) 765-772.
<https://doi.org/10.1007/BF02651371>
10. Y. Wang, K. H. Lu, V. Gupta, L. Stiborek, D. Shirley, S. H. Chae, J. Im and P. S. Ho, Effects of Sn grain structure on the electromigration of Sn-Ag solder joints, *J. Mater. Res.* 27(8) (2012) 1131-1141.
<https://doi.org/10.1557/jmr.2012.10>
11. S. H. Kim, B. R. Lee, G. T. Park, J. M. Kim, S. H. Yoo and Y. B. Park, Effects of PCB surface finishes on the Mechanical and Electrical Reliabilities of Sn-0.7Cu Pb-free Solder Bump, *J. Microelectron. Packag. Soc.* 53(10) (2015) 735-744.
<https://doi.org/10.6117/kmeps.2012.19.4.057>
12. Y. Kim, J. Kwon, D. Yoo, S. Park, D. Lee and D. Lee, Influence of Nickel Thickness and Annealing Time on the Mechanical Properties of Intermetallic Compounds Formed between Cu-Sn Solder and Substrate, *Korean J. Met. Mater.* 55(3) (2017) 165-172.
<https://doi.org/10.3365/KJMM.2017.55.3.165>
13. S. K. Lim, Physical Design for 3D System on Package, *IEEE Design and Test of Computers.* 22(6) (2005) 532-539.
<https://doi.org/10.1109/MDT.2005.149>
14. M. Dong, F. Santagata, R. Sokolovskij, J. Wei, C. Yuan and G. Zhang, 3D system-in-package design using stacked silicon submount technology, *Microelectron. Int.* 32(2) (2015) 63-72.
<https://doi.org/10.1108/MI.11.2014.0050>
15. J. H. Lan, Evolution and Outlook of TSV and 3D IC/Si Integration, *2010 12th Electronics Packaging Technology Conference*, Singapore (2010)
<https://doi.org/10.1109/EPTC.2010.5702702>
16. B. H. L. Chao, X. Zhang, S. H. Chae, P. S. Ho, Recent advances on kinetic analysis of electromigration enhanced intermetallic growth and damage formation in Pb-free solder joints, *Microelectron. Reliab.* 49(3) (2009) 253-263.
<https://doi.org/10.1016/j.microrel.2009.01.006>
17. S. Baek, Y. Park, C. Oh, E. Chun and N. Kang, Modeling and Experimental Verification of Intermetallic Compounds Grown by Electromigration and Thermomigration for Sn-0.7Cu Solders, *J. Electron. Mater.* 48(1) (2019) 142-151.

- <https://doi.org/10.1007/s11664-018-6786-4>
18. S. Li, X. Wang, Z. Liu, Y. Jin, S. Zhang, J. Geng, X. Chen, S. Wu, P. He and W. Long, Corrosion behavior of Sn based lead free solder alloys: a review, *J. Mater. Sci.* 31 (2020) 9076-9090.
<https://doi.org/10.1007/s10854-020-03540-2>
19. P. Zhang, S. Xue, J. Wang, P. Xue, S. Zhong and W. Long, Effect of Nanoparticles Addition on the Microstructure and Properties of Lead-Free Solders: A Review, *Appl. Sci.* 9(10) (2019) 1-20.
<https://doi.org/10.3390/app9102044>
20. J. Lee, K. Kim and S. Huh, Development of Sn-Zn Based Low Temperature Lead-Free Solder for Improvement of Oxidation Resistance, *J. Korean Weld. Join. Soc.* 29(5) (2011) 514-521.
<http://dx.doi.org/10.5781/KWJS.2011.29.5.514>
21. J. Lee, K. Kim, M. Inoue, J. Jiang and K. Sukanuma, Effects of Ag and Cu addition on microstructural properties and oxidation resistance of Sn-Zn eutectic alloy, *J. Alloy. Compd.* 454 (2008) 310-320.
<https://doi.org/10.1016/j.jallcom.2006.12.037>
22. R. Darveaux and K. Banerji, Constitutive Relations for Tin-Based-Solder Joints, *IEEE Trans. Compon. Hybrids. Manuf. Technol.* 15(6) (1992) 1013-1024.
<https://doi.org/10.1109/33.206925>
23. I. Artaki, A. M. Jackson and P. T. Vianco, Evaluation of Lead-Free Solder Joints in Electronic Assemblies, *J. Electron. Mater.* 23(8) (1994) 757-764.
<https://doi.org/10.1007/BF02651370>
24. J. Y. Park, J. P. Jung and C. S. Kang, The Analysis of the Withdrawal Force Curve of the Wetting Balance Curve, *IEEE Trans. Compon. Hybrids. Manuf. Technol.* 22(3) (1999) 372-377.
<https://doi.org/10.1109/6144.796538>
25. M. Kim, K. Shin and J. Jung, Research Trends of Sn-Ag Based Pb-Free Solders, *J. Weld. Join.* 19(1) (2001) 15-20.
26. P. T. Vianco and J. A. Rejent, Properties of Ternary Sn-Ag-Bi Solder Alloys: Part II—Wettability and Mechanical Properties Analyses, *J. Electron. Mater.* 28(10) (1999) 1138-1143.
<https://doi.org/10.1007/s11664-999-0251-3>
27. J. Lee, H. Kim, Y. Lee and Y. Choi, Interfacial Properties with Kind of Surface Finish and Sn-Ag Based Lead-free Solder, *J. Korean Weld. Join. Soc.* 27(1) (2009) 20-24.
<https://doi.org/10.5781/KWJS.2009.27.1.020>
28. K. Lee, K. Kim and K. Sukanuma, Electro-migration Phenomenon in Flip-chip Packages, *J. Microelectron. Packag. Soc.* 17(4) (2010) 11-17.
29. R. A. Islam, B. Y. Wu, M. O. Alam, Y. C. Chan and W. Jillek, Investigations on microhardness of Sn-Zn based lead-free solder alloys as replacement of Sn-Pb solder, *J. Alloy. Compd.* 392 (2005) 149-158.
<https://doi.org/10.1016/j.jallcom.2004.08.079>
30. M. Date, T. Shoji, M. Fujiyoshi, K. Sato and K. N. Tu, Ductile-to-brittle transition in Sn-Zn solder joints measured by impact test, *Scr. Mater.* 51 (2004) 641-645.
<https://doi.org/10.1016/j.scriptamat.2004.06.027>
31. P. Xue, S. Xue, Y. Shen and H. Zhu, Interfacial microstructures and mechanical properties of Sn-9Zn-0.5Ga-xNd on Cu substrate with aging treatment, *Mater. Des.* 60 (2014) 1-6.
<http://dx.doi.org/10.1016/j.matdes.2014.03.052>
32. R. S. Lai, K. L. Lin and B. Salam, Suppressing Growth of the Cu₅Zn₈ Intermetallic Layer in Sn-Zn-Ag-Al-Ga/Cu Solder Joints, *J. Electron. Mater.* 38(1) (2009) 88-92.
<https://doi.org/10.1007/s11664-008-0579-0>
33. X. F. Zhang and J. D. Guo, Reverse polarity effect from effective charge disparity during electromigration in eutectic Sn-Zn solder interconnect, *J. Mater. Res.* 23(12) (2008) 3370-3378.
<https://doi.org/10.1557/JMR.2008.0413>
34. M. L. Huang, Q. Zhou, N. Zhao, X. Y. Lin and Z. J. Zhang, Reverse polarity effect and cross-solder interaction in Cu/Sn-9Zn/Ni interconnect during liquid-solid electromigration, *J. Mater. Sci.* 49 (2014) 1755-1763.
<https://doi.org/10.1007/s10853-013-7862-z>
35. M. Huang, Z. Zhang, N. Zhao and X. Feng, Reverse Polarity Effect in Cu/Sn-9Zn/Ni Interconnect under High Current Density at High Temperature, *2014 15th International Conference on Electronic Packaging Technology*, Chengdu China (2014)
<https://doi.org/10.1109/ICEPT.2014.6922690>
36. M. L. Huang, Z. J. Zhang, N. Zhao and Q. Zhou, A synchrotron radiation real-time in situ imaging study on the reverse polarity effect in Cu/Sn-9Zn/Cu interconnect during liquid-solid electromigration, *Scr. Mater.* 68 (2013) 853-856.
<http://dx.doi.org/10.1016/j.scriptamat.2013.02.007>
37. S. Kuo and K. Lin, Polarity effect of electromigration on intermetallic compound formation in a Cu/Sn-9Zn/Cu sandwich, *J. Mater. Res.* 23(4) (2008) 1087-1094.
<https://doi.org/10.1557/jmr.2008.0142>
38. M. Zhao, L. Zhang, Z. Lin, M. Xiong and L. Sun, Structure and properties of Sn-Cu lead-free solders in electronics packaging, *Sci. Technol. Adv. Mater.* 29 (2019) 421-444.
<https://doi.org/10.1080/14686996.2019.1591168>
39. F. Hung, T. Lui, L. Chen and N. He, Resonant characteristics of the microelectronic Sn-Cu solder, *J. Alloy Compd.* 457 (2008) 171-176.
<https://doi.org/10.1016/j.jallcom.2007.03.026>
40. L. Yang, Y. Zhang, J. Dai, Y. Jing, J. Ge and N. Zhang, Microstructure, interfacial IMC and mechanical properties of Sn-0.7Cu-xAl (x = 0-0.075) lead-free solder alloy, *Mater. Des.* 67 (2015) 209-216.

- <http://dx.doi.org/10.1016/j.matdes.2014.11.036>
41. A. A. El-Daly and A. E. Hammad, Enhancement of creep resistance and thermal behavior of eutectic Sn-Cu lead-free solder alloy by Ag and In-additions, *Mater. Des.* 40 (2012) 292-298.
<http://dx.doi.org/10.1016/j.matdes.2012.04.007>
 42. M. Heo, N. Kang, S. Park, J. Kim and W. S. Hong, Kinetics of Intermetallic Compounds Growth Induced by Electromigration of Sn-0.7Cu Solder, *Korean J. Met. Mater.* 54(12) (2016) 908-915.
<https://doi.org/10.3365/KJMM.2016.54.12.908>
 43. H. Lee, Y. Chen, Evolution of Ag₃Sn intermetallic compounds during solidification of eutectic Sn-3.5Ag solder, *J. Alloy. Compd.* 509 (2011) 2510-2517.
<https://doi.org/10.1016/j.jallcom.2010.11.068>
 44. B. Guo, A. Kunwar, N. Zhao, J. Chen, Y. Wang, H. Ma, Effect of Ag₃Sn nanoparticles and temperature on Cu₆Sn₅ IMC growth in Sn_xAg/Cu solder joints, *Mater. Res. Bull.* 99 (2018) 239-248.
<https://doi.org/10.1016/j.materresbull.2017.11.022>
 45. Y. Jung and J. Yu, Electromigration induced Kirkendall void growth in Sn-3.5Ag/Cu solder joints, *J. Appl. Phys.* 115 (2014) 083708:1-9.
<https://doi.org/10.1063/1.4867115>
 46. Y. Park, J. Bang, C. M. Oh, W. S. Hong and N. Kang, The Effect of Eutectic Structure on the Creep Properties of Sn-3.0Ag-0.5Cu and Sn-8.0Sb-3.0Ag Solders, *Met.* 7(12) (2017) 540:1-12.
<https://doi.org/10.3390/met7120540>
 47. A. T. Tan, A. W. Tan and F. Yusof, Evolution of microstructure and mechanical properties of Cu/SAC305/Cu solder joints under the influence of low ultrasonic power, *J. Alloy. Compd.* 705 (2017) 188-197.
<http://dx.doi.org/10.1016/j.jallcom.2017.02.165>
 48. M. Z. Yahaya, N. A. Salleh, S. Kheawhom, B. Illes, M. F. M. Nazari and A. A. Mohamad, Selective etching and hardness properties of quenched SAC305 solder joints, *Solder. Surf. Mount Technol.* 32(4) (2020) 225-233.
<https://doi.org/10.1108/SSMT-01-2020-0001>
 49. S. Kim, G. Park, B. Lee, J. Kim, S. Yoo and Y. Park, Effects of PCB Surface Finishes on in-situ Intermetallics Growth and Electromigration Characteristics of Sn-3.0Ag-0.5Cu Pb-free Solder Joints, *J. Microelectron. Packag. Soc.* 22(2) (2015) 47-53.
<http://dx.doi.org/10.6117/kmeips.2015.22.2.047>
 50. J. Choi, S. Jun, H. Won, B. Jung and T. Oh, Electromigration Behavior of Flip-Chip Bonded Sn-3.5Ag-0.5Cu Solder Bumps, *J. Microelectron. Packag. Soc.* 11(4) (2004) 43-48.
 51. K. Kim, W. Seo, S. Kwon, J. Kim, J. Yoon and S. Yoo, Effects of Ni-P Bath on the Brittle Fracture of Sn-Ag-Cu Solder/ENEPIG Solder Joint, *J. Weld. Join.* 35(3) (2017) 1-6.
<https://doi.org/10.5781/JWJ.2017.35.3.1>
 52. S. Huh, J. Lee and S. Ham, Reliability of Sn-Ag-Cu Solder Joint on ENEPIG Surface Finish: 1. Effects of thickness and roughness of electroless Ni-P deposit, *J. Microelectron. Packag. Soc.* 21(3) (2014) 43-50.
<http://dx.doi.org/10.6117/kmeips.2014.21.3.043>
 53. J. Yoon, B. Noh and S. Jung, Comparative Study of ENIG and ENEPIG as Surface Finishes for a Sn-Ag-Cu Solder Joint, *J. Electron. Mater.* 40(9) (2011) 1950-1955.
<https://doi.org/10.1007/s11664-011-1686-x>
 54. J. Yoon, J. Bang, C. Lee and S. Jung, Interfacial reaction and intermetallic compound formation of Sn-1Ag/ENIG and Sn-1Ag/ENEPIG solder joints, *J. Alloy. Compd.* 627 (2015) 276-280.
<http://dx.doi.org/10.1016/j.jallcom.2014.11.208>
 55. C. Ho and J. Duh, Quantifying the dependence of Ni(P) thickness in ultrathin-ENEPIG metallization on the growth of Cu-Sn intermetallic compounds in soldering reaction, *Mater. Chem. Phys.* 148 (2014) 21-27.
<http://dx.doi.org/10.1016/j.matchemphys.2014.06.072>
 56. J. Back, S. Yoo, D. Han, S. Jung and J. Yoon, Interfacial Reactions and Mechanical Strength of Sn-3.0Ag-0.5Cu/0.1 μ m-Ni Thin ENEPIG Solder Joints, *J. Weld. Join.* 35(6) (2017) 51-58.
<https://doi.org/10.5781/JWJ.2017.35.6.8>
 57. J. Kim, S. Jung and J. Yoon, Effect of Ni(P) thickness in Au/Pd/Ni(P) surface finish on the electrical reliability of Sn-3.0Ag-0.5Cu solder joints during current-stressing, *J. Alloy. Compd.* 850 (2021) 156729: 1-11.
<https://doi.org/10.1016/j.jallcom.2020.156729>
 58. J. Back, B. Lee, S. Yoo, D. Han, S. Jung and J. Yoon, Solderability of thin ENEPIG plating Layer for Fine Pitch Package application, *J. Microelectron. Packag. Soc.* 24(1) (2017) 83-90.
<https://doi.org/10.6117/kmeips.2017.24.1.083>