

A REVIEW ON RECENT ADVANCES IN TRANSIENT LIQUID PHASE (TLP) BONDING FOR THERMOELECTRIC POWER MODULE

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Abstract. In this study, the authors have reviewed recent advances on the transient liquid phase (TLP) bonding technology for various applications especially power module packaging in view of the recent increasing demand for the production of vehicles, smartphones, semiconductor devices etc. TLP bonding is one of the potential technologies from clean technology that can replace the Pb-base solder technology without causing any serious environmental issues. It is based on the concept of both brazing as well as diffusion bonding. During TLP bonding, the liquid phase is transiently formed at the bonding interface. At this point, the melting point of filler metal increases due to the diffusion of element which degrades the melting point from liquid phase to base metal. Subsequently, the bonding occurs by isothermal solidification at the bonding temperature of liquid phase. Here, after bonding, the melting temperature of the joint layer becomes higher than bonding temperature. This review introduces the various aspects of TLP bonding including its principle, materials, applications, advantages and properties in detail.

1. INTRODUCTION

1.1. TLP bonding

Transient liquid phase (TLP) bonding first introduced in 1950s by Lynch et al. is known as combination of diffusion bonding and brazing. During TLP bonding, the liquid phase is formed transiently at the bonding interface like brazing [1-6]. Here, similar to the diffusion bonding, the melting point of filler metal rises due to diffusion of element which degrades the melting point from liquid phase to base metal while maintaining their bonding temperature. Subsequently, they are bonded by isothermal solidification at bonding temperature of liquid phase. TLP bonding has been applied to the heat-resistant alloys which require high temperature properties and bonding of structural alloys such as stainless steel

[7,8]. In addition, TLP bonding can provide easy dissimilar metal joining due to the minimization of changes in bonding area, and it has also a merit of smaller heat affected zone (HAZ). Moreover, the bonding strength is almost equal to the base metal unlike conventional brazing and diffusion bonding [9-11].

Conventional TLP bonding known as diffusion bonding is the bonding technology in which filler metal is alloyed with boron and phosphorus for decreasing melting point while joining Ni, Fe, and Cu alloys [12,13]. This technology is based on the concept of both brazing and diffusion bonding basically is the liquid diffusion bonding of filler metal at bonding temperature unlike solid diffusion bonding with both solid phases. In other words, isothermal solidification which increases filler melting point is used

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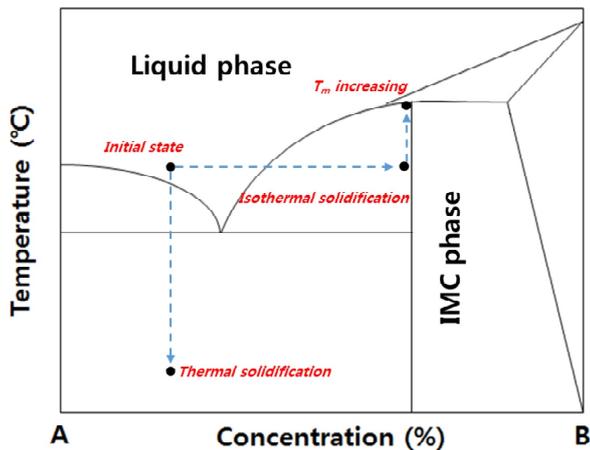


Fig. 1. Thermal and isothermal solidification at TLP bonding as well as at conventional soldering with virtual equilibrium phase diagram.

for this technology causing diffusion of filler metal to base metal with solid-liquid inter-diffusion after filler melts at a lower melting temperature than operating temperature.

The TLP bonding used mostly for joining in microelectronic packaging industry where the isothermal solidification at joint occurs by formation of IMCs and metal phase melted at higher temperature than bonding temperature with composition change of the joint [14-17]. Fig. 1 shows the isothermal solidification by solid-liquid interdiffusion at TLP bonding as well as thermal solidification by cooling at conventional soldering with virtual equilibrium phase diagram. This TLP bonding is also called as solid liquid inter-diffusion (SLID) bonding, transient liquid phase soldering (TLPS) and isothermal diffusion soldering (IDS) [18-20].

1.2. Power module and its bonding technologies

Recently, interest in thermoelectric power modules has been increased manifolds as a power source of vehicles, an economical source of energy generation and distribution. The power module are used for supply, distribution and conversion of electric power, and power semiconductors based on power module consist of insulated gate bipolar mode transistor (IGBT), metal oxide silicon field effect transistor (MOSFET), diode, etc. [21-30].

The trend of power semiconductors has gradually been miniaturized and highly densified because it requires high operation voltage causing high amount of current and heat unlike other semiconductor devices [31]. The power module consisting

of these power semiconductors is the key component for operating electric and eco-friendly vehicles.

Moreover, the power modules used in automobile industries require higher reliability of the joint because of loss in stability, safety concerns and unstable operating environment at high temperature [32]. The joint is exposed to a temperature of less than 150 °C (junction temperature of Si) resulting in continuous thermal/physical shock. In addition, the duration and reliability of the joint is severely degraded by stresses, pores and cracks during solidification of melt as well as by coefficient of thermal expansion (CTE) mismatch between ceramic substrates and metals [33]. Fig. 2 indicates the typical joint of die and substrate in power module. Overall, there are two types of attached part like die attach area as shown in Fig. 2a and substrate attach area as shown in Fig. 2b in the conventional power module.

Conventional Pb-base solder is used for bonding materials in joining of power modules. However, the use of Pb-Sn solder has been restricted since the end of life vehicle (ELV) and restriction of hazardous substances (RoHS) regulations [34-46]. In addition, the joint can be exposed at a high temperature conditions with downsizing or removing of heatsink due to the trend of transformation from Si to SiC in power semiconductors [31]. SiC-based semiconductor has a higher band gap and it has the excellent properties for dielectric strength breakdown, electron saturation velocity, and thermal conductivity as compared to the Si-based semiconductors. In other words, SiC power semiconductors have many advantages such as miniaturization of the device, improvement of fuel efficiency and feasible operation at high temperature based on aforementioned characteristics, however, it can be exposed to the higher temperatures greater than 200 °C [47].

Thus, high temperature reliability and Pb-free solder materials for die and substrate bonding are required to meet this current trend. In order to meet this demand, the different types of bonding materials such as Au [48], Bi [49,50], Zn [51,52] which have higher melting point than Sn-based solder have been reported and TLP bonding and Ag sintering bonding have been actively studied [53].

In the case of Zn and Bi based solder with lower thermal/electrical conductivity and corrosion resistance which can cause thermal damage due to higher melting point and lower thermal conductivity. In addition, they may degrade the device and substrate at a higher bonding temperature [54,55]. For Au based bonding material, it has the merit of high corrosion resistance, superior thermal/electric conduc-

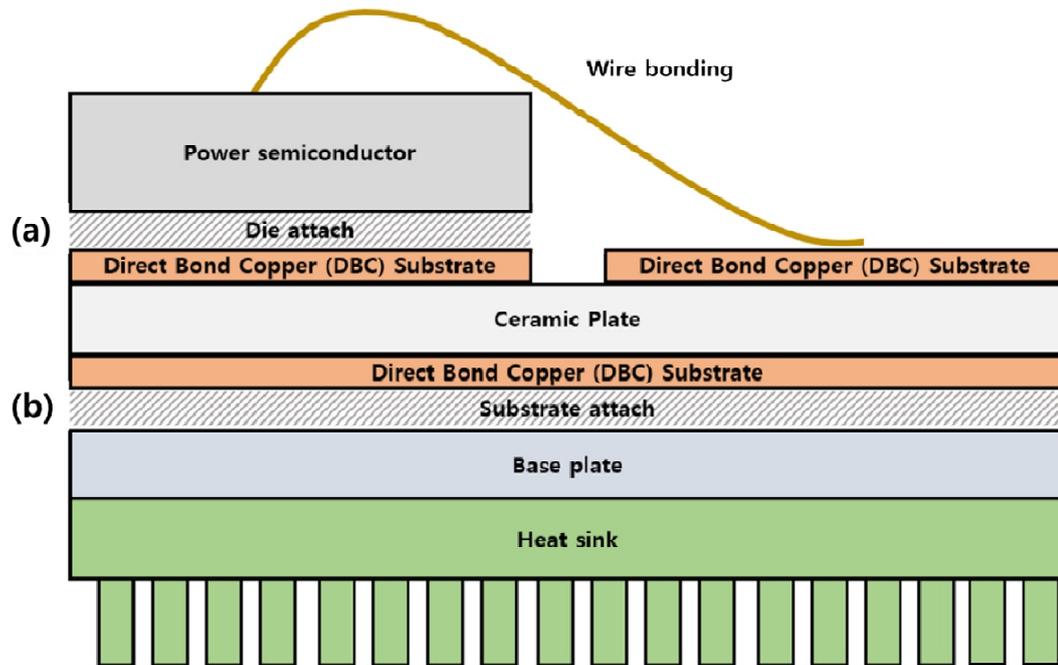


Fig. 2. Schematic illustration of (a) die attach part and (b) substrate attach part in the conventional power module.

tivity and flux-less bonding in the atmosphere, however it is very expensive [56].

In case of Ag nanoparticles (≈ 100 nm) sintering at temperature of 200°C provides both high electrical conductivity, bonding strength and stabilization at high temperature because of an increase in melting point ($>700^\circ\text{C}$) after bonding [53]. However, there is a high possibility for device and substrate to be degraded due to the pressure of $1\sim 20$ MPa for bonding and presence of a large number of pores in the bonding area. In addition, it is hardly compatible with conventional soldering facility [57]. In order to solve this problem, a pressure-less sintering bonding was studied in literature but it is limited due to its high cost [53].

There are also some bonding technologies such as solid diffusion bonding, friction stir welding and TLP bonding to obtain an excellent bonding strength between two materials without melting of base metal. In this review, among the various bonding technologies as aforementioned, the research trend of TLP bonding, especially, for power modules will be introduced and overviewed in detail.

2. PRINCIPLE AND PROCESS OF TLP BONDING

The TLP bonding has been used with a variety of methods and its basic principle is as below [58].

2.1. Design of initial joint

Fig. 3a shows the initial joint of TLP bonding using both metal foil having low melting point and metal bump having high melting point. In this state, called as initial preparation step for bonding, low melting point material is placed as a sandwich structure between two high melting point materials before bonding. After that, state of low melting point material moves to melting and wetting state with increasing bonding temperature.

Similarly, there are various methods such as deposition for low melting point metal on the surface of bump [59], the usage of conventional solder alloy [19], and mixing of high and low melting point metal powders.

2.2. Melting and wetting

The molten metal is wetted on the surface of high melting point metal by heating of designed initial joint to the melting temperature of low melting point metal as shown in Fig. 3b. It means that only filler metal is melted and bonded due to the heat at bonding temperature because its melting point is higher than bonding temperature and lower than melting point of base metal.

The void may occur at the joint, or IMC may not form when interface of solid-liquid is not formed through entire joint due to the poor wettability. As it

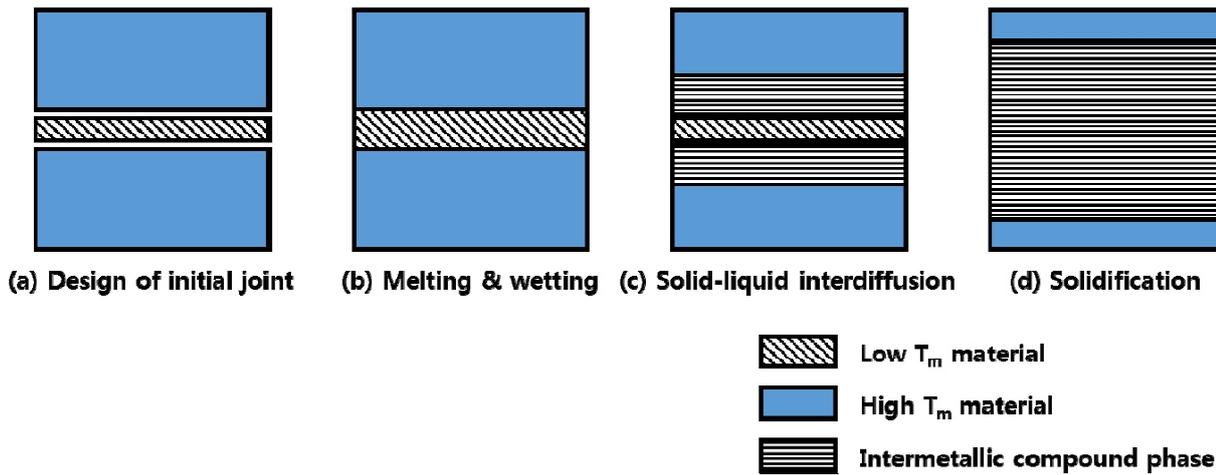


Fig. 3. Schematic diagrams of (a) design of initial joint, (b) melting and wetting, (c) solid-liquid interdiffusion and solidification for TLP bonding.

causes, degradation of mechanical and thermal properties of the joint [60], a surface treatment such as Au [61] and organic solderability preservative (OSP) coating can be used to improve a wettability. Normally, the pressure less than 1 MPa is applied at this stage but some studies on pressure-less TLP process have been also reported by increasing wettability [58].

2.3. Solid-liquid inter-diffusion

The growth of IMC begins to increase at the center of joint interface by dissolution of low melting point molten metal to high melting point metal as shown in Fig. 3c. After that, the joint is solidified with growth of IMC at bonding interface by continuous diffusion even without any change of temperature [17].

In other words, the isothermal solidification for liquid phase occurs at bonding temperature after liquid phase transient during bonding because the melting point of filler metal increases by diffusion of its element for decreasing melting point from liquid phase to base metal if the bonding temperature is retained. In general, bonding time can be reduced by extending interface of solid-liquid phase because liquid diffusion is three times faster than solid diffusion [62], and the joint may become extinct and united by inter-diffusion between the base metal and the joint after homogenization heat treatment.

2.4. Isothermal solidification and homogenization

During diffusion of element for reduced melting point to the base metal, the solidification of liquid filler metal occurs at bonding temperature known as iso-

thermal solidification due to the decrease in average composition of element for reduced melting point at liquid phase of filler metal. The thickness of IMC can be increased by maintaining the constant temperature at the entire joint area as shown in Fig. 3d. If the bonding time can be fully maintained, all of the liquid phase disappear and homogenization is proceeded to make a composition of joint similar to a base metal after isothermal solidification [14]. In this case, the mechanical property at high temperature is superior to the brazing method because the joint is almost similar with base metal chemically [63].

However, low melting point metal that is not consumed with base metal can cause degradation in reliability of the joint during high temperature operation [64]. A process plan considering thicknesses and materials of the joint is necessary because the formation of complete joint may be difficult by consumption of a metallization layer when there are a number of low melting point metals. For this, C. Ehrhardt et al. have suggested Eq. (1) to make complete Cu_6Sn_5 bonding area in TLP bonding and calculated mixing ratio of Cu and Sn with 39:61 as below [65].

$$\text{wt.}\%(\text{Cu}) = [6m_A(\text{Cu})] / [6m_A(\text{Cu}) + \delta m_A(\text{Sn})], \quad (1)$$

where m_A is the molar mass (g/mol).

TLP technology has a higher stability due to the similarity of bonding materials with the base metal. In addition, TLP bonding provides excellent bonding quality and high heat-resisting property in comparison to at low operation temperature [17,47]. However, there is a difficulty of obtaining initial process parameters because transition of the joint for complete IMC formation is necessary.

Table 1. Comparison of various TLP bonding systems, data from [57].

Material	Temperature (°C)		Relative market price*	Relative conductivity*		Note
	bonding	re-melt(IMC)		Thermal	Electrical	
Cu-Sn	280	415 (Cu ₆ Sn ₅) 676 (Cu ₃ Sn)	Cu: 0.5 Sn: 0.8	Cu: 4.4	Cu: 4.1	Complex phase
Ni-Sn	300	800 (Ni ₃ Sn ₃)	Ni: 1 Sn: 0.8	Ni: 1	Ni: 1	Conventional packaging materials for high temp. device
Au-Sn	250	419 (AuSn)	Au: 2600 Sn: 0.8	Au: 3.5	Au: 3.1	Free from oxidation
Ag-Sn	250	480 (Ag ₃ Sn)	Ag: 63 Sn: 0.8	Ag: 4.7	Ag: 4.4	-
Ag-In*	200	495	Ag: 63 In: 37.5	Ag: 4.7	Ag: 4.7	-
Au-In	175	880	Au: 2600 In: 37.5	Au: 3.1	Au: 3.1	Most expensive

* Relative values are normalized to Ni.

On the other hands, the process of isothermal solidification comprise a vast majority of TLP bonding because it requires more than 10 minutes heating time for a uniform IMCs across the joint. Here, the productivity can be increased by reducing the time required. And for this one, a wide range of TLP bonding technologies are presented such as TLP bonding with multi metal layer [66-68], powder [69-75], ultrasonic assisted TLP bonding [76,77], current assisted TLP bonding [78] using electromigration by the movement of electron from current applying and TLP bonding using temperature difference of joint [79].

3. TLP BONDING MATERIALS

TLP bonding materials can widely be classified into tin (Sn) and indium (In) based metal which have melting points of 231.9 and 156.6 °C, respectively. In the case of Sn based, Ni-Sn, Cu-Sn, Au-Sn, and Ag-Sn have been frequently used for TLP bonding [80-82]. Among them, Cu-Sn and Ni-Sn have been paid more attention as the potential candidates in view of their cost. Ni-Sn has already been used as bonding material in LED industry at high temperature but it has poor electric property as compared to the Cu-Sn. On the other hand, Cu-Sn has a problem of oxidation and a complicated equilibrium phase diagram. In addition, it can degrade the bonding reliability due to the growth of Cu₆Sn₅ as well as Cu₃Sn IMCs. Indium has been used for TLP bonding as Au-In and Ag-In alloys but these also have cost and

oxidation issues. To prevent the oxidation, Au can be coated on the surface of TLP layers [61]. If there exists an oxidation layer, wetting and diffusion won't happen resulting in some defects like void and pore. Table 1 shows the various materials and their properties for TLP bonding.

4. TLP BONDING FOR POWER MODULE

Among the various candidates for TLP bonding in power module, Cu-Sn and Ni-Sn systems have been more popular nowadays to get a good bonding quality as well as reduce a bonding time. The various TLP bonding technologies both with layer and powder as shown in Table 2.

4.1. TLP bonding with metal layer

Fig. 4a shows the TLP bonding with metal layer obtained by the vacuum evaporation machine. In this case, high process cost and complex process steps are required including vacuum evaporation and pre-treatment of the substrate [58]. Moreover, stress induced from the coefficient of thermal expansion (CTE) mismatch between substrate and the joint can occur because of the metal layer [33], and it requires high processing cost and bonding time. The bonding technology using low melting point metal processed with thin film layer has been studied with mechanical process [76-78,83-85]. In the TLP bonding, the thickness of IMC (χ) depending on bonding

Table 2. Various TLP bonding techniques.

No	Technique	Type	Notes	System	Reference
1	Conventional method	Layer	Deposition was used for TLP layer	Cu-Sn	[80]
			Flux-less bonding (Au finish)	Ni-Sn	[61]
			Ti(adhesion layer), Ni(diffusion barrier)	Ag-Sn	[82]
2	Inserted foil TLP	Layer	Sn foil was used for TLP bonding Sn/Cu(thick interlayer)/Cu foil was used	Ni-Sn Ag-Sn	[57] [85]
3	Improved foil TLP	Layer	Electroplating was used for TLP layer	Cu-Sn	[68]
			Foil structure: Cu-Sn-Cu-Sn	Ag-Sn	[66]
			Foil structure: Ag-Sn-Ag-Sn-Ag, Ag-In-Ag-In-Ag Low vacuum	Ag-Sn	[67]
4	Current assisted bonding	Layer	Flux-less Bonding with electric current (900 A) Sn foil was used for liquid phase Bonded within 250 ms	Cu-Sn	[78]
5	Ternary TLP	Layer	Sn foil was inserted between Ag and Cu plate $2 \cdot 10^{-3}$ Pa vacuum was used for bonding	Ag-Sn-Cu	[83]
		Powder	Sn-Bi solder paste + Cu powder Sn-Bi solder paste used for liquid phase	Sn-Bi-Cu	[70]
		Powder	Powder mixture: Ni, Cu, Sn paste Organic binder was used for paste	Ni-Cu-Sn	[69]
6	Ultrasonic assisted TLP	Layer	Sn foil was used for liquid phase. Joint was formed within 8s	Cu-Sn	[76]
		Layer	Sn-0.7Cu foil was used for liquid phase Diffusion barrier (Ni) formed on substrate Joint was formed within 10 s	Cu-Sn	[77]
		Powder	Powder mixture (Ni, Sn) was used Joint was formed within 10 s	Ni-Sn	[72]
7	Sn Coated Cu ball	Powder	Ni flake, Sn powder was used	Ni-Sn	[73]
		Powder	Sn was electroplated on Cu ball. Reduce bonding time (within 1 min)	Cu-Sn	[74]
		Powder	Sn was electroplated on Cu ball Pressure-less bonding	Cu-Sn	[33]
8	Thermal Gradient Bonding	Layer	Single side IMC growth Thermal gradient of 100 °C, from 300 to 200 °C IMC growth rate was 3-10 times faster than TLP.	Cu-Sn	[79]
9	Solder paste TLP	Powder	Conventional solder paste was printed on the substrate. Liquid solder reacted with substrate to form IMC.	Cu-Sn	[19]

10	Sintering	Powder	Sn residue in joint Porous joint Cu cores were observed over the joint	Cu-Sn	[58]
			Formic acid gas for activation of Cu surface After activation, liquid solder infiltrate into Cu ball.	Cu-Sn	[65]

time can be predicted by Fick's diffusion law as Eq. (2) below [68].

$$\Delta x^2 = Dt, \tag{2}$$

where D is inter-diffusion coefficient and it can be expressed by Arrhenius relation as Eq. (3) below.

$$D = D_0 \exp\left(\frac{-Q}{RT}\right), \tag{3}$$

where D_0 is intrinsic diffusivity, Q is activation energy, R is gas constant, and T means absolute temperature. Therefore, D_0 and activation energy Q value needed for the IMC growth can be different from their bonding process and material. The research on reliability of the joint during TLP bonding has been studied to achieve a high temperature stability. The main factors that affect the reliability of the joint are the formation and growth of IMC.

In TLP bonding, the isothermal solidification occurs by formation of IMC where high melting point metal is dissolved by low melting point metal. Here, a solution velocity which is required for melting high melting point metal into the low melting point metal can be expressed Eq. (4) as below [86].

$$\frac{dc}{dt} = k \frac{S}{V} (C_s - S). \tag{4}$$

The solution velocity can be influenced by dissolution rate constant (k), saturated solubility of high melting point metal melted to the molten metal at the reaction temperature (C_s), current concentration of the high melting point metal melted in the molten metal (C), volume of the molten metal (V) and interface area between molten metal and high melting point metal (S). Here, the bonding time can be reduced by extending the solid and liquid interface area because solution velocity is proportional to the interface area of solid-liquid.

4.2. TLP bonding with metal powder

TLP bonding with metal powders has been proposed as shown in Fig. 4b. Here, the particle size of metal powder is an important parameter. If the particle size is big, it is difficult to print out the paste and the formation of IMC will consume more because of a smaller surface area of the liquid-solid phase. On the other hand, if the particle size is smaller, the agglomeration issue of the particles can take place in the molten metal although it can reduce bonding time due to the high surface area of the liquid-solid phase [65].

In case the metal powder is mixed with an organic binder, the oxidation of Cu particles can be suppressed and the paste can be used for bonding with conventional soldering process. H. Greve et al.

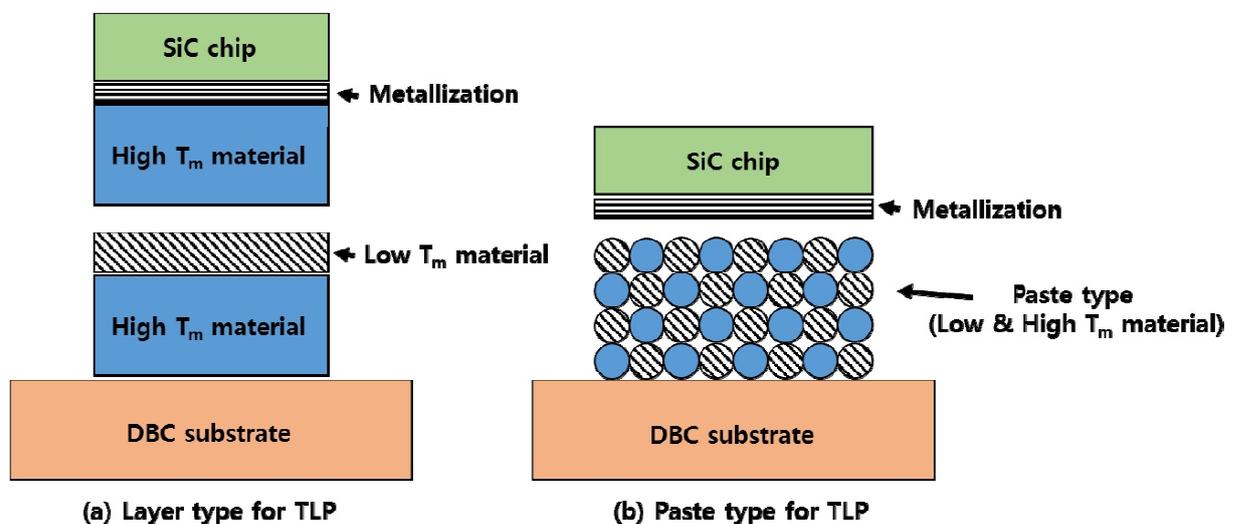


Fig. 4. Schematic illustration of TLP bonding technologies; (a) layer type and (b) paste type.

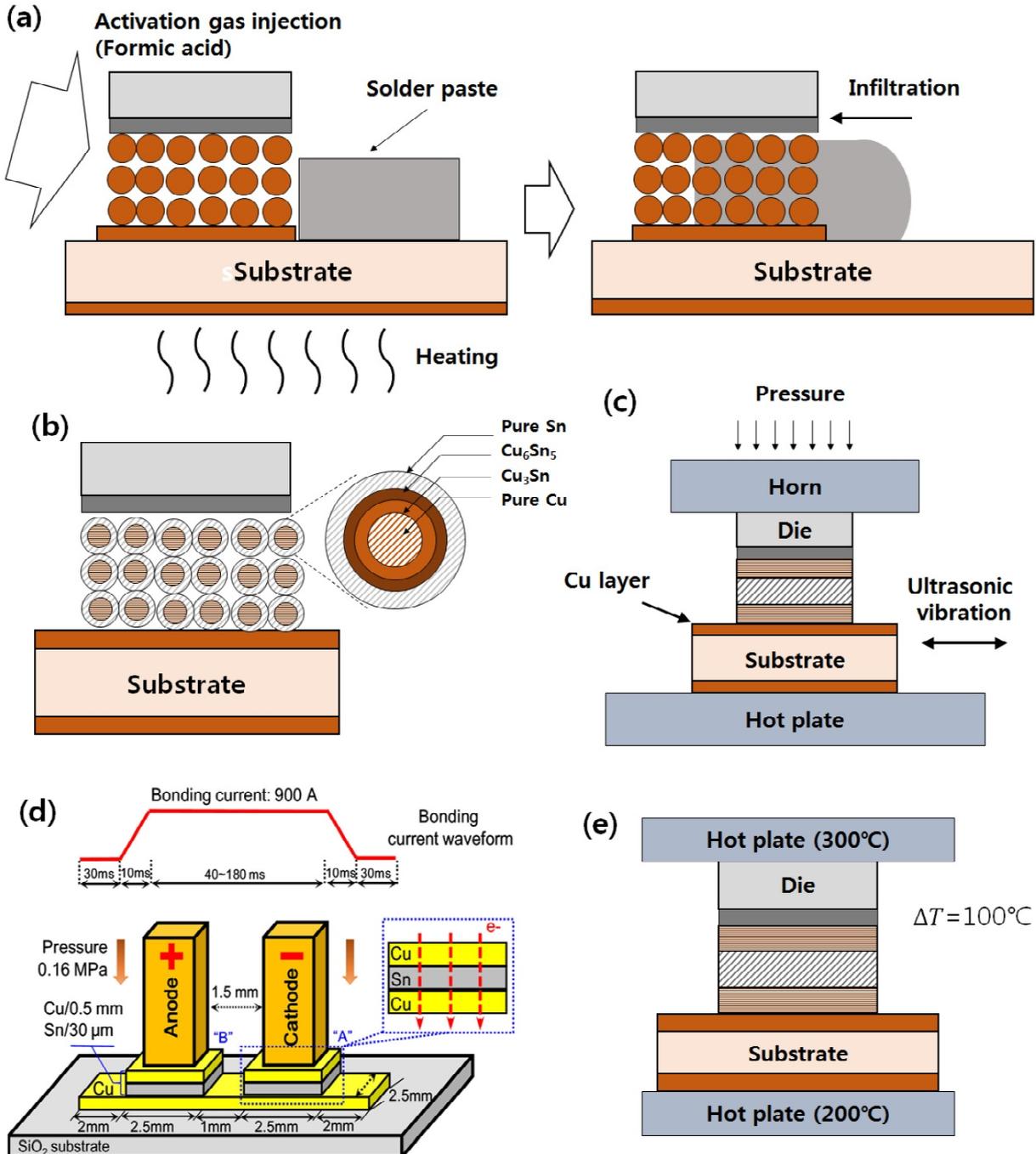


Fig. 5. Schematic illustration of various TLP bonding technologies; (a) liquid infiltration (adapted from [60]), (b) Sn coated Cu ball (adapted from [74]), (c) ultrasonic assisted TLP (adapted from [77]), (d) current assisted TLP (adapted from [78]) and (e) thermal gradient bonding (TGB) (adapted from [79]).

have presented the densification of the joint of molten metal and the high melting point metal by the capillary effect at an optimal ratio of powder and organic binder with good wettability [58].

On the other hand, the several defects during wetting and counter diffusion can occur in widely used Cu-Sn system in TLP bonding. This phenomenon is one of the causes of voids in joint and Sn residues degrading the high temperature stability.

To solve this issue, Strogies et al. have formed the joint without any void by infiltrating molten Sn to the Cu particles after applying Cu paste to the joint and activating the surface of Cu particle as shown in Fig. 5a [60]. According to their research, the method of employing reducing gas before Sn melting, mixing flux with Cu and Sn particles and applying plasma to surface of Cu particles can be proposed to activate surface of oxidized Cu particles.

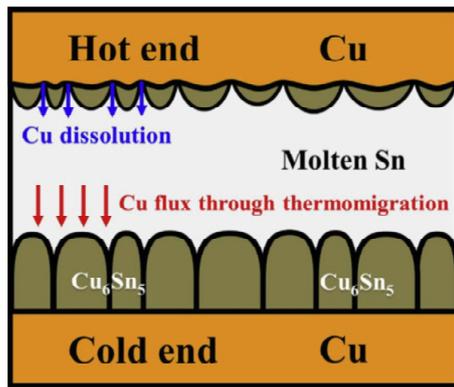


Fig. 6. Schematic mechanism for the TGB method (adapted from [79]).

In addition, Liu and Hu et al. have used Sn electroplating of surface of Cu particles in TLP bonding as shown in Fig. 5b [33,74]. In accordance with their studies, the Cu residue which is not reacted with Sn in the joint can be observed although IMC growth was encouraged by counter diffusion due to formation of IMC between Cu particles and Sn coated layer.

4.3. Recent TLP bonding

TLP bonding has an issue of Sn residue causing degradation in reliability of the joint and longer bonding time and heat treatment. Therefore, current TLP bonding processes have been focused on the formation of joint consisting of IMC in short time. According to this trend, ultrasonic assisted TLP bonding is shown in Fig. 5c. This technology has been studied with Sn foil, Sn-Cu solder foil, Ni-Sn powder mixture, and Ni flake-Sn powder mixture [72,73,76,77]. The results show that the solder joint has been formed consisting of IMCs by applying ultrasonic treatment after Sn alloy got melted within 20 s. When applying ultrasonic waves to molten Sn, Cu was quickly melted into Sn by streaming effect and cavitation erosion resulting in pits micro sized damages in substrate was formed by colliding a voids by ultrasonic with substrates explosively.

On the other hand, it can damage diffusion barrier layer or Cu circuit of substrate [77]. In other words, ultrasonic assisted TLP bonding can reduce process time but can damage the substrate and device by ultrasonic waves. Current assisted TLP bonding presented by Liu et al. is shown in Fig. 5d [78]. Heating was done to 450 °C by Joule-heating without heating and solder joint and the joint consisted of complete IMC within 260 ms by applying current of 900 A. For counter diffusion between joint compositions, electro-migration (EM) was used by

supplying high current of 900 A. Because of this phenomenon, IMC grew to dendrite phase and finally formed the joint without any voids. However, in this study, there is a problem with damage in device due to the small area of solder joint.

Yang et al. have proposed thermal gradient bonding (TGB) as shown in Fig. 5e [79]. This TLP bonding technology known for utilizing temperature difference between upper side of joint and bottom by the precipitation of IMC in molten Cu at the low temperature area by dissolution at high temperature. At this point, the IMCs on the interface grew in one direction as shown in Fig. 6. At the hot end, Cu from the substrate and thin layer of Cu_6Sn_5 IMCs dissolved into the molten Sn. This made the Cu_6Sn_5 IMC layer thin as compared to the cold end. In addition, this process made the interface at the hot-end exhibit a much wavier morphology. This technology is different with conventional TLP bonding in a sense that the IMCs grew in the interface of both solid-liquid phases. Moreover, it enables the formation of solder joint three to ten times faster than conventional TLP bonding. In addition, higher reliability is expected because there is no grain boundary line in growing IMC in the both interface. Therefore, Cu layer should be designed very thick to promote the dissolution at Cu layer which is melts at high temperature.

5. OTHER APPLICATIONS

5.1. TLP bonding for electronic materials

TLP bonding is a technology for making IMCs (intermediate phases) at the joint after molten low melting point metal wets the high melting point metal by heating to the specific temperatures. Afterward, the joint which has uniform composition of high melting point can be obtained by inter-diffusion between liquid and solid [87]. In other words, the melting temperature of bonding area ($T_{\text{re-melting}}$) is higher than bonding temperature (T_{bonding}) after bonding. TLP bonding has widely been researched with these properties at various industries for generating enormous of heating during operation such as power semiconductor, LED, aero-space, and sensors [88]. Especially, this technology has been coupled with nano-Ag sintering technology in response to the environmental change of power semiconductors for vehicle and restriction of lead based solder for high temperature, lately.

Low temperature nano-Ag sintering technology has been studied to obtain a stability at high tem-

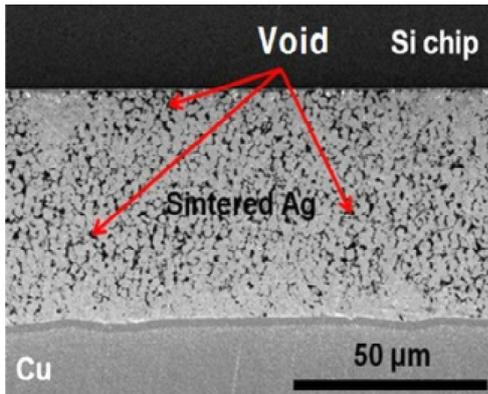


Fig. 7. Cross-sectional image of sintered Ag joint using micro-sized chestnut-burr-like Ag particle paste (adapted from [53]).

perature. In this technology, materials can be bonded with sintering for a long time below 300 °C after applying Ag nano paste to the bonding surface. However, it can degrade bonding strength, long term reliability and conductivity due to the defects like void in Ag sintered as well as increases material cost by using Ag. In addition, it requires pressure to bond resulting in increasing manufacturing cost [53]. Fig. 7 shows the void from the low temperature sintering process with Ag nano particles.

However, TLP bonding has a competitive price of material, bonding and higher productivity as compared to Ag sintering because of a lower bonding time of less than 30 minutes. Moreover, it is superior to conventional brazing for bonding because it can produce higher bonding strength over base material and resistant to hot cracking because the base metal does not melt during bonding.

A favorable TLP bonding has been reported with Ag-Sn and Ni-Sn bonding materials having a bonding strength of around 60.4 MPa in accordance with the research of Lis et al [80]. Table 3 shows the properties of TLP bonding in electronic packaging industry with method such as nano Ag sintering process etc. The bonding properties under the operation of devices can differ from the homologous temperature (TH) according to Eq. (5) as shown below:

$$TH = T_{\text{operation}} / T_{\text{melting}} [K / K], \quad (5)$$

where $T_{\text{operation}}$ is operation temperature of the device, T_{melting} is melting temperature of insert metal. Here, the mechanical properties increase with decreasing TH value. In other words, the higher melting point compared to the operating temperature, better the shear strength and thermal shock property [61]. TH value vary from 0.37 to 0.7 considering

Table 3. Several bonding techniques for electronic packaging.

	Conventional solder	High temp. solder	Silver sintering	TLP bonding
Material	Sn base alloy	Bi, Zn base alloy	Micro/Nano size	Cu-Sn, Cu-Ni silver powder
High temp. sustainability	Re-melting temp. = process temp. Depend on M.P. of solder		Re-melting temp. > 900 °C (performance varies)	Process temp. 400~900 °C (depends on materials)
Process temperature	<250 °C	300~450 °C	250~280 °C	200~300 °C (except Au-Sn)
Process pressure	non or low	non or low	<5 MPa	<1 MPa
Materials cost	Low (Conventional)	Low	High (Nano materials and Silver)	Low (except Au, Ag, In)
Compatibility	High (Conventional)	High (Conventional)	Low	High Similar to conventional soldering process General materials used in power semiconductor packa (Cu, Ni, Sn)
Drawback	Low melting temp.	High process temp.	High pressure High material cost	Long process time Hard to set process condition

its operating condition at 200 °C because Ag sintering at higher than 900 °C and TLP bonding from 400 to 900 °C of $T_{\text{re-melting}}$ temperature.

On the other hand, conventional Sn-3.0%Ag-0.5%Cu (SAC305) solder has the TH value of 0.97. By using bonding process below 300 °C, thermal defects to the device due to CTE mismatch between substrate and device can be reduced.

5.2. TLP bonding for aerospace application

Cai et al. have studied Ti2AlNb TLP bonding for advanced aerospace application [89]. According to their research, Ti2AlNb alloy was used as the base metal and Ti and Ni foil were used as the interlayer to TLP bonding. Here, Ti/Ni interlayer foils were placed with sandwich type between two Ti2AlNb layers. About less than 3 KPa pressure was applied to bond using vacuum furnace with the atmosphere of 2.0×10^{-3} Pa.

The results showed that the Ti2AlNb/Ti/Ni/Ti2AlNb joint was successfully obtained with TLP bonding. In addition, they defined two distinct zones which were isothermal solidified zone I (ISZ) and a thermal solidified zone II (ASZ). Here, ASZ was compressed and the isothermal solidification became the dominant process for the formation of a sound joint with increasing of bonding temperature and time.

5.3. TLP bonding for superalloys

For dissimilar superalloys bonding, brazing, fusion welding, and diffusion bonding were the common bonding processes before. However, as mentioned in previous sections, they have several limitations like IMC growth at the joint, crack propagation in HAZ, and requiring high pressure to bond. Shamsabadi et al. have applied TLP bonding instead of conventional bonding technologies using IN-718, IN-738 superalloys and Ni-base interlayer called MBF-20 to suppress these defects [90]. As a result, dissimilar TLP joint for IN-738/IN-718 system were obtained with MBF-20 interlayer without any pressure at various bonding times and temperatures. According to their study, Larson-Miller equation as shown in Eq. (6) was proposed to estimate the required time for completion of the isothermal solidification since the isothermal solidification rate is controlled by diffusion.

$$P = T_b [C + \ln(t_b)], \quad (6)$$

where T_b is the bonding temperature in Kelvin, t is the bonding time in minutes and C is a system dependent constant. The P value is generally used for analyzing creep rupture data.

Ghomi et al. have also presented TLP bonding for dissimilar Ni-based superalloys of IN738LC and Nimonic75 with Ni-15Cr-3.5B interlayer called MBF-80 at temperatures of 1080 to 1180 °C for different bonding times. As a result, the morphology of the joint consists of three eutectic phases such as α solid solution, Ni and Cr-rich boride by addition of boron into the base metal. In addition, by adding boron, diffusion occurred in the base metal from the interlayer causing DAZ precipitation during a solid-state transformation [91].

6. RELIABILITY AND PROPERTY OF TLP BONDING

The mechanical properties and their reliabilities in TLP bonding can vary with the process parameter, bonding material as well as the change of microstructures. Bajwa et al. have measured the shear strength after thermal cycle of 1000 in SiC TLP bonding using Sn-Ag [67]. The shear strength showed 39.8 MPa as bonding and decreased 37.5 MPa after 1000 cycle, respectively. It was considered that the crack occurring from the edge of the joint interface by CTE mismatch of the bonding material propagates to the center of joint area resulting in degradation of shear strength as shown in Fig. 8. In addition, the shear strength at various bonding pressures were also evaluated with Sn-Ag by Nobeen et al. It was shown that the shear strength of the joint increased with increasing the bonding pressure [82]. Zhang et al. have calculated the activation energy

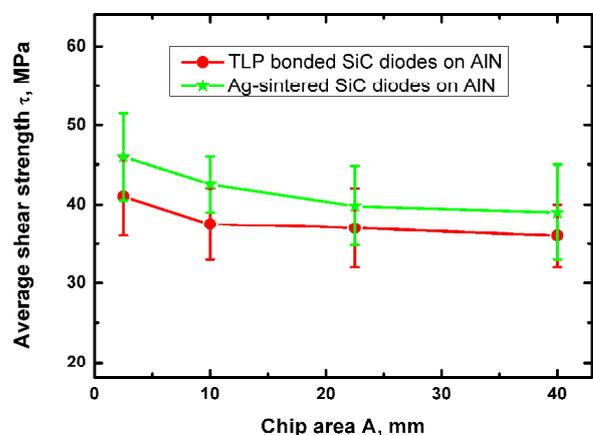


Fig. 8. Average shear strength of TLP bonded and Ag-sintered diodes on AlN substrate with various chip sizes, recalculated from [67].

(Q) which is necessary for IMC growth according to Arrhenius equation (Eq. (3) in Au/In TLP bonding for 3-D chip packaging [92].

The results showed that the activation energy value was measured to be 0.46eV above 150 degrees and 0.23eV below 150 degrees. These values for activation energy are similar with that reported in the studies of Liu and Bjontegaad et al. [93,94].

Afghahi et al. have studied for fatigue properties of temperature gradient transient liquid phase (TGTL) diffusion bonding for Al7075-T6 alloy using liquid gallium interlayer [95]. The sample for fatigue test was bonded at 460 °C under the pressure of 10 MPa for 10 minutes. The experimental results showed that the fatigue life for Al7075-T6 alloy was achieved under 90 MPa and it decreased to 1.2×10^6 cycles by applying the stress amplitude of 90 MPa.

7. CONCLUSIONS

In this study, TLP bonding has been introduced in terms of device bonding method requiring high temperature property of the power module. TLP bonding has been widely used in electronic industry lately and progressed since the beginning of the 1970. It has many advantages such as material and process cost, reduction of bonding time and high temperature reliability. Moreover, it is not necessary for bonding to apply pressure unlike Ag sintering. This tendency for using TLP bonding will be accelerated for near future because of the various restrictions against usage of Pb and expansion of the SiC semiconductor in power module lately. However, it needs more study and interest because there is still room for improvement of exist property in TLP bonding. As it aforementioned, the bonding time for TLP bonding technology is quite long resulting in productivity issues. In order to solve these issues, ultrasonic assisted, current assisted TLP bonding, which can increase the productivity have been suggested but they cause the damage in device and substrate and require the complicated facility as compared to the conventional process. Although the TLP bonding with powder and thermal gradient bonding (TGB) can save a little process time, powder TLP has a defect like Sn residue and pore in the joint and TGB also has a difficult to obtain a process parameter and additional facility. Thus, the demand for TLP bonding is expected to increase because it is possible to use the existing facilities. In addition, the study for inhibition of defect in the joint

and formation of complete IMC reaction between two materials will be important in TLP bonding.

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REFERENCES

- [1] J. F. Lynch, L. Feinstejn and R. A. Huggins // *Weld. J.* **38** (1959) 85.
- [2] W. Welch, J. Chae, S. Lee, N. Yazdi and K. Najafi, In: *13th International Conference on Solid-State Sensors, Actuators and Microsystems* (Seoul, Korea, 2005), p. 1350.
- [3] W. D. Macdonald and T. W. Eagar // *Annu. Rev. Mater. Sci.* **22** (1992) 23.
- [4] G. O. Cook III and C. D. Sorensen // *J. Mater. Sci.* **46** (2011) 5305.
- [5] M. S. Park, S. L. Gibbons and R. Arroyave // *Acta Mater.* **60** (2012) 6278.
- [6] T. C. Illingworth, I. O. Golosnoy, V. Gergely and T. W. Clyne // *J. Mat. Sci.* **40** (2005) 2505.
- [7] J. P. Jung and C. S. Kang // *Mater. Trans.* **37** (1996) 1008.
- [8] J. P. Jung and C. S. Kang // *Mater. Trans.* **38** (1997) 886.
- [9] J. P. Jung, C. D. Lee and C. S. Kang // *J. Kor. Inst. Met. Mater.* **31** (1993) 323.
- [10] J. P. Jung and C. S. Kang // *J. Kor. Inst. Met. Mater.* **33** (1995) 1302.
- [11] J. P. Jung and C. S. Kang // *J. Kor. Weld. Join. Soc.* **13** (1995) 147.
- [12] T. Shinmura, K. Ohsasa and T. Narita // *Mater. Trans.* **42** (2001) 292.
- [13] J. E. Ramirez and S. Liu // *Weld. Research.* **1** (1992) 365.
- [14] M. J. Kim, Y. Zhou and J. P. Jung // *Soldering Surf. Mount Tech.* **19** (2007) 3.
- [15] J. S. Lee, W. Bang, J. P. Jung and K. H. Oh // *Mater. Trans.* **45** (2004) 783.
- [16] J. S. Lee, W. H. Bang, J. P. Jung and K. H. Oh // *Mater. Sci. Forum* **475** (2005) 1869.
- [17] O. G. Cook and C. D. Sorensen // *J. Mater. Sci.* **46** (2011) 5305.
- [18] K. E. Aasmundtveit, T. A. Tollefsen, T. T. Luu, A. Duan, K. Wang and N. Hoivik, In: *European Microelectronics Packaging Conference* (Grenoble, France, 2013), p. 1.

- [19] A. S. Khaja, C. Kaestle, A. Reinhardt and J. Franke, In: *Proc. of the 36th International Spring Seminar on Electronics Technology* (Alba Iulia, Romania, 2013), p. 11.
- [20] B. Gollas, J. H. Albering, K. Schmut, V. Pointner, R. Herber and J. Etzkorn // *Intermetallics* **16** (2008) 962.
- [21] J. Millan, In: *Proc. International Semiconductor Conference* (Sinaia, Romania, 2012), p. 57.
- [22] K. B. Pedersen, L. H. Ostergaard, P. K. Kristensen, P. Ghimire, V. N. Popok and K. Pedersen // *J. Mater. Sci.: Mater. Electron* **27** (2016) 1938.
- [23] D. Venkatramanan, A. K. Adapa and V. John // *Sadhana* **42** (2017) 1.
- [24] A. B. Vinogradov, A. N. Sibirtsev and I. Y. Kolodin // *Rus. Elec. Eng.* **79** (2008) 293.
- [25] O. V. Ryazancev, M. V. Kylik and A. S. Manukyan // *Radioelectronics and Communications Systems* **53** (2010) 442.
- [26] M. Roy and M. Sengupta // *Sadhana* **42** (2017) 153.
- [27] M. V. Kulik and O. V. Ryazancev // *Radioelectronics and Communications Systems* **59** (2016) 369.
- [28] M. B. Barannik, A. N. Danilin, B. V. Efimov, V. V. Kolobov, P. I. Prokopchuk, V. N. Selivanov, A. N. Shevtsov, Y. A. Kopytenko and A. A. Zhamaletdinov // *Seismic Instruments* **46** (2010) 49.
- [29] O. Alavi, M. Abdollah and A. H. Viki // *J. Comput. Electron.* **16** (2017) 1.
- [30] S. Ma, M. Zhang, L. Xia, X. Zhang, C. Wang and K. Yu // *J. Fusion. Energ.* **34** (2015) 261.
- [31] I. W. Suh, H. S. Jung, Y. H. Lee and S. H. Choa // *J. Microelectron. Packag. Soc.* **21** (2014) 7.
- [32] S. S. Kim, In: *Microjoining and Packaging Community Conference* (Seoul, Korea, 2016), p. 149.
- [33] T. Hu, H. Chen and M. Li // *Mater. Des.* **108** (2016) 383.
- [34] S. Kumar, D. H. Jung and J. P. Jung // *IEEE Trans. Compon. Pack.* **A3** (2013) 441.
- [35] S. Kumar, S. Agarwal and J. P. Jung // *Rev. Adv. Mater. Sci.* **34** (2013) 185.
- [36] A. Sharma, S. Kumar, D. H. Jung and J. P. Jung // *J. Mater. Sci.: Mater. Electron.* **28** (2017) 8116.
- [37] S. Kumar, D. H. Jung and J. P. Jung // *J. Mater. Sci.: Mater. Electron.* **24** (2012) 1748.
- [38] S. Kumar, S. Mallik, N. Ekere and J. P. Jung // *Met. Mater. Int.* **19** (2013) 1083.
- [39] D. H. Jung, A. Sharma, K. H. Kim, Y. C. Choo and J. P. Jung // *J. Mater. Eng. Perform.* **24** (2015) 1107.
- [40] D. H. Jung, S. Agarwal, S. Kumar and J. P. Jung // *J. Microelec. Electron. Pack.* **12** (2015) 161.
- [41] D. H. Jung, W. G. Lee and J. P. Jung // *J. Kor. Inst. Met. Mater.* **49** (2011) 635.
- [42] D. H. Jung, A. Sharma, D. U. Lim, J. H. Yun and J. P. Jung // *Met. Mater. Trans. A* **48** (2017) 4372.
- [43] A. Sharma, H. R. Sohn and J. P. Jung // *Met. Mater. Trans. A* **47** (2015) 494.
- [44] A. Sharma, B. G. Baek and J. P. Jung // *Mater. Des.* **87** (2015) 370. .
- [45] D. H. Jung, A. Sharma and J. P. Jung // *J. Mater. Sci.* **52** (2017) 1.
- [46] A. Sharma, Y. J. Jang and J. P. Jung // *Surf. Eng.* **31** (2015) 458.
- [47] H. Greve, S. A. Moeini and F. P. McCluskey, In: *IEEE 64th Electronic Components and Technology Conference* (Orlando, USA, 2014), p. 1314.
- [48] H. S. Chin, K. Y. Cheong and A. B. Ismail // *Met. Mater. Trans. B* **41** (2010) 824.
- [49] Y. Takaku, I. Ohnuma, Y. Yamada, Y. Yagi, Y. Nishibe, Y. Sutou, R. Kainuma and K. Ishida // *J. Jap. Inst. Electron. Packg.* **11** (2008) 141.
- [50] Q. Jiang, S. Mukherjee, A. Dasgupta, D. Shaddock and L. Yin, In: *15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems* (Las Vegas, USA, 2016), p. 1236.
- [51] K. S. Kao, S. C. Chung, C. W. Fan, J. Y. Chang and T. C. Chang, In: *Proc. 2015 International Conference on Electronics Packaging and iMAPS All Asia Conference* (Kyoto, Japan, 2015), p. 546.
- [52] Y. Yamada, Y. Takaku, Y. Yagi, I. Nakagawa, T. Atsumi, M. Shirai, I. Ohnuma and K. Ishida // *Trans. Jap. Inst. Electron. Packag.* **2** (2009) 79.
- [53] R. H. Roh, H. Nishikawa and J. P. Jung // *J. Microelectron. Packag. Soc.* **22** (2015) 15.
- [54] K. Sukanuma and K. S. Kim // *J. Mater. Sci. Mater. Electron.* **18** (2006) 121.
- [55] Z. Mei and J. W. Morris // *J. Electron. Mater.* **21** (1992) 599.
- [56] H. Chin, K. Cheong and A. Ismail // *Met. Mater. Trans. B* **41** (2010) 824.

- [57] S. W. Yoon, M. D. Glover and K. Shiozaki // *IEEE Trans. Power Electron.* **28** (2013) 2448.
- [58] H. Greve, L. Y. Chen, I. Fox and F. P. McCluskey, In: *IEEE 63rd Electronic Components and Technology Conference* (Las Vegas, USA, 2013), p. 435.
- [59] J. F. Li, P. A. Agyakwa and C. M. Johnson // *Acta Materialia* **58** (2010) 3429.
- [60] J. Strogies and K. Wilke, In: *Proc. of the 5th Electronics System-integration Technology Conference* (Helsinki, Finland, 2014), p. 1.
- [61] T. A. Tollefsen, A. Larsson, O. Lřvvik and K. Aasmundtveit // *Met. Mater. Trans. B* **43** (2012) 397.
- [62] C. C. Lee, C. Y. Wang and G. Matijasevic // *J. Electron. Packag.* **115** (1993) 201.
- [63] J. P. Jung and C. S. Kang // *Kor. Weld. Join. Soc.* **13** (1995) 125.
- [64] F. Lang, H. Yamaguchi, H. Nakagawa and H. Sato, In: *Proc. 13th Int. Conf. Electron. Packag. Tech. High Dens. Packag.* (Guilin, China, 2012), p. 157.
- [65] C. Ehrhardt, M. Hutter, H. Oppermann and K. D. Lang, In: *Proc. 64th Electron. Compo. Tech. Conf.* (Orlando, USA, 2014), p. 1321.
- [66] A. A. Bajwa, Y. Y. Qin, R. Zeiser and Wilde, In: *CIPS 2014; 8th International Conference on Integrated Power Electronics Systems* (Nuremberg, Germany, 2014), p. 1.
- [67] A. A. Bajwa and J. Wilde // *Microelectron. Reli.* **60** (2016) 116.
- [68] C. Honrao, T. C. Huang, M. Kobayashi, V. Smet, P. M. Raj and R. Tummala, In: *IEEE 64th Electronic Components and Technology Conference* (Orlando, USA, 2014), p. 1160.
- [69] H. Greve, S. A. Moieni, F. P. McCluskey and S. Joshi, In: *66th Electronic Components and Technology Conference* (Las Vegas, USA, 2016), p. 2561.
- [70] O. Mokhtari and H. Nishikawa // *Adv. Powd. Tech.* **27** (2016) 1000.
- [71] O. Mokhtari and H. Nishikawa // *J. Mater. Sci.: Mater. Electron.* **27** (2016) 4232.
- [72] H. Ji, M. Li, S. Ma and M. Li // *Mater. Des.* **108** (2016) 590.
- [73] H. Ji, M. Li and M. Li, In: *17th International Conference on Electronic Packaging Technology* (Wuhan, China, 2016), p. 295.
- [74] X. Yu, S. He and H. Nishikawa // *Scripta Materialia* **110** (2016) 101.
- [75] H. Ikeda, S. Sekine and R. Kimura, In: *66th Electronic Components and Technology Conference* (Las Vegas, USA, 2016), p. 426.
- [76] H. Y. Zhao, J. H. Liu, Z. L. Li, Y. X. Zhao, H. W. Niu, X. G. Song and H. J. Dong // *Mater. Lett.* **186** (2017) 283.
- [77] H. Ji, Y. Qiao and M. Li // *Scripta Materialia* **110** (2016) 19.
- [78] B. Liu, Y. Tian, J. Feng and C. Wang // *J. Mater. Sci.* **52** (2017) 1943.
- [79] T. L. Yang, T. Aoki, K. Matsumoto, K. Toriyama, A. Horibe, H. Mori, Y. Orii, J. Y. Wu and C. R. Kao // *Acta Materialia* **113** (2016) 90.
- [80] A. Lis and C. Leinenbach // *Min. Met. Mater. Soc.* **44** (2015) 4576.
- [81] N. S. Bosco and F. W. Zok // *Acta Materialia* **53** (2015) 2019.
- [82] N. S. Nobeen, R. Imade, B. Lee, E. Phua, C. Wong and C. Gan, In: *Proc. of 15th Electronics Packaging Technology Conference* (Singapore, Singapore, 2013), p. 647.
- [83] H. Shao, A. Wu, Y. Bao, Y. Zhao and G. Zou // *J. Mater. Sci.: Mater. Electron.* **27** (2016) 4839.
- [84] J. H. Liu, H. Y. Zhao, Z. L. Li, X. G. Song, H. J. Dong Y. X. Zhao and J. C. Feng // *J. Alloys Compd.* **692** (2017) 552.
- [85] H. Shao, A. Wu, Y. Bao, Y. Zhao and G. Zou // *Mater. Sci. Eng. A* **48** (2017) 221.
- [86] V. I. Dybkov // *J. Phys. Chem. Solids.* **53** (1992) 703.
- [87] G. Humpston, D. M. Jacobson and S. P. S. Sangha // *Endeavour* **18** (1994) 55.
- [88] H. Chin, K. Cheong and A. Isnauk // *Met. Mater. Trans. B* **41** (2010) 824.
- [89] X. Q. Cai, Y. Wang, Z. W. Yang, D. P. Wang and Y. C. Liu // *J. Alloys Compd.* **679** (2016) 9.
- [90] A. Y. Shamsabadi, R. Bakhtiari and G. Eisaabadi // *J. Alloys Compd.* **685** (2016) 896.
- [91] M. K. Ghomi, S. Nategh and S. Mirdamadi // *Mater. Tech.* **50** (2016) 365.
- [92] W. Zhang and W. Ruythooren // *J. Electron. Mater.* **37** (2008) 1095.
- [93] Y. M. Liu and T. H. Chuang // *J. Electron. Mater.* **29** (2000) 405.
- [94] J. Bjontegaard, L. Buene, T. Finstad, O. Lonsjo and T. Olsen // *Thin Solid Films* **101** (1983) 253.
- [95] S. S. S. Afghahi, A. Ekrami, S. Farahany and A. Jahangiri // *Trans. Nonferrous Met. Soc. China* **25** (2015) 1073.