Interconnection Technology Based on InSn Solder for Flexible Display Applications

Kwang-Seong Choi, Haksun Lee, Hyun-Cheol Bae, Yong-Sung Eom, and Jin Ho Lee

A novel interconnection technology based on a 52InSn solder was developed for flexible display applications. The display industry is currently trying to develop a flexible display, and one of the crucial technologies for the implementation of a flexible display is to reduce the bonding process temperature to less than 150°C. InSn solder interconnection technology is proposed herein to reduce the electrical contact resistance and concurrently achieve a process temperature of less than 150°C. A solder bump maker (SBM) and fluxing underfill were developed for these purposes. SBM is a novel bumping material, and it is a mixture of a resin system and InSn solder powder. A maskless screen printing process was also developed using an SBM to reduce the cost of the bumping process. Fluxing underfill plays the role of a flux and an underfill concurrently to simplify the bonding process compared to a conventional flip-chip bonding using a capillary underfill material. Using an SBM and fluxing underfill, a 20 μm pitch InSn solder SoP array on a glass substrate was successfully formed using a maskless screen printing process, and two glass substrates were bonded at 130°C.

Keywords: Flexible display, InSn solder, solder-on-pad technology, maskless screen printing technology, fluxing underfill, solder powder, low-temperature bonding.

Kwang-Seong Choi (corresponding author, kschoi@etri.re.kr), Haksun Lee (hlee435@etri.re.kr), Hyun-Cheol Bae (hcbae@etri.re.kr), Yong-Sung Eom (yseom@etri.re.kr), and Jin Ho Lee (leejinho@etri.re.kr) are with the IT Convergence Technology Research Laboratory, ETRI, Daejeon, Rep. of Korea.

I. Introduction

Flexible displays and electronics are remarkable owing to market demand. As a solution, transparent plastic films have been developed for display applications. Anisotropic conductive films (ACFs) have been widely used as interconnection materials in both flat panel display and semiconductor packaging applications [1]. Since the electrical contacts of ACF interconnections rely on the mechanical contacts between the conductive particles in the ACF and metal electrodes on a substrate, as shown in Fig. 1(a), they inherently exhibit high electrical contact resistances and low adhesion. In addition,
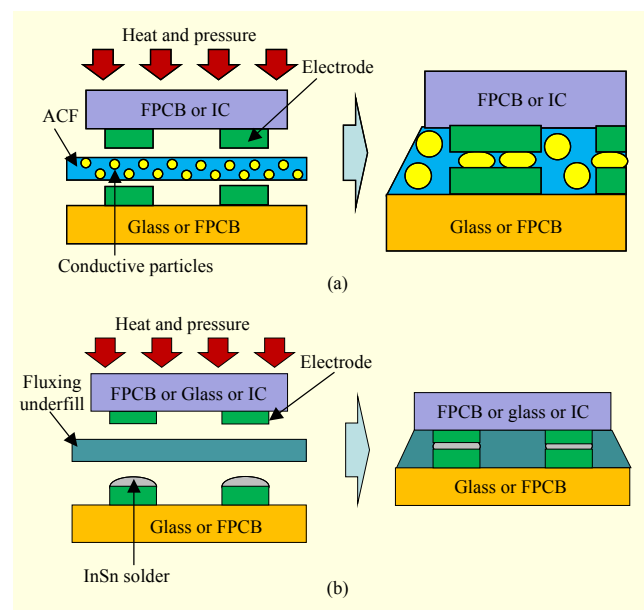

Fig. 1. Bonding process using: (a) ACF and (b) InSn solder and fluxing underfill.

the usual bonding temperature during ACF bonding is higher than 150°C, which may lead to a permanent deformation of flexible substrates such as polyethylene terephthalate and polyethersulfone during the bonding process.

To reduce the bonding temperature of an ACF display interconnection, several technologies have been proposed. Conductive nano-scale films with nano-silver powder at a bonding temperature of 180°C were formulated [2]. Instead of using conductive particles in an ACF, SnBi solder powder and nanofiber were used through an ultrasonic bonding method to generate a bonding temperature of 200°C [3]. Combinations of acrylic-based film, SnBi solder powder, and an ultrasonic-assisted thermocompression bonding method were proposed to reduce the ACF bonding temperature to 150°C [4]. UV curing of an ACF using a photo-active curing agent (PA-ACF) was introduced to decrease the bonding temperature to 110°C [5]. These studies show a similar approach in using conductive particles as a conductive medium so that the electrical resistance between electrodes may increase, especially for a fine-pitch application of less than 40 μm owing to a limited number of conductive particles in a small electrode area. The material formulation and process for PA-ACFs are considered to be complicated.

In this paper, we propose a novel interconnection technology using 52InSn solder-on-pad (SoP) and fluxing underfill technology for display applications. Figure 1(b) shows the novel process; that is, InSn SoP on the metal electrodes on a substrate is formed, and two substrates are bonded using a fluxing underfill. Since the melting point of InSn solder is 118°C, low-temperature bonding below 150°C is achievable. The whole electrode area is used for the electrical contacts, whose joints show a lower electrical contact resistance than with an ACF, which achieves its electrical contacts through the mechanical point contacts between conductive particles in the ACF and electrodes on a substrate. In addition, a solder joint usually forms an intermetallic compound with a UBM layer on the metal electrodes; thus, it exhibits higher adhesion strength. To implement such a novel technology, novel materials were designed; that is, a solder bump maker (SBM) for the bumping process and a fluxing underfill for the bonding process. An SBM is based on the rheological behavior of the solder in a resin [6]–[17]. The resin used is distinguishable as having low viscosity around the melting point of the solder, a deoxidizing capacity of the oxide layer on the surface of the solder, and no out-gassing related with the solvents during the bumping process. A maskless screen printing process, at a low cost, was developed using an SBM for implementing a fine-pitch SoP. A conventional flip-chip bonding with a capillary underfill usually requires more than six steps to complete the bonding process: dispensing a flux on a substrate, pitch and place of a

chip on the substrate, reflow process, cleaning process of flux residues, drying the substrate, displensing an underfill, and curing the underfill. The fluxing underfill was designed to have the characteristics of a flux and underfill at the same time without forming voids inside the underfill during the bonding process. Therefore, only three steps for the bonding are necessary: dispensing a fluxing underfill, the alignment of two substrates, and thermocompression bonding. We evaluated the wetting behavior of InSn solder in the SBM and fluxing underfill resins on Au- and Cu-finish electrodes, respectively. An InSn SoP array with a 20 μm pitch is made using a maskless screen printing process. A differential scanning calorimetry (DSC) analysis of the fluxing underfill was carried out to determine the proper bonding process. After that, low-temperature bonding below 150°C for two glass substrates using a fluxing underfill was successfully performed, and the microstructure of the bonded joint was analyzed.

II. Materials and Experiments

1. Materials

The resin of an SBM consists of a polymer matrix, a deoxidizing agent, and additives. The roles and requirements of the constituents of the resin were reported in previous studies [6]–[17]. To control the surface tensions in the bumping process, we investigated several candidate materials for the polymer matrix and additives of the SBM. After choosing the proper materials, the effects of the mixing ratio between the polymer matrix, deoxidizing agent, and additives was investigated to obtain the proper interactions between the solder powder and the metal pads during the bumping process. As in previous reports, the solvent was not mixed in the resin to minimize the out-gassing from the resin during the bumping process. For the bumping process, InSn solder powder is blended with the resin. Figure 2 shows the particle-size distribution of InSn solder powder. The average size of the solder is 2.43 μm, and its range is from 0.8 μm to 9 μm. The volumetric mixing ratio between the resin and solder powder
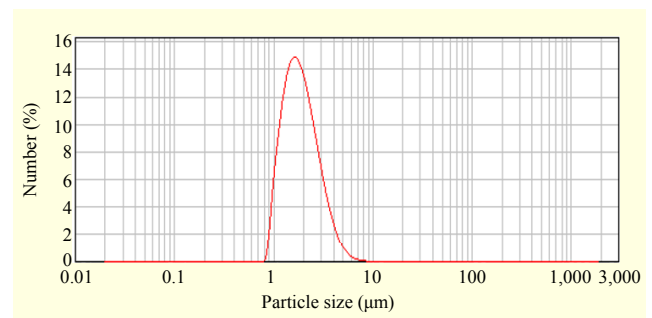
Fig. 2. Particle-size distribution of InSn solder powder.

was 8:2.

The resin of the fluxing underfill consists of a polymer matrix, a deoxidizing agent, a hardener, and additives. A hardener reacts with a polymer matrix, which leads to curing. The cured fluxing underfill enhances the mechanical and environmental reliability of the bonded joint. The material design of the fluxing approach is quite similar with that of the SBM. However, a careful material design is necessary to prevent a chemical reaction between a deoxidizing agent and a hardener. This reaction may disturb the function of the fluxing underfill. Additionally, the reaction order between the constituents of the fluxing underfill is important. A deoxidizing agent reduces the oxide layers of the solder powder and metal pads on a substrate with temperature, and then chemical reactions between a polymer matrix and hardener then occur, allowing the underfill to be cured. If the reaction order is reversed, then the bonding cannot be appropriately conducted.

2. Experiments

For investigation of the compatibility between the 52InSn solder and resin systems of an SBM and fluxing underfill, the wetting phenomenon of an InSn solder ball used in the resins was observed. The electrodes are made of an electro-plated Au and Cu finish on a laminated FR-4. The peak temperature for the wetting test was 150°C. For bumping using an SBM and fluxing underfill, an under bump metallization (UBM) pad array with a pitch of 20 μm on a glass substrate was prepared. The UBM structure was made of Ti/Ni/Cu/Au, and its length was 0.8 mm.

The whole bumping process using SBM was developed as shown in Fig. 3. First, the SBM was placed on a glass substrate. Its working area and thickness were defined using a guide. The thickness of the guide is 35 μm. The guide is not a conventional mask in that it does not isolate each metal pad on the substrate by apertures. We did not use a mask owing to its unsuitability for fine-pitch applications of less than 130 μm, because of the process faults related with the mask with the miniaturized apertures, and because of the high fabrication cost of fine-pitch masks. As in the screen printing process, a blade was used to make the thickness of the SBM uniform. The temperature of the substrate was increased to 150°C in an oven. The dwell time at the peak temperature was 1 min. The oxygen amount in the oven was controlled at 1,000 ppm. A cleaning process was then performed to remove the remaining SBM on the substrate.

An isothermal DSC at various temperatures was conducted using a fluxing underfill to characterize the curing behavior. The proper bonding conditions using the fluxing underfill were determined from the results of the DSC analyses. To confirm
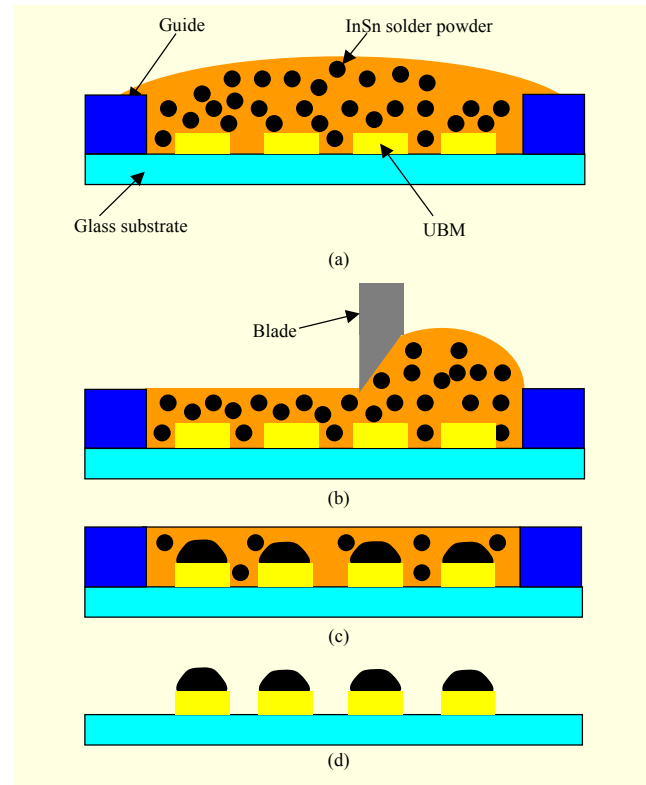

Fig. 3. Process flow of SoP using SBM: (a) putting SBM on a substrate with a guide, (b) printing process, (c) bump formation with temperature, and (d) cleaning process.
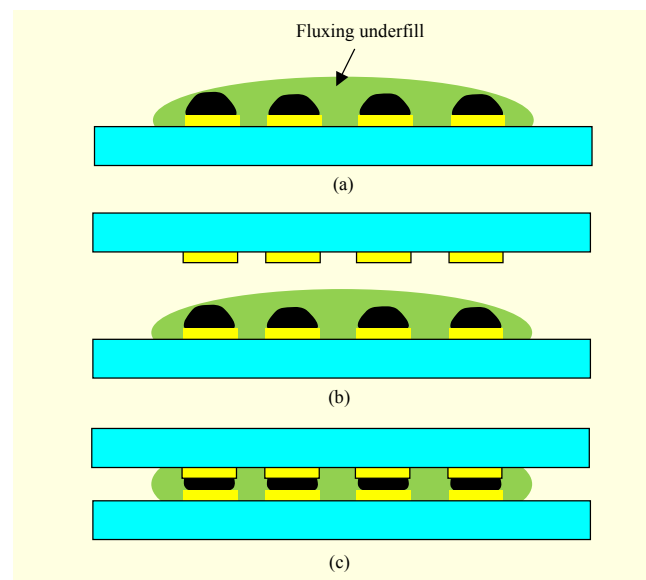

Fig. 4. Bonding process using fluxing underfill: (a) dispensing fluxing underfill, (b) align two glass substrate, and (c) thermocompression bonding.

the bonding condition, we visually observed the behavior of an InSn solder lump in the fluxing underfill based on temperature. The melting and wetting behaviors of the solder lump were

also dynamically measured based on temperature.

Figure 4 shows the bonding process of two glass substrates. An InSn solder bump array was formed on a glass substrate and only a UBM layer was on the other substrate. The fluxing underfill was dispensed using a syringe. The glass substrate was aligned using a flip-chip bonding machine. Thermocompression bonding was done using this machine. After bonding, a cross-section SEM image of the bonded joint was observed to investigate its microstructure.

III. Results and Discussion

Figure 5 shows the wetted InSn solder balls on the Au- and Cu-finished electrodes (Figs. 5(a) and 5(b), respectively) in the resin for the SBM, and on the Au- and Cu-finished electrodes (Figs. 5(c) and 5(d), respectively) in the resin for the fluxing underfill. No pressure was applied on the solder balls during the wetting test. The wetting angles of the solders on the Au- and Cu-finished electrodes in the resin for the SBM were 42.3° and 27°, respectively. The wetting angles of the solders on the Au- and Cu-finished electrodes in the resin for the fluxing underfill were 30° and 23°, respectively. Both resins show lower wetting angles of the solder on the Cu-finished electrodes than those on the Au-finished electrodes. The deoxidizing agent can effectively reduce the oxide layers on both the Cu-finished electrodes and the solder. The deoxidizing capability of the fluxing underfill is better than that of the SBM. This means that the resins enable the wetting of the solders regardless of the types of surface finish, showing the versatility of the resins.

An SEM image of the InSn SoP array formed using the SBM is shown in Fig. 6. A quite uniform SoP array was obtained using a maskless screen printing process, which is a low-cost process. A single guide can be used many times because there is no aperture in the guide for this process; thus, there are no process faults such as a skipping or slum observed during the screen printing process with a mask.

Figure 7 shows the proposed bumping mechanism during the reflow process as described in Fig. 3(c). The solder powder is dispersed evenly in the resin of the SBM after the printing process, as shown in Fig. 7(a). As temperature is increased, the viscosity of the resin is reduced, as shown in Fig. 7(b), and the solder powder tends to settle down on the substrate because of the gravity force on the solder powder. Then, the deoxidizing agent reduces the oxide layer on the solder powder so that they can combine with each other or they can react with the UBM pads on the substrate to decrease the surface energy of the solder powder. The bumping process is considered to be confined only near the UBM pads. It is inferred that the solder powder in the distance could not participate in this bumping
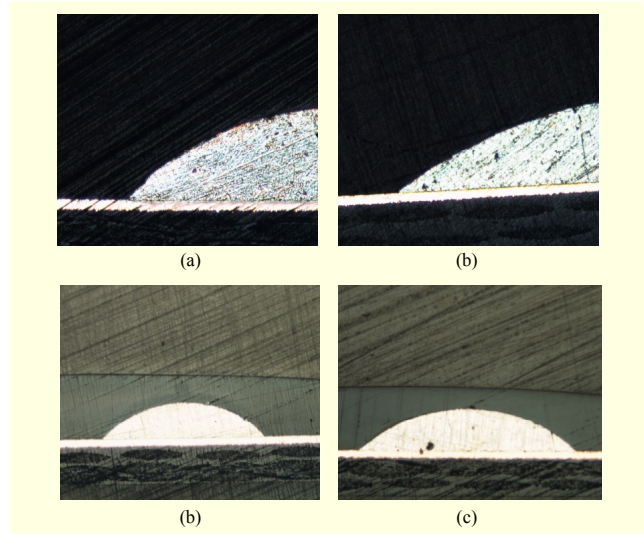

Fig. 5. Wetted InSn solder balls on (a) Au- and (b) Cu-finished electrodes in resin for SBM, and on (c) Au- and (d) Cu-finished electrodes in resin for fluxing underfill.
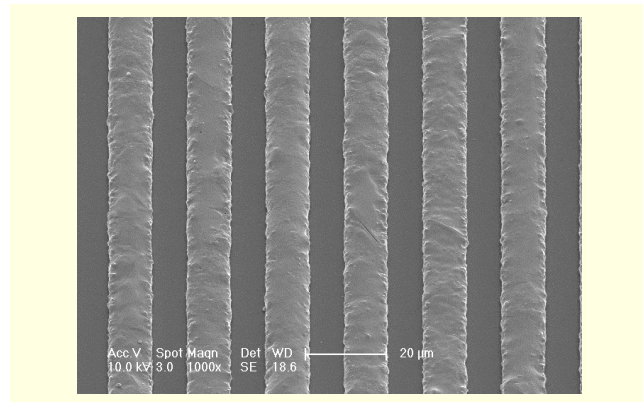

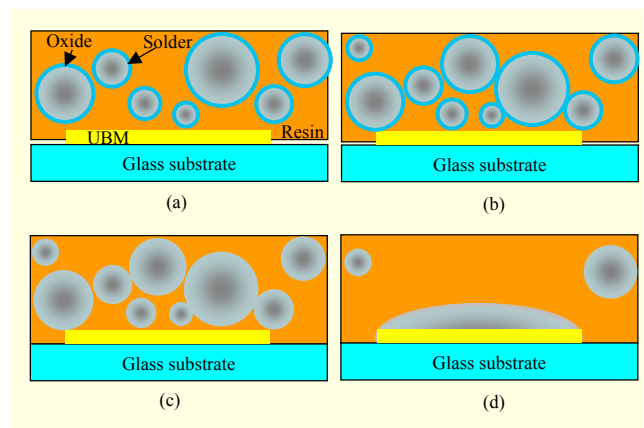Fig. 6. SEM image of InSn SoP array formed with a pitch of 20 μm.

Fig. 7. Proposed bumping mechanism during reflow process: (a) printed SBM, (b) settling down of solder powder at elevated temperature, (c) reduction of oxide layer on solder powder, and (d) formed solder bump on UBM pad.

Table 1. Comparison of interconnection technologies based on ACF, screen printing, and SBM.

Items	ACF	Screen printing	SBM
Electrical conducting medium	Polymer beads coated with Ni and Au	Solder, usually, SnAgCu	Solder, InSn, in this study
Contact mechanism	Mechanical contact between conducting particles and metal pads	Intermetallic compounds between solder and UBM pads	Intermetallic compounds between solder and UBM pads
Process of conducting medium	Electroless plating of Ni and Au on polymer beads, 30 μm pitch	Screen printing with a mask and reflow, limited to a pitch of 130 μm	Maskless screen printing process, applicable to 20 μm and a finer pitch

process and hence remained in the resin. If the time spent at peak temperature is increased, then the solder bridges between the SoP array can be observed. This means that there is a process window for this process, which is one of the on-going study topics for the user of our model.

The diameter of the solder powder for the bumping process is generally necessary to be less than one-fifth of the width of the UBM pad on a substrate for good solder bumping using screen printing. Therefore, the diameter distribution shown in Fig. 2 may be considered inappropriate for a UBM with a 20 μm pitch on a glass substrate. Although the pitch is as small as 20 μm, the length of the UBM is as large as 0.8 mm; thus, the ratio between the maximal diameter of the solder powder and the longitudinal length of the UBM is about 0.1, which is small enough to obtain a uniform SoP array. The peak temperature of the bumping process needs to be lower than 150°C, which is the on-going topic of this study.

Table 1 compares the interconnection technologies based on ACF, screen printing, and SBM. As explained earlier, ACF features mechanical contacts between polymer beads coated with Ni and Au and metal pads on a substrate. The process flow of the screen printing process is almost the same as that of SBM, except for whether to use a mask or not. The screen printing process uses a solder paste, which includes a lot of solvents. During the bumping process, the solvents are vaporized so that the viscosity of the solder paste increases suddenly. Because of that, the solder bump array through the screen printing process would be shorted without a mask. Even when a mask is used, the process cannot be used for a pitch less than 130 μm because of the difficulties of making a mask with such a fine pitch.

On the contrary, the bumping process using the SBM can be applicable to such a fine pitch of 20 μm without a mask. No solvents are added into the SBM, and the chemical reactions
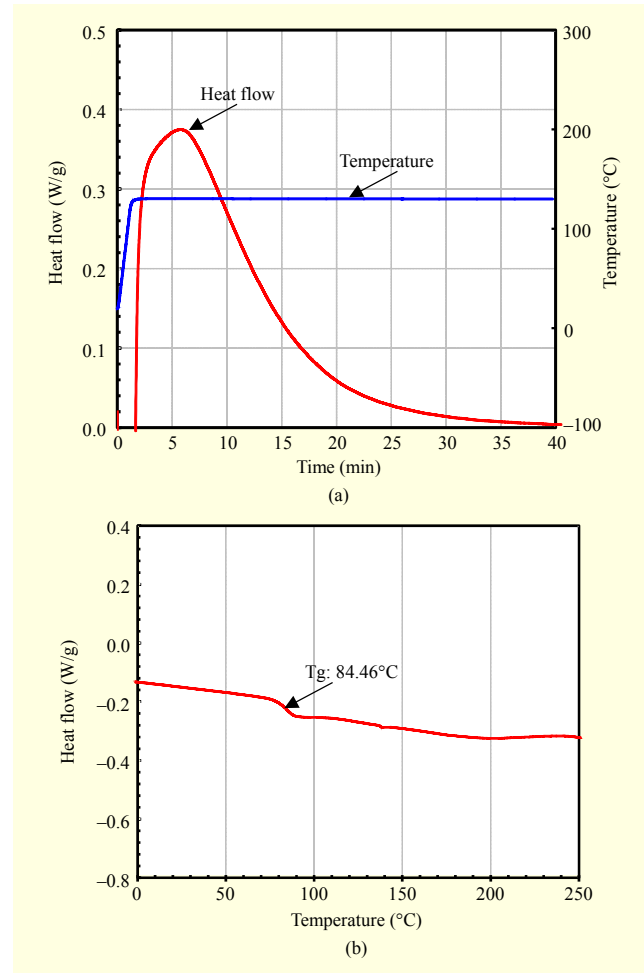
Fig. 8. (a) Isothermal DSC scan of fluxing underfill at 130°C and (b) dynamic DSC scan of fluxing underfill in (a).

between the polymer matrix and other chemical components are controlled to make the cleaning process possible after the reflow process. Therefore, the viscosity of the SBM after the reflow does not need to be increased by much. The remaining solder powder in the polymer resin, after the reflow process, stays isolated from each other by the polymer resin and can be washed away with the resin during the cleaning process. Figure 8(a) shows the measured isothermal DSC scans of the fluxing underfill at 130°C. The heat of the chemical reactions in the fluxing underfill tended to increase, decrease, and then saturate as time passed. Figure 8(b) shows the measured dynamic DSC scans of the fluxing underfill in Fig. 8(a), scanned isothermally at 130°C. Here, the heating rate is 10°C/min. We observed the glass transition temperature of the fluxing underfill, cured during the isothermal DSC scan. There was almost no chemical reaction at up to 250°C, which means that the fluxing underfill was fully cured during the isothermal DSC scan at 130°C.

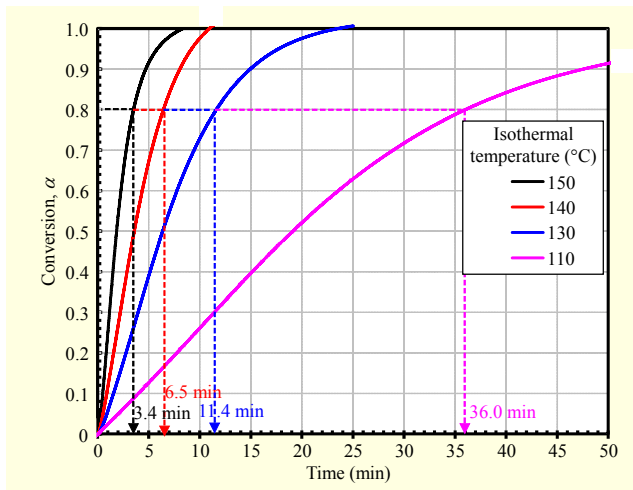We measured the isothermal DSC scans at various

Fig. 9. Dependence on the degree of conversion of the fluxing underfill based on the temperature.

Fig. 10. Dynamic visual observation of behavior of InSn solder lump in fluxing underfill with temperature.

temperatures and analyzed the dependence of the degree of conversion of the fluxing underfill with temperature, as shown in Fig. 9. As the temperature increased, the time to reach the degree of curing or a conversion of 0.8, which is a criterion of the cured polymer used in this study, was decreased. The degree of conversion was obtained by calculating the ratio between the measured heat of the reaction of the fluxing underfill at a specific time and the measured total heat of the reaction of the fluxing underfill. The conversion times at 110°C, 130°C, 140°C, and 150°C were 36 min, 11.4 min, 6.5 min, and 3.4 min, respectively. Since the bonding temperature using the fluxing underfill should be below 150°C, the bonding at 130°C is considered proper, though the duration of 11 min is considered somewhat longer than in conventional flip-chip bonding. However, if we consider the post-curing process of the bonded joints, then the bonding time can be shortened.

To confirm the process temperature, we observed dynamically the behavior of an InSn solder lump in the fluxing underfill with temperature, as shown in Fig. 10. The heating rate was 2°C/s. When the temperature reached 126°C, the InSn solder lump started to melt. When the temperature reached above 128°C, the InSn solder was fully wet on the metal. This therefore proves that solder can melt, and the deoxidizing agent in the fluxing underfill can effectively remove the oxide layers on the InSn solder. It should be noted that the time for the solder lump to wet on the substrate is less than 10 s. So, the bonding time can be set at around 10 s, which is long enough for a high throughput of the bonding process. From the results in Figs. 9 and 10, it can be concluded that the proper temperature of the bonding process for InSn solder using a fluxing underfill is 130°C.

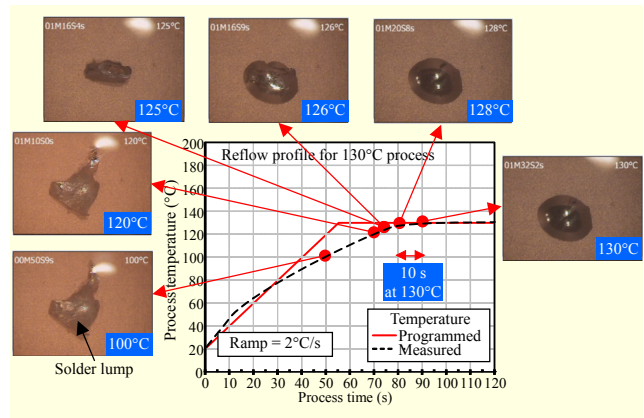The thermocompession bonding of a glass substrate with an InSn SoP array and a glass substrate with an UBM array was
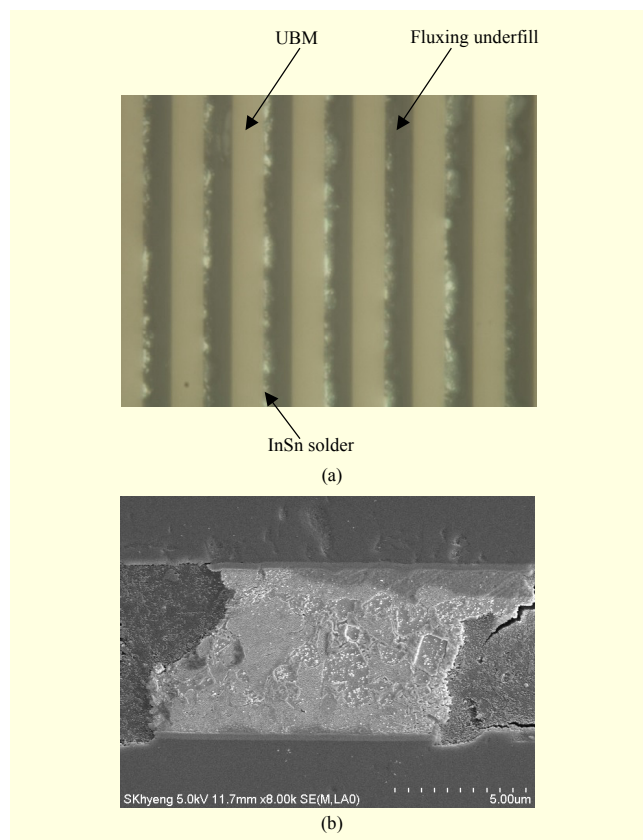

Fig. 11. (a) Optical photograph of top surface of bonded substrates and (b) cross-sectional SEM image of InSn joint.

performed under a process temperature of 130°C. Figure 11(a) shows an optical photograph of the top surface of the bonded two-glass substrate. InSn solder was partly observed next to the UBM, owing to the misalignment during the bonding. Figure 11(b) shows the InSn solder joint and interface between the solder and UBM layer. The misalignment observed was about 2 μm. The intermetallic compounds were observed at the

interface between the solder and UBM pads. It can be concluded that the bonded InSn solder joint is mechanically reliable with the UBM layer owing to the presence of the intermetallic compounds at the interface.

IV. Conclusion

A novel interconnection technology based on 52InSn solder was developed for display applications. Using a novel bumping material, SBM, with InSn solder powder and a maskless screen printing process, an InSn SoP array with a 20 μm pitch on a glass substrate was successfully formed. To accomplish low-temperature bonding at below 150°C with a simplified process, a fluxing underfill was developed. Using the fluxing underfill, the bonding temperature for an InSn SoP array on a glass substrate was decreased to 130°C. The bonded joint shows a good mechanical robustness owing to the presence of intermetallic compounds between the InSn solder joint and UBM layer on a substrate.

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Kwang-Seong Choi received his BS degree in material science and engineering in 1995 from Hanyang University, Seoul, Rep. of Korea and his MS degree in electronic material science and engineering in 1995 and PhD degree in telecommunication engineering in 2008 from the Korea Advanced Institute of Science and Technology, Daejeon, Rep. of Korea. From 1995 to 2001, he was with Hynix Semiconductor Ltd., Incheon, Rep. of Korea, where he was involved in the development of chip scale packages, PoP, and high-speed electronic packages for DDR, Rambus, and RF devices. Since 2001, he has been with the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea, where he is currently working as a principal member of the engineering staff. His research interests include the development of materials and processes for 3D ICs with through-silicon via, next-generation displays, and silicon photonics.

Haksun Lee received his BS degree in electrical engineering from Purdue University, West Lafayette, IN, USA, in 2010 and his MS degree in electrical engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 2012. Since 2012, he has been a researcher with the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea. His research interests include the development of novel interconnections and fine-pitch flip-chip technologies.

Hyun-Cheol Bae received his BS and MS degrees in electrical engineering from Dongguk University, Seoul, Rep. of Korea, in 1999 and 2001, respectively and his PhD degree in electrical engineering from Chungnam National University, Daejeon, Rep. of Korea, in 2009. Since 2001, he has been with the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea, where he is currently working as a senior researcher. His current research interests include the design and fabrication of integrated passive devices, 3D stacked chip packaging using through-silicon via, and wafer-level packaging for MEMS devices.

Yong-Sung Eom received his BS degree in aerospace and mechanical engineering from the Korea Aerospace University, Seoul, Rep. of Korea, in 1988; his MS degree in aerospace engineering from the Korea Advance Institute of Science and Technology, Daejeon, Rep. of Korea, in 1991; and his PhD degree in material science and engineering from École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, in 1999. From 1991 to 1995, he was a design and process engineer for the composite materials of the MD-11 Aircraft Spoiler with the Korea Institute of Aeronautical Technology at Korean Air Ltd., Seoul, Rep. of Korea. From 2000 to 2001, he worked at Hynix Semiconductor Ltd., as a packaging engineer for memory devices. Since 2001, he has been with the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea, where he is currently working as a principal member of the engineering staff. His research interests include the development of interconnection materials based on polymer for electronic packaging and process design for 3D-IC and MEMS packaging.

Jin Ho Lee received his BS degree in physics from Kyungpook National University, Daegu, Rep. of Korea, in 1980; his MS degree in physics from Korea University, Seoul, Rep. of Korea, in 1982; and his PhD degree in physics from Kyungpook National University in 1998. Since 1982, he has been with the Electronics and Telecommunications Research Institute (ETRI), Daejeon, Rep. of Korea, where he has been involved in the development of semiconductor devices and advanced flat-panel display devices, such as memory devices, TFTs, flexible devices, and power devices. He is currently the managing director of the IT Components and Materials Industry Technology Research Department in ETRI.