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Novel Silver Solid-State Bonding Designs Between Two Copper Structures

Yi-Ling Chen and Chin C. Lee

Abstract—Both copper (Cu) and silver (Ag) have been studied extensively for electrical conductor applications. To expand the applications, two bonding designs were implemented in this paper. For the first design, a 50- μm Ag layer was annealed at 400 °C to increase Ag grain size, thereby making it more ductile. For the second design, a 5- μm Ag layer with cavities was created to release the thermal induced stress and allow easier plastic deformation for the bonding medium. For both designs, the resulting Cu substrates were bonded to Cu chips by the solid-state bonding process. The cross sections of bonded samples show no visible voids or gaps on Cu/Ag and Ag/Cu interfaces. The breaking forces of ten samples tested far exceed the requirement specified in the military standards MIL-STD-883J Method 2019.9. The successful demonstrations of solid-state bonding between Ag and Cu should open the possibility of bringing alternatives for bonding methods in the field of electronic packaging.

Index Terms—Copper (Cu), die attachment, electronic packaging, high-temperature electronics, silver (Ag), solid-state bonding.

I. INTRODUCTION

IN ELECTRONIC devices and packages, bonding of two objects is often needed on various interfaces of the packages. The resulting joints provide structure buildup, electrical connection, and heat dissipation. Fundamentally, all bonding methods can be divided into two categories. The first type of method involves molten phase of the bonding medium. The most popular example is the soldering process [1], [2]. The other method utilizes solid-state process. An example of solid-state bonding is the wire bonding process for interconnection using thermal and ultrasonic energy [3]. For either bonding method, various bonding media are available in the market for different applications. Traditional bonding media include conductive adhesives, lead-free tin-based solders, and gold–tin (Au–Sn) eutectic solders [4]–[6]. The conductive adhesives and lead-free solders cannot sustain temperatures higher than 150 °C [7]. The maximum operating temperature of eutectic Au–Sn solders is 200 °C [8]. For high-temperature electronic modules incorporating silicon carbide and gallium-nitride-based devices, a new bonding

medium for high-temperature applications is the nanosilver (Ag) paste [9]. After sintering, the paste can be turned into pure Ag and then would be able to handle high operating temperature. The sintering process often requires relatively high temperature and pressure [10], [11]. The resulting Ag joints cannot be made pore-free.

In this paper, the solid-state bonding processes between two copper (Cu) pieces using Ag as the bonding medium have developed successfully. The upper Cu piece emulates the semiconductor chip, and the lower one is the substrate. Chips of Cu instead of Si were chosen to ensure that the breakage during shear test does not start inside the chip. On the Ag/Cu bonding interface, Ag and Cu need to deform and flow so that the Ag and Cu surface profiles can mate within atomic distance to realize solid-state bonding [12]. Thus, the bonding processes were performed at 300 °C with the pressure of 6.89 MPa (1000 psi) to bring the Ag and Cu surface profiles within atomic distance. It is worth mentioning that this pressure is less than 10% of what is used in industrial thermocompression processes [13]–[15]. Some preliminary results were presented recently [16].

In this paper, the fracture modes and fracture surface analyses were studied. In addition, an innovative structural design of creating cavities in the Ag bonding layer is reported to make easier plastic deformation occur in the solid-state bonding process. With this design, the flow distance is not set by the chip size. That is determined by the pattern on the Ag bonding layer. In other words, the material flow distance is made independent of the chip size. Importantly, the structures bonded with the Ag solid-state process are expected to sustain high operating temperatures, constrained only by the 780 °C eutectic temperature of the Ag–Cu binary system. In the bonding designs, electromigration is also not a concern. The Ag joints are mainly used as die attach joints to provide a mechanical fixation of the die on its substrate. No current flows through the Ag joints. On the other hand, if current flow through Ag joints, current density would be relatively small because of the large bonding area. For another form of migration, which is caused by bias, it will not occur in this bonding design due to the absence of dielectric layer [17].

In what follows, the experiment designs and procedures are presented first in Section II. The experimental results are reported and discussed in Section III. A summary is then given in Section IV.

II. MATERIALS AND METHODS

The fundamental concept of solid-state bonding refers to the atomic interaction between solid material A and solid

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Fig. 1. Fabrication steps of Ag layer with cavities. (a) Photoresist coating on Cu substrate with Ag layer and UV exposure through a photomask. (b) Photoresist development. (c) Electroplating Ag on the Cu substrate. (d) Ag layer with cavities after photoresist stripping.

Fig. 2. SEM images of Ag morphologies on Cu substrates. (a) Ag layer was not annealed. (b) Ag layer was annealed at 400 °C for 5 h to grow grains.

material B when A atoms and B atoms are brought within atomic range. On the interface, bonding between materials A and B will occur where A atoms and B atoms can share outer electrons. The ability to share outer electrons depends on the electronic configurations. The bonding theory based on quantum mechanics was recently reported [12]. According to the solid-state quantum bonding theory, Ag and Cu atoms must be brought within atomic distance for the Ag and Cu atoms on the interface to share outer electrons and bond. The distance

required is 1 nm or less. It is necessary to develop bonding methods to deform the Ag layer in order to conform to the Cu surface profile.

A. Fabrication Steps of Ag Layer With the Annealing Step

For the first design, the fabrication steps of bonding Cu using Ag layer without cavities are as follows. A Cu sheet of 0.8 mm in thickness and 99.9% in purity is

Fig. 3. Cross-sectional optical microscopic images of a bonded sample that used 50- μm Ag joints with the annealing step.

diced into $8 \times 10\text{-mm}^2$ Cu chips and $12 \times 12\text{-mm}^2$ Cu substrates, respectively. The upper piece is called the chip, and the lower one is the substrate. Both Cu chips and substrates are slightly polished to remove contamination and Cu oxide. Cu substrates are electroplated with 50- μm Ag layer at room temperature. The electroplating solution contains 5% potassium hydroxide and 6% silver oxide. The plating current density is 13 mA/cm^2 . Before the solid-state bonding process, the Ag (50 μm)/Cu substrates are annealed at 400°C for 5 h to increase Ag grain size to reduce the yield strength for the Ag layer so that it can deform more easily [18], [19]. The assembly is to fix the position of samples on the heating graphite platform with a static pressure in a vacuum chamber [20]. The Cu chip is placed over the resulting Cu substrate, and a spring-loaded fixture is mounted over the assembly to apply a static pressure of 6.9 MPa (1000 psi) to ensure intimate contact. The chamber is pumped down to 1.33×10^{-5} MPa. The graphite platform is heated to 300°C with a dwell time of 3 min and cools down to room temperature naturally. The bonding time, 3 min, is constrained by the furnace. In theory, it should take a few seconds rather than minutes for solid-state bonding to occur. The bonded samples are mounted in epoxy resin, cut into halves, and polished for cross-sectional examination. Based on previous experimental results, the electroplating Ag layer is not able to bond to Cu chips without the annealing step at the same bonding condition [16].

B. Fabrication Steps of Ag Layer With Cavities

For the second design, the fabrication steps of Ag joints with cavities at room temperature are presented. A 0.8-mm-thick Cu sheet, 99.9% pure, is diced into $7 \times 7\text{-mm}^2$ Cu chips and $23 \times 23\text{-mm}^2$ Cu substrates, separately. Both Cu chips and Cu substrates are slightly polished to remove Cu oxide and clean the samples. Cu substrates are first electroplated with a 10- μm Ag layer to prevent the formation of Cu oxides inasmuch as Cu oxidizes easily. After rinsing and drying, the Cu substrate is heated to 120°C for 5 min to remove water residue. The photolithography process of Ag layer with cavities is depicted in Fig. 1. Drops of photoresist AZ4620 are dispensed on the Cu substrate, which is spun on a Laurell spinner at

2500 r/min for 30 s to coat a uniform photoresist layer. The approximate thickness of the photoresist is 9 μm , as measured by the Dektak 3 surface profilometer. After the soft baking, the sample is placed below a glass photomask and exposed with UV light of a Karl Suss MA6 mask aligner. The photomask has the pattern of a 2-D array of black dots on clear background. The sample is then developed using diluted AZ4620 developer. After rinsing and drying, it is baked at 120°C for 10 min to increase the adhesion and strength of the resulting photoresist pattern. Using this photolithographic process, the photoresist pattern with 50×50 array of columns with a 50- μm diameter and a 100- μm pitch is produced. Afterward, the 5- μm Ag layer is electroplated on the Cu substrate with photoresist columns at room temperature. Thus, Ag is deposited everywhere except where the photoresist columns are. The photoresist is stripped by soaking in acetone until it is removed completely. The resulting sample has 50×50 array of 5- μm deep cavities on a 10- μm -thick Ag layer on the Cu substrate. The bonding area is 44.1 mm^2 by subtracting the area of cavities from the total area of the Cu chip. The bonding conditions of samples with cavities are the same as those without cavities: at 300°C with 6.89 MPa of pressure for 3 min. Using the same procedure as before, the bonded samples are mounted in epoxy resin, cut into halves, and polished for cross-section examination.

An optical microscope and a scanning electron microscope (SEM) are used to examine the bonding quality and the microstructure. A standard shear test, performing by the Nordson Dage 4000 multipurpose bond tester, is used to measure the breaking force. The fracture surfaces are studied using an optical microscope, an SEM, and energy dispersive X-ray spectroscopy (EDX).

III. RESULTS AND DISCUSSION

A. Bonding Design of Ag Layer With the Annealing Step

Based on Hall–Petch relation, the yield strength of crystalline metallic materials is related to its grain size, as expressed in

$$\sigma_y = \sigma_o + k_y(d)^{-1/2} \quad (1)$$

where σ_y is the yield strength, σ_o and k_y are the constants of a specific material, and d is the average grain parameter [19], [21]. Hence, the yield strength depends on grain size while the grains are not extremely coarse or ultra-fine [22], [23]. For the first design, to reduce the yield strength by increasing the grain size, the 50- μm Ag layers electroplated on Cu substrates were annealed at 400°C for 5 h [18]. As shown in Fig. 2, the Ag average grain size has grown from tens of nanometers to a few micrometers. A lower yield strength is expected to make the Ag layer deform more easily during the bonding process.

After the annealing step, the resulting Cu substrate was bonded to the Cu chip by the solid-state bonding process. The bonding quality is examined by an optical microscope and an SEM, as shown in Fig. 3. The thickness of Ag layer is approximately 50 μm . The Cu/Ag bonding interface and Ag/Cu plating interface are sharp. Both cross-section images

Fig. 4. SEM images of the Ag layer on Cu substrate of sample #5 after shear test. (a) 1000 $\times$ magnification showing Ag surface being flattened on some regions. (b) 5000 $\times$ magnification zooming in three hilltops that were clearly flattened during the solid-state bonding process.

Fig. 5. Images of Cu chip that was sheared off from sample #5. (a) Optical microscopic image of Cu chip showing Ag traces. (b) SEM image of Cu chip with Ag traces and EDX analysis locations.

Fig. 6. Original image of Fig. 5(a) that has been processed by image processing software.

demonstrate that the Cu chip is well bonded to the Ag joints on the Cu substrate without visible voids or gaps.

To evaluate the breaking force, a standard shear test was performed on five bonded samples. During the shear test, the sample was fixed on the stage, and a tool wedge pushed

TABLE I
SHEAR TEST RESULTS OF FIVE SAMPLES OF THE Cu CHIP BONDED TO THE Ag LAYER WITH THE ANNEALING STEP ON THE Cu SUBSTRATE

Samples	Breaking force (kg)	Bonding area (mm ²)	Shear strength	
			(MPa)	(psi)
#1	81.6	80	10.0	1400
#2	50.2	80	6.1	900
#3	44.9	80	5.5	800
#4	50.9	80	6.2	900
#5	90.2	80	11.0	1600

the entire 8-mm width of the edge face of the Cu chip at a constant speed of 300 μm/s. The breaking forces of five samples, ranging from 45 to 90 kg, are presented in Table I. It corresponds to a shear strength from 5 to 11 MPa. Based on MIL-STD-883J Method 2019.9 in a semiconductor die attachment, the breaking force requirement depends on the

Fig. 7. (a) Simple bump on the Ag layer. (b) Cavities inside the Ag layer.

Fig. 8. Images of fabricating steps. (a) Photoresist with columns with a 50-μm diameter and a 100-μm pitch made on the 10-μm Ag layer on a Cu substrate. (b) After electroplating 5 μm thick Ag. (c) After removing photoresist. (d) Focusing on the cavity bottoms to ensure that the photoresist was removed completely. (e) Ag layer with an array of 50 × 50 cavities.

bonding area [24]. In this case, the bonding area of the sample is larger than 4.1 mm^2 ($64 \times 10^{-4} \text{ in}^2$). A breaking force larger than 5 kg is considered to be an absolute pass of the die shear test. All samples tested far surpass this requirement.

During shear test, a ductile metal such as Ag normally goes through a few microstructural changes before fracture occurs. At present, there is no means to observe the deformation, voids coalesce, and crack formation actions during shear test.

TABLE II

EDX DATA ON THE Cu CHIP THAT WAS SHEARED OFF FROM SAMPLE #5

Location	Compositions (atomic %)	
	Cu	Ag
*1	100.0	0.0
*2	96.5	3.5
*3	95.4	4.6

Fig. 9. Cross-sectional SEM image of a sample of Cu chip bonded to the Ag layer with cavities plated on a Cu substrate.

Accordingly, it is important to study the fracture modes. Both the Cu chip and the Cu substrate are examined in detail. Basically, there are two modes:

Mode I: the breakage occurs at the Cu/Ag bonding interface;
Mode II: the breakage occurs inside the Ag joints.

Fig. 4 exhibits SEM images of the Ag joint on Cu substrate of sample #5 after shearing off. Fig. 4(a) gives a 1000 $\times$ magnification view. It is seen that only the hilltops are flattened and contact the Cu chip. Most of the Ag surface does not contact the Cu surface and thus is not bonded. Fig. 4(b) zooms in the regions that are flattened where the Ag hilltops are deformed to become flat-topped. The fractured marks on the three hilltops are clearly seen. The Ag hilltops were sheared, deformed, and broke. The fracture mode is ductile if it occurs within Ag and would appear brittle if it occurs along the Cu–Ag interface. The Cu chip of sample # 5 after shearing off is shown in Fig. 5. The optical image in Fig. 5(a) shows Ag traces of a 5–25- μ m size on the Cu chip. The EDX analysis on the SEM image of Fig. 5(b) was performed. The EDX data points of 2 and 3 in Table II contain small amounts of Ag. In contrast, the EDX data point of 1 in Table II contains only Cu. The EDX data confirm that the traces are indeed Ag. These traces are Ag that remained bonded on the Cu chip after shear test. On these traces, the breakage occurs in the Ag layer rather than on the Cu/Ag bonding interface. The percentage of Ag traces on the entire area was estimated using image processing software. Due to enhanced contrast, the area taken by Ag traces can be identified and calculated, as seen on Fig. 6. It is approximately 8%. This indicates that only 8% of the entire bonding interface is strongly bonded.

Fig. 10. Close-up SEM image of a single cavity.

For solid-state bonding to succeed, the Cu atoms and Ag atoms on the interface must be brought within an atomic distance so that they share electrons. Since the Cu and Ag surfaces are not atomically flat, the Ag surface must deform so that it would mate the Cu surface within atomic distance. Since the pressure applied is very low compared to conventional thermocompression bonding, only the hilltop regions can deform and achieve this requirement. Therefore, only a small portion of Ag is bonded to Cu. If the entire interface is all bonded strongly, the shear strength could be increased from 11 to 137 MPa, and the breaking force could increase to 1100 kg.

Based on shear test results, the strongest sample gives a breaking force of 90 kg. Fracture mode analysis indicates that only 8% of the 8×10 -mm² chip area was strongly bonded. It could be said that the Ag bonding surface did not conform fully to the Cu surface profile within atomic distance. In order to form atomic contact between Cu and Ag, the Ag surface region has to deform and flow along the lateral direction for some distance to mate the Cu surface within atomic distance. One way to achieve this is to apply high pressure to force materials to move and flow. An example is the thermocompression bonding technique in industries where the pressure is higher than 68.95 MPa (10 000 psi) [25], [26]. For advanced applications, such a high pressure is not an option. The challenge is how to increase strong bonding area without increasing bonding pressure.

B. Bonding Design of Ag Layer With Cavities

During the solid-state bonding process, the Ag layer needs to deform and conform to Cu surface within atomic distance to achieve bonding. Typical Ag surfaces are far from being atomically flat. Their roughness is much larger than the atomic distance. For illustration purpose, Fig. 7(a) exhibits a simple bump on the Ag layer. Even a bump height of a few micrometers is too much for achieving atomic contact with the Cu surface. Thus, pressure is applied to flatten the bump. The extra material in the bump would need to move (flow) and distribute over the entire Ag layer. The longest movement distance is half of upper Cu chip. If two cavities are fabricated adjacent to the bump, as shown in Fig. 7(b), the extra material in the bump can move into the space provided by the cavities. The maximum flow distance needed is half of the pitch of

Fig. 11. SEM images of Ag layer with cavities on a Cu substrate that was sheared off from sample #8. (a) Ag material near the cavities was flattened. (b) Ag surface between cavities was flattened.

Fig. 12. Images of Cu chip that was sheared off from sample #8. (a) Optical microscopic image showing that Ag traces remained bonded to the Cu chip. (b) SEM image showing Ag traces on the Cu chip with EDX analysis locations.

the cavity array. Accordingly, the maximum flow distance is reduced from half of the chip size to half of the pitch of the cavity array. That is, it is reduced from global dimension to local dimension.

For the second design, the novel idea is to build cavities in the Ag layer for excess Ag to flow into. The fundamental concept is to reduce the flow distance and facilitate plastic deformation. Therefore, the flow distance is now independent of the chip size, so is the bonding pressure. The flow distance is determined by the pitch of the array of cavities. As a result, the annealing step was not required to be done. The Cu chips can be bonded to the Cu substrates with the same conditions as the first design.

To build Ag layers with cavities, photolithography and electroplating processes were developed. Fig. 8 exhibits the optical images of the sample at major fabrication steps except that Fig. 8(e) is an SEM image. Fig. 8(a) shows the AZ4620 photoresist pattern with array of columns with a 50- μm diameter and a 100- μm pitch on the Ag layer plated over Cu. Fig. 8(b) shows the same sample after the additional Ag layer was plated over the photoresist pattern. The additional Ag

thickness is approximately the 60% height of the photoresist columns. After the photoresist columns were removed, cavities were created, as shown in Fig. 8(c) and (d). In Fig. 8(c), the microscope was focused on the top surface. In Fig. 8(d), the microscope was focused on the bottom of cavities to observe if the photoresist was stripped completely. Fig. 8(e) shows the resulting sample with an array of 50×50 cavities. Afterward, the bonding conditions were kept the same at 300 °C with the pressure of 6.89 MPa (1000 psi) for 3 min. The Cu chip was bonded to the Ag layer with cavities on the Cu substrate by the solid-state bonding process. Fig. 9 shows the cross-sectional SEM image of a representative bonding region. The thickness of Ag joint is 15 μm including the 10- μm Ag layer and the 5- μm Ag layer with cavities. No visible voids and gaps are observed at the Cu/Ag bonding interface. Fig. 10 shows a typical cavity, 50- μm diameter, before the bonding process. The diameter is used as reference to examine the deformation of Ag layer. As seen in Fig. 9, the diameter of cavities shrank to 45 μm , while the edge-edge distance extended to approximately 55 μm . On average, the diameter of the cavities has reduced from

TABLE III
SHEAR TEST RESULTS OF FIVE SAMPLES OF THE Cu CHIP BONDED TO THE Ag LAYER WITH CAVITIES ON THE Cu SUBSTRATE

Samples	Breaking force (kg)	Bonding area (mm ²)	Shear strength	
			(MPa)	(psi)
#6	35.3	44.1	7.8	1100
#7	38.0	44.1	8.4	1200
#8	48.4	44.1	10.8	1600
#9	41.9	44.1	9.3	1300
#10	21.8	44.1	4.8	700

50 to 45 μm , i.e., 10% of reduction of diameter, after the bonding process. That indicates that some Ag deformed and flowed into the cavities. Surprisingly, some Cu on the Cu chip also protruded and got into the cavities during the bonding process. As a result, the cavities seem completely filled. However, the shear test results to be presented below show otherwise.

A standard shear test was performed on five bonded samples to determine the bonding strength. The breaking forces are given in Table III. They range from 22 to 48 kg, corresponding to the shear strength from 5 to 11 MPa. Since the sample size is larger than 4.1 mm² ($64 \times 10^{-4} \text{ in}^2$), all five samples well exceed the 5-kg breaking force requirement in the MIL-STD-883J standards. It is vital to study the fracture modes and surfaces. As mentioned earlier for the bonding design without cavities, two fracture modes were observed, designated Mode I and Mode II. Fig. 11(a) and (b) shows the SEM images of two representative regions on the substrate of sample #8 after the Cu chip was sheared off. Fig. 11(a) and (b) shows a representative cavity and a region between two cavities, respectively. The Ag material near and between cavities can deform and flow easily because of the space provided by the cavities. It is displayed that the hilltops on the Ag layer were flattened. Examination of the entire Ag terrain shows that the deformation is global, exhibiting that all the hilltops were flattened to mate the Cu surface and achieve solid-state bonding.

Fig. 12 exhibits the SEM images of the Cu chip that was sheared off from sample #8. Fig. 12(a) clearly shows numerous Ag traces at 500 $\times$ magnification that were still bonded to the Cu substrate after the shear test. It also provides some crucial information as to whether Cu filled the cavities. If Cu indeed filled the cavities, the circles should have protruded by 5 μm . At 1000 $\times$ magnification, the optical microscope was able to focus on the circles and the chip surface at the same time. This demonstrates that the circles are on the same plane as the substrate within 0.5 μm , which is the depth of the focus of the microscope objective. The Cu that appears filling the cavities could be caused by smearing during the polishing process. Fig. 12(b) zooms in the image to display the Ag traces more clearly. The EDX data points of 1–3 in Table IV, which are located outside the circle in Fig. 12(b), contain large

TABLE IV
EDX DATA ON THE Cu CHIP THAT WAS SHEARED OFF FROM SAMPLE #8

Location	Compositions (atomic %)	
	Cu	Ag
*1	6.6	93.4
*2	40.3	59.7
*3	43.1	56.9
*4	100.0	0.0
*5	100.0	0.0

amounts of Ag. In contrast, the EDX data points of 4 and 5 in Table IV, which are located inside the circle in Fig. 12(b), contain only Cu. Based on EDX data, all white marks are Ag traces. The percentage of Ag traces on the entire bonding area is 22%, which can be calculated using image processing software. On these trace locations, the Ag joints break inside the Ag layer rather than along the Cu/Ag interface. These are the regions where the Ag is strongly bonded to the Cu chip. If the entire bonding area were strongly bonded, the shear strength would have increased from 11 to 42 MPa and the breaking force could increase to 220 kg.

It is essential to observe the strongly bonded percentage in two bonding designs. Using the Ag layer with cavities, the strongly bonded percentage has been increased from 8% to 22% compared to the design without cavities. Therefore, the result of building cavities inside Ag joints is encouraging.

IV. CONCLUSION

Solid-state bonding processes were successfully developed between Cu chips and Cu substrates using two different types of bonding designs. In this paper, two bonding designs were presented to meet the requirements for different applications. For the first design, a 50- μm Ag layer was plated over the Cu substrate and annealed at 400 °C for 5 h to make the Ag layer easier to deform during bonding. The photolithographic process is not required. For the second design, a 10- μm Ag layer was plated over the Cu substrate,

followed by another 5- μm Ag layer with cavities. Note that in the first design, the electroplating Ag layer is not able to bond to Cu chips without the annealing step at the same bonding condition. The purpose of this new design with cavities inside the Ag bonding layer is to reduce the flow distance and acquire more plastic deformation. Thus, the annealing step is not necessary for bonding the chips to the substrates. The percentage of the Ag layer that is strongly bonded in the second design is 22%, which is higher than 8% of the Ag layer that is strongly bonded in the first design.

For both designs, Cu chips were placed on Cu substrates so produced and bonded to them at 300 °C with a 6.9-MPa pressure in a 1.33×10^{-5} MPa vacuum for 3 min. This is a solid-state bonding process. No molten phase was involved, and no flux was used. The shear strength of ten samples was tested and reported. The shear test results of ten samples show that both Ag joints are strongly bonded and far exceed MIL-STD-883J Method 2019.9. It eliminates the concern about bonding strength from industries for practical applications. Based on the phase diagram, typically, Ag joints with Cu do not contain any intermetallic compound (IMC). Compared to solder joints used in industries, most reliability issues associated with the IMC and IMC growth do not exist. The bonded structure consists of only Cu/Ag/Cu, which has the 780 °C eutectic temperature of the Ag–Cu binary system. In addition, both Cu and Ag have relatively high electrical/thermal conductivities and superior mechanical properties. This bonding structure may be applied to electronic devices where a high thermal performance or high operating temperature is required.

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