A Hermetic Chip to Chip Bonding at Low Temperature with Cu/In/Sn/Cu Joint

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Abstract
A bonding joint between Cu metallization and evaporated Sn/In composite solder was produced at temperature lower than 200°C in air in this work. The isothermal solidification and subsequent interdiffusion of Cu and Sn/In took place along the bonding couples held at 180°C for 20 minutes. The interfacial reaction and the bonding quality is studied and evaluated. Scanning electron microscopy (SEM) exhibits the joint is uniform along the bonding interface and no crack or voids present, which has an interfacial tensile strength of 52 kg/cm². The overall bonding is examined by C-mode scanning acoustic microscope (C-SAM). Fine leak rate test shows the leak rate is about 5.8x10⁻⁹ atm·cc/s which indicates a hermetic sealing. Intermetallic compounds (IMCs) such as AuIn₂, Cu₅Sn₃ and Cu₁₁In₉ have been detected by means of X-ray diffraction analysis (XRD) and transmission electron microscopy (TEM) accompanied with energy dispersive X-ray (EDX). The chemical composition analysis also reveals that solder interlayers, Sn and In, have been completely converted into IMCs by reacting with Cu. All IMCs formed in the joints have re-melting temperature above 300°C according to Cu-In, Cu-Sn and Au-In phase diagrams. Therefore, the joint can sustain high service temperature due to the presence of IMCs. Such technique producing the joints with the good bond quality and high re-melting point has great potential in electronics and microelectronics packaging such as MEMS packaging and photonic packaging.

Introduction
A low temperature wafer bonding process with hermetic sealing is desirable for MEMS and sensor packaging because high bonding temperature may degrade the performance and sensitivity of the functional devices. Conventional hermetic wafer bonding technologies, like fusion bonding, anodic bonding, Au-Sn eutectic soldering, Cu-Cu bonding and frit glass bonding can only be conducted at the processing temperature above 250°C. Hence, a low temperature bonding at less than 200°C is necessary to fulfill industry requirements.

In-Sn based alloy is a very attractive lead-free solder for a bonding joint due to its low melting temperature which is lower than 230°C. Especially the eutectic In-48at%Sn alloy has received considerable attention due to its lowest melting point of 120°C. For the solder alloy as a bonding interlayer, one of the application methods on a substrate is by physical vapor deposition (PVD) technology. The thin film of In/Sn is deposited on substrates like Cu. Under certain bonding condition, the solder interact with Cu to form a bonding joint. In the process a soldering reaction occurs in between the solder interlayer and metallization material which often involves a so-called diffusion soldering process.

The diffusion soldering process is a joining method that combines features of conventional soldering and diffusion bonding processes. The process relies on reaction between a thin layer of molten solder and metal on the components to form one or more IMCs that are solid at the bonding temperature [1]. Under certain temperature, bonding pressure and time duration, when all the low melting point interlayer has transformed into IMCs, the resulting joint allows application at service temperature much higher than the bonding temperature.

Much attention has recently been paid on thin film technology to apply a composite solder interlayer [2-5] because this technique requires less raw materials and achieves mass production. In these works, it is often to see the solder interlayer, Sn and In, are evaporated or sputtered sequentially on the substrate to form a multilayer structure. Such characteristic multilayer structure has been employed in low temperature wafer bonding for microelectronic packaging [3-5]. However, the interfacial reaction between the thin film solder and Cu and the consequent issue of re-melting temperature of joints produced has not yet been studied and discussed. Lack of the knowledge of interfacial reaction of Cu/In/Sn thin film solder makes it difficult to optimize the bonding process condition and design the optimal multilayer structure such as thin film thickness and layer sequences. Many works have been done on the study of interface reaction between Cu substrate and bulk solder [6-12] where the eutectic solder In-48at% Sn is either applied on the substrate mostly by dipping [6-9] or pressed in the form of a thin foil [10-12]. However, the reaction between Cu and bulky solder is thought to be different from the thin film case because in the later case only limited amount of solder material contacted with the substrate and inhomogeneous chemical composition present in solder layers [13].

In this work, a low temperature bonding based on Sn/In composite solder has been developed and the interfacial reaction between Cu and solder is studied by means of SEM, TEM/EDX and XRD. The bonding quality is evaluated by means of pull test and fine leak rate test.

Experimental Procedure
A 8” silicon wafer as a base wafer was prepared with a feature of cavity and bonding ring structure. The cavity size was designed for hermetic fine leak rate testing, which has the size of 6 mm x 6 mm x 250 µm. The bonding ring has the width of 300 µm, and size of 8 mm x 8 mm. Very thin layers of SiO₂/Si₃N₄/Ti/Cu were sequentially evaporated on Si wafers along bonding ring area to enhance the adhesion of subsequent layer and also to serve as a seed layer for the following copper electroplating. Their thickness is 300Å,
1500Å, 500Å and 1000Å, respectively. A uniform 3 µm copper layer was electroplated on top. In the final step, 1.6 µm indium layer followed by 1.4 µm tin layer and 50 nm Au were deposited on Cu surface sequentially using E-beam evaporation. The thin layer of Au was deposited on the Sn layer to inhibit oxygen penetration, which can happen when the samples are removed from the vacuum chamber and exposed to air [3, 4]. To perform the bonding, another silicon wafer was prepared in the same way except no cavity and no In/Sn/Au layer as a cap wafer. The bonding pair with multilayer structure is schematically shown in Fig. 1.

![Fig. 1](image)

(a) Schematic of patterned die featured with cavity and bonding ring; (b) multilayer structure on bonding ring

Both cap wafer and base wafer were then diced into 10 mm x 10 mm small pieces. Before bonding, the base die was first cleaned with the acetic acid to remove the copper oxide layer. The bonding was carried out with a flip chip bonder (SUSS FC 150). The small bonding couples were thermocompressed in air at 180°C for 20 minutes, with a static pressure of 1.5 MPa. RMA flux (FLUXOT-84032, Indium Co.) was applied on sample surface before bonding.

After bonding, the specimens were cut along the cross section, ground with SiC paper, and polished with 1.0 µm and 0.3 µm alumina powders. SEM was employed to characterize the as-received evaporated coating surface and the cross section of the bonding interface.

To evaluate the bonding strength, tensile strength of the joints was characterized by pull test. The bonded couples were glued with a customized fixture and mounted on a tensile-tested Instron machine, as shown in Fig. 2. The pull test was preformed at a crosshead speed of 0.01mm/s. The strength value was averaged from 5 samples tested. Helium leak rate tests (MIL-STD-883) were use to check the hermeticity of the bonding.

Right after the pull test when a bonded couple was separated by force, the fracture surface is examined by XRD using Cu Kα radiation. This is to study the microstructure and phase formed in the bonding interface. TEM/EDX examination was also performed on the joint cross section. The thin foil preparation for TEM was carried out following the procedure indicated in Ref. 14.

![Fig. 2](image)

Fig. 2. Photograph of customized experimental set up for pull test

Results and Discussion

Surface and Joint Microstructure

The SEM image of as-received evaporated coating surface is displayed in Fig. 3a. The evaporated surface is very rough which comprises a granular structure with the size of 2-3 µm. A similar structure obtained by evaporation has been reported by Lee et al [5]. In order to bond surfaces with the rough features, a molten solder layer and high pressure is necessary to fill up the gaps between surfaces. It was found that the joint obtained at the given bonding condition shows void free contact, as shown in Fig. 3b. The thickness of the joint is uniform throughout the whole contact area with a typical value of 6.2 ± 0.5 µm. It suggests that the joint couples are in a good solid contact and the solder interlayers melt during the bonding process, and leveled off the rough between granules.

![Fig. 3](image)

(a) SEM images of as-received evaporated composite coating surface (a) and cross section of joint interface (b)

Bonding Quality Assessment

The quality of die bonding was first examined by C-SAM, which is a straightforward method to assess the overall bonding quality. Fig. 4 shows the SAM image of the package bonded with In/Sn. The whole bonding ring is in a uniform grey color indicating no voids or delamination detected.
between two contacted surfaces. The pull test results gave an average interfacial tensile strength of 52 ± 5 kg/cm², which is comparable with that reported by Chuang et al, who used thin film of Sn and In as interlayer to bond Au and Cu substrates, and obtained a maximum tensile strength of 48 kg/cm² [2]. The helium leak rate of the obtained package gave an average value of 5.8x10⁻⁹ atm-cc/s for 5 tested samples, which indicates the sealing is hermetic.

**Fig. 4** CSAM image of a package bonded with Cu/Sn/In/Cu at 180°C for 20 minutes with pressure of 1.5 MPa

**Cu/In/Sn/Cu Interfacial reaction**

To have a better understanding of the interfacial reactions and interdiffusion occurred in the Cu/In/Sn/Cu joint, XRD was used to examine the IMCs evolved in the bonding reaction zone. The AuIn₂, Cu₆Sn₅ and Cu₁₁In₉ phases were found in XRD analysis, as shown in Fig. 5. No peak of Sn or In has been detected.

Since the IMC layers are relatively thin, TEM technique was chosen because it provides local chemical analysis. Fig. 6 shows TEM images on the region close to the base material silicon and interfacial reaction region between Cu and solder interlayers. It is seen from Fig. 6a that on the top of the silicon the first layer is silicon oxide, followed by silicon nitride, titanium and copper. The interfaces between each layer are void free and uniform. Silicon oxide layer and nitride layer provide good adhesion layers between the subsequent metal layer and silicon base.

**Fig. 5** XRD results of interface after pull testing

**Fig. 6** TEM images (a) at silicon region and (b) at interface region; and (c) element composition profile along the direction marked as the white line in (b).
Although the current bonding temperature 180°C is not high enough to melt Sn, which has the melting temperature of 230°C, the molten In layer is mixed with solid-state Sn layer and forms a thin eutectic In-Sn layer at their interface. This eutectic layer has a lower melting point of 120°C. Liquid In and solid Sn gradually interdiffuse into each other and as a result the eutectic In-Sn layer grows at the expense of single In and Sn layer until both solder layers been completely consumed. Noticed that the initial overall composition of In and Sn in the deposited film is the eutectic composition, i.e. 48 at% Sn. With such eutectic liquid layer, the intrinsic roughness of the evaporated surface can be overcome and thus a good joint interface is observed as described above. During the soldering process, the subsequent interdiffusion of Cu and Sn/In took place in the interface region and form various Cu-In-Sn IMCs.

Table 1 Summary of point EDX analysis along the interface shown in TEM image

<table>
<thead>
<tr>
<th>Point</th>
<th>Composition (at%)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cu</td>
<td>In</td>
</tr>
<tr>
<td>1</td>
<td>99.5</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>99</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>56.0</td>
<td>28.5</td>
</tr>
<tr>
<td>4</td>
<td>54.6</td>
<td>31.3</td>
</tr>
<tr>
<td>5</td>
<td>52.1</td>
<td>30.4</td>
</tr>
<tr>
<td>6</td>
<td>51.4</td>
<td>28.3</td>
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<td>8</td>
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<tr>
<td>10</td>
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<tr>
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<td>5.9</td>
<td>59.0</td>
</tr>
<tr>
<td>12</td>
<td>5.1</td>
<td>60.2</td>
</tr>
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</table>

The composition analysis and XRD results also suggested that no unreacted In or Sn material present after bonding. The solder materials have completely transformed into IMCs by reacting with copper. The finding implicates that the bonding joint produced at low temperature can withstand high service temperature due to the presence of high melting point of IMCs. From a consideration of the phase diagrams, the melting point of Cu6Sn5, Cu11Sn9 and AuIn2 are 430°C, 320°C and 580°C, respectively. Therefore, the thermal stability of the joint is expected to be higher than 300°C. Such joints with the good bond quality and high re-melting point produced by the diffusion soldering process is very much desirable in microelectronic packaging such as MEMS and photonic packaging since most of these devices to be packaged are either high-temperature sensitive, or may suffer from bonding-induced stress problem.

To further explore the low temperature bonding using thin film In-Sn solder, several other materials configurations in terms of the composite solder layer sequence and layer thickness have been designed based on phase equilibria calculations [18]. It is found that with a proper material design and an optimal bonding condition, bonding temperature as low as 120°C is feasible without compromising its bonding quality.

Conclusions and Recommendations

A good bonding between Cu and In/Sn composite layer is produced at 180°C in air. The bonding quality and interfacial reaction behavior has been studied using pull test, SAM, fine leak rate test, SEM, TEM/EDX, and XRD. Some important results and recommendations are summarized in the following:

1. At the bonding temperature of 180°C, with the pressure of 1.5 MPa for 20 minutes, the joint interface is found to be very uniform and no voids or crack appeared.

2. The joint exhibited an interfacial tensile strength of 52 kg/cm², and with hermeticity of 5.8x10⁻⁹ atm-cc/s, indicating a hermetic package.

3. The interfacial reaction between Cu and solder materials result in the formation of Cu6(Sn, In)5, Cu11(In,Sn)9 IMCs. AuIn2 is also formed at the very top layer of interface although Sn layer is in between Au and In layers. It may likely be due to Au is more thermodynamically preferably reacted with In than Sn.

4. No unreacted solder materials are detected in interface after bonding. All IMCs formed in the joints have re-melting temperature above 300°C according to Cu-In, Cu-Sn and Au-In phase diagrams. Therefore, the joint can sustain high service temperature due to the full presence of IMCs.

5. More works need to be done to develop a fluxless process at lower temperature for chip to chip and wafer to wafer bonding.

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