Application of the Transient Liquid Phase Bonding to Microelectronics and MEMS Packaging

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For high performance microelectronics and MEMS packaging, ceramic-based packages are preferred over plastics. There are a number of ways that ceramic-to-metal joining is of important concern in such applications. In this paper, the partial transient liquid phase bonding (PTLPB) method for ceramic-to-metal joining is reviewed. This method does not require high joining pressure and stringent surface preparation for cleanliness as in diffusion bonding. With proper selection of filler metals, this method can produce more heat-resistant joints than those manufactured by brazing. In this study, Si$_3$N$_4$ has been successfully joined to Inconel 718 using PTLPB with thin multi-layers of Ti-Cu, Ti-Ni and Ti-Cu-Ni at temperatures lower than 1000 °C. The interfacial structure has been investigated using SEM and TEM. The processing conditions for high joint strength are also discussed.

INTRODUCTION

Packaging provides mechanical support for the different electronic components in a device and protects the device from the environment. Much of this technology applies also to the microelectromechanical systems (MEMS) and the packaging processes developed for microelectronics offer many insights for MEMS packaging and bonding [1].

For high performance packages in which excellent thermal stability and impermeability are essential, ceramic-based packages are preferred over plastics [2]. Soldering and brazing have been most frequently used in microelectronics packaging when attaching a silicon chip to metallized ceramic substrates (chip carriers) or when encapsulating the assembly. Soldering is a low temperature joining method, and can be used with a wide range of materials without degrading their properties at high temperature. The physical reversibility of the soldering process also makes this method attractive in terms of repairability. However, soldering cannot be used in systems that require thermal stability at high temperatures. For MEMS packaging, especially in optical devices, the flux residuals can degrade the optical devices and the reliability of the interconnect.

Gold eutectic bonding has been used in wafer-level packaging. Gold forms a eutectic alloy melt with silicon at low temperatures of 363 °C. Extended heating at the bonding temperature allows isothermal solidification and forms diffusion-bonded like joints. Eutectic bonding is an extension of traditional transient liquid phase (TLP) bonding used for superalloys. In TLP bonding, the high joining pressure and stringent surface cleanliness are not required as in diffusion bonding. Since the liquid phase resolidifies at the bonding temperature, TLP bonding can produce joints at lower temperature than the operational temperature and can provide more heat-resistant joints than those manufactured by brazing.

TLP bonding technology also has been extended to manufacturing ceramic-to-metal joints for high temperature applications. When one of the components is a ceramic, the process is called partial transient liquid
phase bonding (PTLPB) [3, 4], because the ceramic is not involved in the diffusion of the melting point depressant. During PTLPB process, the filler metal including reactive elements melts and then reacts with the ceramic. With proper selection of filler metals, this method can be used for joining devices to various ceramic substrates and joining silicon wafers with deposited layers such as Si₃N₄, Al₂O₃, and SiC for electrical insulation, passivation, or increasing mechanical performance [5].

In this work, PTLPB developed for joining ceramic to metal is reviewed. In addition, Si₃N₄ to Inconel 718 joints with various filler metals have been produced using PTLPB using varying processing conditions. The interfacial structures of high strength joints are discussed with reference to the processing conditions.

EXPERIMENTAL PROCEDURES

Hot pressed Si₃N₄ and Inconel 718 (1 cm x 1 cm x 1 cm) were used as the ceramic and the metal, respectively. Three different sets of filler metals have been used (Table I). The filler metal consists of microfoils of Ti or Ti/Cu and 100 μm-thick core layers of Cu or Ni. Prior to joining, the surfaces of the Si₃N₄ and the Inconel 718 were polished using SiC emery paper and diamond paste to a 1 μm surface finish. All the materials were cleaned in acetone using ultrasonic vibration and dried in a warm oven.

The whole assembly was joined in a high vacuum furnace and the bonding time and temperature were varied to investigate the effect on interfacial structure and joint fracture. The vacuum pressure was maintained as approximately 5×10⁻⁸ torr and the joints were bonded with a load of 2 MPa or less. The bonding temperature ranges from 850 °C to 1000 °C and the holding time was from 10 to 100 min. The heating rate was 8 °C/min and the cooling of the joint was 2 °C/min within the vacuum furnace.

The microstructure of the joints has been analyzed using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), electron microprobe analysis (EPMA) by wavelength dispersive spectrometer (WDS) and transmission electron microscopy (TEM).

RESULTS AND DISCUSSION

Compared to ceramic-to-ceramic systems, relatively little works have been reported on PTLPB of ceramic-to-metal systems. Residual stress developed during cooling due to thermal mismatch between the ceramic and the metal limits the mechanical reliability of these dissimilar material systems. In this work, Cu or Ni layers as thick as 100 μm were used to accommodate the residual stresses (Table I).

The joint systems studied in this work and the experimental results are summarized in Table I. Ti is used as a reactive element in the filler metals, which diffuses into Cu or Ni and forms a liquid phase. While held at bonding temperature, the liquid phase wets and reacts with the surface of the Si₃N₄.

Some of the joint systems with Ti/Ni or Ti/Cu/Ni filler metals failed at the interface during cooling or handling. This was caused by incomplete wetting of the liquid phase on the ceramic surface. When produced under different processing conditions, joints with the same filler metals withstood the entire metallurgical sample preparation steps including cutting.

The joint strength seems to depend significantly on bonding temperature and holding time at the bonding temperature. On the other hand, the load imposed across the joint seems to have little effect, which is an encouraging result for mass production. As the holding time was increased to 100 min., the joints with Ti/Ni filler metals showed high interfacial reliability. Fig. 1 shows the X-ray mapping of the interfacial microstructure of the joint. Based on the Ti
distribution, good wetting seems to be achieved and a continuous reaction layer has formed at the interface. EPMA analysis suggests that the layer adjacent to the ceramic is rich in Ti and N, and may be TiN.

With Ti/Cu filler metals, a strong interface is obtained at temperatures lower than 1000 °C for relatively short holding times. Fig. 2 are optical micrographs of the interfacial structures of the joint bonded at 930 °C for 100 min. A ~2 μm-thick continuous reaction layer has formed at the interface with the Si₃N₄. Previous research on Si₃N₄ joining with the same filler metals showed that this layer consists of two continuous layers of TiN and Ti-Si-Cu-N compound [3].

In joints with Ti/Cu/Ni filler metals, thicker (5 μm) Ti microfoils were used for good wetting. Joints made with 2 μm Ti foils or using shorter holding time caused interfacial debonding after cooling. The debonded Si₃N₄ surface in Fig 3 indicates poor wetting under these processing conditions. The black areas denoted by arrows are the surfaces of the Si₃N₄ that has not been wetted with filler metals.

Since Ni has a strong chemical affinity for Ti, more complicated reaction compounds were formed along the interface. TEM analysis showed that the reaction layer is composed of five different layers of compounds or reaction phases. The optical micrograph of interfacial structure in Fig. 4-(a) shows that 12 μm-thick reaction layers were formed at the interface. Fig. 4-(b) schematically describes the structure of five different reaction layers from the TEM analysis results.

TEM analysis revealed that Si has diffused over 2 μm into the filler metals and there is residual unreacted Cu layer. This indicates that in addition to the formation of thin Ti-nitride layer, diffusion of Si into the reaction layer also contributed to the strong bond formation. However, it is evident that the diffusion of Si and Ni is limited to the layer next to Si₃N₄ since the continuous α-Cu layer seems to produce a barrier layer against the further diffusion.

Compared to the previous work on joining Si₃N₄ with the Ti/Cu/Ni filler metals [6], strong joints can be made at 300 °C lower temperatures with thinner Cu layers. The Cu layer forms a liquid phase with Ti and plays a beneficial role by preventing excessive reaction of Ni with Ti. However, since the oxidation resistance of Cu is poor, thick Cu layers need to be avoided for applications where oxidation is possible.

Since a limited amount of liquid phase is formed compared to soldering or brazing, selected areas can easily be made using PTLPB by depositing filler metals on selected areas. With Ti/Cu and Ti/Cu/Ni filler metals, joints can be made at relatively low temperatures (<1000 °C). If combined with local heating techniques [7, 8], the residual stress can also be reduced, hence more heat resistant joints of high mechanical integrity can be produced.

To investigate the fracture resistance of the interfacial structures in detail,
mechanical test should be made. To control the thickness of each reaction layer and the nature of reactive phase formation, a kinetic study is also required in addition to microstructural analysis.

References
Table I Joint systems, Processing Conditions, and Experimental Results

<table>
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<tr>
<th>Filler Metals</th>
<th>Thickness of Ti (µm)</th>
<th>Thickness of Cu (µm)</th>
<th>Thickness of Ni (µm)</th>
<th><strong>Tb</strong> (°C)</th>
<th><strong>t_b</strong> (min.)</th>
<th>Load (MPa)</th>
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<td>1000</td>
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*Tb*: bonding temperature  
**t_b**: holding time at the bonding temperature
Fig. 1 Back scattering image and X-ray mapping of the interfacial structure of the PTLPB joint with Ti/Ni filler metals
Fig. 2 Optical micrographs of joints bonded with Ti/Cu filler metals
Fig. 3 (a) Optical micrograph of the interfacial area of the joint with Ti/Cu/Ni filler metals (b) A schematic description of reaction layers.
Fig. 4 SEM image of fractured interface of the joint with Ti/Cu/Ni filler metals