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Journal Item

A new method for liquid-phase bonding of copper plates to aluminum nitride (AlN) substrates used in high-power modules

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Abstract

A new method for liquid-phase bonding of copper plates to an aluminum nitride (AlN) substrate was developed in this work. A newly developed proprietary interlayer composed of titanium and silver powders was deposited on the AlN substrate using a screen-printing machine. The eutectic reaction between printed silver and copper at 850 °C led to formation of a liquid phase at the joint interface. A total of 42 samples were prepared using 7 and 6 different amounts of silver and titanium, respectively. The microstructures of all samples were analyzed by scanning electron microscopy and energy-dispersive X-ray spectroscopy, and an ultrasonic flaw detector was used to assess joint integrity. The optimum composition of the Ti-Ag brazing alloy for producing defect-free joints was determined. The formation of a continuous TiN layer was found to be essential for achieving sound joints between the copper plates and AlN substrate.

1. Introduction

Ceramic substrates sandwiched between copper or aluminum plates have many applications in high-power electronics, such as the manufacturing of insulated gate bipolar transistor (IGBT) modules, which are used in all hybrid and electric cars and trains. The primary application of aluminum nitride (AlN) is as an IGBT substrate, due to its near-zero electrical conductivity and high thermal conductivity. This rare combination of properties allows heat to be extracted from IGBT modules while maintaining electrical insulation between the silicon chips [1-3].

Copper-bonded ceramic substrates have been industrially produced for several decades using two well-developed methods: direct bonding copper (DBC) and active metal bonding (AMB). DBC relies on the Cu-Cu_2O eutectic reaction, such as when bonding Cu to Al_2O_3 [4] or to surface-oxidized AlN [5]. In contrast, the AMB method relies on Cu-Ag-based brazing fillers that contain Ti as an active metal [6-10]. In this work, the conventional Cu-Ag-Ti paste was replaced with a printed layer of Ag-Ti when bonding copper plates to an AlN substrate. In both methods, melting occurs due to the Cu-Ag eutectic reaction at 780°C, but unlike the transient liquid phase (TLP) bonding processes, the liquid phase solidifies thermally when it is cooled below its melting point [11-16].

The interfacial reactions and resulting microstructures when using the new printed brazing alloy were studied in this work. The formation mechanism of TiN, a key factor in achieving strong bonds between Cu and AlN, is discussed in detail.

2. Experimental procedures

Commercially available polycrystalline AlN substrates (40×40×0.63 mm) and oxygen-free copper plates (37×37×0.30 mm) were brazed in this work. Silver and titanium powders were added in various ratios into an organic medium, containing α-terpineol (96%), 2,2,4-trimethyl-1,3-pentanediol (98.5%), and polymethyl methacrylate (Mitsubishi Rayon), and were mixed using a mechanical mixer (ARE-250, THINKY) to produce the proprietary brazing paste. The paste was applied onto AlN substrates using a screen-printing machine, which could precisely control the thickness of the deposited layer. After drying the substrates at 150 °C for 10 min in air, each coated AlN substrate was sandwiched between two copper plates. All assembled samples were placed inside a vacuum furnace and brazed at 850 °C for 30 min under a constant pressure of 0.1 MPa. A schematic of the bonding step is shown in Fig. 1. A total of 42 samples were brazed using 7 and 6 different amounts of silver and titanium, respectively.

Metallography samples were mounted in an acrylic polymer at room temperature and polished using standard metallographic techniques and an argon-based ion beam polisher (SM-09010, JEOL). The microstructures of all samples were analyzed using a scanning electron microscope (SEM; ULTRA 55, Carl Zeiss AG) equipped with an energy-dispersive X-ray spectrometer. The adhesion and uniformity of the copper/AlN interface were assessed using an ultrasonic flaw detector (FineSAT200, Hitachi Power Solutions).

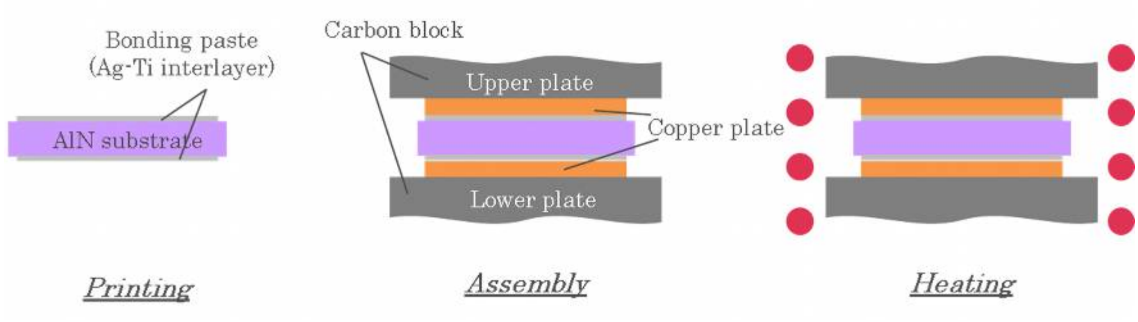


Fig. 1. Procedure used for brazing copper to AlN substrates.

3. Results and discussion

The typical method for bonding copper to AlN relies on the Cu-Ag eutectic reaction, which occurs within the Cu-Ag-Ti brazing filler when it is heated above the eutectic temperature of 780 °C. A similar Cu-Ag eutectic reaction occurs in the method newly developed in this work, except that the Cu is supplied from the copper plate itself. It must be emphasized that none of these methods is a TLP process. This is because the brazed alloy solidifies when the temperature is dropped below its melting point, as in conventional brazing processes.

Figure 2 shows 35 out of 42 brazed samples were classified into 4 types: A, B, C, and D. The classification is based on certain features observed at the joint interface, mainly the formation of TiN and/or the presence of interfacial voids when using printed brazing pastes containing various amounts of titanium and sliver. The remaining 7 bonded samples (shown by solid diamond symbols in Fig. 2) were weak and failed during handling, and so their microstructures could not be examined.

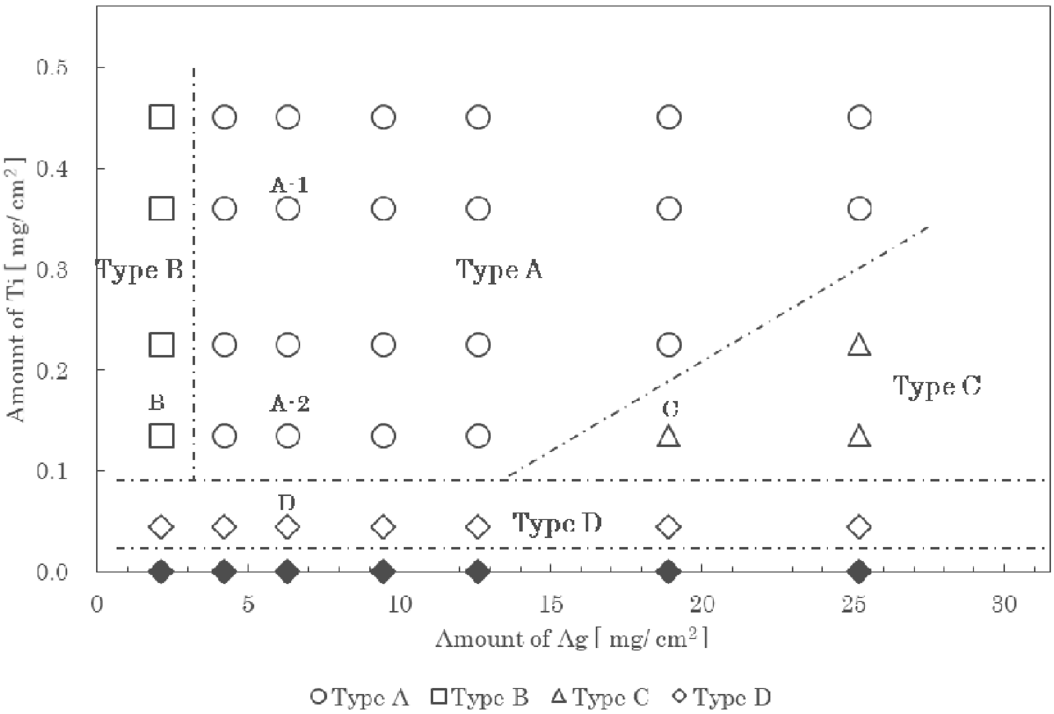
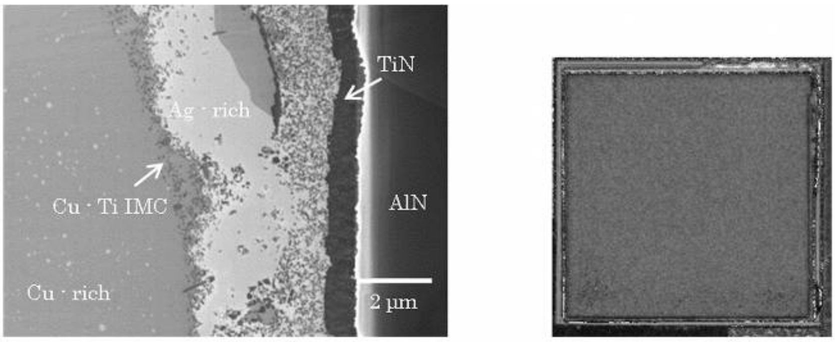
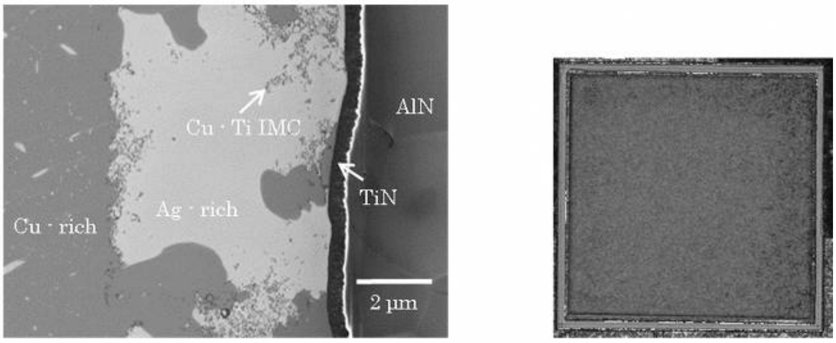


Fig. 2. Classification of bonded copper/AlN samples based on their interfacial microstructure when using various concentrations of Ti and Ag in the brazing paste. All samples were brazed at 850 °C for 30 min under a constant pressure of 0.1 MPa

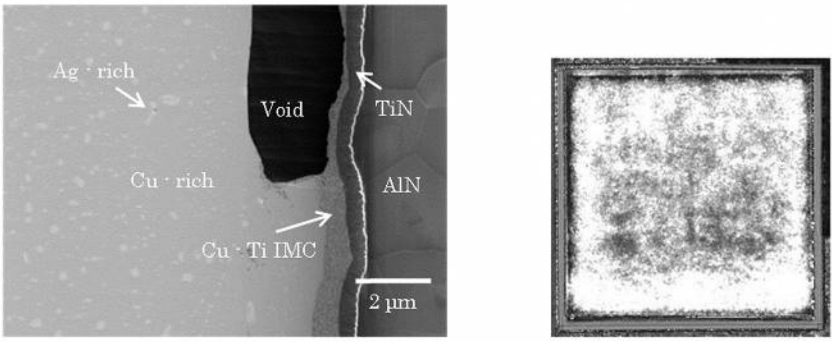
Sample A-1



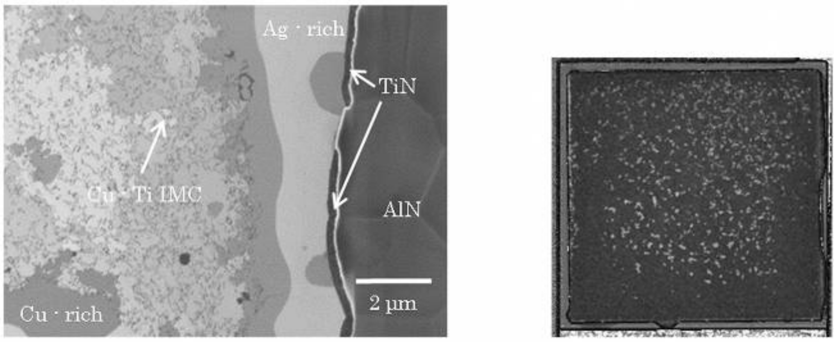
Sample A-2



Sample B



Sample C



Sample D

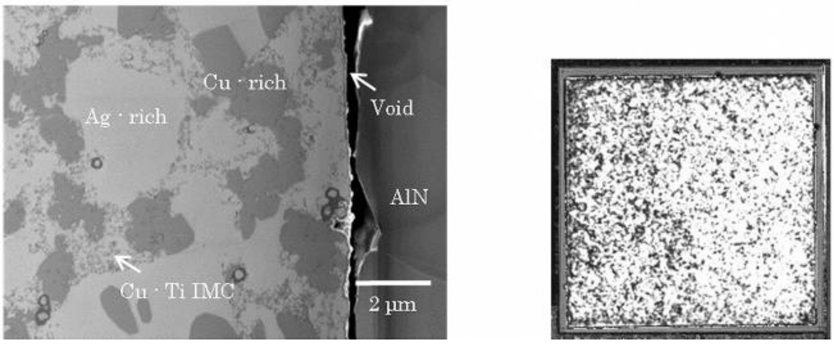


Fig. 3: SEM micrographs and corresponding ultrasonic images of five selected brazed Cu/AlN samples (marked in Fig. 2).

Type A samples are characterized by the presence of a continuous titanium nitride (TiN) layer within a virtually void-free copper/AlN interface. Type B and Type C samples also have a continuous TiN layer but contain large voids or small discontinuities, respectively. Type D samples were the weakest samples with large unbonded areas and no apparent TiN layer. Type D samples largely resemble the 7 unbonded samples marked by solid diamond symbols in Fig. 2. The interfacial microstructures of all samples consisted of silver- and copper-rich phases, and dispersed Cu-Ti intermetallic compounds. A continuous TiN layer, as key requirement for achieving a high-strength bond, was found at the copper/AlN interface for all samples except Type D, probably due to a lack of Ti, which was the active element in the brazing paste.

Closer examination of Type A samples showed a near-linear correlation between the concentration of Ti and the thickness of the continuous TiN layer. For instance, Sample A-1 contained almost 3-fold more Ti and had a 3-fold thicker TiN layer compared with Sample A-2 (Figs. 2 and 3). The presence of homogeneous dark areas on the ultrasonic images taken of Type A samples implies that the Cu plates were fully bonded to the AlN substrates without any visible interfacial gaps or discontinuities (Fig. 3).

Figure 3 also shows a typical microstructure of a Type B sample. The presence of a large void in Sample B is attributed to inadequate progress of the Cu-Ag eutectic reaction as a result of the silver deficiency in the samples containing less than 3 wt.% Ag. The microstructure of Sample B, which was similar to that of the other Type B samples, is consistent with the bright areas seen on the corresponding ultrasonic image, indicating the widespread presence of interfacial gaps or voids.

Sample C is a typical example of the Type C samples (Fig. 3). The discontinuity in the TiN layer at the Cu/AlN interface correspond to the bright spots seen on the corresponding ultrasonic image, thus indicating some unbonded areas.

All samples with the same Ti content in their brazing paste contain a TiN reaction layer and Cu-Ti intermetallics, as seen by comparing Samples A-2, B, and C in Figs. 2 & 3. However, it appears that the location of the Cu-Ti intermetallics gradually shifted away from the Cu/AlN interface with increasing Ag content. For instance, Cu-Ti intermetallics were pushed toward the copper-rich side as the Ag content was increased from 2% to 6% and then to 19% in Samples B, A, and C, respectively. These results suggest that the formation of TiN was suppressed by the diffusion of Ti into the Cu-Ag liquid phase. The rapid absorption of Ti into the liquid phase led to insufficient Ti at the joint interface, thus forming a thinner or discontinuous TiN reaction layers.

In contrast to Types A, B and C, no TiN layer was found at the Cu/AlN interface of the Type D samples (Fig. 3). The SEM micrograph of Sample D and the corresponding ultrasonic image show limited bond formation at the Cu/AIN interface. These results show that Ti has a stronger tendency to form Cu-Ti intermetallics than TiN. In Type A, B and C samples with higher Ti content, the amount of Ti was sufficient for partitioning to occur and both Cu-Ti intermetallics and the TiN reaction layer to form.

Based on comprehensive examinations of the bonded samples, it was concluded that Type A samples had superior adhesion between their Cu plates and AlN substrate, and were characterized by the presence of a void-free and continuous TiN layer at the Cu/AlN interface. Therefore, formation of TiN at the joint interface was considered a crucial factor in obtaining high-integrity joints. More detailed examination of the bonded samples revealed that at least 0.14 mg of Ti per 1 cm^2 of the joint is required to ensure the formation of a continues TiN layer at the joint interface. Furthermore, at least 4.20 mg of Ag per 1 cm^2 of the joint is necessary to produce a sufficient amount of liquid phase and prevent the formation of voids or gaps.

4. Conclusions

Copper plates were bonded onto an AlN substrate using a proprietary screen-printed brazing alloy containing titanium and silver powders. The results of microstructural examination and ultrasonic imaging led to following conclusions.

1. Formation of a continuous and defect-free TiN layer at the Cu/AlN interface was essential for achieving high-integrity joints.

2. Having a sufficient amount of Cu-Ag liquid phase is also a key factor to ensure adequate wetting of the AlN substrate, which is necessary to prevent void formation.

3. The titanium-to-silver concentration ratio must be carefully controlled in order to obtain good adhesion between the copper plates and AlN substrate.

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