Bonding with brazing alloys as high-temperature interconnection filler through self-propagating exothermic reaction

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Abstract

There has been growing interest in wide bandgap (WBG) semiconductors including SiC and GaN due to the increasing demands for electronic devices serving at high temperatures. However, to maximise the potential capacity of WBG devices, new high-temperature interconnection materials and processes are indispensable as the current existing Sn-based solder alloys and bonding processes developed for Si devices are unable to meet the reliability requirements. In the present work, reactive brazing alloys including Cu-15Ag-5P and Incusil (Ag-27.25Cu-12.5In-1.25Ti) with melting points above 600°C have been utilized as the interconnection materials which offer excellent properties under high operation temperature. The self-propagating exothermic reaction (SPER) was applied for the bonding process via an intense rapid local heating and cooling at a millisecond scale. The strong Cu/Cu-15Ag-5P/Cu and Cu/Incusil/Cu sandwich bonded structures have been created with the assistance of SPER, where the nanofoil was applied from the outside of stacked structures as an external heat source and the bonding process was conducted in the ambient atmosphere without using flux. It has been found that the P element in Cu-15Ag-P alloy has the self-flux effect, which is beneficial for the ultra-fast interfacial reaction process. The experiments where the nanofoil was placed inside of stacked structures between two sheets of brazing alloys have also been conducted, which exhibited the well-bonded interface microstructures between nanofoil and brazing alloys. The outlook on the design for practicality and industrial uses for SPER-assisted bonding with brazing alloys has also been discussed, as a potential viable assembly route for the high-temperature and high-power electronics packaging.

Key words

Self-propagating exothermic reaction; Cu-15Ag-5P brazing alloy; Incusil alloy; high-temperature electronics packaging

I. Introduction

With the increasing requirements of electronic devices serving at high-temperature conditions, wide bandgap (WBG) semiconductors including SiC and GaN have obtained growing interest, which can operate up to 600 °C in theory [1]. However, the benefits for application of WBG devices are still constrained by the limitation of high-temperature interconnection materials and bonding methods [2]. Currently, only soft solders have been applied in electronics packaging, which have melting points below 450 °C. In comparison, the hard solders or brazing alloys have liquidus temperatures above 450 °C, but there has been a very limited attempt intending to apply brazing alloys in electronics assembly due to their high process temperature if using the conventional reflow method [3]. It is desirable if Pb-free interconnection materials with high melting points can be assembled by low-temperature processing technology. For instance, it is promising if brazing alloys which exhibit superb high temperature properties can be applied as the interconnection material in high-temperature electronics packaging.

Self-propagating exothermic reaction (SPER) can provide ultra-fast local heat, which has already been applied in electronics packaging [4]. As a typical SPER material, Ni/Al nanofoil has large heat energy (1050-1250 J/g) and a fast propagating speed (7-10 m/s) [5]. Therefore, the electronics packaging processes with typical bonding areas can be completed at microsecond scale by SPER [6]. The SPER-assisted bonding requires a good wettability of solder since the duration of filler in the melted and liquid stage is very short [7]. It demands careful consideration to select a suitable brazing alloy and bonding conditions for SPER-assisted bonding.

This work investigated the SPER-assisted bonding processes with brazing alloys including Cu-15Ag-5P and Incusil (Ag–27.25Cu–12.5In–1.25Ti, wt.%) alloy. The bonded structures and their interfacial reaction mechanism during SPER were analysed. The potential design of bonding structures for industrial application based on this processing route has been discussed.

II. Experimental procedures

A. Materials preparation

The reactive Cu-15Ag-5P and Incusil brazing alloy were supplied by the VBC group from UK, which have thicknesses of 120µm and 100 µm, respectively. As shown in Fig. 1(a), there are three distinct phases in Cu-15Ag-5P microstructure including Cu, Ag, and Cu-Ag-Cu_3P eutectic phase. Among them, the Cu-Ag-Cu_3P eutectic phase has the lowest melting point (646°C) [8]. As shown in Fig. 1(b), the microstructure of Incusil brazing alloy mainly contains Ag-rich solid solution phase and Cu-rich sloid solution phase [9]. Ti was mainly distributed in the Cu-rich phase and In has the same distribution as Ag. The Incusil brazing alloy has a solidus point of 605°C [10].

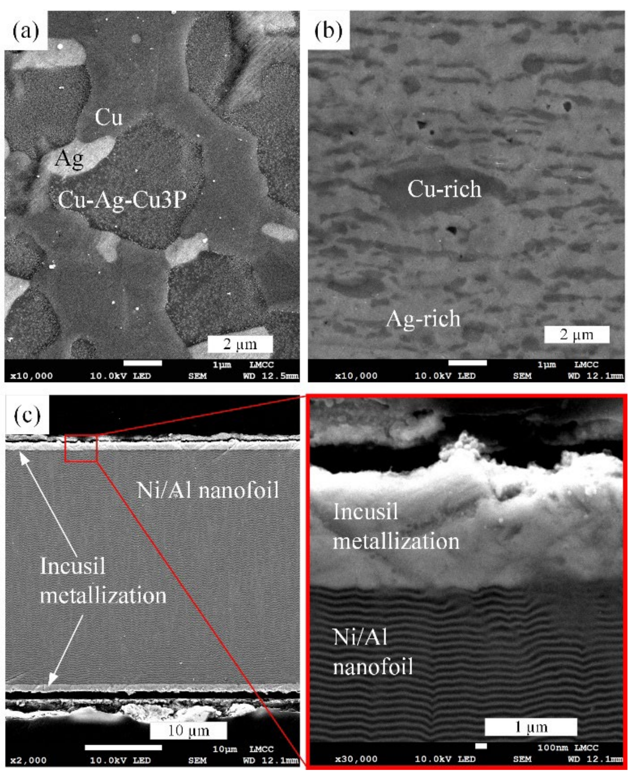

Fig. 1. Microstructures of (a) Cu-15Ag-5P alloy, (b) Incusil brazing alloy and (c) Ni/Al nanofoil.

The Ni/Al nanofoil with a thickness of 40µm was provided by Indium Corporation from USA, as shown in Fig. 1(c), which has a 1:1 atomic ratio of Al to Ni consisting of alternating Al (60 nm thick) and Ni (40 nm thick) nanolayers. In addition, there is an Incusil top layer on the surface of nanofoil with a thickness of around 1µm.

B. Bonding process and characterization

As shown in Fig. 2, two stacking structures for the SPER-assisted bonding have been designed depending on the location of nanofoil. Fig. 2(a) exhibits the structure that Ni/Al nanofoil is placed on the outside of the Cu/brazing alloy/Cu sandwich structure as an external heating source, where the heat generated from SPER of nanofoil transfers through the Cu sheets to achieve the interfacial bonding between brazing alloy and Cu substrates. After bonding, the Ni/Al nanofoil can be stripped off from the Cu sheet since there is no sufficient interfacial bonding between nanofoil and Cu. In Fig. 2 (b), the nanofoil is located between two sheets of brazing alloys, in such a case, the reacted nanofoil is bonded directly with brazing alloys and remains inside the joint.

For both structures, glass was used as the thermal barrier to reduce heat dissipation. All these metal sheets were cut into a square of 5mm × 5 mm. A constant pressure of 2 MPa was applied to maintain good contact between these multiple layers. The nanofoil was ignited by a direct current of 1A at a voltage of 5V. Scanning electron microscopy (SEM, Jeol 7800) was performed to observe the cross-section of bonded joints.

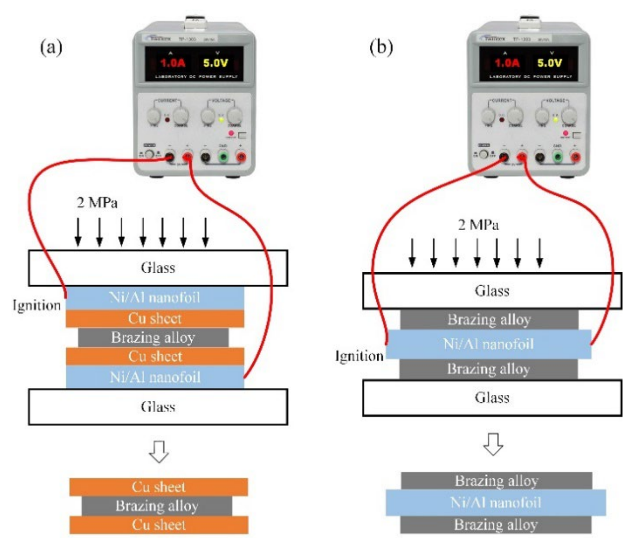

Fig. 2. Diagram of SPER-assisted Cu/Cu-15Ag-5P/Cu bonding process: a) bonding with nanofoil as external heat source; b) bonding with nanofoil located between two sheets of brazing alloys.

III. Results and discussion

A. Nanofoil applied as an external heat source

The cross-sections of the bonded Cu/Cu-15Ag-5P/Cu and Cu/Incusil/Cu sandwich microstructures are shown in Fig. 3. In this case, nanofoil was applied as an external heat source and placed on the outsides of the bottom and top Cu sheet. As shown in Fig. 3(a), there is no clear boundary between the Cu sheet and the Cu phase in the Cu-15Ag-5P alloy at the interfaces, which means the Cu-15Ag-5P alloy has already been bonded with the Cu sheet in most of the area.

The mechanism of Cu-15Ag-5P/Cu interfacial reactions during SPER can be analyzed based on the obtained results. Compared to the original microstructure shown in Fig. 1(a), the Cu-15Ag-5P alloy maintains the phase microstructures after bonding (Fig. 3(a)). It can be concluded that only the top surface of Cu-15Ag-5P was melted, and then react with the Cu sheet to form the joint. The interfacial reaction was divided into 3 stages, As was shown in Fig. 4. Firstly, the nanofoil was ignited and fully self-propagated within microseconds. The generated heat can be easily transferred into the Cu sheet and then the Cu-15Ag-5P sheet. For the second stage, the Cu-Ag-Cu_3P phase was melted firstly due to its lowest melting point. Finally, Cu_3P is prone to react with the oxidation layer on top of the Cu sheet and therefore Cu-15Ag-5P can be bonded with the Cu sheet without the need of flux.

The bonded Cu/Incusil/Cu microstructure and the Cu/Incusil interface are displayed in Fig. 3(b), from which no crack can be visible between the Cu sheet and the Incusil layer at the interfaces, which means the Incusil alloy has already been bonded firmly with the Cu sheet. After the SPER process, the thicknesses of the Cu and the Incusil layer is almost unchanged compared to the original dimensions prior to bonding. Since a constant 2 MPa pressure was applied, it can be concluded that both Cu sheet and bulk Incusil layer (or preform) likely remained solid and were not entirely melted during the SPER. Therefore, the bonding must have been achieved by melting only the surface zones of Incusil alloy, which can subsequently react with the Cu sheet to form the joint. This mechanism follows more or less the same process as the bonding process between Cu and Cu-15Ag-5P assisted by SPER.

The SPER-assisted bonding process is finished in milliseconds, whereas the traditional brazing process needs to melt the entire brazing alloy into liquid and reacted with a substrate for at least several minutes. It is still a question whether this method is feasible for the practical bonding structures since this method has not been practised for industrial use. To take the advantage of the SPER bonding with brazing alloys, viable design for potential application and qualification in the future are required.

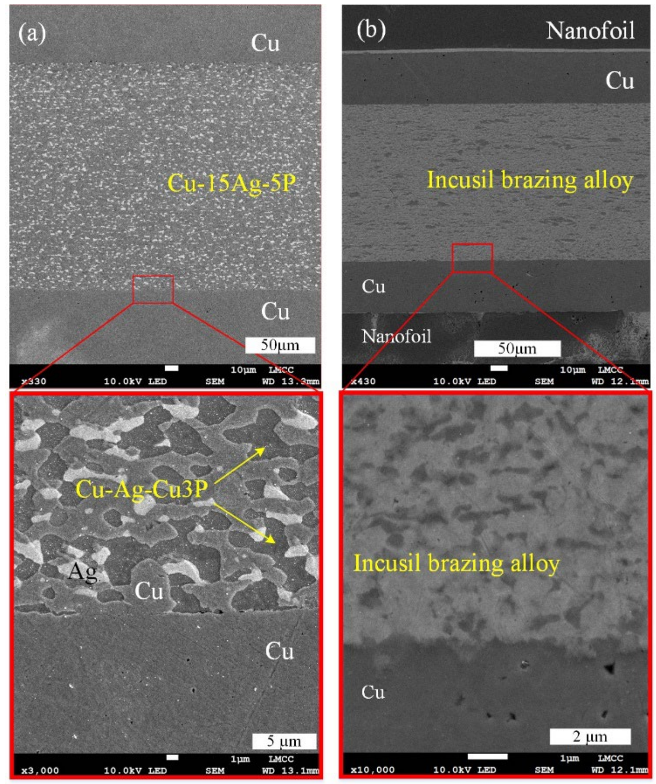

Fig. 3. Cross-section microstructure of (a) Cu/Cu-15Ag-5P/Cu and (b) Cu/Incusil/Cu sandwich joints.

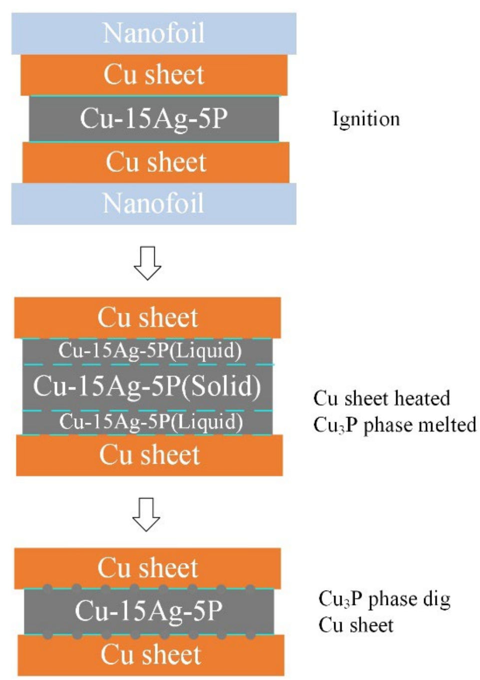

Fig. 4. Diagrams of Cu-15Ag-5P/Cu interfacial reaction mechanism during SPER bonding.

Fig 5 exhibits the outlook on the design of potential structures. The structure of Cu clip bonding is shown in Fig. 5(a), which can potentially enhance the reliability compared to the traditional wire-bonding [11]. There are some reliability issues of wire-bonding such as lift-off, which is more likely to happen in high-temperature conditions [12]. Three interconnection structures have been proposed for nanofoil applied as the external heat source, which can potentially take advantage of the bonding method developed in the current work.

For structure 1 (Fig. 5(b)), there are some demands for Cu-to-Cu interconnection in the Cu clip bonding in a power module. This is the same with the sandwich structure that has been conducted in this work. Nanofoil can be removed after Cu/brazing alloy/Cu joint is formed.

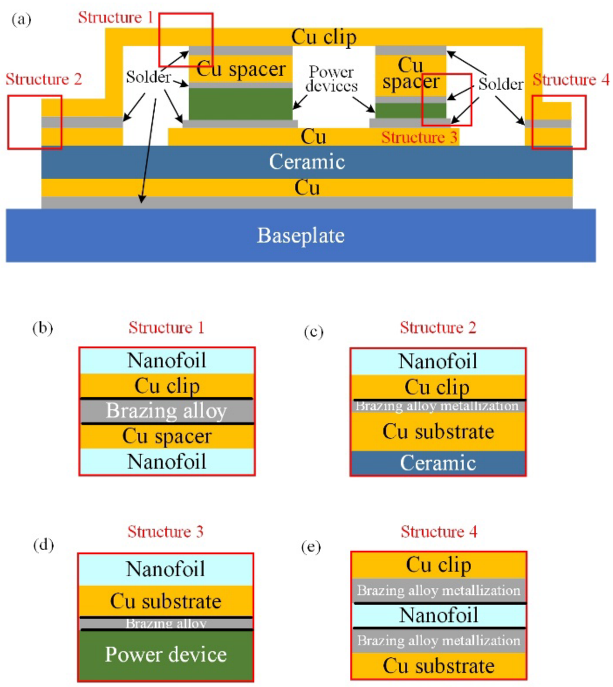

Fig. 5. Diagrams of structures that SPER applied in Cu clip bonding of a power module.

There are also some cases in which the nanofoil can be only placed on one side of the joint, as shown in structures 2 and 3 from Fig. 5(c) and Fig. 5(d). It is impossible to place the nanofoil on the bottom of a substrate since it is too thick to transfer the generated heat effectively. If the heat source can only be generated from one direction, e.g. the top side, then only the top Cu/brazing alloy interface may be firmly bonded, unless the heat generated is sufficient to penetrate through the solder layer. Structure 2 (Fig. 5(c)) promoted the use of a pre-deposited or bonded brazing layer of several micrometres on the Cu substrate, which requires less heat to only bond the top Cu/brazing alloy interface. For structure 3 (Fig. 5(d)), if a brazing alloy sheet with a thickness as thin as 10μm can be used, there is the chance to be fully melted by nanofoil. The structural design 4 is a conventional approach with the nanofoil inserted between two thin metallized brazing alloys, as shown in Fig. 5(e).

B. Nanofoil placed between two sheets of brazing alloys

The nanofoil can be bonded with Cu-15Ag-5P brazing alloy through SPER bonding directly by placing the nanofoil between two sheets of brazing alloys (Fig. 2b), forming a uniform interface, as shown in Fig. 6(a). It can be found that the Incusil layer on the nanofoil has been fully reacted and diffused into the Cu-15Ag-5P brazing alloy. Interestingly, when examining the interface from the Cu-15Ag-5P side, mainly the Cu phase was present, indicating that most of the Cu-Ag-Cu_3P phase and the Ag phase in the surface region of brazing alloy in direct contact with the Incusil layer on nanofoil had been consumed due to the reactions with Incusil layer. It is understood that the Cu-Ag-Cu_3P phase and the Ag phase both have lower melting points, which were likely to be melted during the SPER bonding, thus reacting with the Incusil layer, however, the Cu phase can remain solid due to its much higher melting temperature.

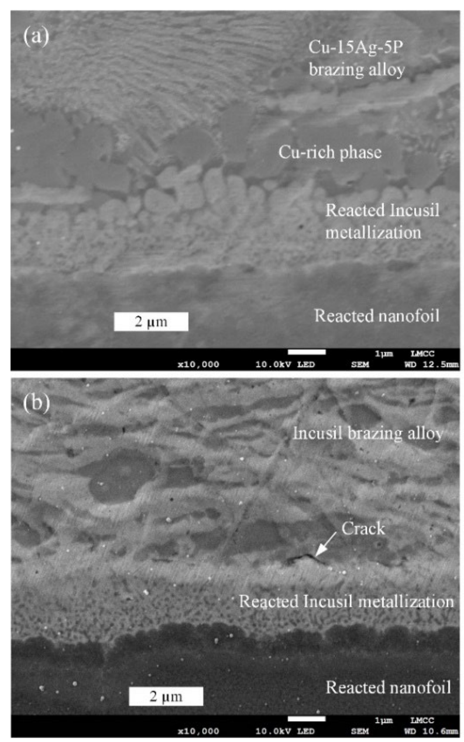

Fig. 6. Cross-section microstructure of SPER bonded (a) nanofoil/Cu-15Ag-5P and (b) nanofoil/Incusil interface.

The interface between the reacted nanofoil and the Incusil brazing alloy was shown in Fig. 6(b). It can be seen from this image that the Incusil metallization on nanofoil has merged with the Incusil brazing alloy, forming an intermediate transition region at the interface. Given both sides at the bonding interface have the same composition, once molten during SPER they can be blended or combined with each other in the liquid state. However, in some local areas close to the brazing alloy, some cracks can be observed, which has appeared to be correlated with the Cu-rich phase, which is likely due to the existence of solid Cu and its oxides involved in the bonding process.

Cu is the most widely used lead frame material, and brazing alloys including Cu-15Ag-5P and Incusil can also be the potential alternatives due to their high melting points and good high-temperature properties. However, the cost will be a concern when applying brazing alloy as the lead frame material. As schematically illustrated in Fig. 5(e), an approach to the optimal design of bonding structures as the potential solutions have been proposed given the underlying challenges. A metallization or coating of brazing alloy on the substrate is potentially useful for the interfacial bonding through the SPER process. With a brazing alloy pre-coated on the substrate, only the interfacial reactions between nanofoil and brazing alloy need to be initiated, thus forming a strong bond, which can be highly reliable.

IV. Conclusion

This study investigated the feasibility of brazing alloy applied in high-temperature and high-density electronics packaging by SPER bonding. From the obtained results and discussions, the main findings could be summarised as follows:

(1) The Cu/Cu-15Ag-5P/Cu and Cu/Incusil/Cu sandwich structures have been bonded through SPER by applying nanofoil as the external heat source. The robust bonded structures can be achieved within milliseconds under the ambient atmosphere without flux, which are expected to have good reliability during high temperature operations.

(2) The Cu-Ag-Cu_3P phase in Cu-15Ag-5P brazing alloy was melted first and then diffused into the Cu sheet. The self-flux mechanism of P element in the reactive brazing alloy is beneficial for the Cu-15Ag-5P/Cu interfacial reactions, which can lead to high bonding adhesion at the interfaces.

(3) Both Cu-15Ag-5P and Incusil can be bonded directly with the Incusil metallization on the surface of nanofoil. The current work provides a potential manufacturing route of exploiting brazing alloy for high-power electronics packaging if a full consideration can be given in terms of a suitable structural design.

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