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Short communication

Rapid formation of Ni_3Sn_4 joints for die attachment of SiC-based high temperature power devices using ultrasound-induced transient liquid phase bonding process

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ABSTRACT

High melting point Ni_3Sn_4 joints for the die attachment of SiC-based high temperature power devices was successfully achieved using an ultrasound-induced transient liquid phase (TLP) bonding process within a remarkably short bonding time of 8 s. The formed intermetallic joints, which are completely composed of the refined equiaxial Ni_3Sn_4 grains with the average diameter of 2 μm, perform the average shear strength of 26.7 MPa. The sonochemical effects of ultrasonic waves dominate the mechanism and kinetics of the rapid formation of Ni_3Sn_4 joints.

High temperature power devices operated from 300 °C to 500 °C are widely desired by aerospace applications, nuclear power instruments, satellites, space exploration, geothermal wells and sensors [1,2]. Silicon carbide (SiC) is one of the wide band gap semiconductors with superb electronic, physical, chemical and mechanical properties that enable it to operate at 300 °C and higher [3–5]. Therefore, SiC has been identified a potential semiconductor wafer for the future generation of high temperature power devices. However, one big challenge posed before the availability of SiC power devices is how to solve the lifetime problems of die attach materials at the high operating temperature. Conventional bonding materials for die attachment, such as Pb-free solder, always have the melting temperature below 300 °C, once the device operating temperature resulted from either harsh environment, power dissipation or a combination of both, exceeds the melting temperature of die attach materials, the devices will face a risk of failure. Thus, even for SiC power devices, their maximum operating temperatures are sometimes limited by the packaging.

To operate at a higher temperature, many bonding methods for die attachment, including soft soldering, nanosilver sintering and nanocopper sintering, have been developed, but each method has achieved very little success in mass production so far [6–13]. Soft soldering using eutectic alloys, such as Au-Sn and Au-Ge that have the melting temperatures of 280 °C and 356 °C respectively, are interesting candidates for high temperature applications, however, they all require the extremely high bonding temperature identical to their melting temperature, which is less compatible with common industrial reflow soldering process [6,7]. Nanosilver sintering is another popular alternative due to that Ag nanoparticles can be easily produced and sintered at low temperature, but this method suffers from high material cost and high susceptibility to electromigration [8–10]. Nanocopper sintering has also been investigated as a bonding method instead of nanosilver sintering, because Cu nanoparticles are inexpensive and less susceptible to electromigration, however, extremely high pressure is required for nanocopper sintering in order to obtain robust joints, because the oxidized surface layers of Cu nanoparticles prevent them from sintering and reacting with the substrate [11–13].

Recently, the transient liquid phase (TLP) bonding has been proven to address this technological challenge by synergistically combining reflow soldering and diffusion bonding [14,15]. It can form the full intermetallic joints with a remelting temperature dramatically higher than its bonding temperature under a mild pressure. TLP bonding has been performed in many metallization/interlayer bonding material couples as shown in Table 1, including Au-In

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Table 1
Comparison of Ni-Sn TLP bonding with other available TLP bonding [16–23].

Material	Ni-Sn	Cu-Sn	Ag-Sn	Au-Sn	Ag-In	Au-In
Bonding Temperature (°C)	○ 300	○ 280	○ 250	△ 450	○ 175	○ 200
Remelting Temperature (°C)	○ 794	○ 415	○ 600	◎ 900	○ 880	○ 495
Material Cost	◎	○	△	×	△	×
Relative CTE to SiC	◎ Ni: 4.8	○ Cu: 6	○ Ag: 6.8	○ Au: 5.1	○ Ag: 6.8	○ Au: 5.1
Complexity of Phase Diagram	○ Ni_3Sn_4	× Cu_6Sn_5 & Cu_3Sn	○ Ag_3Sn	× $AuSn_2$ & $AuSn_4$	○ $AgIn_2$	× AuIn & $AuIn_2$

◎: Best, ○: Good, △: Moderate, ×: Bad.

[16,17], Ag-In [18], Cu-Sn [19,20], Ag-Sn [21] and Ni-Sn [16,22,23]. However, some TLP bonding material couples also have their own deficiencies. Au-In and Au-Sn exhibit very high material costs, Ag-In as well as Ag-Sn are susceptible to electromigration, and Cu-Sn has a complex phase diagram, thus forming multiple intermetallic compounds (IMCs) and a nonhomogeneous bonding interface. Compared to other TLP bonding material couples, Ni-Sn demonstrates the most advantages for SiC device packaging. Ni metallizations are widely used in power devices and have a close coefficient of thermal expansion (CTE) match with SiC, furthermore, Ni-Sn TLP bonding is cost-effective and the formed Ni_3Sn_4 joints have the high remelting temperature of 794 °C. However, due to the fact that the rate of dissolution of Ni in Sn-based solder is very slow at the bonding temperature, the traditional Ni-Sn TLP bonding based on the reflow soldering process necessitates a very long bonding time for the growth of Ni_3Sn_4 intermetallic compounds (IMCs), up to tens of minutes [22], which will lead to extra thermal stress and seriously negative effects on the reliability of the packaging devices.

Ultrasonic waves have been widely used to assist material bonding process because their applications can remarkably reduce the bonding times [20,24–26]. Propagation of ultrasonic waves in the molten solder will result in complex sonochemical effects and dramatically affect the physical-chemical interactions at the liquid/solid interfaces [27–31]. It makes sense to assume that the combination of ultrasonic-assisted soldering and TLP bonding may be a creative method to reduce the bonding time necessitated by the formation of full intermetallic joints.

In this study, to prevent drawbacks of the traditional reflow TLP bonding process, a novel Ni-Sn ultrasound-induced TLP bonding method for the die attachment of SiC-based high temperature power devices was developed. The microstructure evolution, grain morphology and orientation relationship, mechanical strength and fracture surface of the Ni_3Sn_4 joints formed by this rapid ultrasound-induced TLP bonding process would be comparatively studied with those characteristics of the intermetallic joints formed by the traditional reflow TLP bonding process.

Fig. 1 shows the sandwich die/Sn/Ni interconnection structure and the ultrasound-induced TLP bonding process. The SiC dies with a dimension of 5 × 5 mm were metalized with 6 μm thick Ni on their surface by evaporation. The substrate was pure Ni plate with a dimension of 5 × 5 mm. The solder interlayer used in our work was one piece of 20 μm thick Sn foil. The bonding temperature, ultrasonic frequency, pressure and power were fixed at 250 °C, 20 kHz, 0.2 MPa and 600 W. The bonding time was selected as the main variable and varied in the range from 2 s to 8 s. The holding time at bonding temperature was equal to the applying time of ultrasonic waves. For comparison, the joints were also formed in the same interconnection structure using a traditional reflow TLP bonding process (without application of ultrasonic waves) at 250 °C with a bonding time varying from 30 min to 120 min.

The formed joint samples were mounted in epoxy and manually ground by 180, 400, 800, 1200 and 2400 grade silicon carbide papers, and then metallographically polished by 3 μm, 1 μm and 0.05 μm polishing agents. The cross sections of the joints were characterized by a scanning electron microscope (SEM) and an electron backscatter diffraction (EBSD) detector. The scanning acceleration voltage was 20 kV and the step size for the EBSD analysis was 0.08 μm. The intermetallic phases were identified by energy dispersive spectroscope (EDS) and Micro-region X-ray diffraction (Micro-XRD) analyzer. In order to evaluate the shear strength of the resulted intermetallic joints, they were tested by a bond tester with a shear speed of 100 μm/s and the fracture surfaces were observed by SEM.

Fig. 2(a)–(d) shows a sequence of cross-section SEM images of the microstructure evolution of the joints formed by the traditional reflow TLP bonding process at 250 °C. As seen in Fig. 2(a), after 30 min isothermal reflow, it was found that a compact layer of IMCs with an average thickness of 4.5 μm formed at the Sn/Ni interface and some detached intermetallic particles also grew in

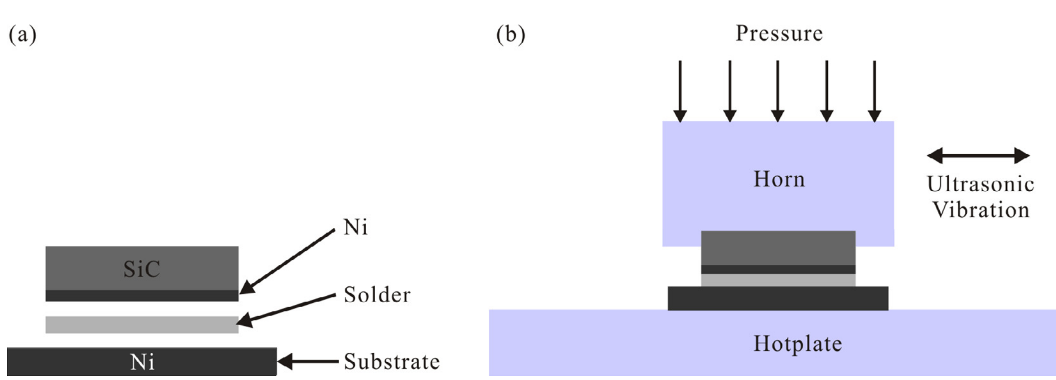

Fig. 1. Schematics of (a) the SiC die/Sn/Ni sandwich interconnection structure, and (b) the ultrasound-induced TLP bonding process.