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Ni_3Sn_4-composed die bonded interface rapidly formed by ultrasonic-assisted soldering of Sn/Ni solder paste for high-temperature power device packaging

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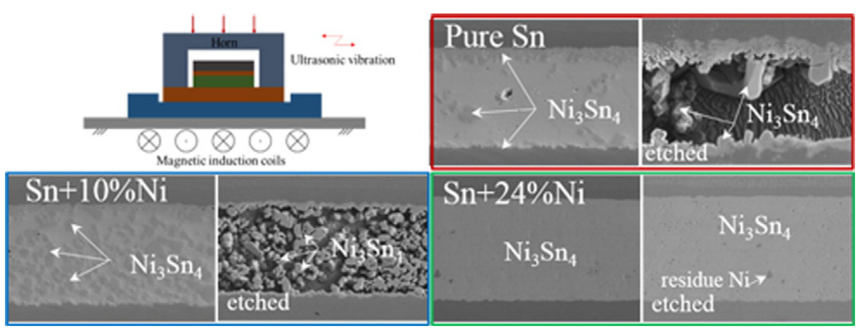
HIGHLIGHTS

- Sn/Ni hybrid solder by pressureless and rapid ultrasonic-assisted soldering was designed for die bonding.
- Nearly sole Ni_3Sn_4 joint was achieved with Sn-24 wt.% Ni solder at 250°C within 10s.
- The microstructure, shear strength and fracture modes of the joint as function of Ni content were systemically investigated.
- High re-melting temperature join with shear strength of 43.4MPa after bonding and 33.4MPa after aging at 300°C was obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

The time-consuming of transient-liquid-phase is a big challenge for the die bonding. In this paper, a novel rapid bonding method plus alloying design was proposed to cheaply fabricate Sn—Ni intermetallic joint for high temperature electronic packaging. The ultrasonic effect and the evolution of the joint microstructures, shear strength as a function of Ni content were systemically investigated. The amount of Ni_3Sn_4 in the joint increased with the addition of Ni, and when the Ni content reached 24 wt.%, the joint consisted of nearly sole Ni_3Sn_4 with a high shear strength of 43.4 MPa was achieved. After aging at 300 °C for 72 h in air, the shear strength of the joint obtained with smaller Ni content solder showed great improvement because of the phase transformation of residual Sn to Ni_3Sn_4, but for the Sn-24 wt.%Ni and Sn-30 wt.%Ni, it showed a little decrease due to the grains coarsening of Ni_3Sn_4. The acoustic cavitation and streaming effects dramatically accelerates the reaction of Ni and Sn during the ultrasonic-assisted soldering. The joint obtained by the Sn-24 wt.%Ni solder has the best potential to be applied in the power electronic packaging.

1. Introduction

The die packaging trend tends to be minimized size, high density, and excellent electrical-mechanical performance [1] with harsh working environments, such as high temperature, large current and humid ambient, leading many challenges for the devices application. At the same time, the wide band-gap semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN) have emerged most potential to replace silicon (Si) used in electronic devices, especially in high power electronics. Therefore, the study of novel interconnection materials and packaging methods to take full advantage of the excellent

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properties of SiC at high temperature has an extremely important practical significance for application in electrified vehicles [2], light-emitting diode (LED) and other power electronics [3].

Presently, the most candidates for the die bonding are Zn-based, Bi-based, noble-metal-based (such as Au—Sn, Au—Ge, Au—Si), nano-metal particles (Ag or Cu nanoparticles) [4–7] and transient-liquid-phase (TLP) bonding [1]. However, a high bonding temperature and poor ductility for Zn-based solder (>420 °C) will cause irreversible damages or accelerate aging affects to the electronic devices [8]; Bi-based solder alloys are still under way mainly due to their inferior thermal and electrical conductivity as well as poor workability [9]. It should be noted that nano-Ag sintering and TLP bonding technology have been proven to be the potential solutions to the power electronic packaging, because their processing temperatures are relatively low and the remelting temperature of produced joints are relatively high. However, nano-Ag sintering still has some drawbacks such as high cost and Ag electromigration, which will influence the stability/reliability of the joints and hinder to universal industry applications [10–12]. Although most materials used in TLP bonding are inexpensive, the process to produce full intermetallic compounds (IMCs) is time-consuming, commonly >60 min, due to relatively low reaction velocity [2,13].

In the literatures, the reaction between Ni and Sn solder of TLP was reported to be feasible for electronic devices operated at high temperature [14–16]. The reason why Sn—Ni system was chosen is that, first of all, Ni_3Sn_4 is the only reaction product after bonding and after aging at 300 °C for 72 h, which is near the highest temperature IMC in the electronic packaging field. Secondly, the diffusion velocity of Ni atom is very slow both at Sn and Ni_3Sn_4 [14], which can postpone the Ni_3Sn_4 transform to Ni_3Sn_2 or Ni_3Sn and prolong the lifetime of the electronic devices. Based on characteristics of Ni, it will take longer time to exhaust all the residual Sn than other materials if the bonding structure only reflow at relatively low temperature. A strategy of reducing the size of the weld, controlled within 10 μm, has been induced, which aims to reduce Ni and Sn diffusion distance during reflow [2,15]. But the reduction of weld size mostly involved large pressure on the die that could cause irreversible damages and accelerate aging affects to the electronic devices. Unfortunately, the consumption of time for Ni/Sn/Ni bonding structure still remains at a high level.

To solve the problem of time-consuming of the TLP and remain the merit of resisting phase transformation in the aging process, an enhanced and low-cost auxiliary measures is necessary to be adopted during bonding process. Ultrasonic-assisted soldering has been proven able to braze dissimilar metals at low temperatures within a very short time [17–19]. In our previous work, a full Cu_6Sn_5/Cu_3Sn IMCs joint through TLP assisted by ultrasonic was obtained [20]. Because of the acoustic cavitation and streaming effect created by ultrasonic waves propagating in molten alloys, the atom diffusion and physical-chemical interactions were accelerated at the liquid/solid interfaces [21–23]. However, a sole IMC joint with single phase has not been fabricated so far. Moreover, the alloy design should be considered and the dissolution of ultrasonic effect on the base materials must be investigated.

In the present study, the die and the substrate were bonded together by an ultrasonic-assisted soldering method using Sn/Ni hybrid solder paste instead of pure Sn. The reason why adding micron-sized Ni powder into Sn is that high surface-to-volume ratio of Ni powder can improve contact area of the solid Ni to molten Sn, and thus can reduce the diffusion distance, reaction time, etc. The purpose of this study is to achieve a short bonding time for the die bonding of power electronics by optimizing the Ni percent in the Sn/Ni solder. Furthermore, the microstructures, shear strength and fracture modes of the joints as function of Ni contents were systemically investigated.

2. Experimental details

In the experiment, to prevent drawbacks of the traditional die bonding, a new bonding principle was adopted by combining TLP with ultrasonic. Fig. 1 shows the sandwich structure of die/Sn + Ni paste/Ni substrate and the ultrasonic-assisted bonding principle. The die with dimension of 5 × 5 mm^2 was deposited with 8 μm thick Ni (Fig. 1a). The solder paste was composed of Sn powders (~40 μm), Ni powers with particle size of 10 μm and flux, which were mixed uniformly in a mechanical way. According to the Sn—Ni binary phase diagram, as shown in Fig. 2, a variety content of Ni (0%, 10%, 20%, 24% (near to the composition of Ni_3Sn_4), 30%, weight percent relative to the Sn—Ni) was added into the paste. The substrate was pure Ni with a dimension of 10 × 10 mm^2. The die and the Ni substrate were ground by 1200 grade silicon carbide paper to remove the surface oxygen compounds or impurities, before the bonding. Then they were immersed in absolute ethyl alcohol and cleaned by ultrasonic cleaner to expose the clean surface. Fig. 1b illustrates the bonding principle of which the hollow horn can effectively prevent the damage to the die because the bonding force was acted on the Ni substrate instead of the die. The ultrasonic vibration was in the horizontal direction. The ultrasonic parameters of ultrasonic frequency, pressure, time and power were fixed as 35 kHz, 0.4 MPa, 10 s and 500 W, respectively. The bonding temperature was set at 250 °C according to the melting point of Sn (232 °C). The holding time for the bonding temperature was equal to the applying time of ultrasonic waves. The heating and cooling rate were about 35 °C/min and 16 °C/min, respectively.

The evolution of the joint microstructures and properties as function of Ni content was focused. For the microstructural analysis, the bonding samples were mounted in epoxy and manually ground by 180, 600, 1200 and 2400 grade silicon carbide papers, then they were polished by 0.05 μm polishing agents. The samples were observed by Scanning Electron Microscope (SEM, Hitachi S-4700) equipped with an Energy Dispersive X-ray Spectrometer (EDS) detector. To observe the interior microstructures, the specimens were deeply etched by 10% hydrochloric acid ethanol solutions for 15 s. The shear strength of the joint was measured by a shear tester with a speed of 200 μm/min and 5 samples for each condition were tested. The maximum and minimum data were used as the error bars. In order to clarify fracture mode and determine the component of the joints formed by different filler metal, the shear samples after bonding and aging were further analyzed by SEM and X-ray diffraction (XRD, Rigaku D/max-2500PC, Cu Kα) immediately.

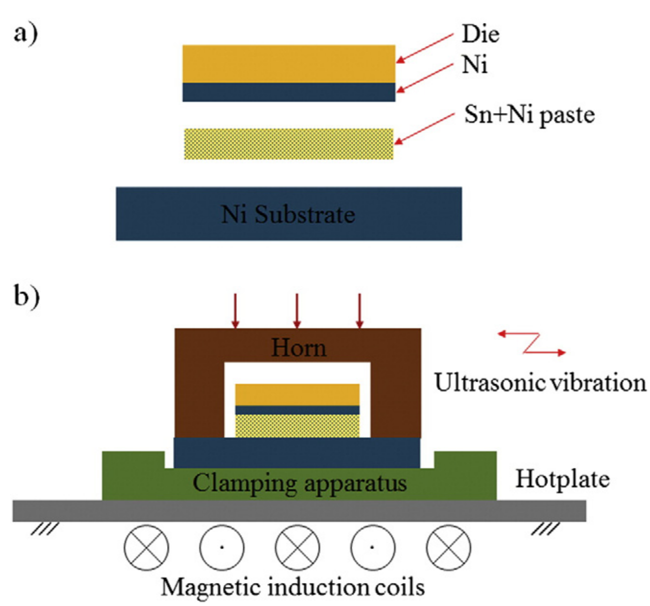

Fig. 1. (a) Schematic of the bonding sandwich structure of die(Ni)/Sn + Ni/Ni substrate, and (b) the ultrasonic-assisted die bonding principle.