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Interfacial microstructures and kinetics of Au/SnAgCu

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Abstract

The gold/lead-free solder system, or Au/SnAgCu is a potential flip chip interconnect solutions for fine-pitch applications. This paper studies the interfacial microstructures and initial isothermal solid–liquid interdiffusion kinetics during the first 3 s of bonding at 230–290 °C. As revealed by Scanning Electron Microscopy (SEM), different morphologies of AuSn, $AuSn_2$ and $AuSn_4$ are observed under different bonding conditions. The initial Au–Sn solid/liquid interdiffusion kinetics is discussed with respect to its microstructures. The rate of Au consumption is used as a measure of the rate of intermetallic compound (IMC) formation. The fitted power law relationship reveals kinetically that Au consumption follows the Arrhenius relationship with a time exponent of 0.5. Isothermal aging at temperatures between 125 °C and 165 °C gives rise to activation energies and the rate of Au consumption in solid–liquid interdiffusion to be two orders of magnitude faster than solid interdiffusion.

Keywords: Solid–liquid interdiffusion; Interfacial microstructures; Kinetics; Au; SnAgCu

1. Introduction

Lead-free soldering has become a global trend in microelectronic packaging due to the registration and implementation of tax for lead containing solders for electronic, automotive, and aircraft industries by 2006 [1,2]. Recent studies have shown that SnAgCu (SAC) solder is a promising Pb-free solder as it possesses excellent wettability, superior mechanical strength and good compatibility with existing assembly processes. Being a tin dominant lead free solder, SAC suffers poor reliability with Au due to its rapid formation of brittle Sn–Au intermetallics [3,4]. This dampens the prospect of SAC as the bonding material with Au studs for low-cost, fine-pitch, flip chip interconnect systems with the underbump metallization removed [5,6].

Both dissolution and reaction play important roles in the early stage of bonding [7]. The total chemical driving force arises from the dissolution of Au in molten solder and the interfacial reaction leads to the formation of intermetallics compounds [8] that are detrimental to joint reliability. Au dissolves and diffuses throughout the molten solder. Shin et al. reported that dissolution of Au with molten SnAg may occur [5]. Simultaneously, Au reacts with molten solder [9] which appears as an instantaneous dissolution. This eventually forms a diffusion barrier, which retards the rate of Au dissolution. Au continues to dissolve into solder either by diffusing through the layer or spall off from the interface [7]. During cooling, the saturated solution then precipitates as $AuSn_4$ [5]. Since silver (Ag) has little solubility with the phases at the interfaces, Ag has no role in forming any intermetallic [10]. Thus, only thermodynamic layer of AuSn, $AuSn_2$ and $AuSn_4$ are formed as Au interacting with molten SnAg.

There is limited literature on the kinetics of Au with molten SAC. Kim et al. [11] report that the Au dissolves quickly into 96Sn4Ag solder, forming pure $AuSn_4$ compounds with a diffusivity of 4×10^{-5} cm^2 s^{-1} at 230 °C for 10 s. Base on plot in Zribi [12,13], the dissolution rate of Au wire in molten eutectic solder is estimated to be 1.3 μm/s at 209 °C. Both studies showed that Au has a fast dissolution rate with molten Sn base solder. In solid diffusion, researchers found that solutes

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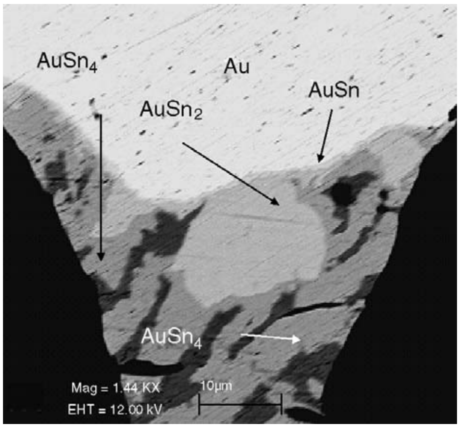

Fig. 1. Interfacial microstructures showing $AuSn_2$ and $AuSn_4$ formation at 230 °C for 0.3s.

in noble metals, such as Au, diffuse rapidly in Sn [14] with a parabolic growth rate. The high Sn content in SAC promotes excessive reaction and growth of IMC [15] than eutectic solder.

2. Experimental procedure

The gold studs with a tip diameter of 25 um were mechanically bumped on aluminium metallized dies using a thermosonic wire bonder. The Au-bumped die was then bond into a corresponding via containing SAC [6]. The height of 50 studs was measured using a high magnification 2D-microscope for analysis. The interaction of Au with molten SAC was investigated at temperatures of 230 °C, 260 °C and 290 °C for durations of 0.3 s, 1 s and 3 s. For the thermal aging growth study, the bond samples were heated at 125 °C, 150 °C, and 165 °C for durations of 100 h, 200 h, 300 h, and 500 h. All bonded samples were directly encapsulated in epoxy and sectioned using a diamond cut-off wheel for metallographic analysis. All microstructure characterizations were carried out in scanning electron microscope (SEM) with an energy dispersive X-ray detector (EDX). Each intermetallic layer was identified by EDX and its thickness measured at different locations across the interface using a digitized SEM micrograph. After bonding and aging, the remaining height of Au stud was measured using a high magnification scope and then subtracted from the average height of the stud as an estimate of the amount of Au consumed.

3. Result and discussion

3.1. Microstructures at different bonding conditions

At bonding temperature of 230 °C for 0.3 s (Fig. 1), intermetallic layer of $AuSn_2$ and $AuSn_4$ are formed at the interface with needle-like $AuSn_4$ phases projected from the interface into the solder. Upon contact, the Au dissolved and diffused throughout the molten SAC while reacting with Sn to form a diffusion layer of $AuSn_2$, $AuSn_4$ or their combination. The formation of this diffusion layer retarded the dissolution rate of Au into molten SAC. During cooling, the saturated Au solution precipitated as $AuSn_4$ phases, in accordance with the Au–Sn binary phase diagram. Thus, needle-like $AuSn_4$ phases were seen throughout the SAC. No traces of Ag_3Sn or Cu contained intermetallic were observed, similar to Kim et al.'s finding [11]. Similar microstructures were observed for 1 s and 3 s sample with thickening IMC layers and growth of needle-like $AuSn_4$ precipitates due to more Au dissolved into molten SAC.

Fig. 2(a) shows the microstructures at 260 °C for 0.3 s. The Au tip was no longer apparent with layers of AuSn, $AuSn_2$ and $AuSn_4$ sequentially laying out from Au into SAC. At 0.3 s, the $AuSn_4$ phase appeared to radiate from the bond interface into SAC. As the bonding time increased to 1 s (Fig. 2(b)), the AuSn and $AuSn_2$ layers thickened with growing $AuSn_2$ dendrites into the SAC. In bulk solder, $AuSn_4$ precipitates were observed with few needle-like $AuSn_2$ precipitates. As time increases to 3 s (Fig. 2(c)), chunks of $AuSn_2$ were surrounded with $AuSn_4$ phases in SAC.

The IMC layers formed were similar to the IMC layers for Au with SnAg [5]. This is a result of thermodynamic constraints. The $AuSn_4$ phases throughout the SAC were likely due to the precipitation of the saturated solution as Au dissolved and diffused throughout SAC. As the bonding time increased, more Au dissolved and generated a thickening of AuSn and $AuSn_2$ layers. Dendritic $AuSn_2$ was seen to grow from the interface and eventually formed spherical chunks of $AuSn_2$ in the middle of the bond interface. This was likely due to the shape of the Au stud which accelerated interaction at the tip. The spheroid structure minimized the adhesion and with its brittleness, self-weight and stresses, the chunks of $AuSn_2$ phases spalled off from the interface into the bulk SAC during cooling. During solidification, non-equilibrium cooling existed

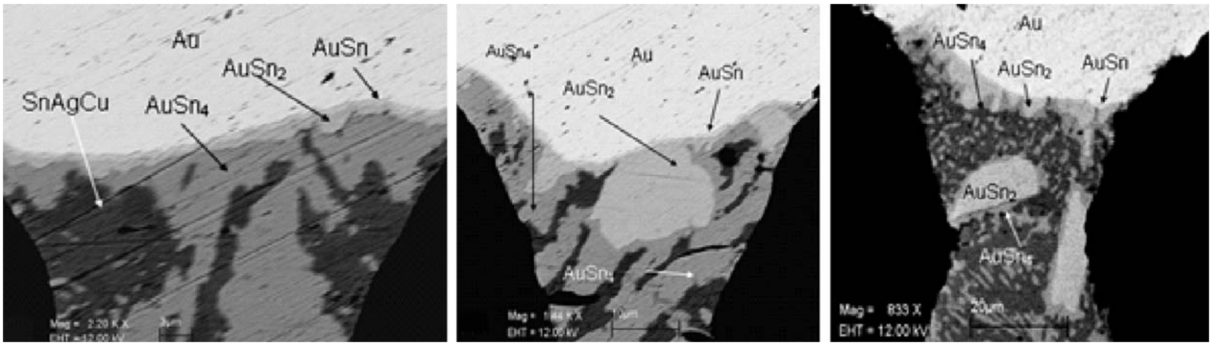

Fig. 2. Interfacial microstructures showing AuSn, $AuSn_2$ and $AuSn_4$ formation at 260 °C for (a) 0.3 s (b) 1 s and (c) 3 s.