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Formation of intermetallic compound (IMC) between Sn and Co substrate

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Abstract

Interfacial reactions between pure Sn and Co at different temperatures were investigated by using EPMA. Different intermetallic compounds were detected in the reaction couples. $CoSn_2$ was formed at 673 and 773 K while CoSn appeared at 873 K in the Sn/Co couples. In order to illuminate the formation mechanism of the intermetallic compounds, the driving force of nucleation, relative stability and Co diffusion through the interface have been taken into account. Consequently, the formation of intermetallic compounds through interfacial reactions has been explained.
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Keywords: Intermetallic compound; Interfacial reaction; Diffusion

1. Introduction

As a mature bonding technique, soldering has been widely used in electronic packaging. During this process, solders may react with various substrates and intermetallic compound(s)—IMC(s) may form at the solder/substrate interface. It is well known that the presence of an IMC between solder and substrate is a feature of metallurgical bonding. A thin and continuous IMC layer is essential for good wetting and bonding. However, due to the inherent brittle nature [1], a thick IMC layer at the solder/substrate interface may degrade the reliability of the solder joint [2,3]. Besides, during storage and service of the device, new IMC(s) may form out of existing IMC(s) [4–6] and cause microstructure changes. Such changes may detriment the reliability of the joint. Moreover, the size of solder joints is getting smaller in modern electronic package, the interfacial reaction between solder and metal pad (or under bump metallization—UBM) has become more important to package reliability [7]. Hence, owing to their importance for circuit integrity, interfacial reaction between solder and substrate attracts much attention from materials scientists and electronic industry.

Due to the consideration of health safety and environmental conservation, Pb-free solders have been developed to replace the traditional Sn–Pb solders in electronic packaging industry [8–14]. Among those Pb-free solders being studied so far, potential candidates are falling into Sn-based systems including Sn–Ag–Cu, Sn–Bi–In, etc. [15–19]. Aside from the solder alloy, selection of appropriate UBM is important in flip chip packaging technology. This is especially true for the adoption of Pb-free solders. Recently, there is a trend to use the UBM layers Co, Co–P or Au/Ni–Co to plate on substrate prior to soldering for electronic packaging [20–25]. Therefore, to study the interfacial reaction between Sn-based alloys and the Co-containing UBM layers should be of help to control IMC(s) formation for suitable packaging process designing.

Up to now, formation of IMC(s) at the interface between Sn and Cu or Ni has been experimentally studied [26–29]. Studies about the interfacial reaction between Sn and Co have already been reported in the literatures [20–23,30]. However, the formation mechanism of those IMC(s) as reaction product remains obscure. The objective of this paper is to experimentally study the interfacial reaction between Sn and Co at 673, 773 and 873 K with hope to illuminate the formation mechanism of the IMC(s).

2. Experimental procedures

Pure Sn ingots and Co slabs of 99.999 and 99.9 wt.%, respectively, were used to make Sn/Co reaction couples. First, Sn ingots and Co slabs of size of

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10 mm × 8 mm × 2 mm were cleaned with acetone and encapsulated in quartz tubes filled with argon. Then the tubes were kept vertically in the furnace at selected temperatures (673, 773 and 873 K) annealing for various durations. Since the reaction temperatures we used here are higher than melting point of pure Sn, the liquid/solid reaction couples were therefore fabricated prior to quench into water.

The reaction couples were mounted by epoxy and polished mechanically. The interfacial reaction zone for each sample was examined using the Electron Probe Micro-Analysis (EPMA) on a JEOL JXA-8800R (Japan Electron Optics Ltd., Tokyo, Japan) microprobe under the operating conditions of 20 kV acceleration voltage, 20 nA current, and a 40° take-off angle.

3. Result and discussion

Figs. 1–3 illustrate representative back-scattered electron (BSE) images of the Sn/Co couples at 673, 773 and 873 K for various durations. The reaction products at the Sn/Co interfaces were determined using EPMA. As illustrated in Fig. 1, no IMC was found at the interface of the couple annealed at 673 K for 30 min, and $CoSn_2$ was formed 10 min later (maintained to 24 h in our study). Similar phenomenon was found at 773 K as shown in Fig. 2, i.e., only $CoSn_2$ exists after 40 min. However, at 873 K the case was different as shown in Fig. 3 with the formation of CoSn after 30 min (no IMC was detected in less than 30 min). It is noteworthy that each IMC was observed to form for at least 30 min in the present work, whereas other works [21] observed shorter period was required even at much lower temperature. The difference is due to the heat transference between furnace and tube, and tube and sample in this work. Referring to previous studies [21,30], it can be concluded that the observed IMC should be the first-formed one, i.e., $CoSn_2$ was formed ahead of other IMC(s) at 673 and 773 K, and it was CoSn formed first at 873 K.

According to the Co–Sn binary phase diagram [31], Co_3Sn_2 and CoSn can exist stably at or under 873 K, $CoSn_2$ can be stable at or less than 773 K and decompose at 873 K, while $CoSn_3$ will be unstable at or more than 673 K. It seems we should be able to see three IMCs (Co_3Sn_2, CoSn and $CoSn_2$) formed at 673 and 773 K, and two IMCs (Co_3Sn_2 and CoSn) at 873 K, but we found only $CoSn_2$ ahead of others formed in the Sn/Co couple at 673 and 773 K, whereas only CoSn as the first one at 873 K. Why only one IMC ahead of others formed at the interface?

Lee et al. [32] have proposed a largest driving force model to predict the first-forming IMC at the interface between two metals. Based on Lee et al.'s work, Choi and Lee [33] have suggested a lowest nucleation energy model considering the effect of interfacial energy. According to their models, the interfacial reactions for the Sn/Co couples at 673, 773 and 873 K have been predicted and the results compared with experimental observations are listed in Table 1. It is CoSn having the largest driving force which should form first at all temperatures according to Lee et al.' model [32]. However, the IMC formed at 673 and 773 K in our work here is $CoSn_2$. While Choi and Lee model [33] indicating it should be Co_3Sn_2 forming first, but only CoSn has been detected at 873 K. Obviously, the models mentioned above cannot predict the real experimental observations. Similar case can be found in other couples such as Sn/Co [30], Cu/In [34], Ni/Bi at 573 K [35,36] and Ni/Sn at 923 K [37], respectively. In order to theoretically resolve this contradiction, it is our goal to provide a qualitative explanation to those experimental observations.

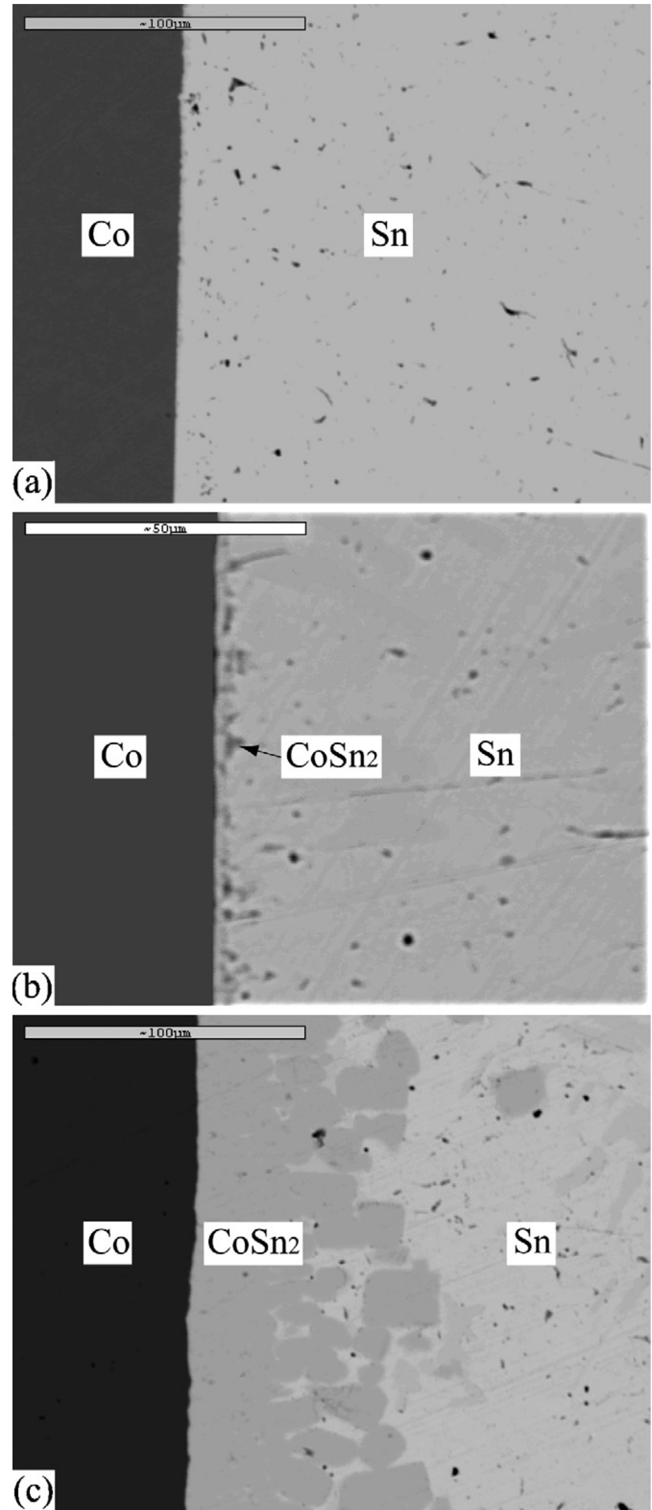

Fig. 1. Back-scattered electron images of interfacial reactions for the Sn/Co couples at 673 K for various durations (a) 30 min; (b) 40 min; (c) 24 h.

As is known, phase transformation which happens by nucleation–growth mechanism, must be a cooperative result of nucleation and growth. For an IMC formation in interfacial reaction, only if the driving force for nucleation of the IMC

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