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Interfacial evolution and bond reliability in thermosonic Pd coated Cu wire bonding on aluminum metallization: Effect of palladium distribution

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ABSTRACT

In this paper, the growth kinetics of Cu–Al intermetallic compounds formed during isothermal annealing of Pd–Cu wire bonds with different palladium distribution at 175 °C are investigated by electron microscopy and compared to bare Cu wire bonds. Transmission electron microscopy (TEM) was used to provide high resolution imaging of the Cu–Al IMCs in the as-bonded state and TEM-EDX used to analyze the concentrations of Pd at the bond interface in the as-bonded state. Cu–Al IMCs were found to grow thicker with increasing annealing duration. The growth kinetics of the Cu–Al IMCs were correlated with the diffusion process during thermal annealing. The IMC thickness for Pd–Cu wire bonds with Pd at the bond interface was found to be thinner as compared to that for Pd–Cu wire bonds with no Pd at the bond interface. Thus, the presence of palladium at the bond interface has slowed down the IMC growth. Nano-voids were found in the Pd–Cu wire bonds with Pd at the bond interface, but not in the Pd–Cu wire bonds with no Pd at the bond interface. The IMC growth rate for the Pd–Cu bonds with no Pd was found to be close to that for bare Cu for the initial annealing durations. Corresponding bond pull testing showed that Pd–Cu wire bonds containing Pd have best preserved the bond strength after 168 h aging at 175 °C due to the beneficial presence of Pd.

1. Introduction

In semiconductor packaging, thermosonic wire bonding is the main technology for fabricating electrical interconnections between chips and substrates. In the past, gold wire was the most popular and commonly used bonding material of choice. In recent years, copper wire has become a mainstream interconnection material and is widely used in fine-pitch applications due to the rising cost of gold [1]. Copper wire has better thermal and electrical conductivity compared to gold [2]. Furthermore, due to the slower intermetallic growth between copper and aluminum bond pads, copper wire bonds have improved thermal reliability compared to gold. However, copper is readily oxidized in air and requires the use of forming gas during the ball formation process [3]. In addition, copper wire has been reported to have poor performance in molded humidity reliability tests such as the pressure cooker test (PCT), and the highly accelerated temperature and humidity stress test (HAST) [4–7]. To overcome these constraints, palladium-coated copper (Pd–Cu) wire was developed and readily adopted in high pin count devices. Pd–Cu wire has a longer shelf life compared to bare copper wire due to the presence of the noble metal Pd layer. Pd–Cu wire bonds are also perceived to perform better in the molded humidity reliability test [4,8,9].

Bare Cu and Pd–Cu wire bonds were subjected to high temperature storage (HTS) at 175 °C. Two IMC layers, namely Cu_9Al_4 and $CuAl_2$, were observed after HTS at 175 °C for 2880 h. For bare Cu wire device molded with green epoxy mold compound (EMC), open failures occurred after 500 h of PCT testing. Cu_9Al_4 layer was observed to disappear and it was replaced by a narrow gap, while $CuAl_2$ was the only remaining IMC. The narrow gap was presumed to be due to the corrosion of Cu_9Al_4 by chloride ions from the EMC. For Pd–Cu wire, after 1000 h of PCT, Cu_9Al_4 and $CuAl_2$ were still detected at the interface. No crack can be seen and it was deduced that the presence of Pd can result in the formation of corrosion resistant IMC. The growth of Cu–Al IMCs in the Pd–Cu wire bond was found to be much slower compared to that for the bare Cu wire bond. Pd was seen to slow down the Cu–Al IMC formation [10]. In another study, palladium was shown to have no marked effect on the growth rate of Cu–Al IMCs. Combined with the fact that there was no detectable Pd signal in the IMCs, it was concluded that Pd atoms do not participate in the interfacial reaction [11].

Optimal formation of IMCs can lead to enhanced bond strength and reliability. However, excessive formation of IMCs and voids during

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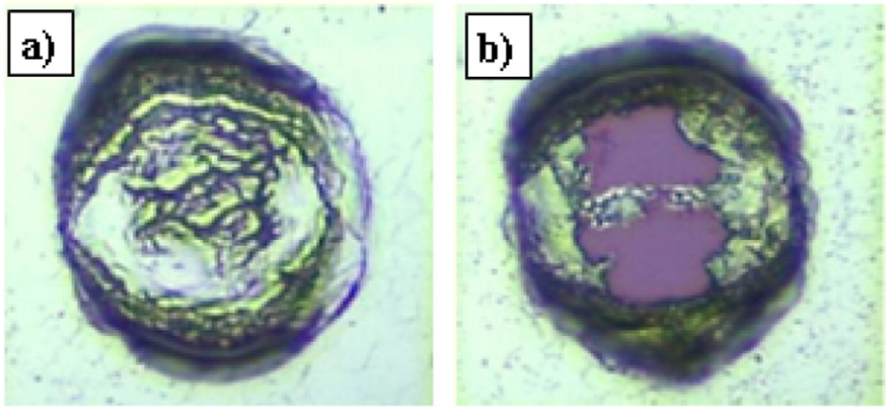

Fig. 1. Optical images of (a) ball lift and (b) pad peel.

thermal annealing can significantly impact the strength and reliability of the wire bonds. In an earlier study [12], it was shown that it is possible to vary the palladium distribution in the Pd–Cu bonded ball by adjusting the electronic flame off (EFO) current during the free air ball formation process where the wire is being melted to form a ball. A high EFO current results in the absence of Pd on the bond interface while a low EFO current gives rise to a Pd-rich layer at the bond interface. The different Pd distribution in the bonded ball results in varying concentrations of palladium at the wire bond interface which can affect Cu–Al IMC growth. Based on reported literature, Pd does have some effect on the IMC growth rate. However, in these reports, only a single condition of Pd–Cu wire bond was studied, and no information was given on the how Pd is redistributed after the EFO ball formation. To date, a comparison of the growth kinetics of Cu–Al IMCs and bond reliability of Pd–Cu wire bonds with different palladium distribution has not been reported.

In this paper, the effect of thermal annealing on the interfacial evolution of Cu–Al IMCs was investigated using Pd–Cu wire bonds with and without the presence of a Pd-rich layer at the bond interface. The wire bonds were annealed at 175 °C in nitrogen to reduce oxidation of the wire bonds and the bond interfacial structure studied as a function of annealing time. The interfacial morphology of the wire bonds on aluminum metallization pads, and the growth kinetics of Cu–Al IMCs, were also examined. The un-molded bond reliability of the Pd–Cu wire bonds with different Pd distributions was analyzed by studying the process responses at various annealing durations. In all these tests, bare Cu is used as a baseline for comparison.

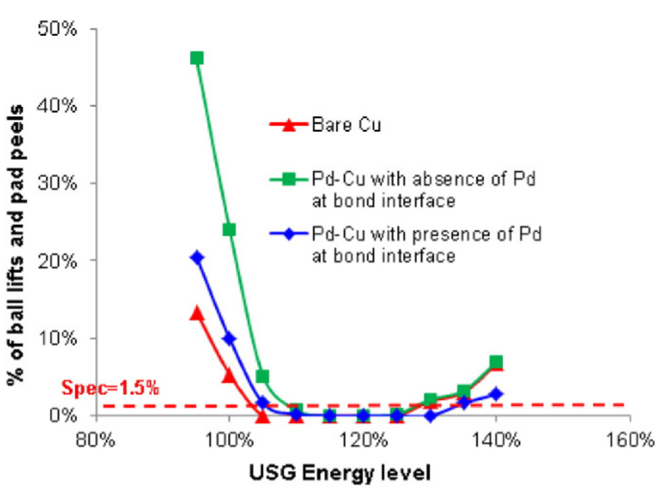

Fig. 2. Process windows for bare Cu bonds and Pd–Cu bonds with different Pd distributions in the as-bonded state.

2. Experimental

In this study, 0.6 mil (15 μm) Cu and Pd–Cu wires were bonded to an aluminum metallization with a thickness of approximately 1 μm attached to a ball grid array (BGA) substrate by employing a Kulicke & Soffa (K&S) IConn ProCu^{PS} automatic ball bonder. The Pd coating on the Pd–Cu wire is approximately 70 nm thick. A K&S Cupra3G capillary with a hole diameter of 18 μm, chamfer diameter of 22 μm and tip diameter of 50 μm was used for bonding. The wire bonding was run with forming gas as an inert gas to limit copper oxidation. The forming gas used consisted of 95% nitrogen and 5% hydrogen. The flow rate of the forming gas was set to 0.5 L/min. Wire bonding was performed at a nominal temperature of 175 °C on the wire bonder workholder.

The electronic flame off (EFO) current was varied to produce Pd–Cu bonds with the following conditions: 1) Pd–Cu wire bonds with the presence of a Pd-rich layer at the bond interface, 2) Pd–Cu wire bonds with no Pd at the bond interface. Bare Cu wire bonds was used as a baseline for comparison. An optimized set of process parameters involving contact velocity (CV), ultrasonic current (USG) and bond force was used to ensure a bonded ball size of 27 μm and a ball height of 7 μm. Process responses such as ball diameter, ball height, ball shear, first bond pull and aluminum pad splash in the USG vibration direction were measured. For the first bond pull test, the wire is pulled at the top of loop near the first bond region. A sample size of 20 bonded balls was used for all the measurements. To accelerate the interfacial evolution of Cu–Al to study the growth kinetics, the wire bonds were annealed at 175 °C for 24 h, 48 h and 168 h in an oven in nitrogen ambient to reduce oxidation on the wire bonds.

After thermal annealing, the Pd–Cu and bare Cu wire bonds were cross-sectioned using a FEI dual beam focused ion beam (FIB) system for observation of IMC growth under SEM. The IMC area was analyzed

Table 1
First bond process response for bare Cu and Pd–Cu bonds in the as-bonded state.

Process response	Pd–Cu (low EFO current)	Pd–Cu (high EFO current)	Bare Cu
Ball diameter (μm)	27.63	27.90	27.20
Ball height (μm)	7.56	7.43	7.31
Aluminum splash (μm)	32.27	32.51	31.75
Shear force (g)	8.54	8.71	8.83
Shear/area (g/mil^2)	9.2	9.2	9.1
IMC coverage (%)	91.5	91.3	92.4
Pull average (g)	5.59	5.73	4.74
Pull min (g)	5.10	5.14	4.12