Microelectronics Reliability 54 (2014) 2555–2563

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Ultra-fine pitch palladium-coated copper wire bonding: Effect of bonding parameters

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A R T I C L E I N F O

Article history:
Received 6 March 2014
Received in revised form 25 April 2014
Accepted 15 May 2014
Available online 11 June 2014

Keywords:
Palladium-coated copper wire
Palladium distribution
Grain structure
Electronic Flame Off current

A B S T R A C T

Copper (Cu) wire bonding has become a mainstream IC assembly solution due to its significant cost savings over gold wire. However, concerns on corrosion susceptibility and package reliability have driven the industry to develop alternative materials. In recent years, palladium-coated copper (PdCu) wire has become widely used as it is believed to improve reliability. In this paper, we experimented with 0.6 ml PdCu and bare Cu wires. Palladium distribution and grain structure of the PdCu Free Air Ball (FAB) were investigated. It was observed that Electronic Flame Off (EFO) current and the cover gas type have a significant effect on palladium distribution in the FAB. The FAB hardness was measured and correlated to palladium distribution and grain structure. First bond process responses were characterized. The impact of palladium on wire bondability and wire bond intermetallic using a high temperature storage test was studied.

1. Introduction

Gold wire has been the popular choice of bonding wire for many years. With the continuous increase in the price of gold, mounting pressure was felt by the electronics industry to look for lower cost alternative bonding wires. Copper wire has been rapidly adopted in high volume wire bonding production due to the cost savings over gold wire [1]. In addition, it has better electrical and thermal conductivity compared to gold wire [2]. However, studies have shown that it is susceptible to corrosion under humidity and electrically biased conditions and package reliability is a concern [3]. Another concern with copper wire is its hardness compared to gold which causes pad cratering after bonding in some devices with fragile bond pads [4]. In recent years, palladium-coated copper (PdCu) wire has seen rapid entry into the market and is widely adopted for fine pitch applications. It has a longer shelf life than bare copper wire due to the noble metal coating and is believed to have enhanced bond reliability under humid and electrically biased conditions [5].

As electronic components continue to shrink and advanced devices require high pin counts, 0.6 ml fine palladium-coated copper wire is actively being qualified before being introduced into manufacturing production lines to accommodate such technological developments [6]. Assembly and packaging companies worldwide are known to use different wires from different manufacturers of their choice. Therefore, there is a need to determine optimized Free Air Ball (FAB) and bonded ball parameters for each wire type to maximize the wire bonding capabilities. In addition, with the recent advancements in copper wire technology, the cost factor, and the implication of a Pd coating to the process response, there is a resurgence of interest from customers to run bare Cu despite the advent of PdCu wire. Currently, most wire manufacturers are still debating how Electronic Flame Off (EFO) conditions affect the Pd distribution in the FAB and bonded ball. The effect of Pd distribution on wire bondability and package reliability has not been well understood.

In this paper, we investigate such ultra-fine pitch processes using 0.6 ml PdCu and bare Cu wires from a variety of wire manufacturers with the aim to determine optimized process parameters on a K&S IConn ProCu ball bonder through a series of systematic FAB and bonded ball experiments. By varying EFO parameters, we were able to observe how FAB repeatability, and ball shape responses, vary to different extents. Next, typical first bond responses for PdCu, in the form of measuring ball size, ball height, ball shear, aluminum pad splash, and wire pull were compared with bare copper wire. All of these bonding experiments were correlated with advanced material analysis to understand the bonding

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http://dx.doi.org/10.1016/j.microrel.2014.05.005
0026-2714/

responses from a materials perspective. Palladium distribution and grain structure of the cross-sectioned FABs were studied and analyzed. These were correlated to the bonded ball hardness using an on-bonder hardness measurement technique. Intermetallic formation and growth under unmolded High Temperature Storage (HTS) were also analyzed. The different wire properties, bonding responses, and material analysis results are presented at the end with conclusions on their correlations and implications on device performance.

2. Experimental

In this study, all FAB and bonded ball testing was performed on a Kulicke and Soffa (K&S) IConn ProCu automatic ball bonder using 0.6 ml PdCu and bare Cu wires. A K&S Cupra3G capillary was used for bonding, with a hole diameter of 18 μm, a chamfer diameter of 22 μm and a tip diameter of 50 μm. The wire bonding was run using two types of cover gas (forming gas and nitrogen) for PdCu wire and only forming gas for bare Cu wire. The forming gas is a gas mixture consisting of 95% nitrogen and 5% hydrogen. The flow rate of forming gas or nitrogen was set to 0.5 L/min. The FAB in this study was prepared using the "Formed FAB" process on the wire bonder and the FAB diameter was verified using a Nikon Nexiv microscope to ensure a ball size ratio (BSR) of 1.6 and a FAB diameter of 24 μm. Ball size ratio is defined as the FAB diameter divided by the wire diameter.

Selected FAB samples were cross-sectioned using a FEI Dual-Beam Focused Ion Beam (FIB) system and the grain structure was analyzed using an EDAX Digiview IV Electron Backscattered Diffraction (EBSD) detector. EDAX Orientation Imaging Microscopy (OIM) analysis software was used for grain size and grain orientation analysis. Pd distribution found within the FAB and bonded ball was analyzed using a JEOL JSM-6610 LV Scanning Electron Microscope (SEM) equipped with an Oxford Instrument Inca Energy Dispersive X-ray (EDX) spectroscope. Pd concentration in the FAB bulk was analyzed using JEOL JXA 8530F Field Emission Electron Probe Micro Analyzer Wavelength Dispersive X-ray (EPMA-WDX).

Thermosonic ball bonding was performed on silicon die with aluminum pads with a thickness of approximately 1 μm die-attached on a BGA substrate, using an optimized set of process parameters involving contact velocity (CV), ultrasonic current (USG) and bond force to ensure a bonded ball size of 27 μm and 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.

3. Results and discussion

3.1. FAB repeatability for PdCu and bare Cu wires

In this study, we compared PdCu FABs from two different wire manufacturers. The Pd content for Type 1 and Type 2 wires provided by Manufacturer A was specified to be 2.8 wt%. The Pd content for Type 1 and Type 2 wires provided by Manufacturer B was specified to be 2.1 wt% and 1.6 wt%, respectively. Forming gas was used to form the FABs unless otherwise stated. EFO firing time was adjusted accordingly to ensure the same ball size ratio of 1.6 for each EFO current setting. FAB repeatability, which is defined by the ability to form the targeted ball size, was tested. Fig. 1 illustrates that FAB repeatability, defined as relative standard deviation or the ratio of standard deviation over the average FAB diameter, generally improves with increasing EFO current, as shown by the decreasing standard deviation at higher EFO currents. The tendency for FAB repeatability to improve with increasing EFO current is a result of more stable plasma at a high EFO current. In addition,

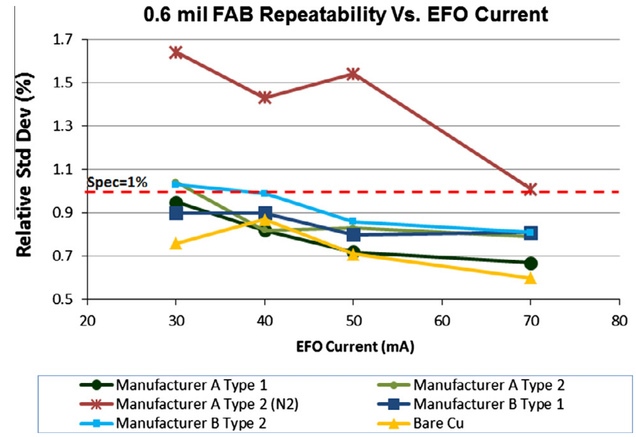

Fig. 1. FAB repeatability for PdCu and bare Cu wires for a range of EFO currents.

at higher current, the fire time is a shorter, so external factor have a reduced influence on the FAB formation process. Conversely, at a lower current and longer fire time, more heat is lost to conduction into the wire causing more variations. Fig. 1 also shows that FAB repeatability is similar for PdCu and bare Cu wires and the relative standard deviation for all the wire types generally meets the specification of 1% of the FAB diameter. In these experiments, the Pd coating thickness did not have a strong influence on FAB repeatability.

Next, we looked at the effect of cover gas type on FAB repeatability. As shown in Fig. 1, FABs formed in nitrogen exhibited degraded repeatability compared to forming gas. This could be due to a higher degree of malformed FABs in nitrogen which could be due to the difference in heating power between nitrogen and forming gas or some remaining oxidation on the FAB in the case of nitrogen. We can conclude that FAB repeatability is affected by EFO current and cover gas type.

3.2. Palladium distribution in the FAB

The effect of Pd on reliability has been an increasingly debated topic and there is a need to better understand the effect of Pd distribution on package reliability. Manufacturer A Type 2 wire was selected for the remainder of the analysis. PdCu and bare Cu FABs were bonded at three different EFO current settings (low, mid and high) with different cover gas types (forming gas vs. nitrogen). The FABs were then cross-sectioned to reveal the palladium distribution in the FAB. Optical images were taken using bright field imaging techniques and Pd rich regions were analyzed. SEM–EDX elemental mapping was then used to verify the grey regions to be Pd rich regions. The optical and EDX analysis results are shown in Fig. 2.

Some malformed balls ("apple bites") were observed for FABs formed at a low EFO current setting in forming gas, as shown in Fig. 3. The degree of malformation is worse for FABs bonded in nitrogen compared to forming gas. This can account for the higher relative standard deviation in FAB diameter when using nitrogen. The apple bite effect can be explained, at least in part, by the different heating effect of forming gas and nitrogen [7]. For bare Cu wire, no malformed balls were observed at both low and high EFO currents. It is to be noted here that this particular PdCu wire tested is a prototype wire and similar test conditions were repeated with the latest wire provided by the wire supplier, and no malformed balls were observed at the low EFO current in nitrogen.

With forming gas and a low EFO current setting, a thin uniform ring of Pd-rich phase was observed around the FAB periphery, with Pd found at the FAB tip. A higher EFO current produces a steeper