Thin Solid Films 547 (2013) 120–124

Contents lists available at ScienceDirect

Thin Solid Films

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

Effect of surface treatment on the high-speed drop reliability of Pb-free solder interconnect

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ARTICLE INFO

Available online 1 May 2013

Keywords:
Pb-free solder
Drop reliability
Shear test
Interfacial morphology
Finite element modeling

ABSTRACT

This study utilized a solder ball shear test to evaluate the mechanical behavior of Sn–3.0Ag–0.5Cu/Cu and Sn–3.0Ag–0.5Cu/electroless Ni-immersion Au solder joints under high speed loading and hence the drop reliability. The combination of the force–displacement graphs captured from the shear tests and the fracture morphology analysis discloses three fracture modes active in our samples, which include a ductile fracture occurring through the solder (Mode I), a brittle fracture along the interface with intermetallic compound (IMC) layer after some plastic deformation in the solder (Mode II), and a brittle fracture through the IMC layer with almost no plastic deformation (Mode III). Identifying a fracture mode dominant in the samples for different solder joints and shear speeds leads us to conclude that the drop reliability of solder joints is highly related to the morphology of the IMC formed at the interface and the strain rate applied to the joints. These results underscore the utility of the experimental methodology adopted in this study to evaluate the drop reliability of solder joints.

1. Introduction

Compared to Sn–Pb solders, Pb-free solders are in general stiffer and more fragile to dynamic loads, which are frequently encountered for portable electronic devices during normal or excessive operating conditions [1,2]. Due to the susceptibility of drop impact damage on solder interconnection, the popularity of portable electronics has led to a great concern on solder joint performance under high strain rate loading conditions. Typical way of examining the effect of drop impact damage on brittle Pb-free solder joint reliability is through a board-level drop test. However, the costly and laborious board-level drop test does not usually meet the time frame of the industry in developing and marketing new electronic products. In addition, the data obtained from the test does not provide much scientific insight into the failure mechanism. Several other test methods, such as high speed ball shear test, ball impact test, high speed cold ball pull test, etc., have been proposed to gain drop reliability data on the chip scale package level [3–5].

Here, we utilized the high speed ball shear test (maximum loading speed, ~3 m/s) to evaluate the mechanical behavior of solder joints under high speed loading and hence the drop reliability. In reality, solder ball interconnection is subjected to combined shear, tensile and peeling stresses. Therefore, a realistic assessment of solder ball integrity should incorporate such loading component simultaneously at the same test. Nevertheless, we employed the high-speed ball shear test for evaluating the drop reliability of the solder joints, because the test could provide a glimpse into the fundamental aspects of the mechanical behavior of solder joints under high-speed loading by generating force–displacement curves over a wide range of strain rates. In addition, it is very simple and convenient to implement.

For the fundamental understanding of the mechanical behavior of solder joints under high speed loading, it is needed to understand the precise mechanics of stress loading event during the high speed shear testing. The understanding of the mechanics would be useful for the conduction of the experiment, which can be achieved by modeling the ball shear assembly. We utilized the finite element modeling for understanding the fracture mechanics of the solder joints under high speed loading. Two solder joint systems were tested and compared, Sn–3.0Ag–0.5Cu/Cu and Sn–3.0Ag–0.5Cu/electroless Ni-immersion Au (ENIG), at various loading speeds that ranged from 0.01 to 3 m/s. Fractured morphologies were examined using a scanning electron microscopy (SEM) to correlate the force–displacement curves obtained from the tests and the fracture modes. Finally, we discussed the experimental results with a couple of computer simulation data sets.

2. Experimental and analysis procedures

Sn–3.0Ag–0.5Cu (SAC; in wt.%) solder balls, 500 μm in diameter, were obtained from Senju Metal Industry Co., Ltd. Two under bump metallizations (UBM) were employed for soldering: Cu (non-treated Cu pad) and ENIG (by electroless plating of Ni-P and gold on the Cu pad). The solder balls were attached to the circular UBM pads with the size of 460 μm on an FR-4 substrate, and were reflowed in a

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http://dx.doi.org/10.1016/j.tsf.2013.04.056

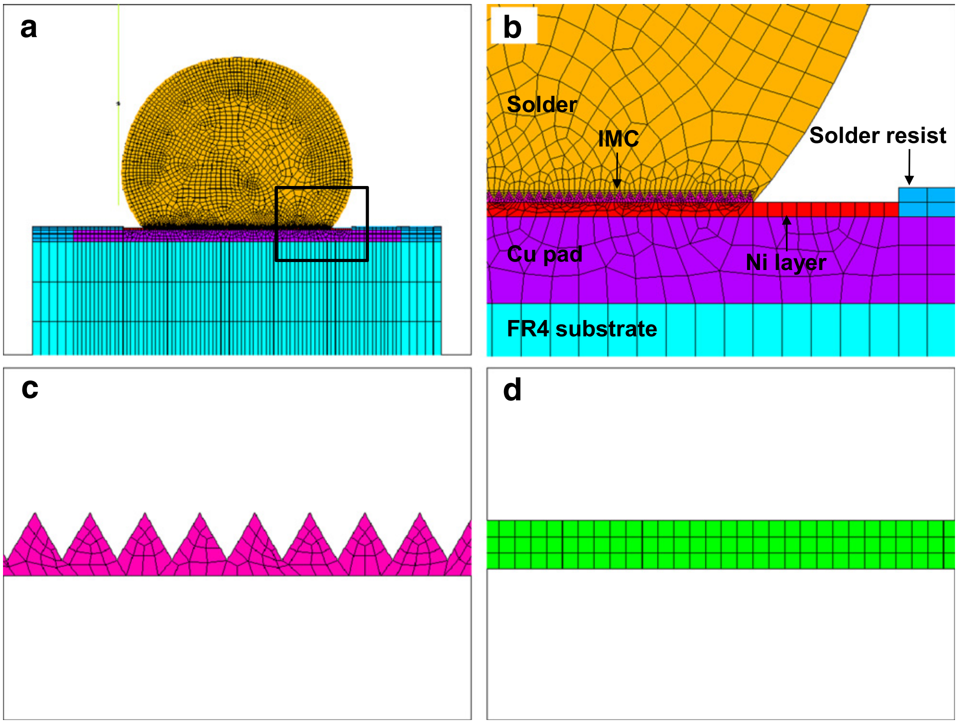

Fig. 1. Finite element model for simulation of solder ball shear test: (a) full model, (b) enlarged view of a squared area in (a), (c) IMC layer for nodular shape, (d) IMC layer for planar shape.

reflow machine (infrared 4-zone reflow machine, RF-430-N2, Japan Pulse Laboratory Co. Ltd., Japan). We characterized the microstructure of the solder joints and the fracture morphology using an SEM (Philips XL40 FEG and/or HITACHI S-3000H operated at 15 kV of acceleration voltage) equipped with an energy dispersive X-ray spectrometer (EDS, spot analyses to multiple points). We also tested the reflowed samples by a high speed ball shear tester (DAGE-4000HS, Richardson Electronics Ltd., USA). The test was done under a displacement control mode and various loading speeds (0.01 m/s, 0.1 m/s, 1 m/s, 2 m/s and 3 m/s) were used. To analyze the deformation behavior, we carried out finite element modeling analysis using a commercial finite element code, ANSYS 10.0. Fig. 1 shows the finite element model constructed for the simulation of the ball shear test event. Fig. 1(c) and (d) shows the different shapes of intermetallic compound (IMC) layers representing the needle type and coarse flatted type layers, respectively. The boundary conditions for the bottom of the substrate are set as clamped and the other part is set free to reflect the real loading conditions of the test vehicle. The SAC solder was considered to have elastic–plastic properties, while the other materials were treated like linear elastic materials. Large deformation was activated to simulate the mechanical deflection of the solder joint structure during a high speed ball shear test.

3. Results and discussion

We firstly investigated the interface of the solder joints. For the samples with an ENIG UBM, as shown in Fig. 2(a), nodular needle shape IMCs formed, which were confirmed to be $(Ni,Cu)_3Sn_4$ by EDS analysis. The thickness of the IMC layer was measured to be around 1.2 μm. Fig. 2(b) shows that scallops of IMC formed at the interface between Cu UBM and SAC solder after a reflow process. At some locations, it is thin or even not discernible. A composition analysis using EDS confirms the scallops to be Cu_6Sn_5, which is consistent with the results found in the literatures [6,7].

We carried out high speed shear test on the reflowed samples and then analyzed the fractured surfaces of the samples to examine the fracture mode active in the samples. From the examination of the fractured surfaces, we could define three fracture modes, which were schematically described in Fig. 3. The three fracture modes summarized in the diagrams of Fig. 3 are a ductile fracture through solder (Mode I), an abrupt fracture after some plastic deformation (Mode II), and a brittle fracture through IMC (Mode III). The Mode I fracture is that the crack is typically starting from a contact region between the end point of shear probe and solder to a middle corner of the other side. Therefore, the fracture occurred

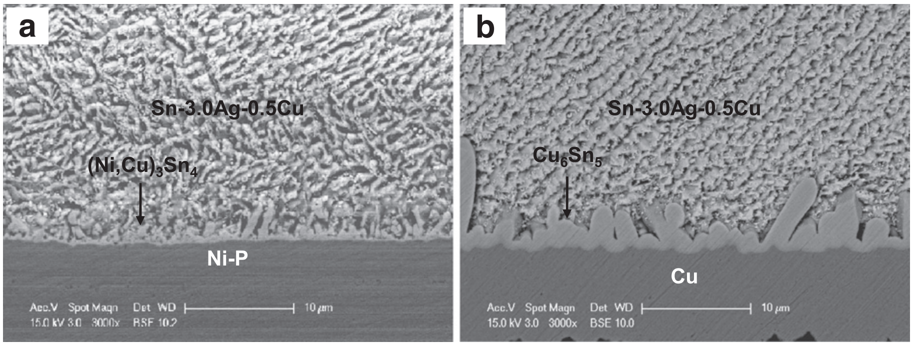

Fig. 2. Electron micrographs taken from solder joints using SEM, which display a cross-sectional view of the IMC layer between solder and a metallization on Cu pad: (a) Sn–3.0Ag–0.5Cu/ENIG, (b) Sn–3.0Ag–0.5Cu/Cu.