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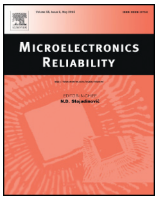

High cycle fatigue testing of thermosonic ball bonds

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ABSTRACT

During operation, miniaturized thermosonic Cu ball bond interconnects on Al pads occurring in microelectronic devices experience thermomechanical cyclic stresses, which lead to a degradation and subsequent fatigue fracture at the bond interface. Standard static tests, however, ignore the performance of such bonds under cyclic loads.

Therefore, a new mechanical fatigue testing method tailored for such interconnects has been introduced, allowing to study their high cycle fatigue behavior in reasonable time. By means of a vibrating system and a special specimen setup cyclic stresses are mechanically induced at the bond interface causing fatigue lift off, where the bond is separated at its weakest site.

For this purpose, two distinct specimen preparation methods basing on industrially applicable soldering techniques are suggested and can be used equally, depending on the focus of the investigation and the availability of the required testing structures.

The first method - “single bond testing” - allows to test each bond individually regardless of the chip layout. In contrast, the second test method - “multiple bond testing” - allows to test several bonds simultaneously. To interpret and analyze the stresses occurring at the bond interface during these tests, finite element analyses were conducted.

In the present study both methods are applied to Cu—Al ball bonds of the same quality and chip layout. It is shown that the aluminum is responsible for the fatigue crack initiation and propagation processes as confirmed by fractographic analyses of the fatigued bond interfaces.

It can be concluded that the proposed fatigue test method is a powerful alternative screening method for such miniaturized bond interfaces, which allows to reveal their mechanical fatigue behavior in reasonable time and to identify the weakest link of the tested bond interface.

1. Introduction

Currently, the standard approach to assess the mechanical reliability of thermosonic ball-bonded interconnects in microelectronic devices are the static destructive wire pull and ball shear tests obeying the JEDEC standard [1,2]. In the following study the focus is set on Cu—Al ball bonded interconnects, which are standardly employed to connect integrated circuits to their outside circuitry. Recently, this interconnect type has been widely investigated, where main focus has been set on the interfacial intermetallic compound formation, which is expected to occur due to high temperature exposure during service [3–7]. In the most recent studies no significant changes of the shear strength obtained by conventional ball shear tests has been found with increased intermetallics formation [5] though Al—Cu intermetallic compounds are brittle and are typically associated with a degradation of the bond interface. Furthermore, it is well-known that microelectronic devices are subjected to temperature excursions and vibrational loads, which causes cyclic stresses at the bond interface leading to a subsequent fatigue degradation and ultimate failure thereof. Thus, it may be concluded that afore-mentioned standard mechanical tests are insufficient to give evidence on the cyclic performance and fatigue behavior of the bond interfaces.

Recently, several studies have been focusing on the reliability of different bond systems occurring in electronic packages when subjected under combined vibration and thermal testing conditions. For example,

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Mirgkizoudi et al. investigated the reliability of Au—Au thermosonic bonds and came to the conclusion that elevated temperatures and vibrational loads (up to 2 kHz) lead to a degradation of the wire bonds [8].

In another study [9] it was shown that an increase in the dwell time results in a decrease of the fatigue life of solder interconnects, which was attributed to increased creep damage of such interconnects. Wong et al. critically reviewed the creep fatigue models of solder joints in [10] and discussed the fatigue damage mechanisms about compounding these damage mechanisms under different approaches.

Thus, it can be concluded that understanding fatigue failure of bond interconnects and solder joints occurring in microelectronic devices are of utmost importance. Khatibi et al. introduced an accelerated mechanical fatigue test technique for thick aluminum wire bonds, where controlled mechanical shear stresses simulating thermo-mechanical stresses are cyclically introduced at the bond interface. After a certain number of loading cycles, fatigue lift-off occurs, where the bonds break at their weakest site [11]. In previous studies carried out in the same laboratory, this fatigue testing method has been adapted to miniaturized Al—Cu ball bonded interconnects where two prototypical approaches – single and multiple bond testing – are presented for this interconnect type [12,13]. To the best of our knowledge, no similar cyclic mechanical testing method for this specific interconnect type has been proposed by other working groups.

A well-known reliability issue of bimetallic interconnects is the role of intermetallic compound formation occurring during their lifetime due to high service temperature exposure fostering interdiffusion of both metals into each other. In [14] the role of intermetallic compounds on the fatigue behavior of the bimetallic bond interfaces were studied by means of an improved single bond testing method, where it could be shown that an increased thickness of the intermetallic layers formed at the bond is detrimental for the fatigue behavior of the Al—Cu bond interface. It could be shown that once the Aluminum has been entirely consumed and the most brittle intermetallic compound AlCu has formed, the reliability is critical. In contrast, standardized shear tests were insensitive to the microstructural evolution showing little to no variation of the bond shear strength as a function of the intermetallics thickness. Mechanical fatigue testing of such bonds, however, allows to identify the weakest sites of the bonds under cyclic loading in reasonable time. Furthermore, the proposed accelerating fatigue testing method offers a powerful tool for rapid screening of cyclic bond reliability, as opposed to time consuming thermal cycling tests.

In the following paper two variations of industrially applicable fatigue testing approaches tailored for miniaturized Al—Cu ball bonds are presented and discussed. The occurring failure mechanisms are interpreted by means of fractographic investigations in combination with detailed finite element analyses. Therefore elasto-plastic material models are employed to quantify the predominant stresses and loading modes occurring at the bond interface during the proposed fatigue tests.

2. Experimental details

2.1. Investigated specimen

For this study unmolded, industrially available chip devices are used, on which several ball bonds are located. The bonds are made of 50 μm thick high purity (99.99%) Cu wires, which are thermosonically bonded to a 5 μm thick Al pad metallization. During the bonding process both materials experience high plastic deformations, as shown in Fig. 1, where a pronounced pad squeeze out parallel to the thermosonic bond direction is visible in the bond periphery.

2.2. Functional principle of high cycle fatigue test

The mechanical fatigue testing principle of miniaturized wire bonded interconnects bases on the controlled induction of cyclic, fully-reversed mechanical stresses at the micro-joint leading to a subsequent fatigue “lift off”, that is, a full separation of the joint at the weakest site of the bond interface (see [11]). To make this possible the said micro-chip is mounted to a vibrating support such that the tested joint acts as a coupling component between two differently inert masses: the mass of the bulk specimen holder and a so-called “active mass” referring to the mass located above the bond interface. Consequently, different inertia leads to a slightly phase-shifted motion between specimen holder and active mass. Thus, the micro-joint is exposed to cyclic shear stresses, which will cause the bond to fail after a certain number of loading cycles. The functional principle of this mechanical test technique is sketched in Fig. 2.

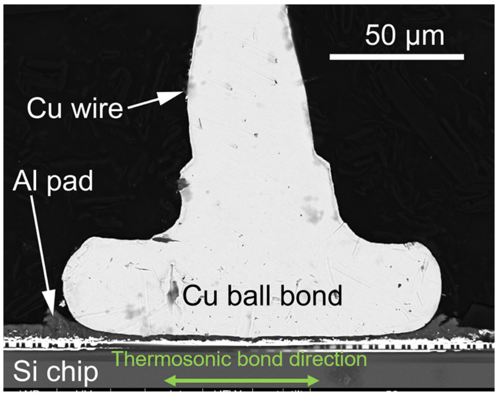

Fig. 1. Cross section of investigated Cu—Al ball bond (bond diameter ~ 135 μm; Cu ball height ~ 35 μm).

Above-mentioned principle is realized with an ultrasonic resonance fatigue system performing longitudinal vibrations at 20 kHz. Since this setup solely operates when the longitudinal resonance condition is fulfilled, the displacement and acceleration amplitudes follow a standing, sinusoidal distribution along the load train. The micro-component is mounted at the end of the sample holder - where maximum acceleration occurs - and is excited to a cyclic to and fro motion. The average shear stress amplitude τ experienced by the bond interface can be estimated by the following Eq. (1)

$$\tau = \frac{F}{A} = \frac{m \cdot a}{A} \tag{1}$$

where F, the force acting at the bond, is proportional to the active mass m and the acceleration a, which is dictated by the ultrasonic resonance system. The bond area A and the mass m are both determined post mortem. Since the acceleration is imposed by the power of the ultrasonic resonance fatigue setup, it is evident from Eq. (1) that a suitable mass-to-area ratio given by the bond geometry is necessary to induce sufficiently high shear stresses causing fatigue failure.

In the case of ball bonded interconnects, a suitable specimen modification is required since the bond area is big compared to the mass of the above situated copper ball (comment: also often called nailhead).

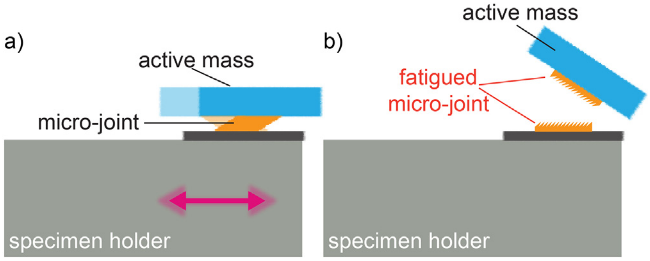

Fig. 2. Schematic principle of fatigue test of micro-joints: (a) vibrating sample holder and phase-shifted vibration of “active mass” causing cyclic shear stresses at the bond interface leading to (b) fatigue “lift off” after several loading cycles.

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