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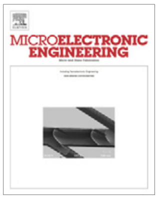

# In situ ultrasonic force signals during low-temperature thermosonic copper wire bonding

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ABSTRACT

Ultrasonic in situ force signals from integrated piezo-resistive microsensors were used previously to describe the interfacial stick-slip motion as the most important mechanism in thermosonic Au wire ball bonding to Al pads. The same experimental method is applied here with a hard and a soft Cu wire type. The signals are compared with those obtained from ball bonds with standard Au wire. Prior to carrying out the microsensor measurements, the bonding processes are optimized to obtain consistent bonded ball diameters of 60 μm yielding average shear strengths of at least 110 MPa at a process temperature of 110 °C. The results of the process optimization show that the shear strength $c_{pk}$ values of Cu ball bonds are almost twice as large as that of the Au ball bonds. The in situ ultrasonic force during Cu ball bonding process is found to be about 30% higher than that measured during the Au ball bonding process. The analysis of the microsensor signal harmonics leads to the conclusion that the stick-slip frictional behavior is significantly less pronounced in the Cu ball bonding process. The bond growth with Cu is approximately 2.5 times faster than with Au. Ball bonds made with the softer Cu wire show higher shear strengths while experiencing about 5% lower ultrasonic force than those made with the harder Cu wire.

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## 1. Introduction

The thermosonic gold wire bonding process is the most widely used method for making interconnections in semiconductor packaging. Research and development in this area is driven by factors such as miniaturization, better performance, higher reliability, manufacturing speed up, and lower costs. One possible way to address these demands is to develop new wire materials. Cu wire has been considered as an alternative to Au because of better mechanical and electrical properties, and lower cost. However, the harder Cu free air ball generally requires application of higher normal and ultrasonic forces which increases the risk of underpad damage. To develop the best possible ball bonding processes with novel copper wires, an understanding of the bonding mechanisms with such wires promises to be helpful.

One of the most suitable methods to this end is to use microsensors to measure the in situ forces caused by the ultrasound induced to the pad during bonding. The Au ball bond on Al pad bonding process was characterized using piezo-resistive microsensors [1–3]. Based on the harmonics of the recorded ultrasonic signal, five bond phases are distinguished during the process. The third harmonic of the ultrasonic force signal was used to explain two friction processes during the ball bonding of Au on Al pads: interfacial stick-slip friction between the Au ball and Al pad before and during bond formation, and friction between ball and capillary after bond formation [4,6]. It is concluded that the relative stick-slip motion between the ball and the pad includes wear which is a pre-requisite for high quality Au ball bonding on Al pads.

The concept of stick-slip friction was further developed in [7] to calculate the friction power delivered to the bond. In [8], a bond quality factor is introduced based on friction power. This model was extended in [9] to include wire deformation during the process.

In this paper, we report Au and Cu ball bonding process optimization and microsensor signals of ball bonding with Au and Cu wires on Al pads. Cu ball bonds are investigated for the same or similar mechanisms observed previously with Au wire. A comparison of the in situ signals obtained with two Cu wire types having different hardnesses is given.

## 2. Experimental

Thermosonic ball-wedge bonding is performed using a fully automatic ESEC 3100 wire bonder manufactured by Oerlikon ESEC, Cham, Switzerland, with a nominal ultrasonic frequency of 128 kHz. The bonding is performed using a standard Au wire, a soft Cu wire (Cu–S), and a hard Cu wire (Cu–H), all 25 μm (1 mil) in

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diameter and provided by MK Electron Co. Ltd., Yongin, Korea. Table 1 shows the basic mechanical properties of the three wire types. The values given as Vicker's hardness were measured on wire cross-sections made perpendicular to the wire main axis. Using the deformability characterization method reported in [10], it is found that the free air ball (FAB) made with Cu–S wire is softer than that made with Cu–H wire.

**Table 1**
Wire properties

| Property | Au | Cu–H | Cu–S |
|---|---|---|---|
| Breaking load (gf) | 10.0 | 12.6 | 10.1 |
| Elongation (%) | 2.8 | 14.9 | 11.2 |
| Vicker's hardness | 50.0 | 57.8 | 55.5 |

**Table 2**
Nominal wedge bonding parameters

| Wire | Impact force (mN) | Bond force (mN) | Ultrasound (%) | Bond time (ms) | Pre-ultrasound, off at impact (%) |
|---|---|---|---|---|---|
| Au | 700 | 350 | 65 | 25 | 0 |
| Cu–H | 700 | 700 | 80 | 65 | 30 |
| Cu–S | 900 | 600 | 75 | 65 | 30 |

**Table 3**
EFO parameters to obtain a 50 μm diameter FAB

| Wire | E–W distance (μm) | Time (ms) | Tail length (μm) | Current (mA) |
|---|---|---|---|---|
| Au | 550 | 0.4 | 500 | 54.8 mA |
| Cu–H | | | | 83.1 mA |
| Cu–S | | | | 83.9 mA |

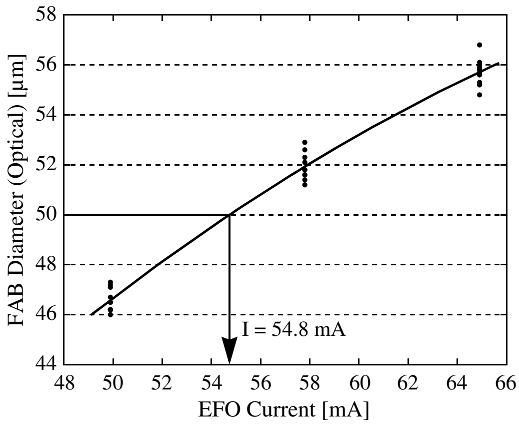

**Fig. 1.** FAB diameter vs. EFO current for Au wire. Thick solid line in center is parabolic fit. EFO time: 0.4 ms.

Bonding is performed at a nominal heater plate temperature of 125 °C resulting in actual chip temperature of about 110 °C. A commercial ceramics capillary having a hole diameter of 35 μm and a chamfer diameter of 51 μm is used. During the formation of FABs with Cu–H and Cu–S wires, a homogeneous mixture of 5% hydrogen and 95% nitrogen serves as shielding gas to prevent oxidation of the molten FAB metal during solidification. The flow rate of the shielding gas is set to 0.48 l/min.

### *2.1. Ball bonding process optimization*

The wedge bonding parameters are optimized including an iterative method reported in [11], and shown in Table 2. These parameters result in symmetrical shapes without signs of fish tailing (peeling). The unit "%" is used for the ultrasonic parameter, where 1% is equivalent to a peak to peak vibration amplitude of 26.6 nm measured at the center of the transducer tip.

Next, the parameters for the electrical flame off (EFO) process are optimized to obtain a 50 μm diameter FAB. To this end, 30 FABs are made with three different levels of EFO current by fixing all other EFO parameters such as tail length, EFO time and electrode-wire (E–W) distance to those indicated in Table 3. The FAB diameters are measured using an optical microscope and fitted with a second order polynomial against the EFO current. From the fitted curve, the EFO current corresponding to a 50 μm FAB is determined. An example plot visualizing this procedure is shown in Fig. 1.

Table 3 shows the resulting EFO currents. Using this optimized EFO current, sample FABs are made as shown in Fig. 2a–c. The diameters are verified to be 50 μm with a standard deviation of less than 0.5 μm.

Previous studies using Au [12] and Cu [13,14] wires reported the use of double-load bonding processes to reduce defects related to bonding stress (e.g. cratering). In such a process, an impact force (pre-load) which is two to three times higher than the bonding force is used. In this study an impact force nominally three times as high as the subsequent bond force is programmed. Ultrasound is present only after the impact. The nominal ball bond parameters are given in Table 4. To verify the nominal impact to bond force ratio, the actual forces applied by the machine are recorded in real-time by the proximity sensor attached to the wire clamp of the bonder [11]. Example force profiles are shown in Fig. 3a–c. It is observed that the actual ratio is about 2.4. This variation between nominal and actual values may be attributed to universal mechatronical limitations of controlling an impact event with the FAB plastically deformed.

The impact force values were adjusted such that the ball geometries were the same with each of the three wires with a target bonded ball diameter measured at the capillary imprint (BDC) of 60 μm. The nominal bonding force is then calculated to maintain the ratio described before.

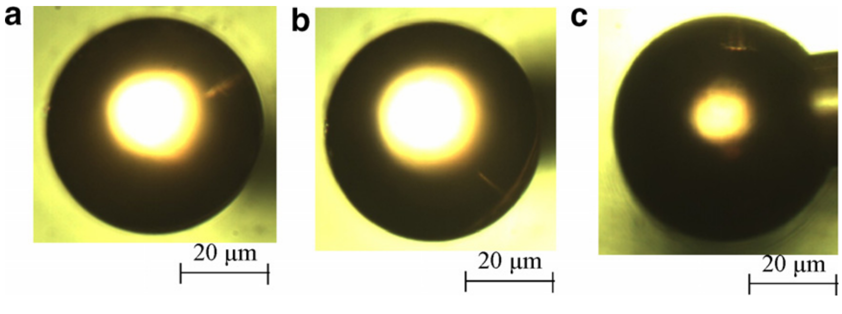

**Fig. 2.** Optical micrographs of example FABs obtained with (a) Au, (b) Cu–H, and (c) Cu–S wires.

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