Evaluation of Ultrasonic Vibration Energy on Cu-Cu Direct Bonding for Flip-Chip Interconnection

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(Received June 23, 2014; accepted September 25, 2014)

Abstract

In this study, we evaluated the ultrasonic vibration energy required for Cu-Cu bonding using flip-chip bonding technology in air atmosphere. The transmissibility of the ultrasonic vibration was assumed to be different in bump structures with high or low stiffness values. Therefore, we investigated the bonding strengths of Cu bumps with different aspect ratios (bump heights of 5 μm, 20 μm, and 40 μm). As a result, we found that the 20 μm-high Cu bumps were properly bonded with sufficient bonding strength by comparison with the other bumps. No significant voids that decrease the bonding reliability were present at the Cu-Cu interface of well-bonded Cu bumps. In addition, coplanarity between the bonding head and the stage surface was found to be an important factor for ultrasonic bonding, because it enabled all bumps to start to bond simultaneously.

Keywords: Cu Bump, Cu-Cu Bonding, Low Temperature Bonding, Ultrasonic Vibration, Flip-chip Bonding

1. Introduction

Flip chip bonding technology based on C4 (controlled collapse chip connection) is widely used in high density and high performance electronics packaging.[1] However, C4 technology is challenging for bump connections with pitches of less than 150 μm because of electrical shorts between the solder bumps. One solution is the use of a solder-capped Cu pillar bump with low solder volume.[2] The gap between chip and substrate for underfilling is maintained by the Cu pillar bump. In the solder connection, IMC (intermetallic compound) formation between the solder and the Cu pillar bump reduces the connection reliability because of the brittleness of IMC, and kirkendall voids originating from IMC growth.[2] Additionally, electromigration of a solder component is a concern at current densities of more than $1 \times 10^4$ A/cm$^2$ because the bump diameter is reduced.[3] Cu-Cu direct bonding without solder is a promising technology that can address the challenges in solder bonding because Cu has higher electromigration resistance and lower resistivity than solder.[4] The proposed Cu-Cu diffusion bonding method requires high process temperatures (250°C–400°C), long bonding times, and flat surfaces fabricated by CMP (chemical mechanical polishing) because of atomic diffusion in the solid phase.[5] As a low temperature bonding process, it was reported that a Cu bump that had been mechanically planarized with a diamond bit was bonded at 200°C.[6] Although low temperature Cu-Cu bonding at less than 150°C has been reported, the bonding technique requires an ultra-high vacuum.[7] However, Cu-Cu bonding has generally been carried out in a vacuum chamber after surface cleaning because Cu surface oxidation prevents the occurrence of Cu atomic diffusion under atmospheric conditions. Cu-Cu bonding using ultrasonic vibration is a promising solution of challenges of Cu-Cu diffusion bonding because the ultrasonic vibration can break the oxide film of Cu surface.[8] In addition, the bonding process can be completed in as little as a few seconds at low temperatures.

In our previous work, the transmissibility of ultrasonic vibrations was assumed to be different in lead structures with high or low stiffness.[9] In this paper, we focused on the transmission of ultrasonic vibrations in electroplated Cu bumps for Cu-Cu direct bonding.[10] It was assumed that the ultrasonic vibration transmissibility could also be different in different bump structures. We therefore investigated the bonding strengths and Cu-Cu interfaces of Cu bumps with various aspect ratios to clarify the effects of stiffness.
2. Experiments

2.1 Sample preparation

Figure 1 shows schematic illustrations of a Si chip and a Si substrate with Cu bumps and a Cu film to be used for Cu-Cu ultrasonic bonding evaluation. Al pads were present under the Cu bumps. These Cu bumps and the film were fabricated by electroplating. The evaporated Ti/Cu was used for the seed layer of electroplating. 1,512 Cu bumps were formed, and these bumps were peripherally patterned in nine sections. The diameter and the pitch of the bumps were 30 $\mu$m and 60 $\mu$m, respectively. The Cu bump heights were designed with 5 $\mu$m, 20 $\mu$m, and 40 $\mu$m. The Cu bump heights and surface roughness was measured using an optical surface profiler (SP-500, Toray Engineering Co., Ltd). The measured value of Cu bump heights designed with 5 $\mu$m, 20 $\mu$m, and 40 $\mu$m were approximately 4 $\mu$m, 19 $\mu$m, and 43 $\mu$m. The height of one bump in each sample was measured. The root mean square (RMS) roughnesses of the Cu bump surfaces with heights of 5 $\mu$m, 20 $\mu$m, and 40 $\mu$m were 0.16 $\mu$m, 0.22 $\mu$m, and 0.30 $\mu$m, respectively, over a measurement area of 18 $\times$ 18 $\mu$m$^2$.

Figure 2 shows scanning electron microscope (SEM) images of the three bump types. The size and the thickness of the chip were 9 $\times$ 9 mm$^2$ and 100 $\mu$m, respectively. In contrast, the Cu film thickness on the substrate was 3 $\mu$m. The substrate size and thickness were 16 $\times$ 16 mm$^2$ and 725 $\mu$m, respectively.

2.2 Ultrasonic bonding process

Figure 3 shows the Cu-Cu ultrasonic bonding process. The chip and the substrate were irradiated by Ar plasma for 3 min to remove any significant organic contaminants and oxide films using a surface treatment equipment (EXAM, Shinko Seiki Co., Ltd.). The Ar plasma irradiation conditions were RF power of 500 W, pressure of 30 Pa, and a gas flow rate of 100 ml/min. After that, the chip was bonded to the substrate using a flip-chip bonding machine (FC3000, Toray Engineering Co., Ltd.) in air atmosphere. The ultrasonic bonding conditions are shown in Table 1. The time indicates the period of applying ultrasonic vibration. The load was linearly applied after the chip was contacted on substrate.

2.3 Evaluation method of bonded sample

2.3.1 Pull test

The pull test flow for bonded sample is shown in Fig. 4.[11] During ultrasonic bonding, the pad underneath the bump was often broken due to too much ultrasonic energy. [9] Therefore, whether bonded sample was well-bonded or pad-cracked bumps was investigated by pull test. The fractures were observed by SEM.

![Fig. 1 Schematic illustration of chip with Cu bumps and substrate with a Cu film.](image1)

![Fig. 2 SEM images of Cu bumps with heights of (a) 5 $\mu$m, (b) 20 $\mu$m, and (c) 40 $\mu$m on chips.](image2)

![Fig. 3 Cu-Cu ultrasonic bonding process.](image3)

![Fig. 4 Pull test flow for bonded sample.](image4)

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<th>Table 1 Conditions of ultrasonic bonding.</th>
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ture mode of bonded bump was observed by SEM.

### 2.3.2 Bump shear test

Figure 6 shows the bump shear test flow diagram. First, the Al pads under the Cu bumps were etched off using a KOH solution. The bonded Cu bumps were remained onto the Si substrate after the KOH etching process. In contrast, the unbonded Cu bumps were lifted off after the etch process. Next, the shear strength of a single Cu bump was measured using a shear tool. The height of the shear tool from the substrate surface was 5 \( \mu \text{m} \). The shear tool speed was 250 \( \mu \text{m/s} \).

### 3. Results and Discussion

#### 3.1 Pull test

Figure 5 shows SEM images of the fracture surfaces on the substrate after pull testing. Pad crack originating from too much ultrasonic vibration was not observed in any of the bumps. The fracture surface was located at the Cu-Cu interface for each bump height. The bonded mark of 5 \( \mu \text{m} \)-high Cu bump was most strong than the others. This indicates that the bonding result depends on the height of bump even in the same bonding condition.

#### 3.2 Bump shear test

The 5 \( \mu \text{m} \)-high Cu bumps were mostly lifted off after Al pad etching, and were not successfully bonded. The reason is that ultrasonic vibration energy was too much as shown in Fig. 5. The 20 \( \mu \text{m} \)-high and 40 \( \mu \text{m} \)-high Cu bumps were mostly remained onto the substrate. The results on shear strength per bump for the (a) 20 \( \mu \text{m} \) and (b) 40 \( \mu \text{m} \)-high bumps were summarized in a histogram, as shown in Fig. 7. The shear strengths of 90 bumps were measured. As a reference for the shear strength, the Cu bump formed on the Al pad was also evaluated. There were two main peaks on the histogram for the 20 \( \mu \text{m} \)-high bonded Cu bumps. One peak was as strong as the reference strength. However, the other peak was at a much lower strength. In contrast, the shear strength of the 40 \( \mu \text{m} \)-high bonded Cu bumps was lower than the reference strength. The reason for the uneven shear strength seemed to be that not all the bumps started to bond at the same time because the bonding head and the stage surface were not perfectly parallel. Therefore, the effect of the coplanarity between the head and the stage surface was investigated with the 20 \( \mu \text{m} \)-high Cu bumps. The surface roughness of Cu bump could be negligible compared to
the coplanarity between the head and the stage surface. The evaluation method involved observation of the fracture surface during bonding. Figure 8 shows a photograph of the fracture surface on the substrate after pull test for bonding times of 0.4 s and 1.3 s. The times indicate the period the applying ultrasonic vibration. The Cu bumps for 0.4 s were only bonded on the upper and right sides because the bonding load was lower than that applied for 1.3 s. To address the uneven bonding process, the coplanarity of the bonding machine was adjusted, and the shear strength of the 20 μm-high Cu bump was measured. Figure 9 shows the shear strength per bump for the 20 μm-high bumps after the coplanarity adjustment. There were no low shear strength results when compared with the results recorded before the coplanarity adjustment. However, the average shear strength was decreased. The reason will be investigated in future work. These results indicate that ultrasonic bonding is more sensitive to the coplanarity of the bonding head and the stage than conventional thermo-compression bonding.

3.3 Cross-section observation of the Cu-Cu interface

The Cu-Cu bonding interface was observed by SEM. Figure 10 and Fig. 11 show cross-sectional SEM and SIM (scanning ion microscope) images of the Cu-Cu interfaces of the 20 μm-high and 40 μm-high bumps. The cross-sections were fabricated by FIB (focused ion beam) processing. The 20 μm-high Cu bump was properly bonded without a significant interface or voids that decrease the bonding reliability in the high shear strength area, as shown in Fig. 10(a). In contrast, gap was detected at the bonding interface in the low shear strength area, as shown in Fig. 10(b). The SIM images show that the grain interface between the Cu bump and the film was clear, and that these grains were not recrystallized because the grain size was not changed. In contrast, the 40 μm-high bump was...
partially bonded with a gap in the high shear strength area, as shown in Fig. 11. This indicated that the shear strength of the 40 μm-high Cu bump was low when compared with the reference strength. In the low shear strength area, the gap exists entirely at the bonding interface.

3.4 Simulation of ultrasonic bonding

The displacement of the Cu bump during ultrasonic bonding was analyzed by the finite element method (FEM) to compare the stiffnesses of 5 μm-, 20 μm-, and 40 μm-high Cu bumps. The FEM analysis was performed using Mechanica (Sentan Digital Co., Ltd.). Figure 12 shows a 3D micro model of the bonding structure. Table 2 shows the material properties used for the FEM analysis model. A load of 0.05 N on the Si chip and a frictional force of 0.025 N (coefficient of friction: 0.5) on the Cu bump surface were used as boundary conditions.

Figure 13 shows the simulated displacement of the Cu bump from the ultrasonic bonding model. As the height of the Cu bump increases, the displacement also increases because a Cu bump with a high aspect ratio produces a large moment. This result indicates that a Cu bump with a low aspect ratio has high stiffness, and can efficiently transmit the ultrasonic vibration. However, in our experiments, the 5 μm-high Cu bump was not successfully bonded. The failure was assumed to be caused by excess applied vibration energy. This therefore indicates that the Cu bump structure and the bonding conditions must be optimized for ultrasonic bonding.

4. Conclusion

In this study, we evaluated the ultrasonic vibration energy required for Cu-Cu bonding using flip-chip bonding technology. We investigated the bonding strengths of Cu bumps with various aspect ratios (bump heights of 5 μm, 20 μm, and 40 μm). Our conclusions are summarized as follows.

(1) Pull test results show that pad crack originating from too much ultrasonic vibration was not observed in any of the bumps, and the fracture surfaces of bonded bumps occurred at the Cu-Cu interface for each bump height.

(2) The 5 μm-high bonded Cu bumps were mostly lifted off after the Al pad etch, and thus were not successfully bonded. The 20 μm-high Cu bumps were properly bonded with sufficient bonding strength. The 40 μm-high Cu bumps were bonded but showed poor strength when compared with the reference strength of the Cu bump before the bonding process.

(3) Cross-sectional SEM observations show that there were no failures at the bonding interfaces of the 20 μm-high Cu bumps in the high shear strength areas. However, gap were detected at the bonding interface in the low shear strength areas. In the 40 μm-high bumps, there were significant gap in all areas. The reason for the uneven shear strength
seems to be that not all bumps started to bond at the same time because of insufficient coplanarity between the bonding head and the stage surface.

(4) FEM analysis indicates that a Cu bump with low aspect ratio has high stiffness, and can efficiently transmit ultrasonic vibration. However, in the experiments, the 5 μm-high Cu bump was not bonded successfully. This was assumed to be caused by the application of excessive vibration energy. This indicates that the Cu bump structure and the bonding conditions need to be optimized for ultrasonic bonding.

Acknowledgement

The authors would like to thank Prof. Shuichi Shoji and Prof. Jun Mizuno of Waseda University for the cross-sectional analysis.

References


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