Feasibilities on Ultrasonic Flip-Chip Bonding in 20 μm -pitch for COC Structure

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COC構造における20 μm ピッチ超音波フリップチップ接合技術に関する基礎検証

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概要 3次元積層LSIにおいては、Siチップを貫通する20 μm ピッチのCu貫通電極間を、微細バンパにより高精度にフリップチップ接合する技術が適用される。一般に超音波接合技術は低温、低荷重接合に適した接合プロセスとして知られている。本報では微細電解めっきAuバンパを用い、チップオンチップ(COC)構造における20 μm ピッチ低温接合について基礎検証を行った。まずスパッタAu皮膜上の基本的な接合性を評価し、超音波の印加とAu表面の清浄化が接合性に大きく影響することがわかった。次に無電解Ni/Au皮膜上の接合性を評価し、プルテストによる接合強度の評価結果から接合強度が得られることを確認した。さらに20 μm ピッチで形成した微細電解めっきAuバンパと無電解Ni/Auバンパを用い、接合断面の解析により、超音波フリップチップによる微細接合の可能性を見出した。上記の基礎評価から得られた結果は、高密度、高機能な3次元実装の実現に向け適用していく。今後の課題は最適な接合プロセスの選定と微細超音波接合における信頼性の確立である。

Abstract

The high-precision flip-chip bonding technologies in 20 μm pitch are applied to connect the copper plugs through the Si devices with the micro bumps formed on the each copper plug for 3D LSI. Generally, it is said that the ultrasonic flip-chip bonding (UFB) technologies are preferable bonding process as the interconnections at low profile and low temperature. In this paper, the possibilities of hyperfine interconnections utilizing electroplated Au bumps in 20 μm -pitch are discussed on the chip on chip (COC) structure as feasibilities. First, the basic bondabilities on the sputtered Au film were evaluated. The effect of the ultrasonic and the sputter cleaning of the bump surface were confirmed. Secondly, the possibilities of the micro-joints were confirmed on the electroless nickel and the gold (Ni/Au) plated film as the result of the evaluation on the tensile strength. At last, the possibilities of the interconnections utilizing UFB in 20 μm -pitch between the electroplated gold bumps and the electroless Ni/Au plated bumps were found out at the cross-section. The all achievement of the basic studies on the packaging process will realize the 3D LSI in the near future, which is proud of the scalabilities and the higher-performance. The subjects are the selection of the optimized process conditions and the establishment of the micro-joint reliabilities utilizing UFB process.

Key Words: Three Dimensional LSI, Flip-Chip Bonding, Electroless Plating, Ultra Sonic

1. Introduction

Nowadays, the demand for the high-speed electronics component is quite general for the consumer information equipment. A national project "Ultra High-Density Electronic System Integration" started in 1999. This project is focused on the electronic devices and systems. The target of the project is the development on the technologies to breakthrough the performance bottleneck of the electronic systems.

The high-precision flip-chip bonding technologies in 20 μm -pitch are applied to connect the copper electrodes through the Si devices with the micro-bumps

formed on the copper electrodes to realize the small and high performance 3D LSI. One of the substantial technologies for the high performance is the hyperfine interconnection¹⁾. Figure 1 shows the 3D LSI structure with the through-hole copper electrodes in the Si devices, which are formed by the reactive ion etching (RIE) process in 20 μm -pitch for the vertical wiring retentions²⁾. Figure 2 shows the interconnection between the opposed electroplated Au bumps in 20 μm -pitch utilizing thermal compression bonding at high temperature. The basic conditions were 350°C at the bonding temperature and 24.5 N at the bonding force. The bonding accuracy was within $\pm 2 \mu\text{m}$ ³⁾.

Fig. 1 3D stacked LSI structure and interconnection

Fig. 2 SEM micrographs of the micro interconnection by the thermal compression bonding at high temperature between the electroplated Au bumps in 20 μm -pitch describing (a) adjacent interconnections and (b) the magnified micro-interconnection

As for the advanced bonding process at low profile bonding to take the advantages over the conventional technologies, the two metallurgical bonding processes were evaluated for the fine-pitch. One is the ultrasonic flip-chip bonding (UFB) utilizing the gold bumps. The other is the copper bump bonding (CBB), which is applied to the simple interconnections with the tin-cap on through-hole electrode (T-COTE)⁴⁾, especially on the 3D LSI. Figure 3 shows a structure of the interconnection for stacked 3D LSI between the electroplated Au bumps and the electroless nickel and the gold (Ni/Au) plated bumps on the backside electrodes. The micro-joint on the electroless Ni/Au plating were considered as one of the candidate processes because the electroless plating was suitable to perform the micro

Fig. 3 Micro interconnection between the electroplated Au bumps and the electroless Ni/Au plated bumps on 3D LSI

pattern on the fine-pitch electrodes selectively⁵⁾ with no photosensitive process.

In this paper, the discussions are focused at the basic bondabilities of UFB utilizing the electroplated Au bumps in 20 μm -pitch on the chip-on-chip (COC) structure for feasibilities. First, the bonding was performed onto the sputtered Au film and the electroless Ni/Au plated film for the comparison on the Si interposer at low temperature. The peak temperature at the bonding was hold down to the cure temperature of the underfill resin at 150°C⁵⁾ as the provisional target. Then, the possibilities of the interconnections in 20 μm -pitch between the electroplated Au bumps and the electroless Ni/Au plated bumps were also confirmed on the COC structure at the cross-section, which lead to realize the stacked 3D LSI in the near future.

2. Experimental Model and Structure

2.1 Bump Structure

The gold bumps were electroplated on the aluminum electrodes of the Si die through the under bump metallurgy (UBM). Figure 4 shows the experimental structure of the electroplated Au bumps. The aluminum pads to locate the bumps were covered with SiN film around the pads as the passivation. For the experiments, the two kinds of the bumps were manufactured on the Si die. Table 1 shows the dimensional specifications of the bumps. As for the Si die indicated as No.1 in the table, the bump size was 12 μm -square, and 1844 bumps were located on the Si die. In addition, the Si die indicated as No. 2 in the table had the

Fig. 4 Experimental structure of electroplated Au bumps in 60 μm -pitch and 20 μm -pitch on Si die

Table 1. Electroplated Au Bumps for Experiments in UFB

	Die Size (mm)	Pitch (μm)	Bump Size (μm)	Pin Count
1	9×9×0.5 ⁱ	20	12×12×7.5 ^h	1844
2	10×10×0.5 ⁱ	60	40×70×20 ^h	1260
			70×70×20 ^h	1332

Fig. 5 Experimental structure of the electroless Ni/Au plated bumps in 20 μm -pitch on Si interposer

variable size of the bumps in 60 μm -pitch as shown in the table. The 1332 bumps were located in 60 μm -pitch totally. Both of the bumps were allocated on the peripheral of the Si die, and the height of the each bump was 7.5 μm and 20 μm , respectively.

Meanwhile, the micro bumps were also manufactured in 20 μm -pitch by the electroless Ni/Au plating. Figure 5 shows the structure of the Si interposer applied to the evaluations. The size of the Si interposer was 18 mm-square and the thickness of the die was 500 μm . The aluminum pads to locate the bumps were covered with SiN film around the pads as the passivation. The electroless Ni/Au bumps were formed at the opening on the aluminum pads selectivity. The height of the bumps was from 3 μm to 5 μm and the thickness of the gold plating capped on the bumps was from 0.03 μm to 0.05 μm .

The thickness of the passivation and the size of the opening of the passivation were common to the electroplated Au bumps and the electroless Ni/Au plated bumps especially in 20 μm -pitch for the comparison of the shear strength. The thickness of the passivation was 0.8 μm and the opening of the passivation was 8 μm -square.

2.2 Experimental Process Conditions

2.2.1 Ar Sputter Cleaning

Both of the surfaces of the electroplated Au bumps and the sputtered Au film on the Si interposer were cleaned with the argon sputtering before UFB⁶⁾. The sputtering conditions were set to etch the gold surface at 30 nm in depth. After the cleaning on the bump surface, the Si die was mounted on to the interposer by UFB. As for the electroless Ni/Au plated film and the bumps, the conditions of the sputter cleaning were set to etch the electroless Au plating at 7 nm in this experiment, because the thickness of the Au plating was thin.

2.2.2 UFB Bonding Profile

Basically, the bonding profile was constant in the experiments. Figure 6 shows the profile of the bonding

Fig. 6 UFB bonding profile for the experiment describing ultrasonic amplitude and bonding force

force and the ultrasonic amplitude. The temperatures of the bonding tool and the stage were set at 150°C as the peak temperature. The ultrasonic amplitude was transferred from the bonding tool to the interconnections through the Si die. The metal tool was kept in the parallel motion at the oscillation for the stable bonding with large die over 10 mm-square.

The two-step bonding force was applied to optimize the amplitude of the ultrasonic with the bump deformation. P1 was set as 5 N in case P2 was smaller than 20 N and P1 was set as 10 N in case P2 was larger than 20 N. The tool amplitude as 3 μm and the time of the ultrasonic oscillation as 300 ms in 50 kHz were constant as shown in the figure.

2.3 Experimental Procedure and Evaluations

2.3.1 Inspections and Analysis of Micro Bumps

The appearance of the bumps was inspected by the scanning electron microscopy (SEM). In addition, regarding with the electroless Ni/Au plated bumps, the cross-section of the bumps were analyzed by the focused ion beam (FIB). Then, the shear strength of the bumps was measured for the comparison between the electroplated Au bumps and the electroless plated Ni/Au bumps in 20 μm -pitch. The conditions applied for the measurement of the shear strength were the shear speed at 50 $\mu\text{m}/\text{s}$ and the tool height at 1 μm above the surface of the passivation on the aluminum pads.

2.3.2 UFB Bondabilities on Sputtered Au Film and Electroless Ni/Au Plated Film

Figure 7 describes the experimental model of UFB bondabilities for the sputtered Au film and the electroless Ni/Au plated film. The size of the Si die was 10 mm-square and 500 μm -thick. The size of the interposer was 18 mm-square and 500 μm in thickness. As

Fig. 7 Experimental model of UFB with electroplated Au bumps onto sputtered Au film and electroless Ni/Au plated film on Si interposer

the metal layers that covered the surface on the interposer, the electroless Ni/Au plating was compared with the sputtered Au film from the standpoint of bondabilities. The electroplated Au bumps were connected on to the surface. The thickness of the sputtered Au film was 200 nm. The nickel plating was from 3 μm to 5 μm in thickness and the thickness of the gold plating was from 0.03 μm to 0.05 μm . The nickel-phosphoric (Ni-P) plating bath and the substitutive flush Au plating were applied to the evaluation. After the bonding with the various bonding force as P2, the tensile strength was measured for the confirmation of the bondabilities. The bonding strength was measured by tensile test at the each condition. The tensile stress against the compressive stress was indicated for the evaluation of the bondabilities for the comparison of the effective bonding force to achieve the sufficient bonding strength independent on the variable bump size⁶⁾.

First, the bondabilities between the electroplated Au bumps and the sputtered Au film were confirmed focusing at the effects of the ultrasonic and the surface cleaning. The Si dies with the electroplated Au bumps in 60 μm -pitch were applied in the evaluations. Furthermore, the bonding interface was analyzed by the transmission electron microscope (TEM) at the cross-section.

Secondary, the bonding tensile strength of the Si die with the electroplated Au bumps in 20 μm -pitch was compared to that with the electroplated Au bumps in 60 μm -pitch, after the dies were mounted onto the sputtered Au film on the Si interposer by UFB.

Then, the bondability on the electroless Ni/Au plating was evaluated. The Si dies with the electroplated Au bumps in 20 μm -pitch and the Si interposers with the electroless Ni/Au plated film were applied to the experiment.

Fig. 8 Experimental model for the evaluation of the bondability by UFB between the electroplated Au bumps on the Si die and the electroless Ni/Au plated bumps on the Si interposer

2.3.3 UFB Interconnections in 20 μm -pitch between the Electroplated Au Bumps and Electroless Ni/Au Plated Bumps at Low Temperature

Finally, the hyperfine interconnections in 20 μm -pitch were confirmed between the electroplated Au bumps and the electroless Ni/Au plated bumps. Figure 8 shows the experimental model for the evaluation. The Si die with the electroplated Au bumps in 20 μm -pitch was mounted on to the Si interposer with the electroless Ni/Au plated bumps shown in Fig. 5 utilizing UFB process as mentioned above. The size of the Si die was 10 mm-square and 500 μm -thick. The size of the interposer was 18 mm-square and 500 μm in thickness. The 1844 bumps were located in 20 μm -pitch at the opposed arrangement on both of the Si die and the Si interposer for the bonding experiments between the electroplated Au bumps on the Si die and the electroless plated Ni/Au bumps on the Si interposer.

After the bonding, the cross section at the interconnections between the electroplated Au bumps and the electroless Ni/Au plated bumps were inspected after cutting by FIB.

3. Results and Discussion

3.1 Inspections and Analysis of Micro Bumps

Figure 9 shows the micrograph of the electroplated

Fig. 9 SEM micrographs of the electroplated Au bumps in (a) 60 μm -pitch and (b) 20 μm -pitch

Au bumps inspected by SEM. As shown in the figures, the straight bumps in the high-aspect-ratio were confirmed. Figure 10 shows the SEM micrographs of the electroless Ni/Au plated bumps. Figure 10(a) shows the perspective view of the adjacent Ni/Au bumps in 20 μm -pitch and Fig. 10(b) shows the magnified bump. As shown in the micrographs, the uniform appearance and the accurate positioning to the opening of the passivation were inspected. The size of the bump was approximately 13 μm square with the round corners.

Figure 11 shows the micrograph at the cross-section of the bump was observed after the cutting by FIB. The sufficient coverage of the gold plating on the nickel plating was confirmed.

Figure 12 shows the results of the shear strength of the electroless Ni/Au bumps compared with the electroplated Au bumps in 20 μm -pitch. Figure 12(a) shows the average of the ten bumps for each plating process. The average strength was 0.12 N per bump in case of the electroless plating and 0.02 N per bump in case of the electroplating. It was considered as the difference of the hardness on the Ni-P plating from the electroplated Au⁷⁾. Figure 12(b) shows the typical pho-

tograph at the breakage after the shear test observed by the optical microscope. All breakage has occurred in the bumps.

As the results, the electroless Ni/Au bumps were manufactured in 20 μm -pitch. Moreover, the bumps indicated larger shear strength than electroplated Au bumps.

3.2 UFB Bondabilities on Sputtered Au Film and Electroless Ni/Au Plated Film

3.2.1 Effect of the Ultrasonic and the Ar Sputter Cleaning for Bondabilities on Sputtered Au Film

Figure 13 shows the results of the bonding tensile stress measured on the each bonding compressive stress. As the results, it found that the effect of the ultrasonic and the surface cleaning for the enhancement of the bonding strength were clear. Especially, the result of the bonding strength with the ultrasonic indi-

Fig. 10 SEM micrographs of the electroless plated Ni/Au bumps focused at (a) the adjacent bumps in 20 μm -pitch and (b) the magnified bump

Fig. 11 Cross-section of the electroless Ni/Au plated bump by FIB

Fig. 12 The results of the shear test indicating (a) the comparison between the electroless Ni/Au bumps and the electroplated Au bumps in 20 μm -pitch and (b) the typical breakage in the bulk observed by optical microscope in case of the electroless Ni/Au bumps

cated the much difference from the strength without ultrasonic. It was considered that the ultrasonic amplitude enhanced the bondability at low temperature and the Ar sputter cleaning contributed to improve the bondability because of the surface activation by etching the most surface of the electroplated Au bumps and the sputtered Au film⁸⁾. The surface cleaning was considered to be as one of the essential technologies for micro joints at solid phase bonding.

Figure 14 shows the TEM micrographs at the cross-section of the bonding interface after UFB. The analysis was performed on the Si die with the Au bumps in 60 μm -pitch. The bonding compressive stress was

Fig. 13 Effect of the ultrasonic and the surface cleaning shown in the tensile strength evaluated after UFB utilizing the Si die with the Au bumps in 60 μm -pitch

77.4 MPa. Figure 14(a) shows the bonding interface, Fig.14(b) shows the magnified micrograph at the interface, and Fig.14(c) shows the lattice image at the interface. As shown in the figure, although the minute defects were observed at the bonding interface between the electroplated Au bump and the sputtered film, the sufficient bonding was confirmed even in the lattice image at the portion with no defect.

Then, the impact of the ultrasonic for the bonding at low temperature was proved.

3.2.2 UFB Bondabilities of Electroplated Au Bumps in 20 μm -pitch on Sputtered Au Film

Figure 15 shows the results of the comparison on the bonding tensile strength of the Si die with the Au

Fig. 15 Comparison of the tensile bonding strength shown as the tensile stress between the Si die with the Au bumps in 20 μm -pitch and the bumps in 60 μm -pitch

Fig. 14 Micrographs analyzed by TEM at (a) bonding interface, (b) magnified bonding interface, and (c) lattice image after UFB, which was performed on the Si die with Au bumps in 60 μm -pitch

bumps in 20 μm -pitch was compared to that with the Au bumps in 60 μm -pitch. As shown in the figure, the tensile stress with the Au bumps in 20 μm -pitch indicated the sufficient result so much as the stress with the Au bumps in 60 μm -pitch. It was considered that the bonding compressive stress was dominant for the bondability indicated by the bonding tensile stress in case of UFB. The difference of the structure was not significant in the experiments.

Therefore, the UFB bondabilities on the micro-joint with the electroplated Au bumps in 20 μm -pitch and the excellent bonding interface on the sputtered Au film at low temperature were confirmed, which was expected as the candidate process as hyperfine interconnection.

3.2.3 UFB Bondabilities of Electroplated Au Bumps in 20 μm -pitch on Electroless Ni/Au Plated Film

Figure 16 shows the results of the tensile strength. The square dots show the results of the tensile stress on the electroless Ni/Au plating and the circle dots show that on the sputtered Au film. As the results, the tensile stress on the electroless Ni/Au plating was not up to that on the sputtered Au film. However, it was found that the bonding force was effective to increase the bonding strength, because the strength was increasing as the bonding force enlarged. Even more, the tendency was close to the results on the sputtered Au film.

Therefore, as the results of the feasibilities, the possibilities of the micro-joints on the electroless Ni/Au plating with the electroplated Au bumps in 20 μm -pitch were confirmed. The optimization of the thick-

Fig. 16 Feasibilities of the bondability on the electroless Ni/Au plating compared with the sputtered Au film after UFB evaluated on the bonding tensile stress utilizing the electroplated Au bumps in 20 μm -pitch

ness of the Au plating and the conditions of the surface cleaning will be the subjects.

3.3 UFB Interconnections in 20 μm -pitch between the Electroplated Au Bumps and Electroless Ni/Au Plated Bumps

Figure 17 shows the results of the inspection. As the result, the sufficient interconnections in 20 μm -pitch were confirmed between the electroplated Au bumps on the Si die and the electroless plating Ni/Au bumps on the Si interposer. The sufficient bonding interface was observed between the electroplated Au bumps and the electroless Ni/Au plated bumps. It was considered that the ultrasonic amplitude enhanced the bondability for the thin Au film by the electroless plating, which was thinner than the sputtered Au film.

Regarding with the hyperfine interconnections on COC structures for the active devices, it will be important that the controls of the micro bump deformation and the damage for the devices. The ultrasonic amplitude enhances the bondability but also increase the deformation of the micro bumps, which cause the electrical short for the hyperfine interconnections. In addition, it is considered that the excessive ultrasonic amplitude through the thin-metal layer with the strain during the bonding causes the damage for the bonding area⁹⁾. From now on, the optimization of the UFB process will be substantial subjects to control the

Fig. 17 The results of the confirmation on the bondability at the cross section between the electroplated Au bumps and the electroless Ni/Au plated bumps, which were connected by UFB and inspected after cutting by FIB

bump deformation during the effective ultrasonic amplitude and the damage under the bonding area. Moreover, the establishment of micro-joint-reliability utilizing UFB will be important.

As mentioned above, the possibilities of the interconnections between the electroplated Au bumps and the electroless Ni/Au plated bumps were confirmed on the COC structure. It will be candidate as the vertical interconnections on 3D stacked LSI.

4. Conclusions

First, UFB bondabilities on the micro joints with the electroplated Au bumps in 20 μm -pitch and the excellent bonding interface on the sputtered Au film at low temperature were confirmed.

Second, the possibilities of the micro-joints on the electroless Ni/Au plating with the electroplated Au bumps in 20 μm -pitch were confirmed. It was considered that the optimization of the thickness of the gold plating and the conditions of the surface cleaning would be the subjects.

Then, the electroless Ni/Au bumps were manufactured in 20 μm -pitch. It showed the uniform appearance, the accurate positioning to the opening of the passivation, the sufficient coverage of the gold plating on the nickel plating, and the larger shear strength than the electroplated Au bumps.

Finally, the sufficient interconnections in 20 μm -pitch were confirmed between the electroplated Au bumps on the Si die and the electroless Ni/Au plated bumps on the COC structure utilizing UFB process. The possibilities of the vertical interconnections on 3D LSI with the electroless Ni/Au bumps were confirmed.

The all achievement of the basic studies on the packaging process will realize the 3D LSI in the near future, which is proud of the scalabilities and the high-performance. The subjects are the optimization of the process conditions to control the bump deformation and the damage during bonding, and the establishment of the micro-joint reliabilities utilizing UFB process.

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