Cleaning challenge of die attach process in FCBGA with larger die sizes and finer bump pitches

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Abstract

With the rapid growth in demand for data center, artificial intelligence, high-performance computing and autonomous vehicles, FCBGA (Flip Chip Ball Grid Array) technology is advancing toward larger die sizes and finer bump pitches. The need for higher I/O counts has driven the demand for smaller bump pitches to increase I/O density. The traditional bump pitches of 150μm are being reduced to 80μm or less. Finer bump pitch introduce significant cleaning challenges as it increases the likelihood of flux residue, affecting product performance and reliability. This article mainly explored the major factors of flux cleaning, including concentration of cleaner, clean speed and wash tank temperature. In this experiment, highly active halogen flux was used for the cleaning test. Due to its chlorine compounds and corrosive, the effects of flux residue can be easily observed through reliability testing. FCBGA packages were subjected to several reliability tests, including: JEDEC Level 3 preconditioning (MSL3); uHAST (96 hours); bHAST (264 hours); HTSL (1000 hours). After these, the functionality of the packages was evaluated using I/V tests. SAT (Scanning Acoustic Tomography) to examine internal structural integrity. If structural issues such as white bumps were detected, SEM (Scanning Electron Microscopy) and TEM (Transmission Electron Microscopy) were employed to observe package interface delamination. EDS (Energy Dispersive Spectroscopy) was used to analyze the elemental composition at delamination position. Overall, the findings of this study indicate that cleaner concentration and clean speed are key factors in flux cleaning process after die attach, that can be adjusted to effectively clean flux residues, thereby enhancing the reliability and performance of FCBGA packages.

Introduction

FCBGA (Flip-Chip Ball Grid Array) packaging technology has become a key enabler in advanced electronics, supporting the demands of high-performance computing, networking, and artificial intelligence applications. With its ability to accommodate high I/O density and deliver excellent electrical performance, FCBGA is widely used in high-end processors such as CPUs, GPUs, and ASICs. The flip-chip architecture, where the die is mounted face-down and connected through solder bumps, reduces signal path lengths, enhances signal integrity, and improves overall package reliability.

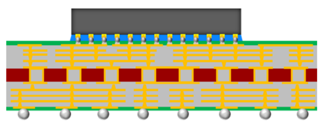
Despite its advantages, FCBGA packaging presents unique challenges during assembly, particularly in the flux cleaning process following the die attach stage. Incomplete flux removal can lead to reliability concerns, especially when halogen-containing fluxes, such as Indium WS-446, are used. Residual halogens like chlorine can contribute to corrosion, delamination, and long-term failure of the interconnect structures. This study focuses on optimizing the cleaning process for a FCBGA package, specifically examining how cleaner concentration, temperature, and cleaning speed influence the effectiveness of flux removal. Furthermore, the study evaluates the reliability implications of insufficient cleaning and investigates root causes of failure using advanced failure analysis techniques such as SEM, TEM, and EDX.

Experimental

The test vehicle selected for this study is summarized in Table 1. It features a Flip Chip Ball Grid Array (FCBGA) package with dimensions of 40 mm × 40 mm, a total of 19,136 I/O connections, and a bump pitch of 130 µm. The die attach process employs Indium WS-446, a water-soluble flux known for its strong wetting properties and compatibility with flip chip bonding. This flux contains halogens, particularly chlorine, which enhances its activity and solderability during the reflow process. However, due to the presence of halogens, thorough post-reflow cleaning is essential to avoid potential corrosion or long-term reliability issues.

The experiment begins with the optimization of two key cleaning parameters: chemical concentration and temperature. This phase aims to identify the most effective cleaning conditions. Once these are determined, the study will proceed to evaluate the impact of various cleaning speeds under the optimized chemical and thermal conditions.

Table 1. The details of the test vehicle.

	FCBGA
Package Structure	
Package size (mm^2)	40 x 40
Die size(mm^2)	21*20
I/O counts	19136
C4 bump pitch (µm)	130
C4 pad opening size (µm)	70

The experimental conditions are summarized in Table 2. Three concentration levels were tested, including low concentration, medium concentration and high concentration to examine the effect of chemical strength on cleaning effectiveness. Cleaning solutions were heated to low temperature, medium temperature, and high temperature, respectively, to evaluate how increased thermal energy impacts the removal efficiency of contaminants. The process was run at three different clean speeds: 0.3 M/min, 0.6 M/min, and 0.9 M/min.

Table 2. Experimental conditions.

Item	Unit	1	2	3
Cleaner Concentration	%	Low	Medium	High
Cleaner Temperature	℃	Low	Medium	High
Clean Speed	M/min	0.3	0.6	0.9

Following the cleaning experiments, the test samples will undergo a series of reliability evaluations, including MSL3(Moisture Sensitivity Level 3), uHAST 96hrs, bHAST 264hrs, and HTSL (High Temperature Storage Life) testing.
The reliability screening will begin with FT (Final Test) to verify the electrical functionality of the test vehicle. In cases where abnormalities are detected, SAT (Scanning Acoustic Tomography) will be used to localize the defect. Further investigation will be conducted using I/V tests, SEM (Scanning Electron Microscopy), TEM (Transmission Electron Microscopy) and EDS (Energy Dispersive Spectroscopy) to identify the defect mode and analyze the potential root causes.

Results and Discussion

A. Effect of Cleaner Concentration on Flux Cleaning Efficiency

Cleaner concentration plays a critical role in determining the effectiveness of flux residue removal, comparison of cleaner concentration are summarized in Table 3. Higher concentrations contain more active components, which enhance the chemical reaction with acidic or fatty substances in the flux. This reaction converts contaminants into water-soluble compounds, improving the overall cleaning performance. In particular, non-polar materials commonly found in flux such as rosin are not easily dissolved in water. A higher cleaner concentration promotes emulsification of these substances, allowing them to be suspended in the cleaning solution and rinsed away more effectively.

However, using a high-concentration cleaner also presents challenges. It can be more difficult to rinse off completely, potentially requiring more water and longer rinse times. Incomplete rinsing may leave behind ionic residues, which can impact long-term reliability. While there is a general positive correlation between cleaner concentration and cleaning efficiency, it is important to balance this with considerations such as material compatibility, rinsability, and cost. Based on this evaluation, a medium cleaner concentration has been selected for the subsequent line speed experiments to maintain effective cleaning while minimizing potential drawbacks.

Table 3. Comparison of cleaner concentration.

Cleaner Concentration	Advantages	Disadvantages
High	1. High active component content. 2. Effectively removes hard to dissolve contaminants (e.g. Rosin)	1.Require more cleaning water and rinse times to remove ionic residues.
Medium	1. Balanced cleaning efficiency and process stability. 2. Moderate cost.	1. Slightly less cleaning efficiency than high concentration
Low	1. Minimal cleaner residue risk. 2. Lowest water usage and cost.	1. Poor cleaning performance.

B. Effect of Cleaner Temperature on Flux Cleaning Efficiency

Cleaner temperature is another key factor influencing the efficiency of flux residue removal, comparison of cleaner temperature are summarized in Table 4. Higher temperatures accelerate the saponification reaction, which is particularly effective for breaking down rosin-based flux residues. Heat softens or even melts the flux, allowing for improved contact between the cleaning agent and the contaminants. This enhances emulsification and makes residues easier to remove.

However, excessively high cleaner temperatures can introduce potential risks. Elevated temperatures may lead to rapid evaporation, reducing the concentration of the cleaning agent or causing foaming issues. Additionally, high-pH cleaners can become more aggressive at higher temperatures, increasing the risk of material corrosion or surface damage.
To strike a balance between cleaning performance and process stability, a medium cleaner temperature has been selected for the upcoming line speed experiments.

Table 4. Comparison of cleaner temperature.

Cleaner Temperature	Advantages	Disadvantages
High	1. Accelerates saponification reaction. 2. Softens Flux residues. 3. Enhances cleaner effectiveness.	1. Cleaner rapid evaporation. →Reduce cleaner concentration. 2. Increasing risk of material corrosion.
Medium	1. Balanced cleaning efficiency and process stability. 2. Reduces risk of evaporation and foaming.	1. Slightly less effective than high temperature.
Low	1. Stable process condition.	1. Reduced chemical reaction rate 2. Lower cleaning effectiveness

C. Effect of Clean Speed on Flux Cleaning Efficiency

In automated cleaning systems used after the die attach process, cleaning speed is a critical parameter that determines the residence time of the sample in each stage saponification, rinsing, and drying. This residence time directly impacts the overall effectiveness of flux removal. Slower cleaning speeds provide longer exposure to cleaning agents and rinse water, which enhances saponification, emulsification, and the removal of flux residues. This extended contact time is especially beneficial for thick or stubborn residues, as it promotes more thorough cleaning. As a result, both organic contaminants and ionic residues are more effectively eliminated, reducing the risk of downstream reliability issues.

On the other hand, excessively fast cleaning speeds can compromise the cleaning process. Shorter contact times may result in incomplete breakdown or emulsification of the flux, leading to residual contamination. Additionally, inadequate rinsing at high speeds can leave behind traces of cleaning agents, increasing the risk of foaming, corrosion, or long-term performance degradation. There is a clear inverse relationship between cleaning speed and cleaning effectiveness: as speed increases, cleaning performance tends to decrease.

To ensure optimal results, cleaning speed must be carefully adjusted according to factors such as the type of flux used, the level of contamination, and the configuration of the cleaning equipment. Sufficient processing time in each cleaning stage is essential for reliable flux removal.

Experiments were conducted using cleaner medium concentration and cleaner medium temperature conditions with different clean speeds, and EDX spectrum was used to analyze whether there was flux residue. The analysis location is shown in Figure 1. Table 5 summarizes the EDX elemental analysis results at cu pillar/underfill interface, with varying cleaning speeds. Under the condition of a line speed of 0.9 M/min, trace amounts of Cl element were detected at the Cu pillar/underfill interface.

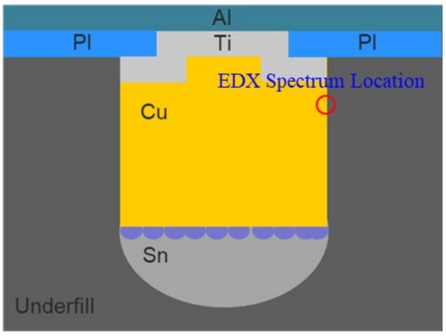


Figure 1. Location of EDX Spectrum.

Table 5. The results of EDX Spectrum.

EDX Spectrum						
Clean Speed (M/min)	0.3		0.6		0.9	
Element	at%	wt%	at%	wt%	at%	wt%
C	52.29	20.95	76.01	50.98	60.67	29.97
O	16.37	8.73	14.56	13.01	23.84	15.68
Al	-	-	-	-	1.25	1.39
Si	3.61	3.38	0.33	0.51	1.50	1.73
Cl	-	-	-	-	0.66	0.96
Ti	-	-	-	-	0.31	0.61
Cu	23.30	49.39	8.05	28.57	3.44	8.99
Sn	4.43	17.55	1.05	6.93	8.33	40.67

D. Reliability Test and Failure Analysis

The reliability of the cleaned devices under different clean speed conditions will be verified, and then it will be confirmed whether the device can pass the FT after the reliability verification. Table 6 summarizes the FT results after reliability verification for devices cleaned. Notably, at the highest speed of 0.9 M/min, Final Test (FT) failures were observed after 264 hours of bHAST testing. This indicates that under these conditions, the cleaning duration was insufficient for complete flux removal. Subsequently, we will explain the results of the failure mode analysis.

Table 6. FT results after reliability verification.

Reliability Test			
Clean Speed (M/min)	0.3	0.6	0.9
MSL3	Pass	Pass	Pass
uHATS 96hrs	Pass	Pass	Pass
bHATS 264hrs	Pass	Pass	Fail
HTSL 1000hrs	Pass	Pass	Pass

The defect location was initially identified using SAT (Scanning Acoustic Tomography), which revealed a distinct white bump is shown in Figure 2. This raised a suspicion of possible delamination at the bump area. To further investigate, I/V curve testing was conducted, showing an increase in resistance is shown in Figure 3, which supported the likelihood of an internal defect.

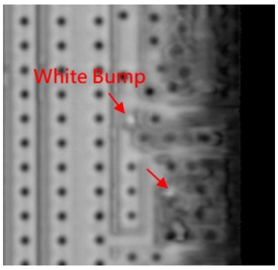


Figure 2. The test result of SAT.

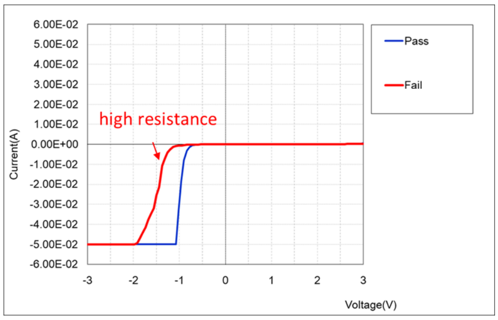


Figure 3. The test result of I/V curve

Subsequently, a FIB (Focused Ion Beam) cross-section was prepared and analyzed using SEM (Scanning Electron Microscopy). The SEM results confirmed delamination between the underfill material and the bump. In addition, separation was also observed the UBM (Under Bump Metallization) peeling, as shown in Figure 4.

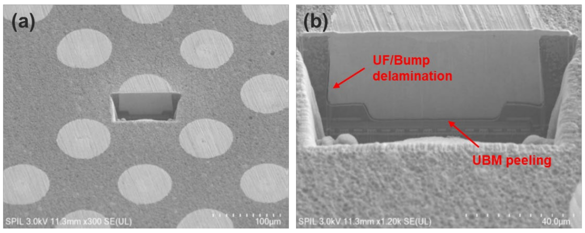


Figure 4. The SEM images (a) FIB cross-section, (b) UF/Bump delamination and UBM peeling.

TEM and EDX analyses were conducted to pinpoint the location of Under Bump Metallization (UBM) peeling, as shown in Figure 5. EDX elemental mapping revealed the chlorine distributed at the Cu pillar sidewall and Cu pillar corner, coinciding with areas of delamination, suggesting that chlorine-induced corrosion played a significant role in the observed peeling.

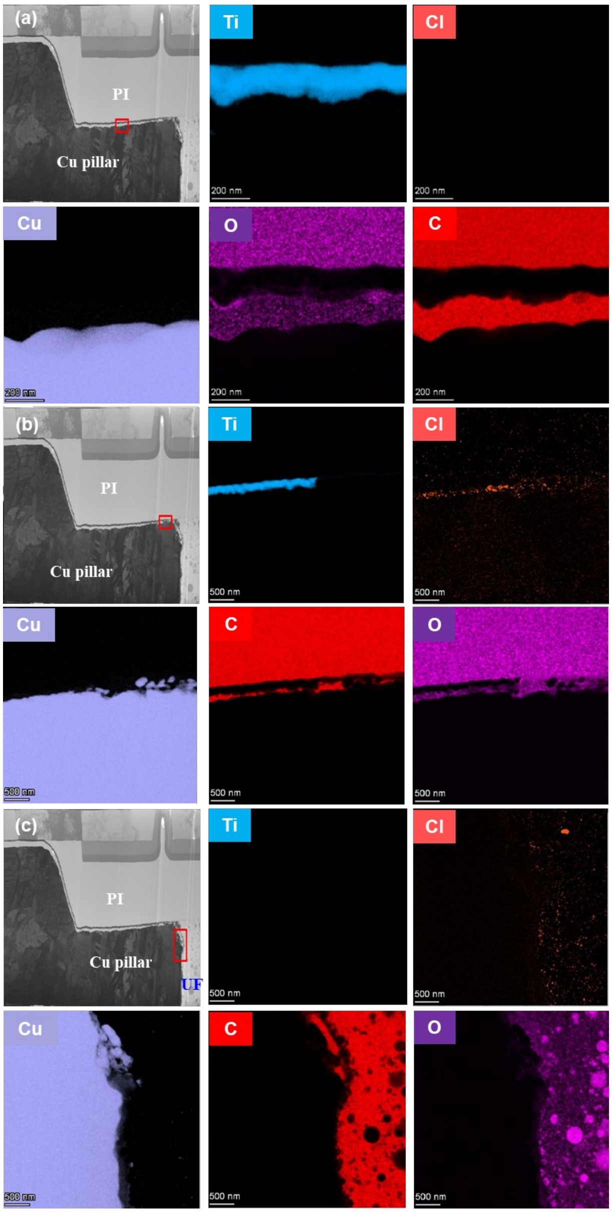


Figure 5. TEM images and EDX elemental mapping (a) Ti/Cu interface, (b) Cu pillar corner, (c) Cu pillar sidewall.

The cleaning process, performed at a line speed of 0.9 M/min, was found to be insufficient for complete flux removal. This inadequate cleaning allowed flux to remain, leading to chlorine-induced corrosion of the Cu pillars and subsequent Ti/Cu delamination. In summary, the combination of TEM and EDX analyses confirmed that residual flux, particularly chlorine-containing compounds, contributed to corrosion at the Ti/Cu interface, resulting in UBM peeling. To mitigate such failures, it is crucial to optimize cleaning parameters to ensure thorough flux removal, thereby preventing chlorine-induced corrosion and enhancing the reliability of Cu pillar interconnects.

Conclusions

This study highlights the critical role of cleaner concentration, temperature, and cleaning speed in achieving effective flux removal during the FCBGA packaging process. Higher cleaner concentrations and elevated temperatures enhance the dissolution of flux residues through improved emulsification and saponification. However, these benefits must be carefully balanced against potential drawbacks such as cleaner foaming and material corrosion. Among the parameters examined, cleaning speed was found to have the most significant impact on cleaning efficiency. Excessively fast speeds reduced the contact time between the flux residues and cleaning agents, leading to incomplete flux removal. Reliability testing revealed that samples cleaned at a line speed of 0.9 M/min failed during bHAST testing, indicating insufficient cleaning under those conditions. Subsequent failure analysis confirmed delamination between the underfill and bump, as well as peeling at the Under Bump Metallization (UBM) layer. Advanced techniques such as TEM and EDX further identified chlorine accumulation at critical interfaces, pointing to chlorine-induced corrosion as the primary cause of failure. These findings underscore the importance of optimizing the cleaning process particularly cleaning speed to ensure thorough flux removal and long-term reliability.

As FCBGA packages continue to increase in size and adopt finer bump pitches, effective flux cleaning becomes increasingly challenging due to tighter spacing, shadowing effects, and more stringent reliability requirements. These complexities are driving the shift toward advanced die bonding technologies that minimize or eliminate the need for flux. Emerging alternatives such as thermo-compression bonding (TCB), no-flow or wafer-level underfill, and fluxless bonding using formic acid are gaining momentum. Looking ahead, hybrid bonding, which enables direct copper-to-copper or oxide bonding without solder or flux, is poised to become a foundational technology for achieving ultra-fine pitch and 3D integration in chiplet and high-performance applications. This transition in bonding methods is essential for meeting the performance, reliability, and scalability demands of next-generation semiconductor packaging.

Acknowledgments

The authors would like to acknowledge the members of SPIL advanced package and technology development team for their efforts and contributions to this paper.

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