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Compatibility of pH-Neutral Cleaning Agent with Under-bump Materials

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Abstract

Flip-chip technology is widely used in advanced packaging assembly due to its higher level integration, multiple functionalities, thinner package, better processing performance &, etc. Due to its many advantages, it is not limited only to advanced packaging, but can also integrated into the power package with flip-chip on lead frame (FCOL) by OEM. Flip-chips are connected to the substrate through bumps formed on the under bumps metallurgy (UBM).

The underfill or molding process is a standard process for flip-chip type of packaging. Common issues in this process include mold delamination or solder extrusion. Typically, to attach the flip-chip to the FR4 substrate or lead frame, flux is needed during the reflow soldering process. After the reflow soldering, it is crucial to remove any flux residues before proceeding with the underfill or molding process. This is done to prevent residues within the package causing electrochemical migration, leakage current, or dendrite growth and potentially affecting reliability.

A defluxing process is implemented after reflow soldering, and an aqueous-based pH-alkaline cleaning agent is traditionally used with spray-in-air cleaning equipment. Improper cleaning processes can cause product reliability issues, such as dendrites growth, voids in the package, mold delamination, or under bump material incompatibility with the cleaning agent leading to solder extrusion.

In this study, real conditions were stimulated by using production materials in collaboration with a customer to create realistic case scenarios for investigating the compatibility of under-bump materials (UBM) with pH-neutral cleaning agents. The study demonstrates the advantages of using pH-neutral cleaning agents in reducing solder extrusion failures when compared to traditional aqueous-based pH-alkaline cleaning agents.

Keywords – flip-chip technology, advanced packaging, lead frame, under-bumps metallurgy, underfill, defluxing, compatibility, cleaning agents

I. Introduction

The automotive industry is currently undergoing a shift towards electrification. Semiconductor devices play a crucial role as the fundamental building blocks of electric vehicle power electronics systems. Among the packages used in automotive applications, other than advanced packaging modules and discrete packages, flip-chip technology is one of the standards adopted due to its advantages like higher integration, multiple functions, thinner packages, improved processing performance, and more. This technology is not confined solely to advanced packaging modules but is also integrated into power discrete packages, such as FCOL. In these cases, the flip-chip is attached to a lead-frame along with passive components and inductors, and then molded into a plastic package.

In flip-chip technology packages, flux is used during the reflow soldering process to attach the bumps of the flip-chip to either the FR4 substrate or the lead frame, and depending on the type of package, it is necessary to remove any flux residues before proceeding with the underfill or molding process. Underfill or molding is a standard process that ensures the reliable connection of the flip-chip, meeting the reliability requirements necessary to withstand mechanical stress or thermal expansion strain on the solder joints. The common challenges or the most detrimental effects on package reliability during underfill or molding processes include delamination, solder smear, or solder extrusion [1].

Flux cleaning is the conventional method for eliminating flux residues after reflow soldering to facilitate surface wetting during the underfill or molding process. Typically, either solvent-based or aqueous-based cleaning agents are employed for flux removal, with the choice dependent on the cleaning application being used, such as ultrasonic or spray-in-air cleaning processes. In general, solvent-based cleaning agents are utilized in ultrasonic cleaning processes. Conversely, spray-in-air cleaning applications typically involve the use of aqueous-based cleaning agents, which in most cases, a pH-alkaline formulated aqueous-based cleaning agents for flux removal.

II. Material Compatibility

"Flip-chip" technology refers to bumps on a semiconductor wafer or chip that are 50-200 µm in height, traditionally created through processes such as electroplating, evaporation (C4), or paste printing process. [2] These flip-chip bumps were created on the under bumps metallurgy – UBM (Figure 1), which is an essential interfacial material between the I/O pads and the solder bumps in all bumping processes, allowing the connection to the integrated circuit (IC). [2] With technology advancement, it has become possible to further reduce the height of the bumps to below 30 µm using micro bumps or copper pillar bump technology.

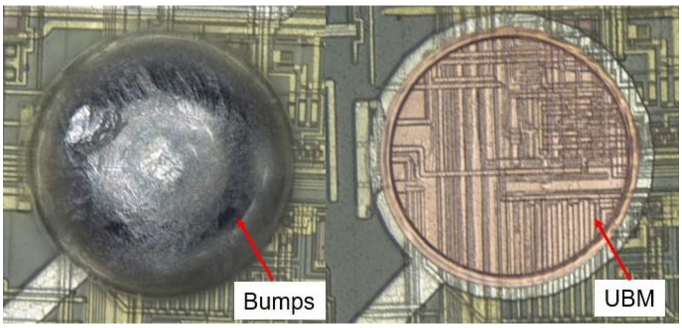

Figure 1: Under bumps metallurgy – UBM

The UBM metalization is important in establishing connections between integrated circuits on a silicon wafer. Generally, the UBM layer consists of sputter Cu, NiV & Al, and the integrated circuits is connected through the Al layer below the passivation of the wafer. Compatibility of UBM metalization (Figure 2) is important to prevent metal diffusion into the IC package, and avoid solder smear/solder extrusion that may occur during underfill or molding process. [3].

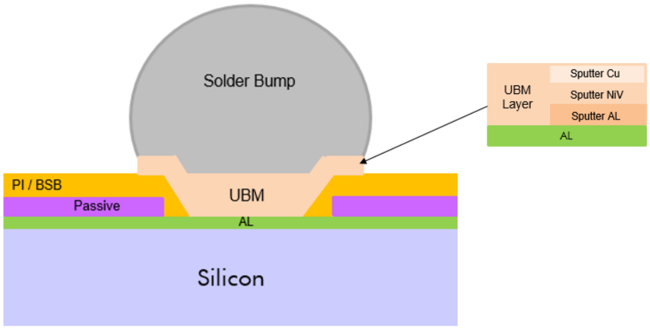

Figure 2: UBM Metalization

III. FCOL Assembly Process

A. Introduction to FCOL Assembly Process

The assembly process for flip-chip on lead-frame (FCOL) packages typically begins with the attachment of the flip-chip to the lead frame using flux, followed by reflow soldering to establish connections between the bumps and the lead frame and then flux removal (defluxing) and molding processes.

In the assembly of flip-chip integrated into the power discrete package, the spray-in-air cleaning process was chosen due to certain cleaning challenges associated with flip-chip technology. There are two key challenges - the low standoff gap between the flip-chip and substrates and compatibility between the metallization and the flip-chip and leadframe materials. The cleaning agent not only needs to be effective in removing flux residue but also must be compatible with all the materials within the package. Incompatibility between the cleaning agents and the metallization of the flip-chip and leadframes can lead to issues like mold delamination, solder smear, or solder extrusion.

Typically, cleaning is performed in a spray-in-air cleaning process using aqueous based cleaning agents.

B. FCOL Process Challenge

Given the unique design and assembly process flows of the package, selecting the appropriate cleaning agent is important, particularly for customers who undergo multiple reflow soldering and cleaning cycles on the same package. Using unsuitable cleaning agents can result in the retention of flux residues on the package, potentially affecting the package's metallization and leading to issues such as delamination or solder smear following the molding process [3].

In this study, our objective is to evaluate existing cleaning agents, specifically the traditional pH-alkaline aqueous-based cleaning agents commonly employed at customer sites, and then proceed to compare their cleaning performance and material compatibility with the latest pH-neutral technology cleaning agents. This new pH-neutral cleaning agent is designed to effectively remove various types of flux residues and exhibit excellent material compatibility with all the metallization components within the package, including the chip, bumps, UBM layers, lead-frames, and other associated components.

In the existing FCOL assembly process, (Figure 3) the package's unique design has to go through three separate reflow soldering processes, each utilizing a different type of flux, and consequently, undergoes three rounds of cleaning processes to address these specific requirements.

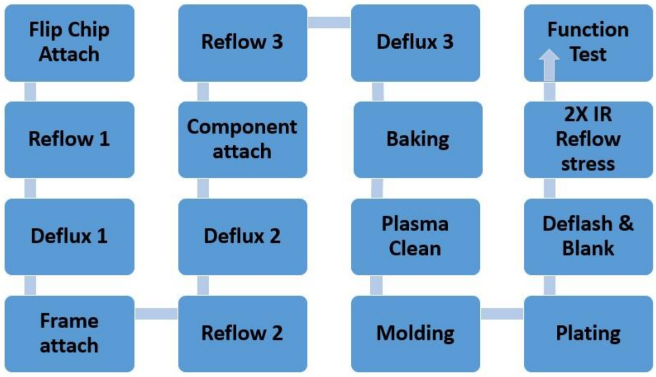

Figure 3: FCOL Process flow

In this study, the primary requirement was the removal of flux residues, specifically from three different types of flux, which included a lead-free activated RMA flux and two no-clean tacky fluxes from three different solder paste suppliers. Simultaneously, the new cleaning agent should be compatible with various materials, including chip and leadframe materials such as copper leadframes, solder alloys, components, chip passivation layers, and UBM layers.

IV. Methodology

A. UBM compatibility VS Solder Smear

Solder smear is one of the key failures in overall FCOL assembly rejects, typically occurring after the molding process. To enhance FCOL manufacturing yield, customers are actively exploring different processes to reduce the rate of rejects caused by solder smears. Among these processes, the defluxing process has been the main focus. While existing aqueous-based pH-alkaline cleaning agents are undoubtedly efficient in eliminating flux residues, it is also essential to look into the material compatibility to better understand their suitability.

In the FCOL assembly process, which involves three reflow soldering cycles and three subsequent cleaning processes, pH-alkaline cleaning agents have proven highly effective in removing flux residues from inside the package. However, concerns have arisen regarding the material compatibility of the UBM layer as minor signs of etching between the solder bump and UBM layer, which are associated with solder smear failures were observed after undergoing three cleaning cycles with a pH-alkaline cleaning agent. Consequently, the use of the latest pH-neutral cleaning agents is recommended as a viable alternative solution.

B. Advantages of pH-neutral Cleaning Agents

For aqueous-based cleaning agents, it is a common practice to incorporate inhibitors into the formulation to protect sensitive metal surfaces from corrosion while ensuring that these surfaces are not adversely affected. While traditional alkaline-based cleaning agents provide good cleaning performance, they do come with certain drawbacks such as poor material compatibility with sensitive metal surfaces, low solubility of certain inhibitors in concentrated chemicals, and the need for neutralization during wastewater treatment.

Cleaning agents with a pH-neutral formulation have become the new standard for environmentally friendly solutions, offering a range of benefits such as the ability to use a wide variety of inhibitors due to the pH range of around 7 (±0.5), as well as the reduced amount of inhibitor required. Such agents can effectively remove flux residues at low concentrations and are easily rinsed during the rinsing step. Importantly, they leave no alkaline constituents inside the packages, as any chemical residues left within the package may lead to corrosion issues. In a pH-neutral environment, it offers users a solution that was previously unavailable, eliminating the need for neutralization processes during wastewater treatment [4].

C. Part 1 - Cleaning Agent Compatibility Study 1

To assess the effectiveness of the latest pH-neutral cleaning agent, a comprehensive study was conducted with an examination and confirmation of the cleaning capabilities concerning three distinct types of flux used in the FCOL package. Subsequently, material compatibility tests were carried out on flip-chips, with a particular focus on the UBM layer. These tests involved evaluating flip-chip units without the solder bumps.

The initial tests were conducted in beakers, using both pH-alkaline and the latest pH-neutral cleaning agents to investigate UBM material compatibility under specific parameters and time intervals. The parameters employed in these tests are as follows:

Cleaning agent	: pH-alkaline & pH-neutral
Concentration	: 5% & 15%
Exposure time	: 15 to 60 minutes
Exposure temperature	: 60°C
Agitation	: stirring @ 500 rpm

The test results were thoroughly analyzed through both visual inspection and scanning electron microscope (SEM) analysis. Under normal conditions, the solder bump sits on top of the UBM pad, with only the edges of the UBM layer coming into contact with the cleaning agent. During the SEM analysis, the UBM pad was titled at an angle of 78 - 88 degrees for a comprehensive examination of the chemical impact of the cleaning agent on the UBM layer.

D. Part 1 Study Results

Visual inspection was conducted using a high-powered microscope, and images were captured for comparative analysis. In the material compatibility testing with pH-alkaline cleaning agents, UBM pads (without bumps) were darkened at a low concentration of 5% and a chemical exposure time of 15 minutes. The outer layer of the UBM pad has a copper surface finish, which reacts by darkening under these conditions. In cases where the concentration is increased to 15% and the chemical exposure time is extended to 60 minutes, a copper oxidation process occurs on the UBM surface, resulting in corrosion of the pads. (Figure 4)

When using a pH-neutral cleaning agent at a concentration of 15% and a chemical exposure time of 60 minutes, no adverse effects were observed on the UBM pad surface. Based on this outcome, it can be confidently stated that the pH-neutral cleaning agent is entirely compatible with the UBM layer and has the potential to prevent UBM etching in real production scenarios.

Subsequently, the samples underwent further analysis utilizing a scanning electron microscope (SEM) where images were captured at higher magnification levels, and the UBM pad was tilted at an angle ranging from 78 to 88 degrees to observe the occurrence of etching at the edge of the UBM layer. (Figure 5)

The SEM analysis showcases a severely damaged surface with significant erosion of the layer evident after exposure to a 15% concentration of pH-alkaline cleaning agent at 60°C for 60 minutes. (Figure 6 & 7)

No adverse effects were observed on the surface of the UBM pad or on the edges of the UBM layer when pH-neutral-based cleaning agents were utilized. (Figure 8 & 9) These findings strongly indicate the potential benefits of pH-neutral cleaning agents for FCOL packaging. However, further testing in combination with actual production conditions is warranted to confirm these advantages and assess their impact on addressing solder smear issues.

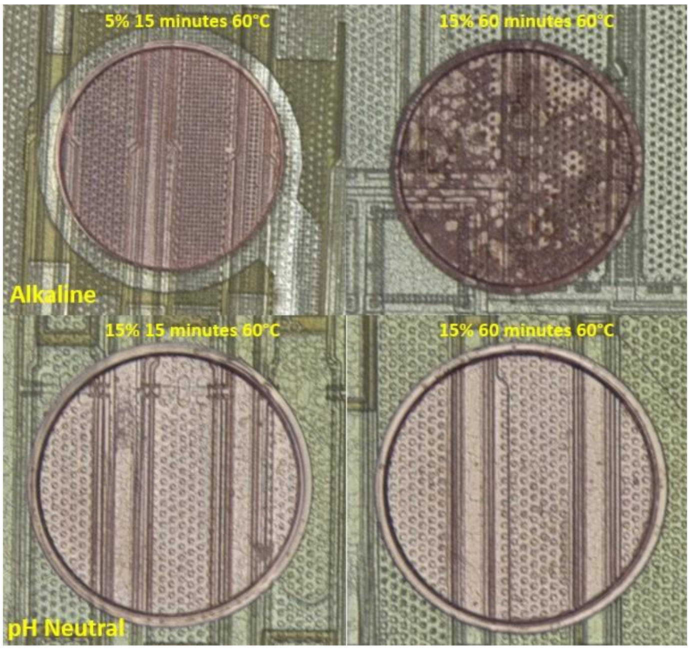

Figure 4: Visual inspection results with high power microscope

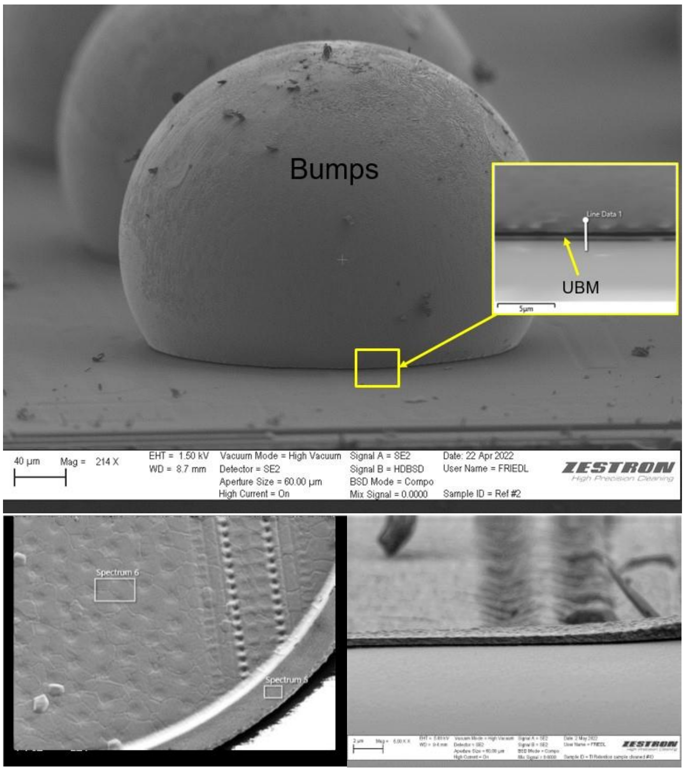

Figure 5: Reference bumps and UBM pad without soldering and cleaning, top view (low left) and tilted side view (low right)

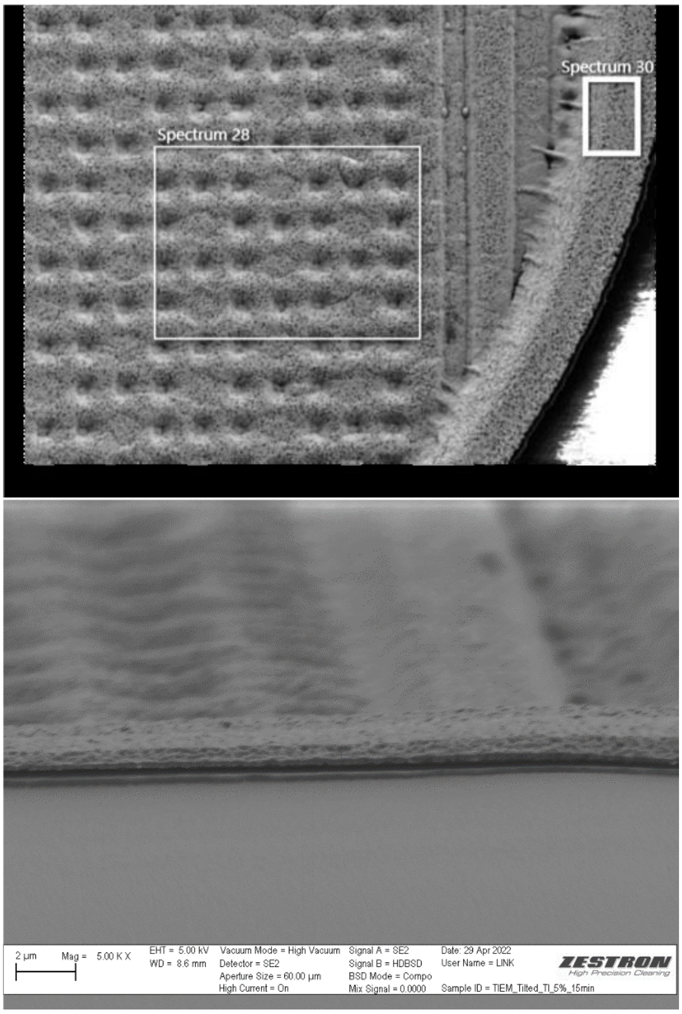

Figure 6: UBM top & titled view after exposure with pH-alkaline 5%, 15 minutes at 60°C

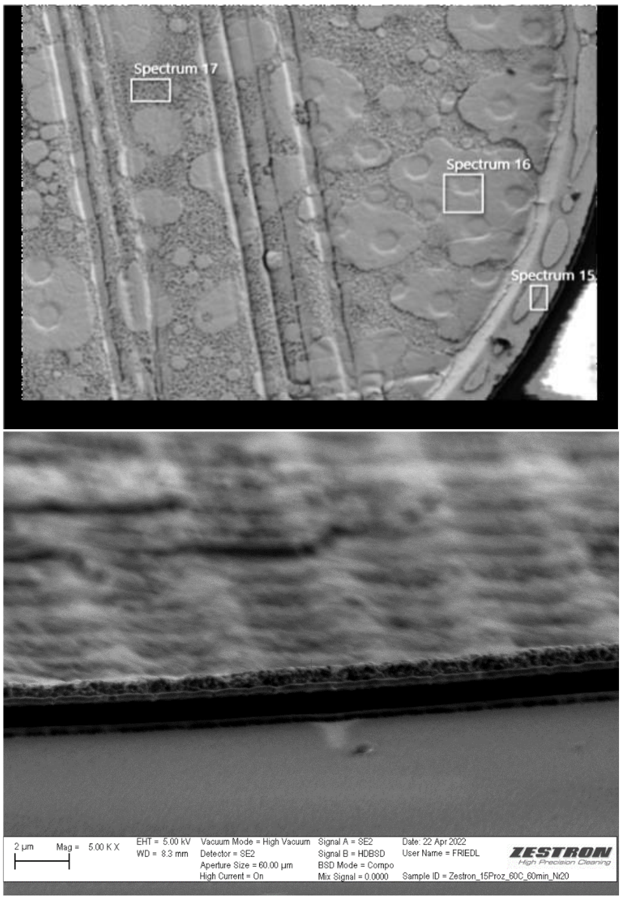

Figure 7: UBM top & titled view after exposure with pH-alkaline 15%, 60 minutes at 60°C

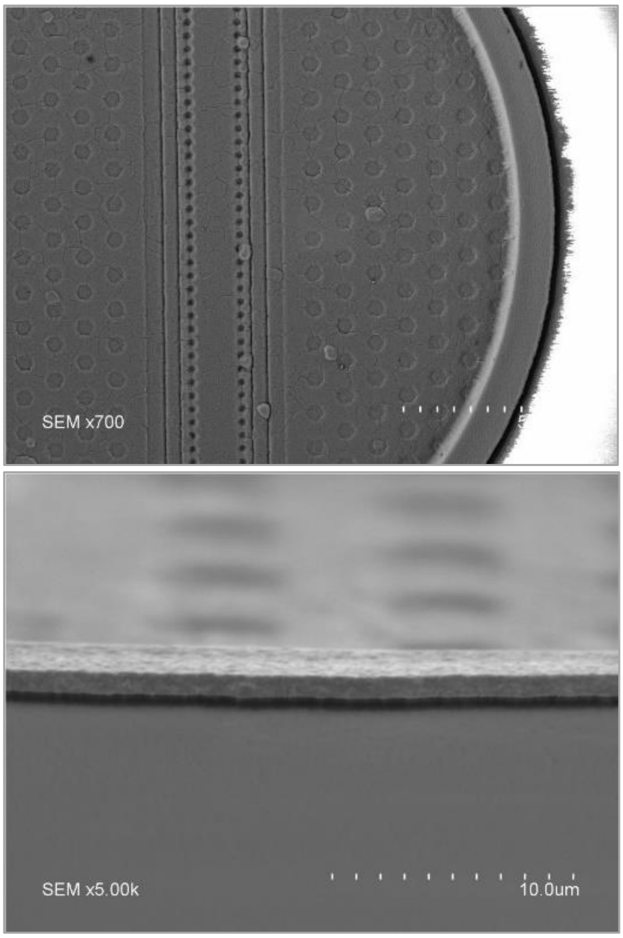

Figure 8: UBM top & titled view after exposure with pH-neutral 15% 15 minutes at 60°C

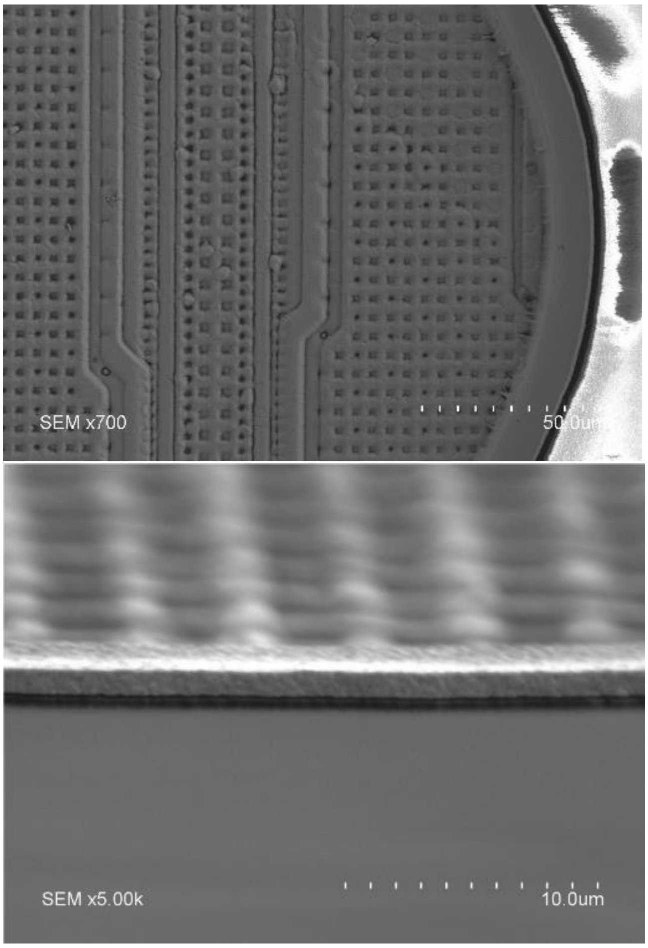

Figure 9: UBM top & titled view after exposure with pH-neutral 15% 60 minutes at 60°C

E. Part 2 - Cleaning Agent Compatibility Study 2

Based on the excellent testing results in the part 1 study, further testing was carried out at the production site in collaboration with the customer involving actual FCOL packaging production batches. The plan was to perform a cleaning evaluation within a batch-type spray-in-air cleaning system, using the latest pH-neutral cleaning agents with cleaning parameters of existing pH-alkaline cleaning agents.

Cleaning agent	: Aqueous-based pH-neutral
Concentration	: 15%
Cleaning Time	: 10 minutes
Cleaning temperature	: 60°C
Cleaning Equipment system	: Batch-type Spray-in-air cleaning

F. Part 2 Study Results

Following the standard FCOL assembly process, 3 production lots with a total of 1680 units went through a standard 3 times cleaning process, before subjected to the molding process. Subsequently, functional testing was performed on entire lots with result of 100% yield.

To understand the etching condition of the UBM layer, a cross-section inspection was performed and no evidence of UBM etching was found after 3 defluxing processes. Based on the cross-section results, no undercutting was observed after 3 rounds of defluxing. (Figure 10) The testing effectively confirmed the enhancement in addressing solder smear issues, resulting in zero defects when utilizing the latest pH-neutral cleaning agent. [5]

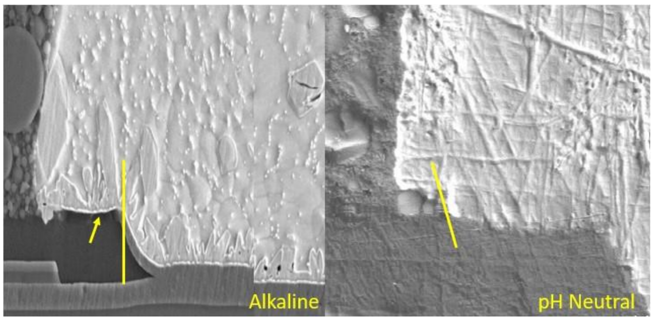

Figure 10: Cross section confirm no UBM etching with pH-neutral cleaning agent

V. Conclusion

This study focuses on assessing the material compatibility of the pH-neutral cleaning agent with the flip-chip UBM material in eliminating the solder smear rejections in the FCOL packaging assembly process.

The initial static testing aimed to compare the effects of pH-alkaline versus pH-neutral cleaning agent for which the results indicated that traditional pH-alkaline based cleaning agent does affect the UBM material on the flip-chip by causing etching of the UBM layer, which may lead to solder smear rejections.

The latest pH-neutral cleaning agent technology demonstrated the ability to prevent UBM material etching. Through the extensive testing involving higher concentration and longer exposure times, no UBM layer etching or solder smear issues were observed in the production lots testing.

A standard 3 times defluxing testing conducted in a batch-type spray-in-air cleaning system using pH-neutral cleaning agents with production lots shown a positive result with cross-section analysis revealed no UBM etching below the bumps, and the functional testing achieved a 100% yield.

The pH-neutral cleaning agent offers a significant advantage in terms of compatibility with sensitive materials like the UBM layer, potentially enhancing the package's reliability. To further validate the performance consistency and advantages of pH-neutral cleaning agents, additional studies with a larger quantity of FCOL packages (in mass production conditions) is required.

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