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ABSTRACT

This paper introduces a recent work by a joint effort between Air Products and Sikama International on alpha trials of a production-scale furnace for flux-free wafer bump reflow based on electron attachment (EA).

INTRODUCTION

Packaging technology for electronics devices has advanced rapidly in recent years driven by feature size reduction, new materials developed, and increased demand on device functionality. The most fundamental among the advanced packaging technology is the use of wafer bumping and wafer-level chip scale packaging.

In a wafer bumping process, fine-pitch electroplated solder bumps are formed over an entire silicon wafer on which integrated circuits have been built, the wafer is then reflowed at a temperature above the solder's melting point to complete metallic interconnection of the bumps with underneath metal pads and convert the bumps from a deposited shape into a ball shape. After the wafer bumping, the wafer is cut into individual chips, which then go through subsequent packaging processes. In the packed devices, the formed bumps serve as electrical, mechanical, and mounting connections. Current study is related to the last step of the wafer bumping process — wafer bump reflow.

One of the keys for successful wafer bump reflow is to remove the native oxide layer and prevent additional oxidation on the bump surface. Any oxide layer on the bump surface will act as a solid skin to constrain molten solder's flow, which in turn causes a non-qualified bump appearance and non-uniform bump shape across a wafer. This oxide elimination is becoming more critical and difficult as the bump size shrinks since the increased surface to volume ratio plus the enlarged surface curvature of the solder bump drives toward a more severe solder oxidation to minimize its surface energy.

Currently, the most common approach is to coat the wafer with a flux and then reflow the wafer in a nitrogen environment. However, such flux-containing reflow process is quite messy since the decomposition of organic fluxes always leaves residues and generates volatiles, which invariably bring contaminants on the wafer and furnace wall. Therefore, a post cleaning of the reflowed wafer is always required. A frequent cleaning of furnace interior surfaces is also needed, causing high maintenance costs and a lot of equipment downtime. In addition, special safety precautions have to be taken for dealing with hazardous disposal of the flux residues and unhealthy exposure of the flux vapor. Besides the cost and inconvenience associated with the cleanings, the flux-containing process directly affects the quality of the reflowed wafer. For example, during reflow the flux can get into the molten solder and create voids inside the bumps, thus degrading mechanical and electrical properties of the solder joints in packed devices. As the pitch and bump sizes are continually decreasing, the need for process cleanliness increases. This has led to increased use of flux-free processing, which is mainly based on using a reactive gas to replace the organic flux for oxide removal.

However, known flux-free technologies all have different problems or limitations. By using formic acid vapor, the process is not completely residue-free and has to be operated in a sealed system. Hydrogen-based flux-free process is clean and non-toxic, but high temperature ($\geq 350^\circ C$) and pure hydrogen (flammable) must be applied to activate and hasten the oxide reduction. Plasma-activated hydrogen can make the oxide reduction efficient at low temperatures, but only vacuum plasma appears to be viable, resulting in a batch process.

Current study is related to a novel flux-free technology based on electron attachment (EA), which can be operated at ambient pressure and normal solder reflow temperatures using non-flammable mixtures of hydrogen (<4 vol%) in nitrogen. The technology is invented by Air Products in recent years, which involves generating a large quantity of low-energy electrons. Some of the electrons can attach to hydrogen molecules, forming active species for oxide removal. The basic concept and the efficiency for oxide removal have been demonstrated in previous studies [1]. The EA-based technology is completely residue-free and has a potential to be widely used in the electronics packaging industry. This paper presents a recent work between Air Products and Sikama International on alpha trials of an EA-enabled prototype furnace for production-scale wafer bump reflow (Fig. 1).

TRIAL RESULTS

As shown in Figure 2, the EA-enabled furnace contains a roller-featured wafer transportation system, which carries wafers through heating and cooling zones with a standard production speed. Before entering a reflow zone, wafers are exposed to EA-activated 4% H_2 in N_2 for removing solder oxides (Fig. 3).

Figure 1: EA-enabled prototype furnace for production-scale wafer bump reflow

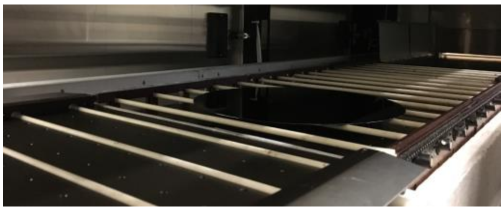


Figure 2: Roller-featured wafer transportation system

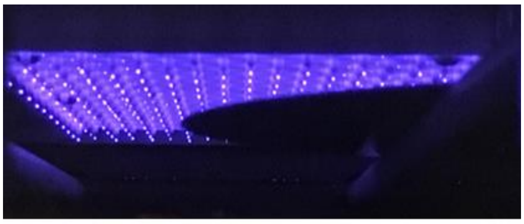


Figure 3: Wafer entering an EA zone for oxide removal

Various dummy wafers (8" and 12") without bump reflow were obtained from different customers and processed in the furnace to evaluate bump reflow quality. Figure 4 shows a cross section of a reflowed tin-based solder bump plated on nickel. The intermetallic compound (IMC) formation controlled by reflow time and temperature is quite acceptable. The effectiveness of EA on oxide removal has been clearly demonstrated in multiple trials. Figure 5 compares bump shapes of a lead-free solder on a wafer undergone different reflow processes. Before reflow, electroplated bumps are in a cylindrical shape (Fig. 5a). Without applying EA in the H_2 and N_2 mixture, reflowed bumps have a rough surface and uncompleted shape conversion (Fig. 5b). With applying EA, reflowed bumps have a smooth surface and spherical shape (Fig. 5c), even better than that of flux-reflowed bumps after cleaning (Fig. 5d). As shown in Figure 6, the EA-based process can ensure a good bump uniformity across the width of a 12" moving wafer. In addition, the surfaces of the post-reflowed wafers are free of extra solder and foreign materials (Fig. 7).

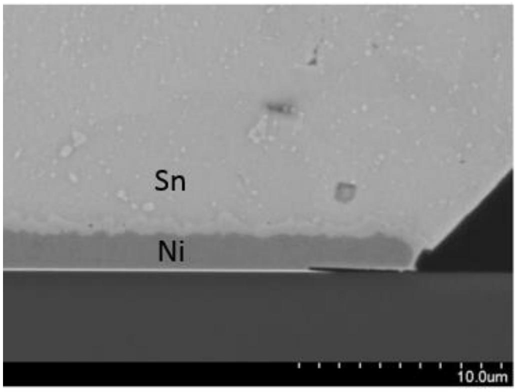
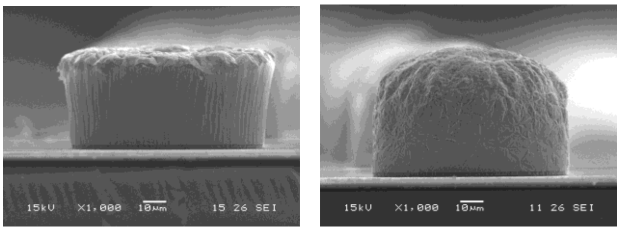
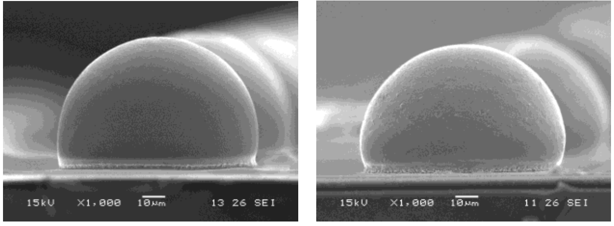


Figure 4: Cross section of the IMC



a) Before reflow *b) Reflow without EA*



b) Reflow with EA *e) Reflow with flux*

Figure 5: Bump shape comparison

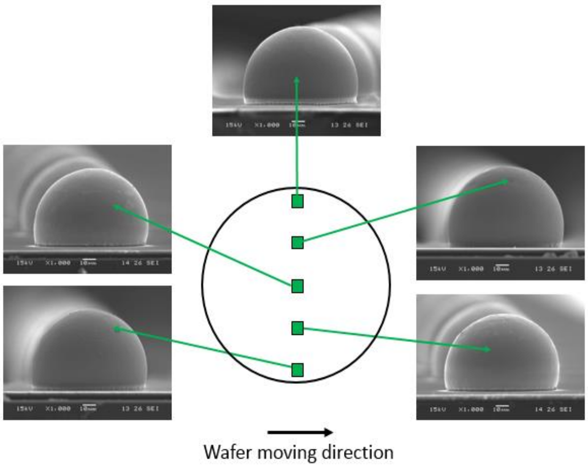


Figure 6: Uniform bump shape by EA-based process

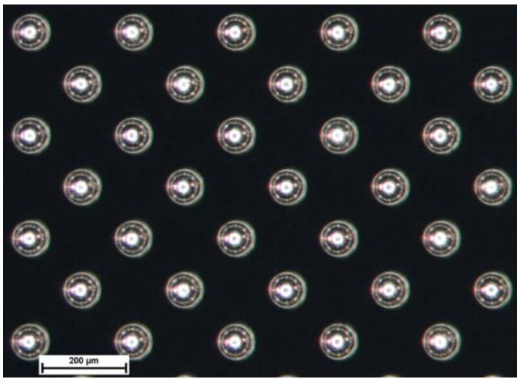


Figure 7: Clean wafer surface after EA-based reflow

Full dummy wafers reflowed in the EA-enabled furnace were also sent back to corresponding customers for standard quality inspections, such as checking bump shape, bump uniformity, shear strength, failure model, and bump voids. Results confirm that the wafers reflowed under the EA-based process indeed meet all specifications. Figures 8 and 9 represent results of automated optical inspection (AOI), which confirm acceptable bump heights (BH) and bump diameters (BD) across an 8" full wafer. Figure 10 shows that all shear failures are within solder bumps and shear strengths well exceed the criterion (> 2 g/mil^2). Figure 11 is an x-ray image of a die on a reflowed wafer, which demonstrates that the number of bump voids (green) is quite low and the size of a typical void is 3% of the bump area, which is much below the specified upper limit (8% of the bump area).

Spec	62 ± 15 um
AVG BH	59.1um
Max BH	62.8um
Min BH	48.7um
BH Sigma	1.42um

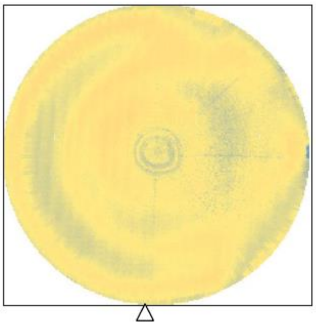


Figure 8: BH distribution map and data

Spec	88 um +20%/-10%
AVG BD	90.2um
Max BD	91.9um
Min BD	88.0um
BD Sigma	0.47um

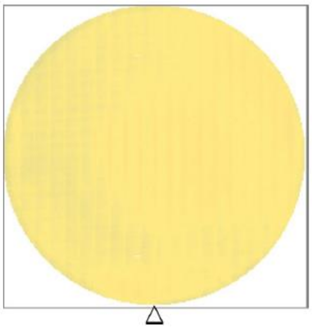


Figure 9: BD distribution map and data

AVG	Max	Min
3.70	4.11	3.34

Spec>2 g/mil2

Figure 10: Bump shear failures and data

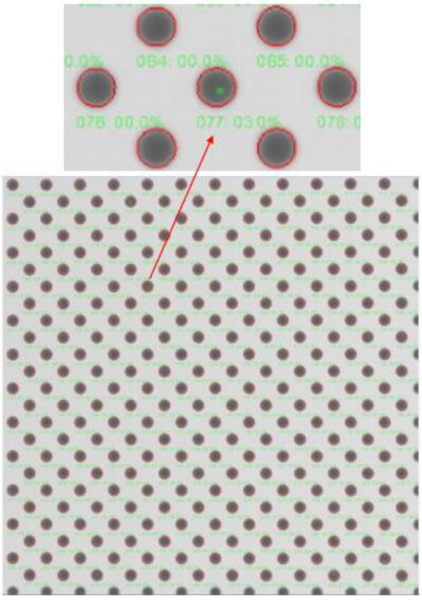


Figure11: X-ray image of a die

CONCLUSIONS

Trial results demonstrate that dummy wafers reflowed in the EA-enabled production-scale furnace meet customer specifications. The EA-based technology offers the following benefits for wafer bump reflow: 1) enhanced bump reflow quality because the flux induced solder voids and wafer contaminations naturally disappear, 2) improved productivity by having in-line process capability, eliminating post wafer cleaning, and avoiding furnace down time cleaning, 3) reduced cost of ownership due to eliminated costs associated with cleaning equipment, solution, labor work, and flux, 4) improved safety by eliminating flux exposure and using a non-toxic and non-flammable gas mixture, and 5) no environmental issues by eliminating organic vapors, hazard residues, and CO_2 emission.

REFERENCES

[1] C. Christine Dong, Richard E. Patrick, Russell A. Siminski, and Tim Bao, “Fluxless soldering in activated hydrogen atmosphere,” Proceedings of CSTIC 2013, Shanghai, China, M11010ar. 15-17, 2016, VIIA 1520-1535.

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