Study of High Adhesion Plating Process Using Metal Oxide on Glass for Advanced Packaging

Kazuhiro Hirooka, Honoka Nakagawa, Mayu Tsukuda, Jun-ichi Katayama, Toshimitsu Nagao
OKUNO CHEMICAL INDUSTRIES CO., LTD
1-10-25, Hanaten-higashi, Tsurumi-ku, Osaka city, Osaka, 538-0044, Japan
Ph: +81-6-6965-4113; Fax: +81-6-6963-0740
Email: k-hirooka01@okuno.co.jp

Abstract

The continuous growth of cloud computing, big data analytics, and artificial intelligence has fueled the demand for high-performance and energy efficient server infrastructure. To address these needs, the semiconductor industry is actively exploring advanced packaging solutions that allow higher I/O density, improved thermal performance, and enhanced power delivery. Modern data centers are under increasing pressure to deliver greater performance within constrained thermal and power envelopes. As transistor scaling reaches its physical limits, advanced packaging technologies are becoming essential to sustain Moore's Law. One such advancement is the use of glass core substrates in processor packaging. For server processors, research and development of glass-based interposers and substrates have been advancing to meet the demands of higher performance and integration.

We have successfully developed a highly adhesive interfacial layer with a nano-anchor structure on glass substrates, where achieving strong adhesion has traditionally been difficult. This was accomplished by employing a metal oxide as an adhesion layer and precisely controlling its deposition behavior and structural characteristics. Furthermore, it was confirmed that the adhesion among the glass, metal oxide, and wiring layers can be significantly enhanced through thermal treatment.

This paper introduces an innovative seed layer formation technology with high adhesion to grass core substrate, aimed at next-generation server processors.

Key words

Advanced packaging, Glass core substrate, Zinc oxide, Chiplet integration, TGV, Though-hole filling

I. Introduction

The transition from organic substrates to glass substrates is essential to achieve the large-area expansion of package substrates in advanced packaging technology. This is because it allows for a larger number of chips to be mounted, resulting in higher density and greater integration.

Improving the adhesion of glass is one of the critical challenges accompanying the rapid advancements in mounting technologies for these electronic devices. Glass substrates have many advantages compared to conventional organic substrates, such as low coefficient of thermal expansion (CTE), high dimensional stability, and excellent electrical insulation properties.

Formation of seed layer on glass substrates is well-known for utilizing the Ti/Cu sputtering. It is widely used as a technique for good uniformity and high-quality metal thin films but has problems in terms of productivity and cost for large-area glass substrates.

Additionally, since the core material of advanced packages requires high-aspect-ratio through-holes with an aspect ratio of 10 or higher, this method cannot form seed layers inside the holes. Due to addressing these challenges, more efficient process designs are required.

We have previously established a process for forming metal oxides on glass using aqueous solution. Zinc oxide has a wurtzite structure in which oxygen and zinc are arranged in an orderly manner and is an n-type semiconductor with a bandgap of 3.3 eV. Because of its wide bandgap, it is transparent in the visible light region and is used in applications such as window materials for solar cells. Furthermore, it exhibits electrical conductivity, and its resistivity significantly depends on the amount of zinc in the lattice [1]-[3].

Initially the purpose of this process was to form electrically conductive transparent film. However, issues arose with electrolytic copper plating and fine pattern formation after film deposition, preventing it from being commercialized.

In recent years, there have been reports that adhesion can be achieved by doping metals into glass or using metal oxides as binders [4]-[6]. Based on these reports, we advanced our research on adapting process to achieve high adhesion on glass. As a result, we developed a process with high surface resistivity after metal oxide formation, as well as excellent adhesion, fine pattern formation, and insulation properties. Since the entire process is an all-wet step, it can accommodate the scaling up of substrate size and offers cost advantage. Moreover, it is also adaptable to conventional mass production equipment.

Through this series of studies, we gained an understanding of the mechanism of adhesion improvement. Here, we report on the mechanism of this advanced adhesion layer formation process on glass.

II. Experimental

A. Process

Table 1 shows the optimized standard plating process for glass substrate.

Glass cleaning involves ultrasonic cleaning to remove micro contaminants from the glass substrate and enhance wettability. If this step is not performed, the subsequent catalyzing will not adhere uniformly, and high adhesion cannot be achieved. Next, a catalyst treatment was performed to form nucleation sites, followed by the deposition of zinc oxide.

Subsequently, the first air atmospheric annealing was carried out to convert all zinc hydroxide, which is generated as a byproduct during zinc oxide formation, into oxide. This was followed by catalyzing and reduction, leading to electroless copper plating. After the entire surface was covered with an electroless copper film, a second air atmospheric annealing was conducted. Following the second thermal treatment, acid cleaning and acid activation were carried out, and acid copper plating was applied to achieve the desired film thickness.

Finally, thermal treatment was conducted in a nitrogen atmosphere to promote metal diffusion within the film and enhance adhesion.

B. Surface Morphology and Cross-Sectional Observation

Surface morphology of the zinc oxide film deposited on the glass substrate was examined using tilted (45º) and cross-sectional images. In addition, elemental analysis of the cross-section was performed on the electroless copper film. All observations and elemental analyses were conducted using a Schottky field emission scanning electron microscope (JSM-7900M) manufactured by JEOL Ltd.

Table 1 Plating process on glass substrate.

Glass cleaning (Ultra sonic)
▼
Catalyzing
▼
Deposition of zinc oxide
▼
Anneal (Air atmosphere)
▼
Catalyzing
▼
Reduction
▼
Electroless copper plating
▼
Anneal (Air atmosphere)
▼
Acid cleaning
▼
Acid activation
▼
Acid copper plating
▼
Anneal (Nitrogen atmosphere)

C. Surface Resistivity of Zinc Oxide

The surface resistivity of sample was measured after deposition of the zinc oxide. The measurements were conducted using the Hiresta-UX model MCP-HT800 and the J-BOX type model MCP-JB04 (both manufactured by Nitto Seiko Analytech), in accordance with the resistivity measurement method specified in JIS K 6911 (General test methods for thermosetting plastics).

D. Peeling Strength Evaluation

The peeling strength was evaluated using a universal testing machine (manufactured by Shimadzu Corporation, model AGS-X). A 25 µm-thick copper layer was deposited on the substrates using acid copper plating, followed by the introduction of a 10 mm-wide incision. Peeling tests were performed under the following conditions: a crosshead speed of 50 mm/min, a peeling angle of 90, and a test stroke of 25 mm.

E. Fine Line Patterning and HAST Evaluation

Patterned substrates were fabricated by performing the same pretreatment process as shown in Table 1, up to the electroless copper plating step. A dry film resist (DFR) from Resonac (RD-3015) was applied, and exposure was carried out using an exposure system manufactured by ADTEC (model: INPREX-4V2).

Subsequently acid copper plating, resist stripping, and seed layer etching were performed, followed by a nitrogen atmospheric annealing.

Preconditioning was conducted in accordance with J. STANDARD, "JESD22-A113D," 2003., consisting of the following three steps: step 1 at 125ºC for 24 hours; step 2 at 60ºC with 60% relative humidity for 40 hours; and step 3 involving three cycles of reflow at 260ºC. Following preconditioning, the high accelerated stress test (HAST) was performed using a chamber manufactured by ESPEC (model:EHS-411M, AMI-050-U-5), in accordance with J. STANDARD, "JESD22-A110B," 1999. The test was conducted at a temperature of 110ºC, relative humidity of 85%, and an applied voltage of 3.5 V, with a measurement duration of 150 hours and threshold resistance of $1.0\times10^{6}\Omega$.

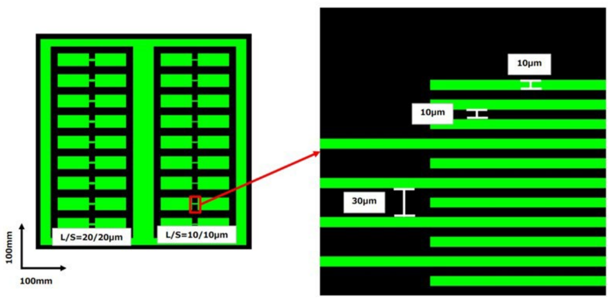

Fig.1 Pattern design for HAST test.

F. Through-hole covering performance

The conformality of the acid copper plating was evaluated using a glass though-hole having a thickness of 0.8 mm and an opening diameter of 80 µm (waist diameter of 60 µm, aspect ratio of 10, alkali-free glass). The plating conditions were set to a target thickness of 5µm and a current density of 1 A/dm^2.

Furthermore, through-hole filling with copper was investigated using the same type of substrate. It was enabled by a combination of pulse-reverse (PR) and direct current (DC).

III. Results and Discussion

Figure 2 shows SEM images of the deposited zinc oxide. It has been reported that zinc oxide can be electrochemically deposited from a simple aqueous solution of zinc nitrate. Using dimethylamine borane as a reducing agent, hydroxide ions are generated through the reduction of nitrate ions. This increases the pH on the substrate surface, leading to the formation of zinc oxide. The deposited zinc oxide formed a pillar-like structure with a film thickness of about 200 nm. We succeeded in changing the shape and increasing reaction sites of the zinc oxide produced intentionally.

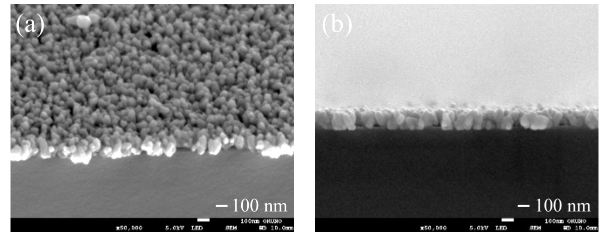

Fig.2 SEM images for zinc oxide. (a) tilt 45º, (b) cross-section.

Figure 3 shows SEM images of cross-sectional elemental analysis of the electroless copper film after thermal treatment. The electroless copper is distributed within the zinc oxide. Since the zinc oxide exhibits a pillar-like structure with gaps between particles, the electroless copper plating solution infiltrates and deposits copper within the structure, resulting in the formation of nanoscale anchor structures. In addition to these nano-anchor structures, the thermal treatment promotes copper diffusion into the zinc oxide, forming Zn-O-Cu bonds, which is suggested to enhance the adhesion strength. In practice, no delamination of the film was observed after thermal treatment, even under minor external stress such as during substrate handling. This indicates improved handling compatibility during subsequent acid copper plating processes and represents a significant advantage in view of mass production.

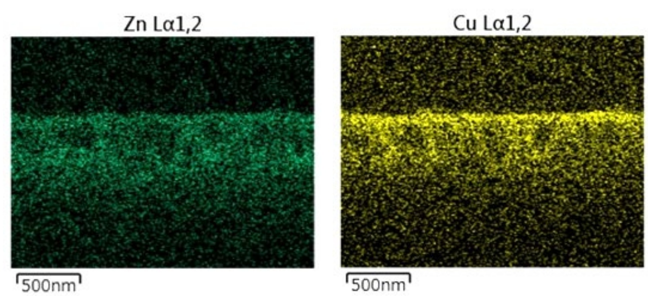

Fig.3 EDS elemental mappings after electroless copper plating.

Figure 4 shows the surface resistivity measurements. For all substrates, no significant change in surface resistivity was observed before and after treatment. This result is attributed to the control of reaction sites and the zinc content during the zinc oxide deposition.

Figure 5 shows the peeling strength measurements for each substrate. The results were as follows: alkaline-free exhibited 14.6 N/cm, borosilicate 10.9 N/cm, quartz 5.1 N/cm and glass-ceramic 6.4 N/cm, respectively. The Ti/Cu sputtered wafer used for comparison exhibited 3.2 N/cm. Compared to conventional sputtered films, superior results were obtained for all types of substrates. Among them, alkali-free demonstrated the highest peeling strength. As all other substrates also achieved peeling strengths exceeding an average of 5 N/cm, it was confirmed that adhesion strength comparable to or greater than that of conventional organic package substrates can be achieved.

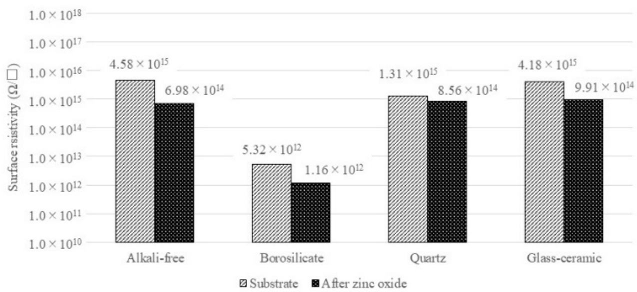

Fig.4 Surface resistivity measurements of various substrate materials.

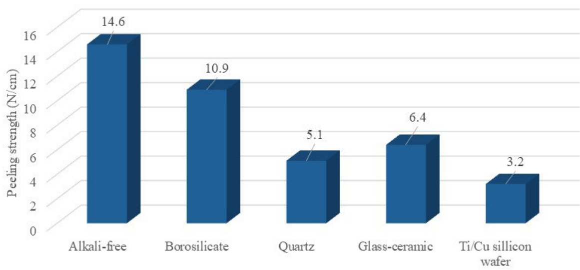

Fig.5 Peeling strength measurements of various substrate materials.

Figure 6 shows SEM images after pattern formation. When the wiring was formed, fine patterns with a line/space of 10/10 μm were successfully fabricated without any undercutting. Zinc oxide is generally soluble in both acidic and alkaline solutions and typically dissolves rapidly during acid cleaning or acid activation. However, the results suggest that thermal treatment promotes metal diffusion, leading to the formation of a layer resistant to etching. As a result, the zinc oxide did not dissolve even after immersion in the aforementioned strongly acidic solution, and no undercutting was observed during the subsequent seed etching.

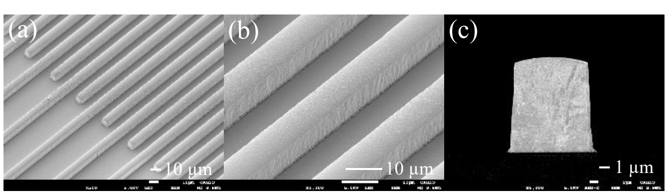

Fig.6 SEM images of the fine pattern. (a) secondary electron image x500, (b) secondary electron image x2000, and (c) backscattered electron image at x5000.

Figure 7 shows the results of the HAST. Both alkali-free glass and borosilicate glass maintained high insulation resistance over a period of 150 hours. Furthermore, no electromigration was observed between the wiring lines as shown in figure 8. These findings indicate that both materials exhibit excellent insulation properties under severe environmental conditions characterized by high humidity, temperature, and pressure. Such performance suggests their potential as reliable interposer substrates in chiplet packaging applications, where increased integration density is anticipated and long-term reliability is of critical importance.

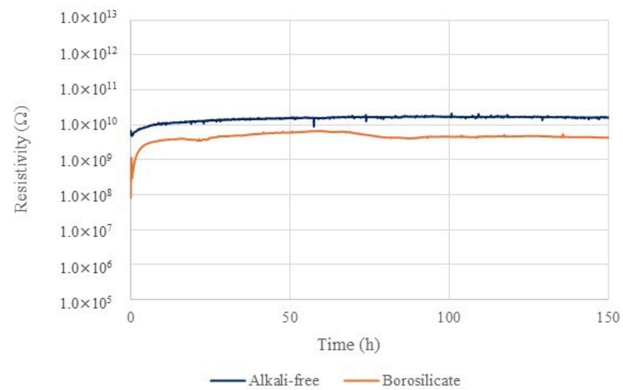

Fig.7 HAST test results for each substrate material.

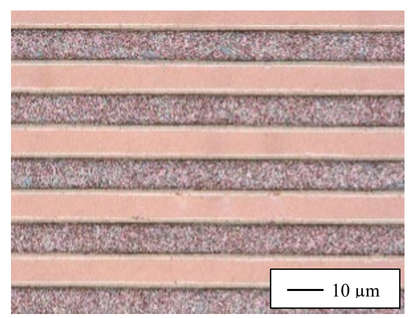

Fig.8 Microscope image of copper wiring after the HAST.

Figure 9 shows the microscope image of the throwing power performance for glass through-holes. Even with an aspect ratio of 10, good throwing power was obtained all the way to the inside of the through-hole. Because this process is a wet plating process, zinc oxide is evenly deposited inside these high aspect ratio through-holes. Therefore, compared to other adhesion layer deposition methods (sputtering method [7], sol-gel method [8]), this process is likely to enable mass production and contribute to improved productivity.

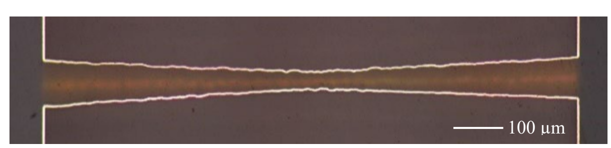

Fig.9 Cross-sectional image of a glass through-hole after acid copper plating.

The cross-sectional and X-ray CT observation results when through-hole filling was performed are shown in Figure 10. It was confirmed that by using PR pulses in combination, copper was filled uniformly without defects (voids).

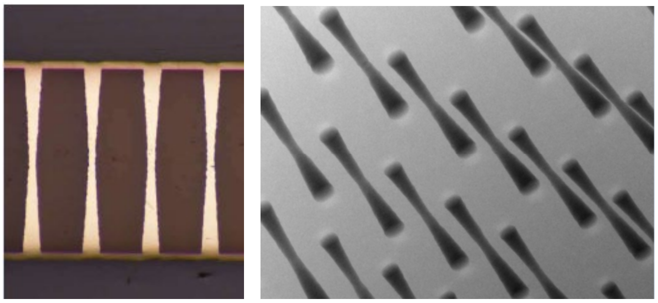

Fig.10 Cross sectional observation after through-hole filling. (a) Microscope, (b) X-ray CT.

IV. Summary

We established a high-adhesion plating process on glass using zinc oxide with high surface resistivity. The mechanism of adhesion improvement is 1) formation of pillar zinc oxide by controlling the shape and film thickness of zinc oxide based on the manipulation of reaction sites, and the nano-anchor structure by filling the gaps with electroless copper plating, 2) diffusion of electroless copper into the zinc oxide layer by air atmospheric annealing, and 3) metal diffusion between glass, zinc oxide, electroless copper, and electrolytic copper by a nitrogen annealing. In addition, it is thought that the diffused Cu replaces the Zn site of zinc oxide with Cu, improving the bonding strength at the atomic level (Zn-O-Cu bond).

We have already successfully processed panel size of 515 × 510 mm as shown in Figure 11 and are currently evaluating the stability of the process and products in preparation for mass production.

In the presentation, we will show the details of adhesion mechanisms using illustrations and announce the progress of ultra fine-pattern formation with a view to the glass interposer as a future development.

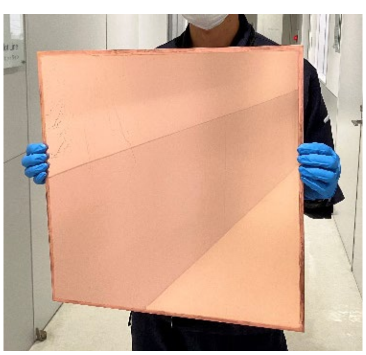

Fig.11 Glass substrate of full panel size fabricated using the proposed process.

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