Optimization of Parameters for Copper Electroplating in Through-Glass Vias

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Abstract

Through-Glass Via (TGV) technology has become a research hotspot in advanced electronic packaging due to its potential for high-density interconnections on glass substrates. However, the insulating nature and low adhesion of glass surfaces pose challenges to the uniform deposition of copper coatings. This study systematically optimizes the process parameters for copper electroplating in TGVs, with a focus on the effects of voltage, temperature, and sample movement speed on coating quality under single-step and multi-step plating conditions. In the experiments, vias were fabricated using picosecond laser drilling combined with wet etching, and direct current electrodeposition was performed after forming a seed layer via electroless copper plating. The results indicate that a lower voltage contributes to a smoother coating surface but requires a longer plating time; an appropriate temperature (30°C) enhances deposition efficiency; and excessively fast sample movement speed reduces filling integrity. Multi-step electroplating (e.g., 0.4 V followed by 1 V) significantly shortens the plating time while maintaining filling quality, thereby improving efficiency. The optimized process achieves void-free, high-adhesion copper-filled TGV structures, providing a feasible technical pathway for the application of glass substrates in high-frequency, high-density packaging.

Keywords

Through-Glass Via (TGV); Copper Electroplating; Multi-step Electroplating.

1. Introduction

With the rapid development of microelectronics technology, device miniaturization, high performance, and high-density integration have become major trends in the industry. Against this backdrop, glass materials have gradually become important substrate materials in high-density interconnection and packaging technologies due to their excellent electrical, mechanical, and thermal properties. Through-Glass Via (TGV) interconnection technology can be traced back to 2008 [1], originating from 2.5D/3D integrated TSV interposer technology, and is primarily aimed at solving problems associated with TSV interposers, such as high-frequency or high-speed signal transmission degradation due to silicon substrate loss, high material costs, and complex processes [2,3]. TGV technology supports a wide range of thicknesses (from 50 μm to 900 μm), large wafer sizes (from 6 inches to 12 inches), and panel sizes (from 510 mm × 515 mm to 1500 mm × 800 mm). The glass-based process is more straightforward, eliminating the need to deposit an insulation layer on the inner walls of TGVs, making the manufacturing cost of glass packaging substrates much lower than that of silicon substrates. Copper electroplating technology for TGVs, as a key process for achieving high-density interconnections on glass substrates, has received extensive attention and research [4,5].

Glass materials possess low dielectric constant, low coefficient of thermal expansion, excellent mechanical strength, and optical properties, which effectively reduce signal transmission delay and loss, meeting the requirements of high-frequency and high-speed circuits [6]. Moreover, the coefficient of thermal expansion of glass substrates is close to that of silicon, facilitating thermal matching in multi-layer packaging. However, because glass itself is an insulating material, depositing metal coatings on its surface and inside vias presents considerable challenges. The glass surface is smooth and exhibits low adhesion to metallic copper, making it prone to phenomena such as metal layer peeling and curling. Onitake et al. [7] used ultraviolet light irradiation to clean the glass surface to enhance the adhesion of the copper layer. Atotech proposed immersing glass in a chemical solution to form a nanoscale metal oxide layer as an adhesion layer to improve the adhesion of electroplated copper [8]. To achieve copper electroplating in TGVs, a series of pretreatment processes, such as surface cleaning, sensitization, and activation, are typically required to ensure the adhesion and uniformity of the copper coating [9].

The application of copper electroplating technology to TGVs can significantly enhance the electrical performance and mechanical strength of devices and is widely used in high-density packaging substrates, microelectronic interconnection structures, and optoelectronic integrated devices. To reduce cracking caused by thermal stress during subsequent annealing and to improve thermodynamic reliability throughout the product lifecycle, the full-filled copper metallization approach for TGV holes generally employs a TGV diameter of less than 50 μm and a TGV thickness of less than 100 μm. For example, the 12-inch TGV interposer technology disclosed by the Industrial Technology Research Institute of Taiwan and GlobalFoundries in 2016 [10,11] follows almost the same process route as TSV interposer technology, offering the advantage of high TGV interconnection density, but the process flow is complex and faces competition at the industrial ecosystem level with TSV interposer technology. Although various electroplating techniques and methods have been proposed and applied to copper electroplating in TGVs [12], issues such as coating uniformity, adhesion, voids, and cracks persist and require further optimization and improvement.

To increase interconnection density and reduce the risk of thermodynamic reliability, combining the advantages of solid filling and conformal metallization in TGV copper electroplating, partial solid filling metallization has gained industry attention. In this approach, a portion of the TGV is solid-filled while the remaining area within the TGV is conformally filled, allowing a balance between copper TGV interconnection diameter and pitch, wide thickness range, electrical characteristics, thermodynamic reliability, plating filling efficiency, and process development difficulty [13]. This study aims to explore and optimize the process parameters for copper electroplating in TGVs, improving coating quality through systematic experimental research and analysis, thereby providing reliable technical support for the development of microelectronics manufacturing and packaging technologies. We will detail the fundamental principles, existing techniques, and methods for copper electroplating in TGVs, and propose improvement strategies and solutions to address current research gaps, offering valuable references for research and applications in related fields.

2. Fundamental Principles and Experimental Details

Electroplating is a process that deposits a metal coating on a substrate surface through electrochemical reactions. Copper electroplating technology is widely used in electronic packaging, printed circuit board (PCB) manufacturing, and microelectronic device interconnections. Its basic principle involves depositing a uniform copper layer on the substrate surface via electrochemical reactions. Existing copper electroplating technologies mainly include electroless deposition, electrochemical deposition, laser-assisted electroplating, and micro/nano electroplating. However, in electroless deposition, the thickness and uniformity of the coating are limited by the reduction reaction rate and solution stability, requiring strict control of process conditions. Laser-assisted electroplating involves complex equipment, high cost, and stringent control of process parameters. Micro/nano electroplating is complex and demands high standards for equipment and environment. Therefore, this study adopts the electrochemical deposition method. This method uses an applied current to reduce copper ions in the electrolyte and deposit them onto a conductive substrate. It offers advantages such as high deposition rate and easy control of coating thickness, making it suitable for large-scale industrial production. However, it requires pre-conductivization of non-conductive substrates, such as sensitization and activation.

The electroplating process is typically carried out in an electroplating bath containing the electrolyte, a power supply, an anode, and a cathode. Its basic principle is based on the power supply providing direct current, with the anode connected to the positive terminal and the cathode to the negative terminal. The electrolyte contains metal ions (e.g., Cu^{2+}). Under the influence of current, metal ions migrate toward the cathode. When they reach the cathode surface, they accept electrons and are reduced to metal atoms, depositing on the substrate surface to form a metal coating. The basic chemical equation for the electroplating reaction is:

$$Cu^{2+}+2e^{-}\rightarrow Cu$$

In the copper electroplating process for Through-Glass Vias (TGVs), the following main steps are involved. First, pretreatment (surface activation): Since glass is an insulator, direct electroplating is impossible. Therefore, the glass surface must be pretreated to become conductive. Common pretreatment methods include: sensitization – adsorbing a reducing agent (e.g., $SnCl_2$) onto the glass surface; activation – depositing a catalyst (e.g., $PdCl_2$) on the sensitized glass surface to form conductive catalytic centers. Second, seed layer deposition: To improve the adhesion of the electroplated copper layer, a thin copper seed layer is typically deposited on the activated glass surface first. This can be achieved by electroless plating (chemical plating). Third, copper electroplating deposition: Electroplating is performed on the conductive seed layer. Electrolyte preparation: The electrolyte typically contains copper sulfate ($CuSO_4$), sulfuric acid (H_2SO_4), chloride ions (Cl^-), and organic additives. Current application: A direct current power supply provides current to the electrolytic cell, and copper ions migrate to the cathode surface inside the TGVs under the electric field. Coating growth control: Parameters such as current density, electrolyte temperature, and agitation speed are controlled during electroplating to ensure a uniform, dense, and defect-free coating.

In this study, fused silica glass substrates measuring 40 mm × 40 mm × 0.3 mm were used for Cu electrodeposition in TGVs. A picosecond pulsed laser with a wavelength of 1064 nm and a pulse duration of 15 ps was used for drilling. After laser drilling, the glass substrates were immersed in a 60% potassium hydroxide (KOH) solution and heated in a water bath at 80°C. During this process, the modified glass was selectively etched to form micron-deep holes. Meanwhile, the remaining unmodified glass was slowly etched, forming deep tapered microhole arrays. The surface was observed under an optical microscope, as shown in Figure 1, revealing a well-arranged microhole array. Cross-sectional observation using scanning electron microscopy, as shown in Figure 2, revealed straight through-holes that are slightly narrower in the middle than at the ends. Each TGV structure is a straight through-hole with a diameter of approximately 50 μm and a pitch of 100 μm. Before copper electroplating filling of the TGVs, ultrasonic cleaning was performed. After cleaning the vias in an ultrasonic bath, copper was filled by electroplating. A bottom-up electroplating method for depositing copper in through-holes, as described by Kannojia et al. [14], was used. First, a 200 nm thick Cu layer was deposited on one side of the glass substrate with TGVs as a seed layer, as shown in Figure 3. The glass substrate with the seed layer was immersed in deionized water for 2 minutes to remove surface dust, then vertically placed in the experimental electroplating apparatus, and an appropriate amount of electrolyte was poured in to submerge the glass sample. The experimental setup is shown in Figure 4. The electrolyte had a pH of approximately 2 and mainly contained copper ions, brighteners, and additives, which significantly affect the flatness and brightness of the deposit and enhance the electroplating effect. Subsequently, copper electrodeposition was performed on the glass substrate in the electroplating cell using a direct current (DC) voltage, with the electric field perpendicular to the glass substrate. To improve electrolyte uniformity, the jet and agitation systems were both turned on during Cu electrodeposition. Copper electroplating involves the reduction reaction $Cu^{2+}+2e^{-}\rightarrow Cu$, which includes two steps: reduction 1 ($Cu^{2+}+e^{-}\rightarrow Cu^{+}$) and reduction 2 ($Cu^{+}+e^{-}\rightarrow Cu$). The jet flow significantly enhances electrolyte hydrodynamics, promoting copper ion transport during electroplating. During electroplating, copper deposition grows upward from the copper tape, hence the term "bottom-up electroplating" [15]. Different experimental parameters (sample movement speed, temperature, voltage) were adjusted for electroplating, with corresponding parameters listed in Tables 1 and 2. Two different DC electroplating methods were used for TGV metallization: Table 1 for single-step electroplating and Table 2 for multi-step electroplating. The electroplating process was stopped when copper began to protrude from the glass substrate, and observation under an optical microscope showed that almost all vias were filled. The thickness of electroplated Cu on the glass surface and TGV walls was approximately 10 μm. The overplated copper on both sides of the glass substrate was then removed by manual polishing, and the samples were polished for cross-sectional observation.

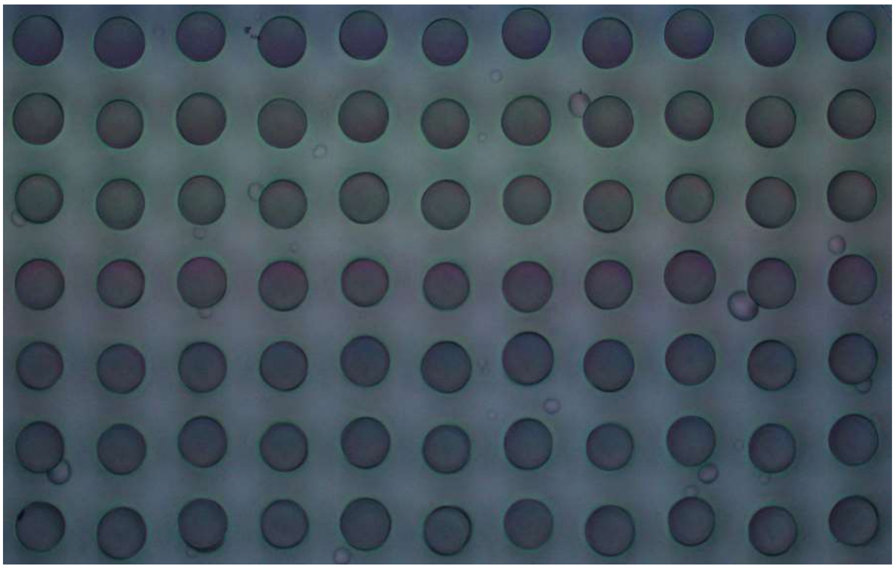

Figure 1. Optical microscope image of the microhole array.

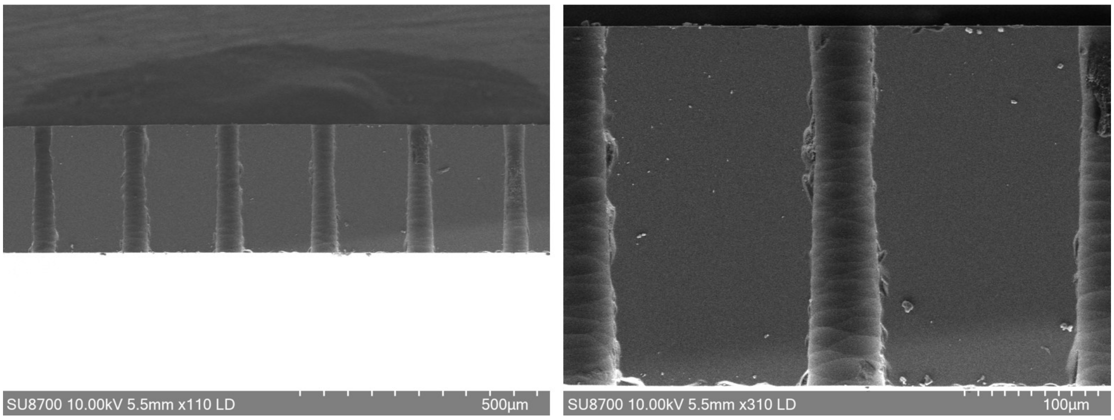

Figure 2. Electron microscope image of the microhole array.

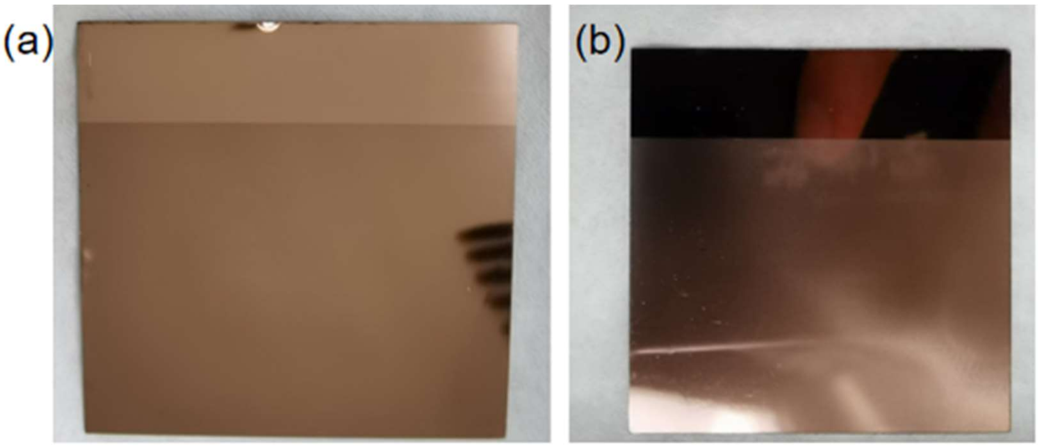

Figure 3. (a) Front view of the sample with deposited seed layer; (b) Back view of the sample with deposited seed layer.

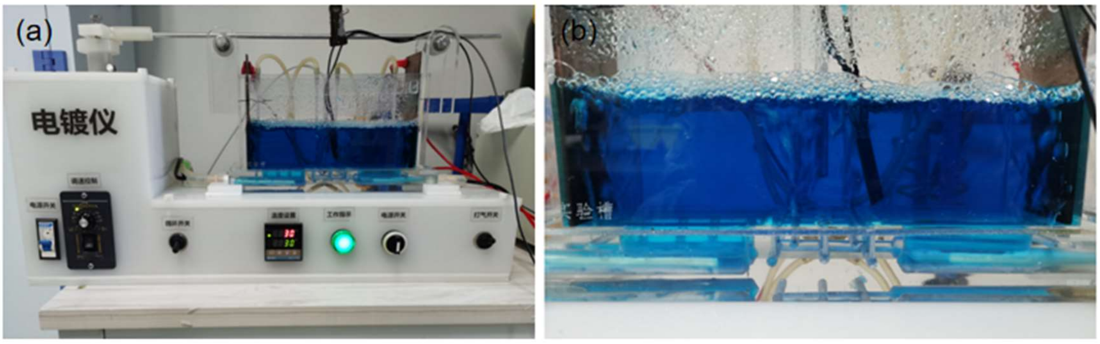

Figure 4. (a) Experimental setup of the entire apparatus; (b) Photograph of the electroplating apparatus during the experiment.

Table 1. Electroplating process parameters

Condition Sample No.	Voltage	Temperature	Movement Speed	Time
1	0.2V	25℃	50	21h
2	0.4V	25℃	50	27h
3	0.4V	30℃	50	17h
4	0.4V	30℃	100	13h

Table 2. Electroplating process parameters

Condition Sample No.	Step	Voltage	Temperature	Movement Speed	Time
5	1	0.4V	30℃	50	5h
	2	0.8V			10h
6	1	0.4V			5h
	2	1V			5h
7 (Without air agitation)	1	0.4V			6h
	2	1V			6h

3. Results and Discussion

Optical images show surface views of selected arrays, as presented in Figures 5 and 6. All TGVs were filled with copper without noticeable voids. After forming redistribution layers and contact pads, these copper-filled TGVs can serve as interconnects in various microsystem packaging applications. Figure 5 shows optical microscopy images of double-sided electroplated copper-filled microhole arrays for Samples 1-4. Analysis of the images and electroplating parameters reveals that during the first stage of single-step electroplating, a comparison of different applied voltages indicates that a lower voltage yields a smoother surface but requires a longer plating time to completely fill the vias. Sample 1 required the longest plating time to achieve complete via filling. Comparing different temperatures, it can be seen that an appropriate temperature accelerates via filling; Sample 2 was processed at a relatively lower temperature and thus needed a longer plating time to achieve complete via filling. By comparing the sample movement speeds in the electrolyte, it is evident that movement speed is also a factor affecting copper plating quality. Excessively fast movement reduces plating efficiency and results in incomplete via filling, requiring a longer plating time to fully fill the vias.

Figure 6 shows optical microscopy images of double-sided electroplated copper-filled microhole arrays for Samples 5-7. Based on the above findings, during the second stage of multi-step electroplating, with temperature and sample movement speed set at appropriate conditions, different voltage combinations were applied. Pre-filling the vias with a lower voltage followed by a higher voltage yielded better filling results while shortening the plating time and improving plating efficiency. Low current density was used for initial deposition, while high current density was used for the via filling process. The thickness of electroplated Cu on the glass surface and TGV walls was approximately 10 μm. The overplated copper on both sides of the glass substrate was then removed by manual polishing, and the samples were polished for cross-sectional observation, as shown in Figures 7 and 8. Figure 7 is an optical microscopy surface image of a polished sample. It can be seen that after polishing off the overplated copper, the microholes of the sample remain filled with copper, indicating that the microhole arrays are completely filled. Figure 8 is an optical microscopy cross-sectional image of a TGV sample after double-sided copper electroplating filling. The cross-section shows that metallic copper has completely filled the entire microhole.

From the experimental results, it can be seen that a higher voltage leads to a higher current density, a faster reduction rate of copper ions, and a higher deposition rate. However, a high current density can result in a rough deposit surface, the formation of voids or dendritic crystals, while an excessively low current density leads to insufficient deposit density. Increasing the temperature accelerates the electrochemical reaction rate and enhances the migration and deposition rate of copper ions. A higher temperature can accelerate the deposit formation rate. High temperatures help obtain fine-grained, dense deposits, but excessively high temperatures may cause decomposition of the electrolyte or deactivation of additives, as well as induce stress and warpage in the deposit. The copper ion concentration in the solution directly affects the deposition rate and deposit thickness. Too low a copper ion concentration may result in a slow deposition rate and a thin deposit; too high a concentration may cause uneven deposition. Appropriate agitation facilitates the uniform distribution of copper ions in the solution, avoiding local concentration differences. Good agitation can prevent defects such as voids and roughness on the deposit surface, improving deposit uniformity and density. The agitation speed must be moderate; excessive speed may increase bubble formation in the solution and cause uneven deposits, while too slow a speed may lead to non-uniform solution conditions. The optimal speed needs to be determined experimentally. Plating time affects the thickness and uniformity of the deposit. Insufficient time results in incomplete plating, incomplete via filling, and inadequate deposit thickness, whereas excessive time may lead to an overly thick deposit and the appearance of defects. In summary, parameters such as current density, temperature, solution concentration, and agitation speed have significant effects on the quality of the copper deposit. By rationally controlling and optimizing these parameters, a uniform, dense, and well-adhered copper deposit can be obtained. This requires experimental adjustment and optimization according to the specific electroplating process and requirements.

In the electroplating process for Through-Glass Vias, the main challenges are uniformity control and surface adhesion. The chemical inertness of the glass surface leads to poor deposit adhesion. Furthermore, achieving uniform copper deposition inside deep vias is difficult, necessitating effective surface activation and seed layer technologies, as well as optimization of electroplating process parameters. Voids and cracks are prone to form during electroplating, affecting the mechanical and electrical performance of the deposit. The application of copper electroplating technology to TGVs requires solving issues related to glass surface conductivity and deposit adhesion. By optimizing pretreatment processes, electrolyte formulations, and process parameters, high-quality copper deposits can be achieved, providing reliable interconnection solutions for microelectronics manufacturing.

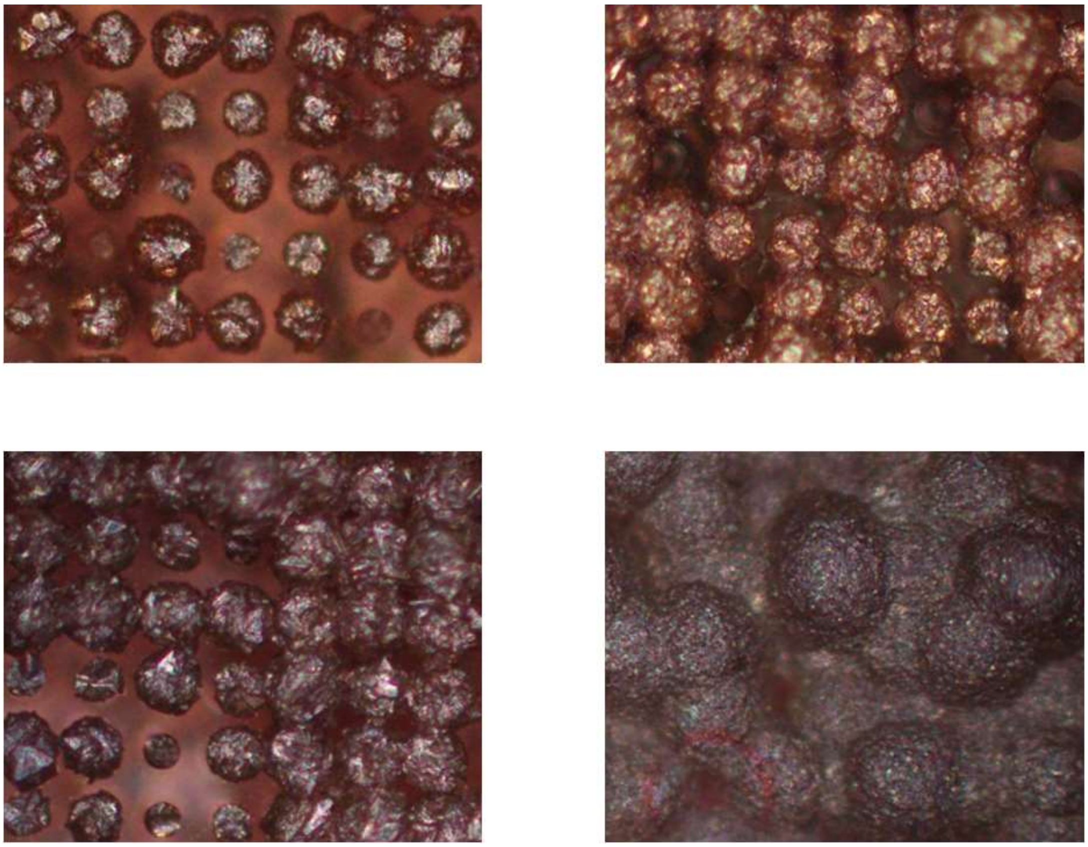

Figure 5. Optical microscopy images of double-sided electroplated copper-filled microhole arrays for Samples 1-4.

Figure 6. Optical microscopy images of double-sided electroplated copper-filled microhole arrays for Samples 5-7.

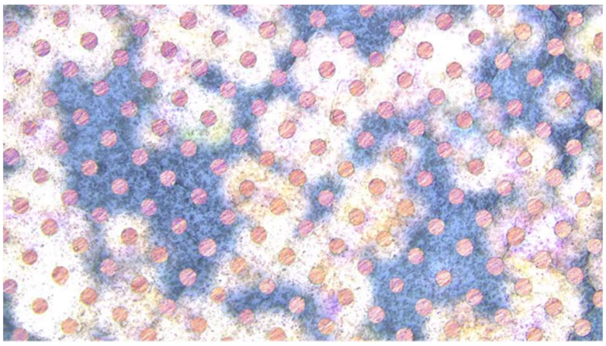

Figure 7. Optical microscopy image of the sample surface after polishing

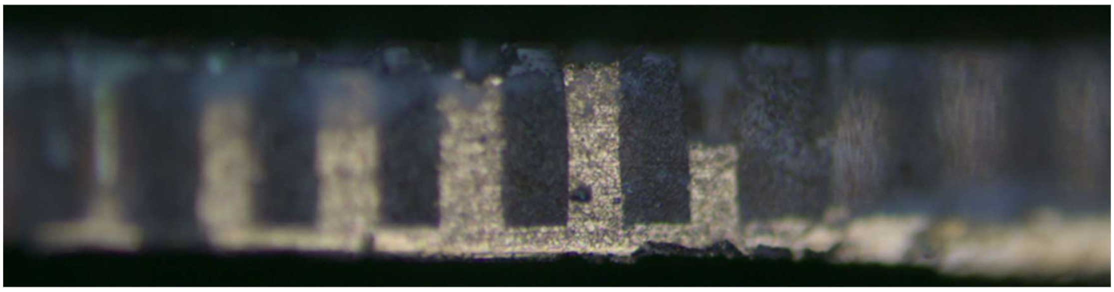

Figure 8. Optical microscopy cross-sectional image of the polished sample

4. Conclusion

Through this study, key parameters in the copper electroplating process for TGVs were systematically optimized, and a relatively optimal combination of electroplating conditions was identified, improving the deposition quality and uniformity of the copper layer. The optimized parameters not only reduced void formation inside the vias but also enhanced deposit adhesion and conductivity. Furthermore, we shortened the plating time and improved both plating efficiency and the uniformity of Cu metallization in TGVs through single-step and multi-step electroplating processes. The improved copper uniformity is attributed to the multi-step electroplating process, which enables uniform distribution of current and copper ions within the via structure. Additionally, the microstructure of the electroplated copper can be appropriately modified using the multi-step process, which can significantly enhance the mechanical characteristics of the copper interconnects, thereby greatly promoting the development of fine-line technology in advanced electronic packaging applications. These improvements help increase the production efficiency of the electroplating process, reduce material waste and cost, and provide reliable technical support for microhole electroplating in electronic component manufacturing. In the future, research can be extended to optimize electroplating processes on other substrate materials or to explore the interactions between different variables in the electroplating process to achieve more precise control.

Acknowledgments

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References

[1] Chae J ,Giachino M J ,Najafi K .Fabrication and Characterization of a Wafer-Level MEMS Vacuum Package With Vertical Feedthroughs[J].Journal of Microelectromechanical Systems: A Joint IEEE and ASME Publication on Microstructures, Microactuators, Microsensors, and Microsystems,2008,17(1):193-200.

[2] Yang F ,Han G ,Yang J , et al.Research on Wafer-Level MEMS Packaging with Through-Glass Vias[J].Micromachines,2018,10(1):15-15.DOI:10.3390/mi10010015.

[3] Yuzhe C ,Jihua Z ,Libin G , et al.An optimized NiP seed layer coating method for through glass via (TGV)[J].Microelectronic Engineering,2022,(prepublish):111735-.DOI:10.1016/J.MEE.2022.111735.

[4] Onitake S, Inoue K, Takayama M, Kozuka T, Kuramochi S, Yun H. TGV (Through-Glass Via) Metallization by Direct Cu Plating on Glass. In 2016 IEEE 66th Electronic Components and Technology Conference (ECTC). IEEE, 2016, 231.

[5] Usman A, Shah E, Satishprasad N B, Chen J L, Bohlemann S A, Shami S H, Eftekhar A A, Adibi A. Interposer technologies for high-performance applications[J]. IEEE Trans. Compon. Pack. Manuf. Technol., 2017, 7 (6):819-828.

[6] Reitz B ,Evertz A ,Basten R , et al.Integrated multimode optical waveguides in glass using laser induced deep etching.[J].Applied optics,2024,63(4):895-903.DOI:10.1364/AO.506670.

[7] Kuramochi S, Kudo H, Akazawa M, Mawatari H, Tanaka M, Fukuoka Y. 2016 6th Electronic System-Integration Technology Conference (ESTC), Grenoble, September 13-15, 2016[C]. Piscataway: IEEE, 2016.

[8] Liu Z, Fu H, Hunegnaw S, Jun Wang, Merschky M, Magaya T, Mieno A, Shorey A, Kuramochi S, Akazawa M, Yun H. Electroless and Electrolytic Copper Plating of Glass Interposer Combined with Metal Oxide Adhesion Layer for Manufacturing 3D RF Devices. In 2016 IEEE 66th Electronic Components and Technology Conference (ECTC). IEEE, 2016, 230.

[9] Chen S ,Wang J ,Liu X , et al.High-frequency characteristics analysis and optimization of coaxial-like TGVs.[J].Scientific reports,2026,16(1):4796-4796.DOI:10.1038/S41598-026-35007-5.

[10] Sukumaran V, Huang IJ, Chadda S, Pannerselvam E, Chok HO. Forming Metal Cap Layer Over Through-Glass-Vias (TGVs), US201715446109, 2023-08-01.

[11] Shorey AB and Lu R. Progress and Application of Through Glass Via (TGV) Technology, In 2016 Pan Pacific Microelectronics Symposium (Pan Pacific), 2016, 43: 6-11.

[12] Wenchao T ,Sixian W ,Wenhua L .Research of Vertical via Based on Silicon, Ceramic and Glass.[J].Micromachines,2023,14(7):DOI:10.3390/MI14071391.

[13] Amortegui X ,Karniely S ,Eldar A , et al.Trout Granulomatous Virus (TGV) infection is associated with disruption of gill morphology, endothelial damage, and local immune responses in rainbow trout.[J].Fish & shellfish immunology,2026,173111266.DOI:10.1016/J.FSI.2026.111266.

[14] Kannojia HK, Arab J, Pegu BJ, Dixit P. Fabrication and characterization of through-glass vias by the ECDM process. J Electrochem Soc 2019;166:D531-8.

[15] Harsh P, Tarlochan S, Pradeep D. Formation of high aspect ratio through-glass vias by the combination of Ultrasonic micromachining and copper electroplating[J]. Journal of Manufacturing Processes,2022,Vol.82: 569-584.