

Comparison of Sintering Behavior of Silver, Aluminum and Copper Thick Films on Alumina Substrates using a Screen-Printing Method

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Abstract

Metal circuits prepared using the screen-printing method demonstrate excellent electrical conductivity and mechanical properties, making them well-suited for applications in flexible electronics, Si-solar cells, multilayer resistors, and microelectronic packaging. The objective of this study is to conduct a comparative analysis of the sintering behavior of thick-film circuits composed of silver, copper, and aluminum on alumina substrates. The investigation encompasses an examination of the surface and cross-sectional morphology, conductivity, and adhesion of the sintered metal circuits at various temperatures subsequent to screen printing. The experimental findings suggest that diverse metals exhibit contrasting microstructures, electrical properties, and adhesion characteristics. Specifically, in comparison to the network structure formed by sintering copper and aluminum films as base metals, the noble metal silver facilitates the formation of a continuous structure. As a result, silver films display lower surface resistance and higher adhesion. By comprehensively comparing the morphology and performance of different metal films, this study will offer valuable insights for the construction of multilayer thick-film circuits.

Keywords: Sintering behavior, noble and base metal, thick films, screen printing

I. Introduction

Thick-film metallization is a crucial technique employed in the fabrication of ceramic substrate circuits, finding widespread applications in flexible electronics^{1, 2}, Si-solar cells^{3, 4}, multilayer resistors^{5, 6}, and microelectronic packaging^{7, 8}. To enhance the component density within packaging structures, the utilization of multilayer circuits has become inevitable^{9–11}. In multilayer thick-film circuits, various types of pastes with distinct properties, including metal paste^{12–15}, insulating paste¹⁶, and resistive paste^{17–19}, are utilized based on the design specifications of the circuit structure. Among these pastes, metal films serve as conductive pathways and play an indispensable role in the overall functionality of the device. Commonly employed metals in thick-film metal circuits encompass noble metals such as silver²⁰, as well as base metals like aluminum^{21–23} and copper²⁴.

In the configuration of multilayer thick-film circuits, achieving effective sintering and bonding of the metal paste with the ceramic substrate is of paramount importance in order to establish a continuous, low-resistance conductive circuit²⁵. The thick-film method primarily involves the preparation of a metal paste with suitable viscosity by means of screen printing, followed by subsequent sintering. The metal paste consists of metal powder, glass binder, and organic solvents²⁶. The metal powder is

the main component of the later metal film, used to form conductive pathways. After melting, the glass phase is distributed directly between the conductor film and the load, providing necessary adhesion. The added organic solvent mainly improves the rheological and thixotropic properties of the entire system, thereby maintaining the appropriate viscosity of the paste and enabling better screen-printing performance. Numerous researchers have focused on enhancing the adhesion of single-layer metals and reducing surface resistance by modifying the glass phase and organic solvent composition^{27–33}. However, the selection of an appropriate metal paste for constructing multilayer thick-film circuits necessitates a comprehensive investigation into the sintering characteristics of commonly employed pastes. This entails observing the sintered surface, analyzing the interface structure between the paste and ceramic substrate, evaluating adhesion performance on the ceramic surface, and assessing the electrical functionality of the formed circuit.

This study investigates the formation modes and conduction mechanisms of metal films following sintering in two categories and three distinct systems of metal pastes. The first category pertains to noble metals, specifically silver paste, whereas the second category encompasses base metals, namely aluminum paste and copper paste. Additionally, the research examines the characteristics of interface formation and bonding methods with ceramics. The objective is to offer valuable guidance for the selection of

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metal films in the construction of multilayer thick-film structures.

II. Experiment Procedures

The main controlling factors in the sintering process of metal paste include atmosphere, sintering temperature, carbonization temperature, and heating rate. We printed three types of metal pastes, Ag, Al, and Cu, on the surface of Al_2O_3 substrate, and then conducted experiments according to the set parameters to obtain different metal film surfaces and interface structures. The specific experimental parameters selected in this study are shown in Table 1.

(1) Atmosphere selection

Due to the characteristics of the metals themselves, thick-film pastes of noble metals such as Ag are not easily oxidized under the air atmosphere during sintering, which would lead to the loss of electrical conductivity of the metal film. However, thick-film pastes of base metals such as Al and Cu are easily oxidized on their surfaces under the air atmosphere during sintering, which affects the conductivity after sintering. It is worth noting that the oxidation of Al only occurs on the surface layer, and it can still achieve the function of conductivity after sintering. However, Cu will continue to oxidize in the oxygen-containing atmosphere, and the oxygen content determines whether CuO or Cu_2O is finally formed. Therefore, Al paste can still be sintered under the air atmosphere, while Cu paste can only be sintered in a high-purity nitrogen or high vacuum environment to avoid affecting the final performance after sintering.

(2) Sintering temperature

In order to better understand the influence of sintering temperature on the sintering characteristics of metal pastes, we have expanded the range of different sintering temperatures on the basis of common temperatures for each type of metal paste. Specifically, the sintering temperature ranges are as follows: Ag paste at $825\text{--}900\text{ }^\circ\text{C}$, Al paste at $500\text{--}825\text{ }^\circ\text{C}$, Cu paste at around $750\text{--}850\text{ }^\circ\text{C}$.

(3) Carbonization temperature

Metal pastes are composed of metal powders and organic vehicles, and the residual organic solvents will affect the performance of the subsequent metal film. Therefore, a carbonization process is generally required before the paste is sintered. In order to fully remove the organic solvents, the carbonization temperature is generally selected between $300\text{--}500\text{ }^\circ\text{C}$. In this study, different carbonization temperatures were chosen based on the sintering temperatures of different metal pastes.

Table 1: Setting of sintering parameters for metal paste.

Paste	Atmosphere	Carbon emission process	Heating rate (K/min)	Temperature ($^\circ\text{C}$)
Silver	air	$400\text{ }^\circ\text{C}\text{--}30\text{ min}$	10	825, 850, 875, 900
Aluminum	air	$300\text{ }^\circ\text{C}\text{--}30\text{ min}$	5	500, 550, 650, 825
Copper	N_2	$400\text{ }^\circ\text{C}\text{--}30\text{ min}$	5	750, 800, 850

(4) Heating rate

Generally, the heating rate of metal pastes has little influence on the pastes. The commonly used reference value for metal pastes is 10 K/min . However, the specific experimental process is greatly affected by the equipment. If the heating rate is fast but the temperature control accuracy is insufficient, it will affect the performance of the metal layer after sintering. The equipment used in our experiment has a temperature control accuracy of $\pm 3\text{ }^\circ\text{C}$. For stable precious metal pastes such as Ag, there is little impact when sintered in equipment with a temperature control accuracy of $\pm 3\text{ }^\circ\text{C}$, so a heating rate of 10 K/min is chosen. The sintering temperature of Al paste is relatively low. In order to prevent the temperature control accuracy from being affected due to the continuation of temperature rise after reaching the sintering temperature, a heating rate of 5 K/min is chosen. Cu paste is always in a high-purity nitrogen environment, which is not conducive to the removal of organic solvents. Therefore, the heating rate is reduced to allow sufficient removal of organic matter before reaching the final sintering temperature. Hence, a heating rate of 5 K/min is also chosen for Cu paste.

(5) Characterization of metal films

The surface and cross-section of the films were investigated with a scanning electron microscope (SEM, Regulus 8100). The particle size statistics were determined using Nano Measure software, and the proportion of surface pores was also calculated using Image Pro Plus software. The sheet resistance was tested with a SZT-2A four-probe tester. The adhesion was tested using the SANS electronic universal stretching machine (CMT5105).

III. Results and Discussion

(1) Microscopic morphology, electrical and mechanical properties of Ag film

Fig. 1 shows the surface SEM of the Ag metal film at different sintering temperatures. From the figure, it can be seen that the surface of the Ag paste after sintering is densely packed, and the grain boundaries are relatively clear. It can be observed that the surface Ag starts to sinter at $825\text{ }^\circ\text{C}$, and the process of increasing the temperature only involves the continuous growth of Ag grains and the continuous reduction of the glass phase. At $825\text{ }^\circ\text{C}$, the Ag metal has already undergone crystallization, and the glass phase is distributed at the grain boundaries. With the increase of temperature, the size of the metal grains gradually increases, and the grain boundaries become clearer, while the content of the glass phase decreases.

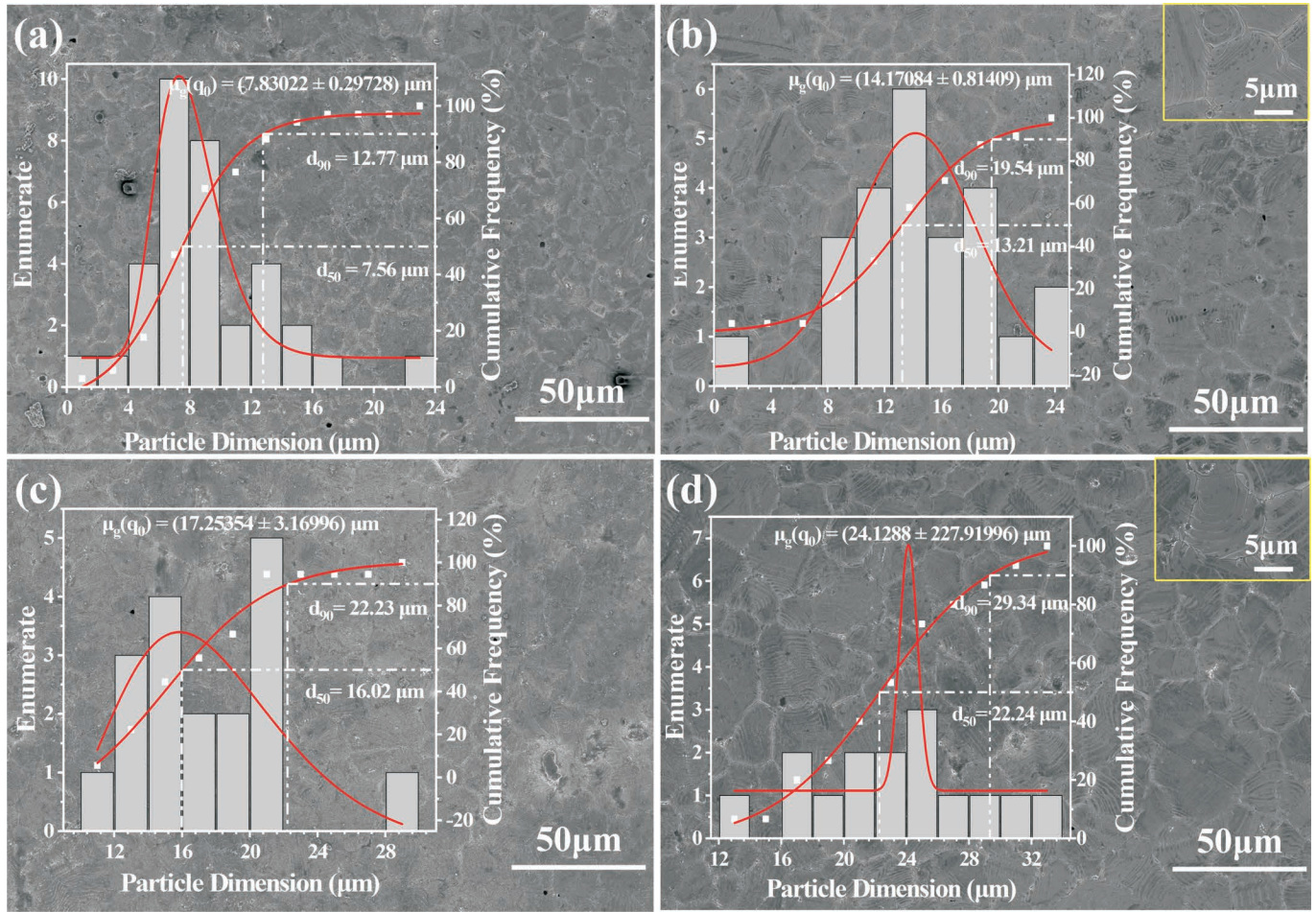


Fig. 1: SEM images of the Ag film surface at different sintering temperatures: (a) 825 °C; (b) 850 °C; (c) 875 °C; (d) 900 °C. The particle size distribution and grain morphology of the Ag grains on the surface are magnified in the figure.

Based on the particle size distribution in Fig. 1, it can be observed that as the sintering temperature increases from 825 °C to 900 °C, the average particle size increases from 7.83 μm to 24.1 μm, and the d_{50} value increases from 7.56 μm to 22.24 μm. This indicates a significant grain growth process occurring during sintering. As the glass phase gradually decreases, the expansion space of the grain boundaries becomes smaller, and the resistance to grain growth increases. Therefore, the growth of grains becomes less significant.

In accordance with Fig. 2, it presents the SEM image displaying the cross-sectional structure between the Ag film and the ceramic. Notably, the Ag film exhibits a relatively uniform thickness, predominantly around 10 μm. It can be observed that at 825 °C, the Ag film undergoes satisfactory sintering. However, due to inadequate sintering of the glass phase, noticeable voids appear at the interface connecting the metal film and the ceramic. As the temperature rises above 850 °C, the sintering process becomes more comprehensive, leading to the virtual disappearance of voids at the interface. Moreover, the glass phase located amidst the particles initiates crystallization and remains within the Ag film. Fig. 2 demonstrates that temperatures exceeding 875 °C result in an upsurge in the presence of crystalline particles within the Ag film, rendering it susceptible to delamination and consequently generat-

ing voids therein. Hence, a sintering temperature of 850 °C is deemed more appropriate.

The electrical properties of thick film circuits were investigated through an examination of the surface square resistance of the Ag film subsequent to the paste sintering process, as depicted in Fig. 3. A lower square resistance can accommodate a higher operating current, thereby enhancing the electrical signal output of electronic packaging components and playing a pivotal role in enhancing the overall stability of packaging devices. When the tests were conducted, it was observed that the surface square resistance of the Ag film reaches its minimum value when sintered at 850 °C. The alteration trend in the surface resistance of the Ag film at various sintering temperatures aligns with the pattern of void formation inside the Ag, wherein the resistance decreases initially and subsequently increases.

Meanwhile, the interfacial adhesion between the metal film and ceramic substrates has a direct impact on the subsequent electronic packaging performance, as illustrated in Fig. 3. The results clearly demonstrate that the highest level of adhesion between the metal film and ceramic substrate is achieved when the sintering temperature is set at 850 °C, which corroborates the previous observations made regarding the changes in interface morphology. At lower temperatures, localized voids are formed at the metal-ceramic

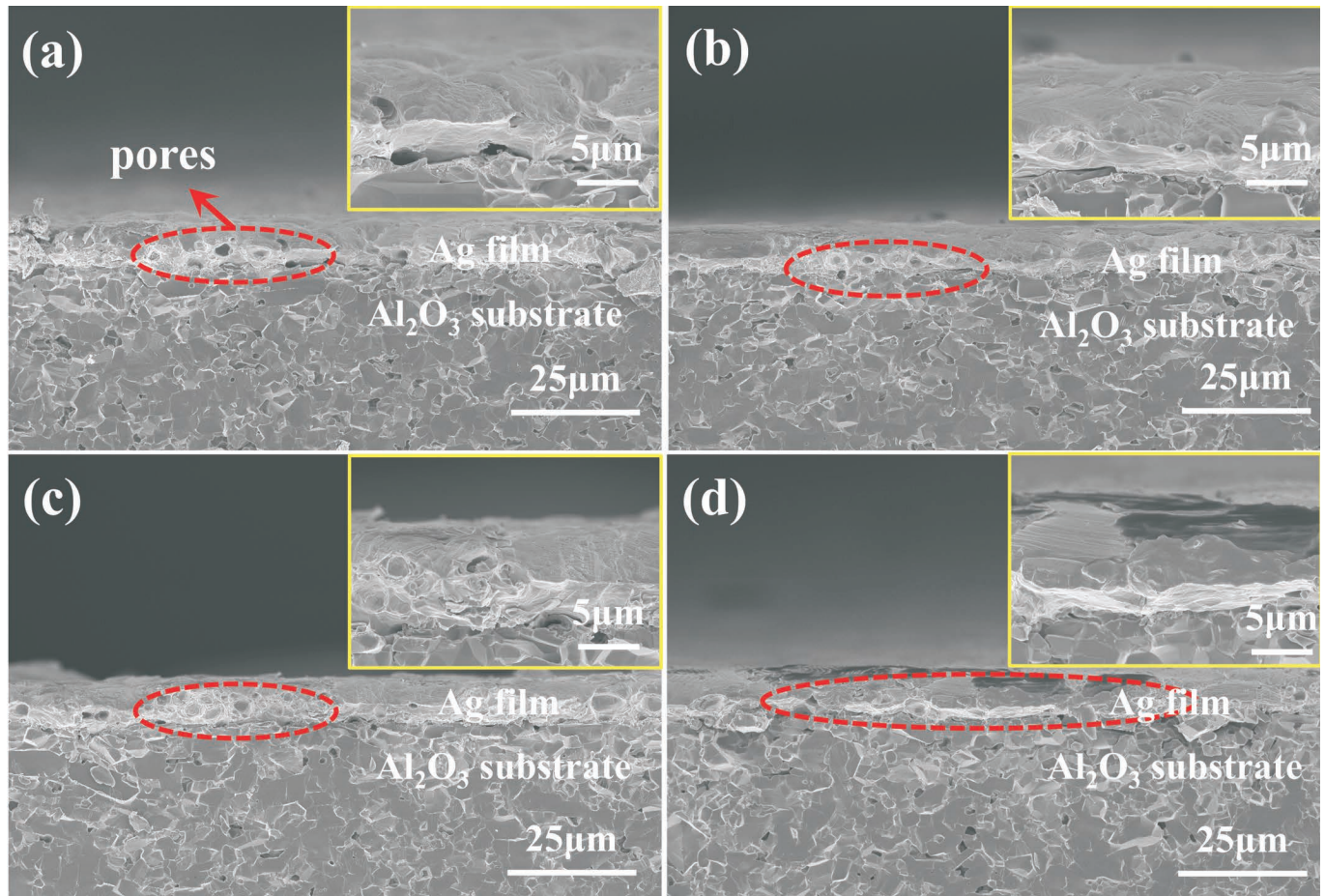


Fig. 2: SEM images of cross-sections of Ag films sintered at different temperatures: (a) 825 °C; (b) 850 °C; (c) 875 °C; (d) 900 °C. Higher magnification micrographs show the cross-section structure inset (a)–(d), respectively.

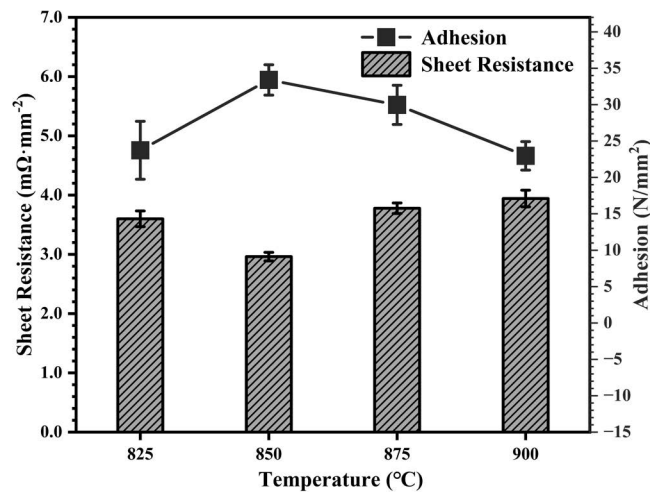


Fig. 3: Changes in surface resistance and adhesion of Ag metal film with sintering temperature.

interface, leading to a discernible effect on the adhesion properties. However, as the temperature gradually increases, the glass phase progressively melts, resulting in a decrease in the number of voids present at the interface and consequently an increasing trend in adhesion. Nevertheless, as the temperature continues to rise, an elevated number of voids emerge within the metal film, negatively impacting the adhesion and subsequently causing a decrease in the adhesion strength.

(2) Microscopic morphology, electrical and mechanical properties of Al film

Fig. 4 depicts the morphological evolution of an Al metal film under different temperature conditions. At 500 °C, prior to glass melting, the surface exhibits scattered metal powder, with spherical Al particles lacking effective interconnectivity. When the temperature is raised to 550 °C, the glass phase within the paste begins to liquefy, promoting particle bonding and the gradual formation of a conductive pathway. At 650 °C, a significant transformation occurs as the glass fully melts, resulting in enhanced inter particle connections. Upon reaching 825 °C, the metal spheres on the surface become enveloped by glass, leading to pronounced crystallization. The higher magnification images within Fig. 4 provide a closer observation of the changes in the glass phase during the Al sintering process. Notably, at 550 °C, the glass phase initiates melting, promoting effective bonding and conductivity among the metal particles. Melting becomes more conspicuous at 650 °C, while at 850 °C, noticeable crystallization of the glass phase is observed.

With increasing temperature, the gradual melting of the glass phase and the variation in porosity of the Al film become more pronounced. Fig. 5 illustrates the distribution of pores within the Al film and porosity changes with temperature.

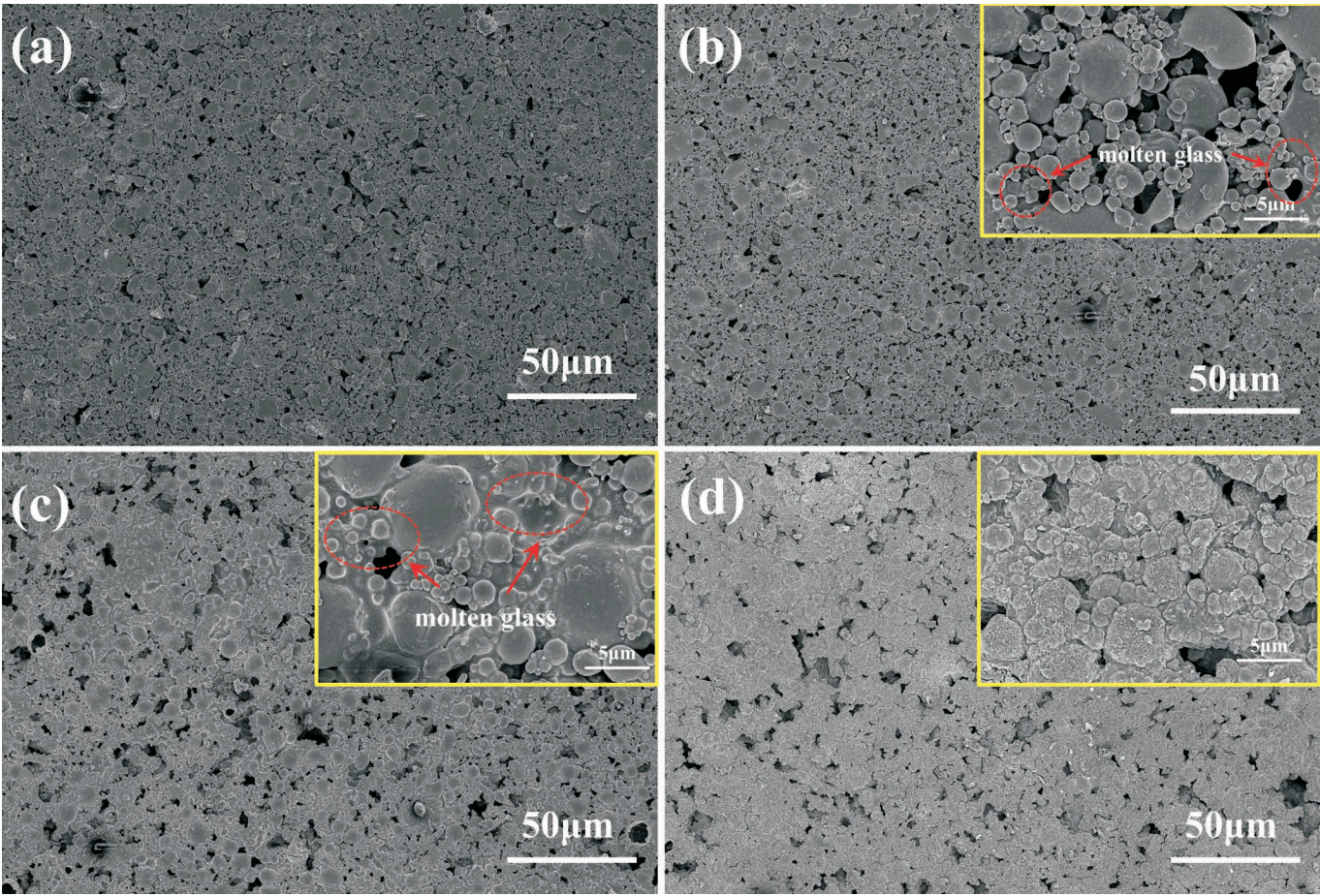


Fig. 4: SEM images of the surface of the Al film sintered at different temperatures: (a) 500 °C; (b) 550 °C; (c) 650 °C; (d) 825 °C. Higher magnification images showing localized changes in glass phase are respectively included within (b)-(d).

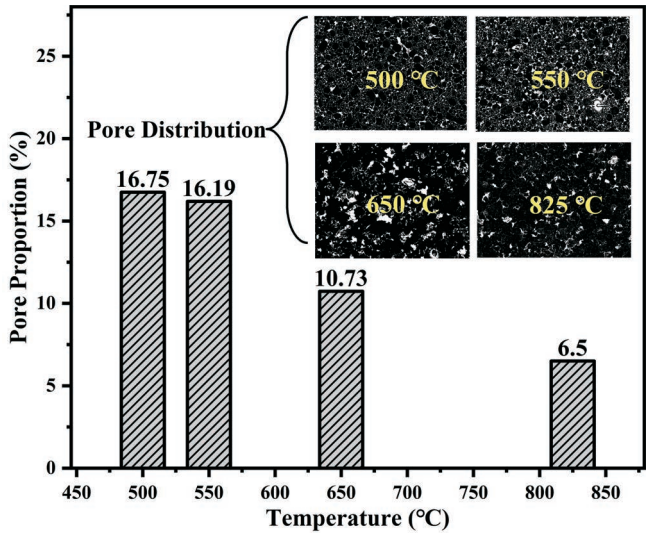


Fig. 5: The relationship between the porosity of the Al metal film and temperature.

The findings indicate that below 550 °C, complete initial sintering did not occur, and the porosity remained relatively constant at approximately 16 %. As the temperature rose, the glass phase fully melted, resulting in larger pores while the overall quantity decreased. Consequently, the porosity decreased to 10.73 % at 650 °C. Upon further temperature increase, the complete melting of the glass

phase caused the encapsulation of aluminum powder and eventual crystallization, leading to a less significant decrease in porosity.

Fig. 6 illustrates the interface structure between the Al paste and the ceramic substrate, following sintering at temperatures of 500 °C, 550 °C, 650 °C, and 825 °C. The obtained results exhibit both similarities and differences when compared to surface observations. Notably, surface examinations revealed an increased presence of pores below 550 °C, while no discernible interface was observed. This suggests that the surface pores are not fully penetrating, but rather shallow blind holes. On the other hand, temperatures surpassing 650 °C led to the complete melting of the glass phase, consequently resulting in a more interconnected metal network structure. As a result, larger through-holes were formed. This particular phenomenon aligns with the observations made on the surface.

Fig. 7 illustrates the overall weak adhesion of the Al film, which can be attributed to its glass system. The relatively low sintering temperature of the glass system contributes to the generally low adhesion strength. However, there is a discernible pattern in the variation of adhesion. At 500 °C, the absence of glass melting results in the mere stacking of metal powder and glass on the ceramic surface, without establishing a well-defined bond. Consequently, the adhesion is exceedingly low. As the temperature increases to 550 °C, the adhesion improves significantly due to

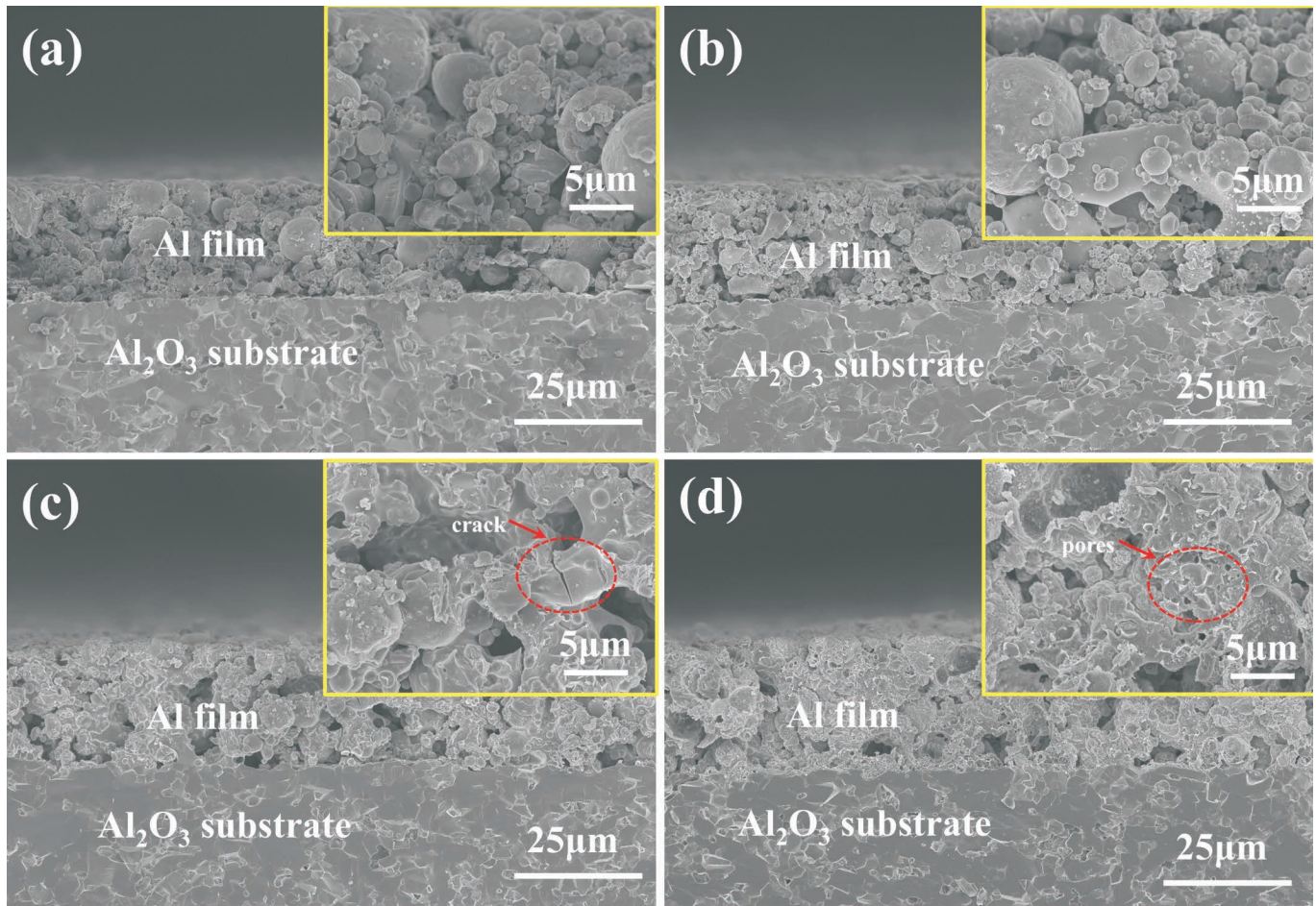


Fig. 6: SEM images of cross-sections of Al film sintered at different temperatures: (a) 500 °C; (b) 550 °C; (c) 650 °C; (d) 825 °C. Higher magnification images displaying the evolution of the Al film in (a)-(d), respectively.

the melting of the glass, reaching a value of 15.6 N/mm². Subsequent glass melting leads to the formation of larger surface pores and the observation of some cracks in the section structure, contributing to a decrease in structural strength. When the temperature reaches 825 °C, although there are fewer pores, they fuse together to form larger pores. Additionally, the network framework exhibits pore defects due to glass crystallization, resulting in a further decrease in adhesion.

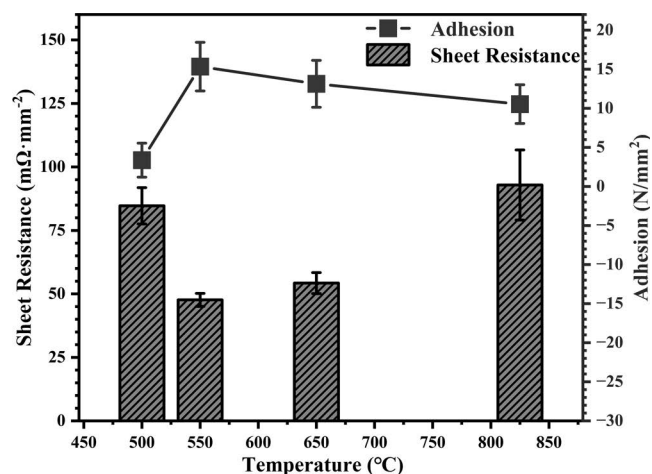


Fig. 7: Changes in surface resistance and adhesion of Al metal film with sintering temperature.

The surface square resistance of the Al film reaches its lowest point during the sintering process at 550 °C. When considering Fig. 6 alongside this observation, it becomes apparent that the internal network structure of the Al film undergoes changes as the temperature varies. At 500 °C, no well-defined network structure is formed, resulting in the distribution of spherical metal powder and some glass phases on the surface. This distribution hinders metal connections and leads to a high surface square resistance. However, at 550 °C, a network structure begins to take shape, facilitating metal connections and thereby reducing the square resistance. Above 650 °C, although more network frameworks are formed, the presence of through-holes causes these frameworks to lack support. As a consequence, cracks appear and there is a slight increase in square resistance. Notably, at 825 °C, the increase in square resistance is primarily attributed to increased glass crystallization. This crystallization process forms holes within the network body's framework and covers the metal powder with glass phases. Consequently, the network becomes disconnected, significantly affecting the electrical performance of the Al film.

(3) Microscopic morphology, electrical and mechanical properties of Cu film

The evolution of the surface morphology of the Cu metal film as a function of sintering temperature is depicted in Fig. 8.

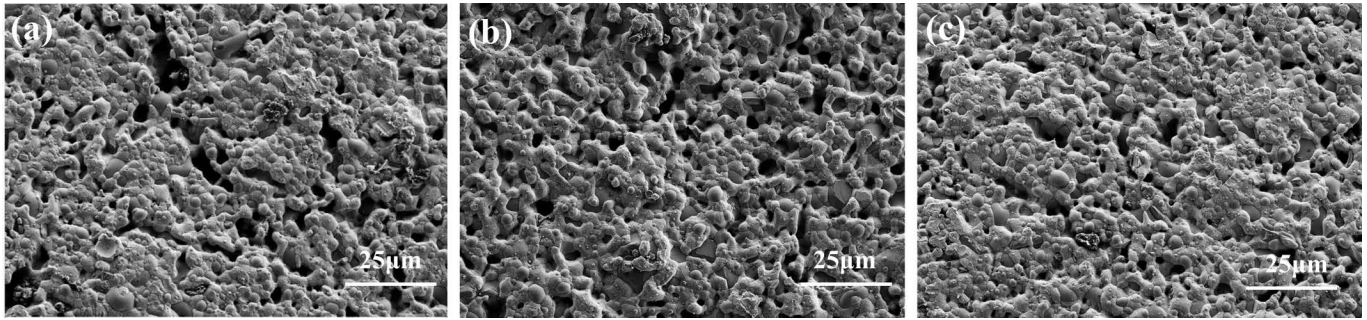


Fig. 8: SEM images of the surface of Cu film sintered at different temperatures: (a) 825 °C; (b) 850 °C; (c) 875 °C.

Similar to the Al film, the surface state of the Cu film exhibits a network-like structure. This network structure facilitates the formation of conductive pathways within the metal film, thereby ensuring its electrical conductivity. As the sintering temperature increases, there is a noticeable reduction in the porosity of the Cu film. At 850 °C, the film's surface appears nearly free from pores, with the metal uniformly spread across the surface. This behavior can be attributed primarily to the melting and continuous bonding of the glass phase at elevated temperatures, leading to the growth and aggregation of Cu particles on the surface. Consequently, a relatively intact and continuous surface is formed. Simultaneously, the glass infiltrates the interface between the Cu film and the ceramic substrate.

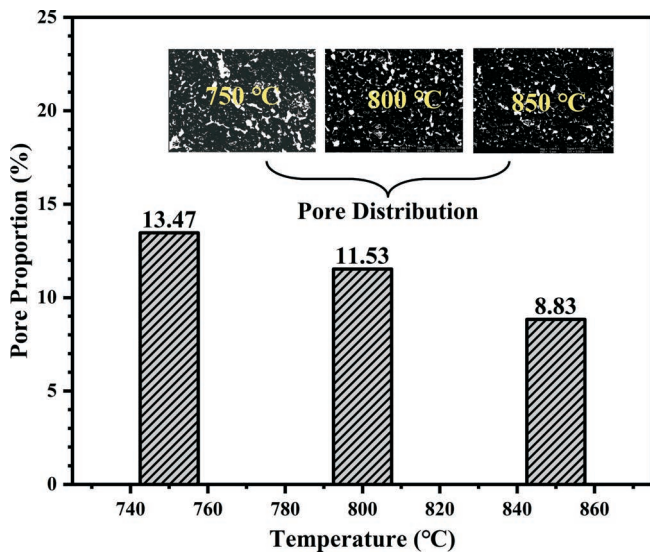


Fig. 9: The relationship between the porosity of the Cu metal film and temperature.

Fig. 9 illustrates the changes in pore ratio on the surface of the Cu film as a function of increasing temperature. The white dots depicted in the figure represent the pores present in the Cu film. It is evident that as the temperature increases, there is a more pronounced melting of the glass phase, resulting in the filling of the pores located between the network structures. Consequently, the number of surface pores decreases, causing a continuous decrease in the overall pore ratio. When compared to the Al film, it can be observed that the variations in pore ratio for the Cu film are relatively smaller. Specifically, as the temperature rises from 750 °C to 850 °C, the pore ratio only decreases from approximately 13.5 % to 9 %. This discrepancy

stems from the fact that the sintering temperature of the Cu film is more than 200 °C higher than that of the Al film. As a result, the melting of the glass phase becomes more sufficient in the Cu film. Moreover, the metallic film employed in the low-temperature co-fired ceramic (LTCC) system comprises a network structure formed through the contact of metal particles. This arrangement allows for a more effective filling of the glass during the melting and flow processes.

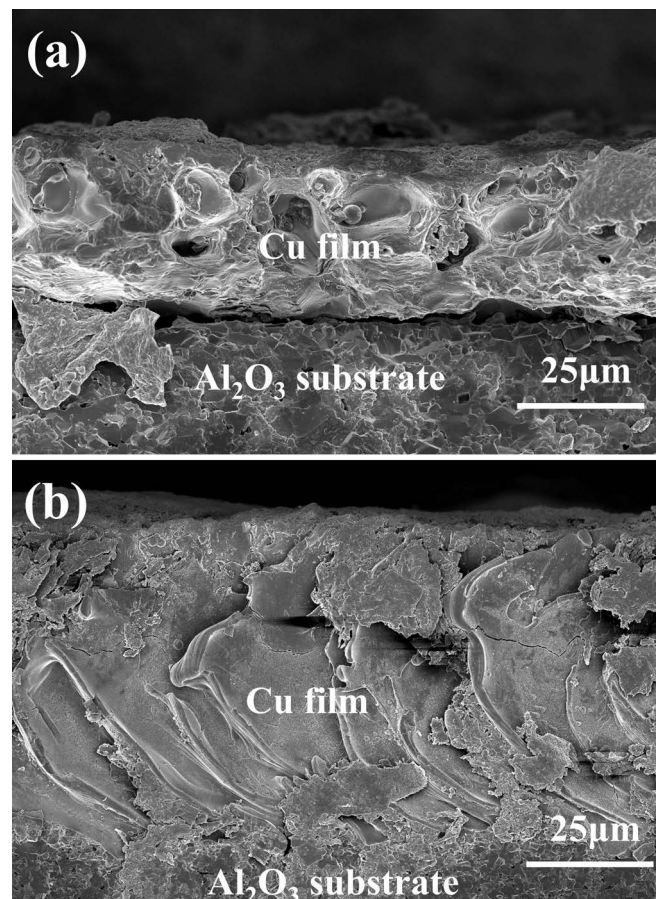


Fig. 10: SEM images of cross-sections of Cu film sintered at different temperatures: (a) 800 °C; (b) 850 °C.

Fig. 10 presents the interface structure of the Cu film sintered at different temperatures. The figure reveals the distribution of the glass phase within the Cu film. Upon creating a brittle fracture section, crystals detach from the structure, leaving behind voids or holes. At 800 °C, these voids become more pronounced, and there are noticeable

gaps observed in the interface layer. The presence of these gaps considerably impacts the adhesion of the metal layer. As the temperature reaches 850 °C, large crystals begin to form at the interface. Subsequently, during the sintering process, rapid grain growth occurs, leading to a substantial reduction in interface voids and the elimination of gaps in the connection between the Cu film and the ceramic substrate. This phenomenon has a positive influence on enhancing performance.

In general, as the sintering temperature rises, the presence of voids in the fracture section of the Cu film gradually diminishes, and crystallization becomes more evident, leading to a denser surface sintering. Consequently, as depicted in Fig. 11, the adhesion strength of the Cu film exhibits an upward trend, increasing from 3.45 to 32.1 N/mm². Similarly, the surface square resistance value experiences a continuous decline, decreasing from 73.59 to 50.34 mΩ·mm⁻².

(4) Sintering behavior mechanism of Ag paste, Al paste, and Cu paste on Al₂O₃ substrates

Before sintering, the metal powder and glass powder in the metal paste are uniformly distributed in the organic solvents. However, different metal pastes exhibit distinct sintering behavior mechanisms, as shown in Fig. 12. Both types of pastes form a network structure, but their composition differs. Noble metals, such as silver, experience continuous growth during the sintering process. The glass phase is distributed between the metal particles, forming a network structure. On the other hand, in base metal sys-

tems like aluminum and copper, metals tend to form a network structure with a pore structure in the center.

Noble metals have a dense structure, resulting in lower surface resistance and higher adhesion on ceramic substrates compared to base metal systems. However, base metals have the advantage of lower manufacturing costs compared to noble metals and they possess unique strengths in certain fields. Therefore, when preparing multilayer circuits, the selection of metal paste should be based on specific requirements and considerations.

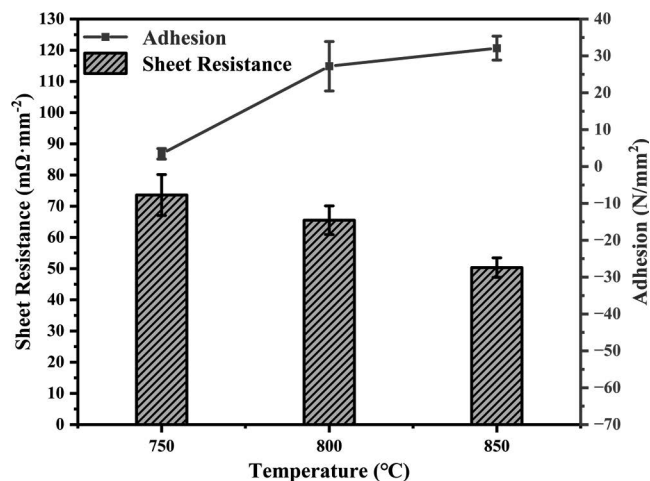


Fig. 11: Changes in surface resistance and adhesion of Cu metal film with sintering temperature.

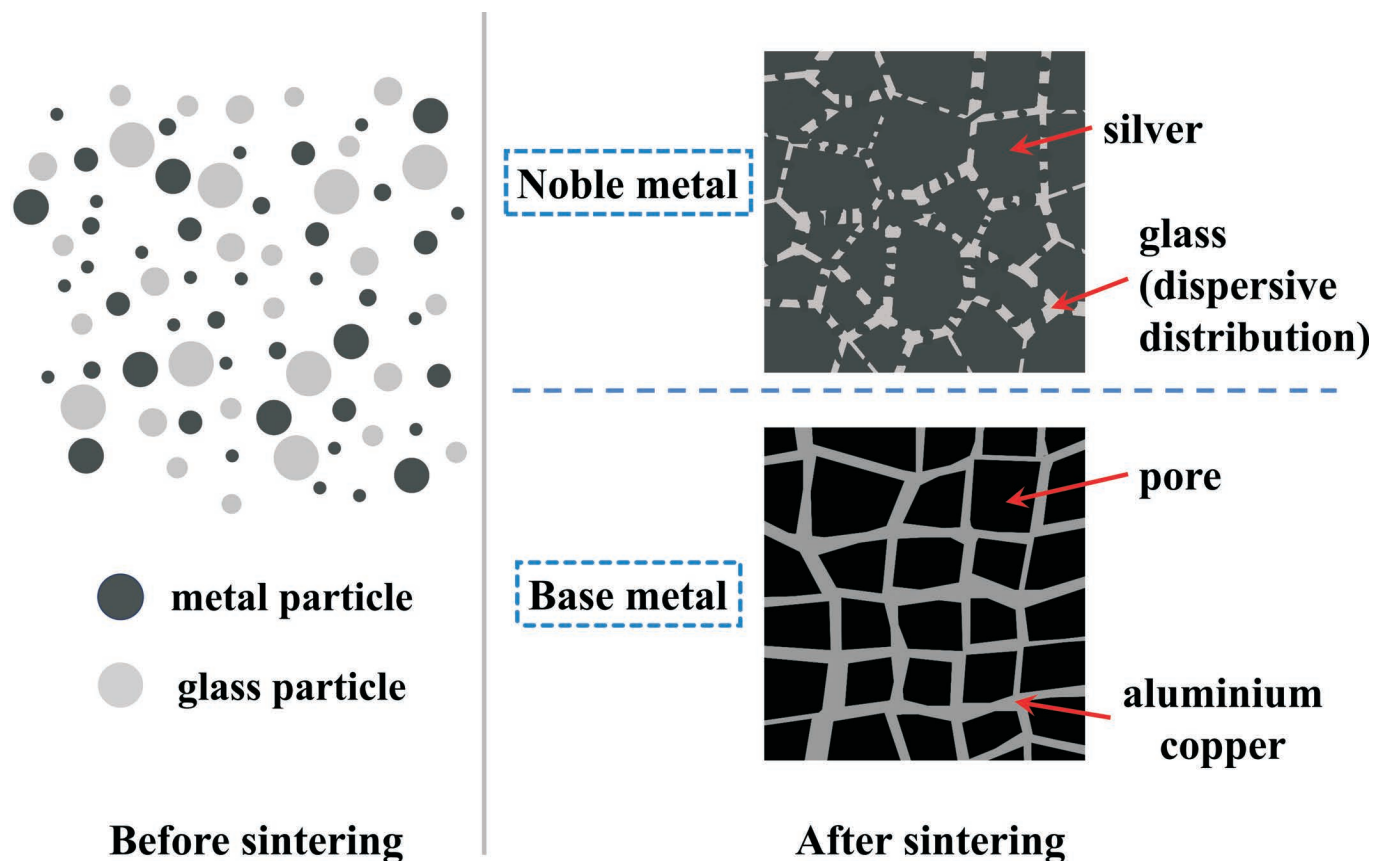


Fig. 12: Sintering behavior mechanism of metal pastes.

IV. Conclusions

This paper aims to test and evaluate the morphology and performance of commonly used silver, aluminum, and copper metal pastes after sintering at various temperatures. The objective is to provide guidance in selecting suitable metal pastes for the fabrication of multilayer thick-film substrates. From the conducting of surface and interface observations, as well as mechanical and electrical performance testing, the following key conclusions have been derived.

The mechanical performance of the metal film formed by the metal paste predominantly relies on the characteristics of the interface structure. The presence of voids or holes within the interface leads to a decrease in mechanical performance. The occurrence of these voids is closely associated with the melting and flow behavior of the glass phase present in the paste. The electrical performance of the metal film is strongly influenced by the surface morphology. Direct contact between the metal particles on the surface facilitates excellent conductivity, while the formation of a network-like structure through the interconnection of surface metal particles results in inferior conductivity.

In general, the optimal sintering temperatures for obtaining the best mechanical and electrical performance using Ag, Al, and Cu pastes are consistent. For Ag, Al, and Cu, the optimal sintering temperatures are determined to be 850 °C, 550 °C, and 850 °C, respectively.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Jun Fang, Tianhong Chen, Yuhong Jiao, Zhen Zhang, Sirui Dong and Zhanjie Huang. The first draft of the manuscript was written by Jun Fang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability Statement

Data available in a publicly accessible repository.

Conflicts of Interest

The authors declare no conflict of interest.

References

- Divya, P., Lee, W.H.: Fabrication of a flexible RFID antenna by using the novel environmentally friendly additive process, *Int. J. Antennas Propag.*, **2023**, 1–12, (2023).
- Väätäjä, M., Kähäri, H., Ohenoja, K., Juuti, J., Jantunen, H.: Direct integration of dielectric all-ceramic thick films on a polymer substrate using room temperature fabrication, *J. Eur. Ceram. Soc.*, **40**, 3984–3988, (2020).
- Zhou, Y.Y., Tong, H., Liu, Y.J., Yuan, S.L., Yuan X.: Rheological effect on screen-printed morphology of thick film silver paste metallization, *J. Mater. Sci. Mater. Electron.*, **28**, 5548–5553, (2017).
- Yüce, C., König, M., Willenbacher, N.: Rheology and screen-printing performance of model silver pastes for metallization of si-solar cells, *Coatings*, **8**, 406, (2018).
- Li, D.Y., Yu J.C., Zheng, X., Yue C.X., Ding, L., Liu Y.: Exploration of tunable, low-depletion novel resistor paste system based on molybdenum-based functional phase modulation, *J. Mater. Sci. Mater. Electron.*, **34**, 1957, (2023).
- Loponov, A.N., Lozinskyy, N.S., Moroz, Ya.A.: Chemical processes accompanying the formation of modified ruthenium resistors and their functional properties, *Russ. Chem. Bull.*, **69**, 1724–1730, (2020).
- Reinhardt, K., Hofmann, N., Eberstein, M.: The importance of shear thinning, thixotropic and viscoelastic properties of thick film pastes to predict effects on printing performance, *2017 21st Eur. Microelectron. Packag. Conf. EMPC Exhib.*, 1–7, (2017).
- Lorenz, M., Travitzky, N., Rambo, C.R.: Effect of processing parameters on in situ screen printing-assisted synthesis and electrical properties of Ti₃SiC₂-based structures, *J. Adv. Ceram.*, **10**, 129–138, (2021).
- Samanta, K.K.: Advanced multilayer thick-film technology and TFMS, CPW, and SIW up to 180 GHz for cost-effective ceramic-based circuits and modules, *IET Microw. Antennas Propag.*, **12**, 1064–1071, (2018).
- Samanta, K.K.: Multilayer thick-film and next generation cost-effective millimetre-wave SoP circuit and system integration techniques, *2015 IEEE MTT- Int. Microw. RF Conf. IMaRC*, 393–395, (2015).
- Markowski, P.M.: Multilayer thick-film thermoelectric micro-generator based on LTCC technology, *Microelectron. Int.*, **33**, 155–161, (2016).
- Reinhardt, K., Koerner, S., Partsch, U.: Thick film paste systems for multifunctional copper power modules. in *CIPS 2020; 11th International Conference on Integrated Power Electronics Systems* 1–7, (2020).
- Tang, J.Y., Mak, C.H.H., Tam, S.K., Ng, K.M.: Formulation of a paste for copper thick film, *J. Nanoparticle Res.*, **23**, 166, (2021).
- Ueyama, R., Ueyama, T., Koumoto, K., Kuribayashi, K.: Dependence of sintered electrode ni paste on dispersed ni paste and ni powder properties, *J. Ceram. Soc. Jpn.*, **109**, 447–452, (2001).
- Hlina, J., Reboun, J., Hamacek, A.: Characterization of thick film pastes for aluminum nitride substrates, *2021 44th Int. Spring Semin. Electron. Technol. ISSE*, 1–4, (2021).
- Wang, M.Z., Dong, H.L., Mao, X.B., Wang, W.F., Xiong J.J., Tan, Q.L.: Thermally matched multilayer ceramic composite insulating layers for high-temperature thick/thin-film sensors on nickel-based superalloy, *Ceram. Int.*, **50**, 3852–3860, (2024).
- Telnikov, Ye. Ya., Chernyshyn, O.G., Nedbailo, O.M., Khmara, I.O.: Structure and mechanism of electrical conductivity of resistive compositions for thick-film metal-ceramic heating elements, *Керамика Наука Жизнь*, 23–28, (2019).
- Hlina, J., Reboun, J., Hamacek, A.: Behaviour of printed resistors compatible with thick film copper technology. in *2022 IEEE 9th Electronics System-Integration Technology Conference (ESTC)*, 228–232, (2022).
- Hlina, J., Reboun, J., Hamacek, A.: Study of copper-nickel nanoparticle resistive ink compatible with printed copper films for power electronics applications, *Materials*, **14**, 7039, (2021).
- Jiang, Q., Li, J.H., Li, A., Zhou, D.D., Zeng, H.D.: Surface hydroxyl modification for silicate-stabilized low-melting glassy tellurite adhesive enabling low resistance of silver conductive paste, *J. Non-Cryst. Solids*, **598**, 121959, (2022).
- Buck, T., Peng, Z.W., Dhamrin, M.: Study on Al metal paste contacting n+ doped Si surfaces for industrial solar cell appli-

- cation. in *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, 1540–1542, (2020).
- 22 Lee, W.H., Puteri, N.G., Kuo, C.R.: Thick film of modified aluminum with conductivity similar to silver, *MRS Commun.*, **13**, 473–479, (2023).
 - 23 Joonwichien, S., Moriya, M., Utsunomiya, S., Kida, Y., Shirasawa, K., Takato, H.: Mechanism of metallization-induced losses in the rear-side of fully screen-printed p-type PERC solar cells, *IEEE J. Photovolt.*, **10**, 407–416, (2020).
 - 24 Hlina, J., Reboun, J., Hamacek, A.: Study of copper thick film metallization on aluminum nitride, *Scr. Mater.*, **176**, 23–27, (2020).
 - 25 Fang, J., Fu, R.L., Gu, X.G., Zhang, X.Y., Li, G.J.: The synthesis of multi-layer silver, copper and aluminum thick films on alumina substrates using a screen-printing method, *J. Ceram. Sci. Technol.*, **11**, 103–110, (2020).
 - 26 Reboun, J., Hlina, J., Totzauer, P., Hamacek, A.: Effect of copper- and silver-based films on alumina substrate electrical properties, *Ceram. Int.*, **44**, 3497–3500, (2018).
 - 27 Liu, Y.C., Zhang L.Y., Yu, X.L., Li, W.C., Li, J.P., Gan, G.Y.: The silver paste containing ZnO-B₂O₃-SiO₂ glass sintered at high temperature with low solid content formed high performance conductive thick film on MgTiO₃ microwave ceramics, *Mater. Res. Express*, **10**, 045201, (2023).
 - 28 Liu, T.X., Wan, J., You, Y.C., Zhuo, N.Z., Wang H.B.: Research of microscale silver particle paste on Al₂O₃, pre-dried dielectric layer and pre-fired dielectric layer substrate by a co-firing process, *Mater. Res. Express*, **7**, 046303, (2020).
 - 29 Sun, Q., Qi, Y., Li, M.Y., Xu, H.B., Li, Y.F.: Synthesis of PVZ glass and its improvement on mechanical and electrical properties of low temperature sintered silver paste, *J. Mater. Sci. Mater. Electron.*, **31**, 8086–8098, (2020).
 - 30 Gao, Y.J., Feng, J.J., Liu, F., Liu, Z.F.: Effects of organic vehicle on the rheological and screen-printing characteristics of silver paste for LTCC thick film electrodes, *Materials*, **15**, 1953, (2022).
 - 31 Ji, S.Y., Shi, Y., Chen, C., Zhang, C.Y., Hu, C.C., Xie, J.J.: Investigation of interfacial properties of Cu/AlN composite ceramic substrates derived from copper paste containing TeO₂-V₂O₅-CuO glass frit, *J. Mater. Sci. Mater. Electron.*, **33**, 13339–13351, (2022).
 - 32 Wang, J.Y., Lin, Y.X., Wu, C.Y., et al.: Effect of mixing glass frits on electrical property and microstructure of sintered Cu conductive thick film, *J. Am. Ceram. Soc.*, **104**, 1707–1715, (2021).
 - 33 Naderi-Samani, H., Razavi, R.S., Mozaffarinia, R.: The effects of complex agent and sintering temperature on conductive copper complex paste, *Heliyon*, **8**, e12624, (2022).