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Electrical and water resistance properties of conductive paste based on gold/silver composites

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Abstract

This study aimed to investigate the effects of a corrosive environment on both the electrical and the water resistance properties of conductive paste based on gold/silver composites. The conductive paste was prepared by incorporating silver and gold powders, polyvinyl acetate, polyvinyl chloride as adhesive components, and methyl isobutyl ketone as a diluent. The gold/silver composite powder was prepared with different mass ratios of gold and silver. The paste was coated on a substrate and heated at 80°C to form the conductive paste film. Characterizations of conductive paste were performed by using FT-IR spectroscopy, electrometry, cyclic voltammetry, and contact angle measurements. Thus, the conductive paste films were tested under two conditions: the absence and the presence of exposure to nitric acid vapor. The results showed that the resistance and the contact angle of the conductive paste were more stable after exposure to nitric acid vapor, particularly in samples of higher gold content. Furthermore, the electrochemical behavior of the conductive paste with gold content remains unchanged after exposure to nitric acid vapor. Results suggest that gold has properties in terms of stability, resistance to oxidation, and maintaining surface characteristics, making it a preferable component for applications requiring resistance to corrosive environments.

1. Introduction

Conductive pastes, including gold paste and silver paste, have been widely used in various industries for applications such as electronic circuitry [1], printed electronics [2-7], solar cells [8,9], and sensors [10-12]. The incorporation of micro-scale particles in conductive pastes, including gold, silver, and other conductive materials, offers improved electrical conductivity, lower processing temperatures, and enhanced adhesion to various substrates, including glass, ceramics, metals, and flexible substrates [13-15]. These advancements have led to their widespread use in applications. Conductive silver paste offers several advantages, including excellent electrical conductivity, good adhesion to various substrates, low resistance, and high thermal conductivity [16,17]. However, conductive silver paste has some disadvantages; silver can oxidize over time, especially when exposed to air, moisture, or certain environmental conditions. This oxidation can lead to increased resistance and degradation of electrical conductivity in the long term. Additionally, conductive silver paste often requires higher sintering temperatures compared to other conductive pastes. This can be a limitation in applications with heat-sensitive substrates or in situations where low-temperature processing is desired. Interestingly, conductive gold paste has several advantages that make it a viable alternative to conductive silver paste in certain applications, including highly resistant to corrosion and oxidation, and excellent electrical conductivity make it highly desirable for applications where high conductivity and low resistance are critical, such as in high-frequency circuits and sensitive electronics, and low contact resistance allowing for efficient power transmission and minimizing signal losses at contact interfaces. While gold itself is generally more expensive than silver, the cost of manufacturing conductive gold paste is higher compared to conductive silver paste. Thus, gold/silver composites can be a viable option to balance both electrical properties and cost considerations.

Conductive pastes typically consist of three main components: metal powder or conductive powder, polymer adhesive, and a diluent. These components work together to provide the desired electrical and mechanical properties of the conductive paste. Typically, conductive pastes consist of the following materials. (1) The metal powder or other conductive powder is the conductive component of the paste and provides electrical conductivity. Commonly used metals in conductive pastes include silver, gold, copper, nickel, and aluminum [17-19]. Additionally, graphite powder is another conductive material that is often used in combination with metals or as a standalone conductive component in conductive pastes. These powder particles are typically micro- or nano-scale in size to enhance conductivity and allow for better adhesion to substrates [6,16,17,20,21]. (2) The polymer adhesive

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serves as a binder that holds the metal powder particles together and facilitates their adhesion to the substrate. The polymer adhesive also contributes to the mechanical strength and stability of the paste. Polymers such as acrylics, epoxies, polyurethanes, or other specialized resins are commonly used as adhesive components [22,23]. (3) The diluent or solvent is a liquid component that helps control the viscosity, workability, and application properties of the conductive paste. It allows the paste to be easily dispensed, spread, or screen printed onto the desired substrate. The choice of diluent depends on the specific paste formulation and can be organic solvents, water, or a mixture of solvents. Examples of diluents commonly used in conductive are acetone, methyl ethyl ketone, isopropyl alcohol, ethyl acetate, N-methyl-2-pyrrolidone, and methyl isobutyl ketone.

This study aimed to investigate the effect of a corrosive environment, specifically nitric acid vapor, on both the electrical properties and water resistance properties of conductive paste based on gold/silver composites. We utilize nitric acid vapor to represent corrosive agents or environments. Nitric acid is renowned for its corrosive nature, particularly towards metals. When the conductive paste contains metal components, exposure to nitric acid vapor may prompt corrosion, resulting in alterations to both the electrochemical and water resistance properties. The conductive paste was prepared by incorporating silver and gold powders as electron carriers, polyvinyl acetate, polyvinyl chloride as adhesive components and methyl isobuthyl ketone as a diluent. The conductive paste was prepared by mixing the gold/silver composite powder with a resin in a specified mass ratio. Polyvinyl acetate and polyvinyl chloride are two types of polymer adhesives used in various industries, including the formulation of conductive pastes. Polyvinyl acetate is a versatile polymer adhesive that is widely used in various applications, including adhesives, coatings, and emulsions due to its excellent adhesive properties, good bonding strength, and flexibility [24-26]. Polyvinyl chloride is a thermoplastic polymer that is widely used in various industries due to its excellent chemical resistance, good adhesion to substrates, mechanical stability, and moisture resistance, making it suitable for outdoor or harsh environment applications [27]. Methyl isobuthyl ketone is an organic solvent that is frequently employed as a diluent in conductive paste formulations and widely used as a solvent for vinyl, epoxy, and acrylic resin production [28]. Methyl isobuthyl ketone has good solvating properties and a moderate evaporation rate, making it suitable for controlling the viscosity and drying characteristics of the paste. The microstructures of the gold and silver powders were characterized using scanning electron microscopy (SEM). The functional groups and chemical bonds of the conductive paste were characterized using Fourier Transform Infrared (FT-IR) spectroscopy. An electrometry and cyclic voltammetry (CV) were carried out to observe resistance and redox characteristics, respectively. Water resistance property was performed using contact angle measurement.

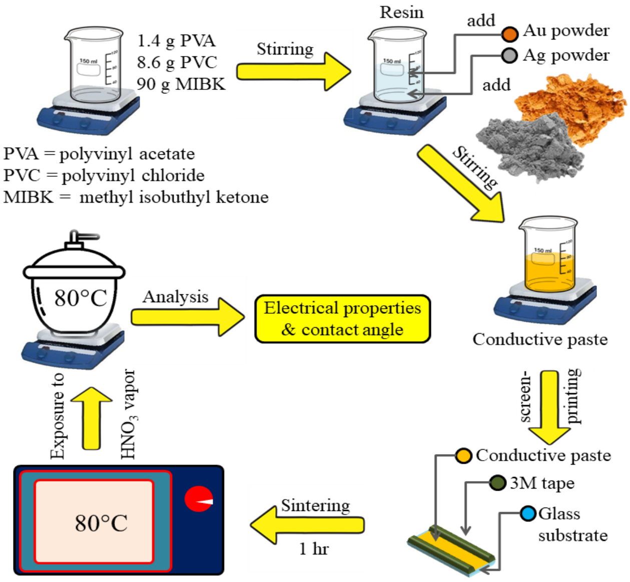

Figure 1. Schematic diagram of the synthesis process of conductive paste and electrical properties and contact angle analysis.

2. Experimental

2.1 The conductive paste synthesis

The conductive paste based on gold/silver composites was prepared by incorporating gold/silver composites powder, and polyvinyl acetate, polyvinyl chloride as adhesive components and methyl isobuthyl ketone as a diluent. Schematic diagram of the synthesis process of conductive paste was showed Figure 1. The gold/silver composites powder was prepared by incorporating silver powders with an average lateral size of approximately 20 µm and gold powder with an average lateral size of about 5 µm. The gold/silver composites powders acted as electron carriers in the paste formulation. To obtain the gold and silver powders, gold and silver foils were milled using ultrasonic wave-assisted vibrating liquid media, as described in reference [29]. This milling process effectively reduced the foils into fine powders. To prepare the 10 wt% resin, a specific amount of polyvinyl acetate, polyvinyl chloride, and methyl isobuthyl ketone were combined. In this case, 1.4 g of polyvinyl acetate, 8.6 g of polyvinyl chloride, and 90 g of methyl isobuthyl ketone were added into a glass bottle. The bottle was then closed with a lid to prevent any evaporation or contamination during the stirring process. Once all the components were added to the bottle, the mixture was stirred thoroughly until a clear solution was obtained. The stirring process ensures that the polyvinyl acetate, polyvinyl chloride, and methyl isobuthyl ketone are well-mixed and dissolved, resulting in a homogenous resin solution. This synthesized resin, consisting of polyvinyl acetate, polyvinyl chloride, and methyl isobuthyl ketone, serves as an adhesive component in the formulation of the conductive paste. The resin helps bind the gold and silver powders together, forming a cohesive paste with desirable adhesive properties. Following the preparation of the resin, the next step involved preparing the gold/silver composites powder. This was achieved by mixing gold powder with silver powder at various mass ratios. The mass ratios used in this study were 0:100, 25:75, 50:50, 75:25, and 100:0. To create the gold/silver composites powder, the gold powder and silver powder were combined in the desired mass ratios. For example, in the 25:75 ratio, 25% of the total mass would be gold powder, while 75% would be silver powder. Similarly, the other ratios were prepared accordingly. In the final step of the process, the conductive paste based on the gold/silver composites was prepared by mixing the gold/silver composites powder with the previously prepared resin. The mass ratio used for this mixing step was 30:70, which means that 30% of the total mass was the gold/silver composites powder, while 70% was the resin. To obtain the conductive paste, the mixing process was carried out under room temperature conditions. The mixture was stirred for 1 h to ensure thorough blending and to achieve a homogenous and viscous paste consistency. The stirring time of one hour allowed sufficient time for the particles to distribute evenly and ensure good interfacial contact between the conductive particles and the resin matrix.

2.2 Microstructural analysis

The microstructures of the gold and silver powders were analyzed using scanning electron microscopy (SEM; JEOL, JSM-6610 LV). SEM allows for high-resolution imaging of the morphology of the particles, providing information about their size, and shape. Additionally, the metal coordination polymers formed between the gold/silver composites powder and the resin were characterized using Fourier Transform Infrared (FT-IR) spectroscopy (Thermo scientific NicoletTMiS). FT-IR spectroscopy is a technique that provides information about the functional groups and chemical bonds present. For the FT-IR analysis, the spectra were observed in the range of 500 cm^{-1} to 4000 cm^{-1}, which is a typical range for identifying various chemical bonds and vibrations [30].

2.3 The electrical properties analysis

To understand the electrical behavior of the conductive paste based on gold/silver composites, the changes in resistance and the redox characteristics of these pastes after exposure to nitric acid vapor were investigated. Resistance measurements were used to evaluate the electrical quantities of the conductive paste. The resistance value indicates the ease or difficulty of electric current flow through the material. Based on their resistance values, conductive materials can be classified into three categories: resistance values in the order of 1 Ω and below are typically classified as low resistance or resistance values ranging from 1 Ω to 100 Ω are generally classified as medium resistances or resistance values on the order of 100 kΩ and above are commonly classified as high resistances. In the present study, the conductive paste based on gold/silver composites showed resistance values ranging from 1 Ω to 100 Ω. The resistance measurement of the conductive paste was carried out using an ohmmeter, which is an appropriate method for this purpose. The ohmmeter method is known for its moderate accuracy, simplicity, and ease of use in resistance measurement. To measure the resistance, the conductive paste based on gold/silver composites was applied onto a glass substrate using a screen-printing technique. Schematic diagram of the preparation of conductive paste film and electrical properties analysis was showed Figure 1. A uniform film with a controlled thickness of approximately 60 μm was achieved by using a tap spacer (3M magic tape 810). After coating the conductive paste onto the glass substrate, the next step involved the sintering process. The conductive paste coated substrate was subjected to a sintering process at a temperature of 80°C for duration of 1 h. This sintering step is crucial as it promotes the fusion and solidification of the conductive particles within the paste, resulting in the formation of a continuous conductive film. After the conductive films were formed on the glass substrate, they were subjected to exposure to nitric acid vapor for various durations. The exposure times ranged from 0 min to 25 min, with intervals of 5 min (i.e., 0, 5, 10, 15, 20, and 25 min). To generate the nitric acid vapor, a glass chamber was utilized. Inside the chamber, a 70% concentration nitric acid solution (specifically, RCI Labscan, 70%) was evaporated. The evaporation process took place at a temperature of 80°C, allowing the nitric acid to vaporize and fill the chamber with the vapor. By exposing the conductive films to the nitric acid vapor for varying durations, we aimed to investigate the effects of the vapor on the electrical behavior of the films. This experimental setup allowed them to simulate the exposure of the conductive films to a corrosive environment and evaluate their resistance changes. In the final step of the experiment, the two-wire resistance measurement of the conductive film was conducted using an electrometer, specifically the Keithley 6517A model. The two-wire method involves applying a known voltage across the film and measuring the resulting current using two probes with a spacing distance of 1 mm. This measurement allows for the determination of the resistance of the conductive film.

The redox characteristics of the conductive film were evaluated using cyclic voltammetry (CV) at room temperature. The CV measurements were performed using an Autolab PGSTAT204 electrochemical station (Metrohm). In the redox characteristics analysis, ten different conditions were observed including: conductive paste based on gold/silver composites with different mass ratio of gold and silver was 0:100, 25:75, 50:50, 75:25 and 100:0, and five conditions for conductive paste based on gold/silver composites after exposure to nitric acid vapor for a prolonged time of 25 min (different mass ratio of gold and silver was 0:100, 25:75, 50:50, 75:25 and 100:0). Cyclic voltammetry involves applying a voltage waveform and monitoring the resulting current response. The potential range for the measurement was set from -1.0 V to 1.0 V, and the potential scan rate was 0.1 $V{\cdot}s^{-1}$. In the study, three different types of electrodes were used: conductive paste coated carbon rod, Pt and Ag/AgCl were used as the working, counter, and reference electrodes, respectively. CV curves typically exhibit two distinct regions: the anodic region (positive current values) and the cathodic region (negative current values). These regions correspond to the oxidation and reduction reactions, respectively, occurring at the working electrode surface. A 0.1M KCl (99.5%, Loba Chemie) was used as an electrolyte. A KCl electrolyte solution was used to provide an ionic medium for the electrochemical reactions to occur during the cyclic voltammetry measurements [31].

2.4 The contact angle analysis

To evaluate the water resistance property of the conductive paste based on gold/silver composites, contact angle measurements were performed. The contact angle is a measure of the angle formed between the liquid droplet (15 μL, distilled water) and the solid surface (the conductive film), and the contact angle was measured for duration of 120 s. The contact angle measurement provides information about the wetting behavior of the water droplet on the surface of the conductive film, which can indicate the water resistance characteristics [30]. Additionally, the conductive films were exposed to nitric acid vapor for different durations of 0, 5, 10, 15, 20, and 25 min. The nitric acid vapor was prepared using the previous procedure mentioned in the experiment. Schematic diagram of the preparation of conductive paste film and contact angle analysis was showed Figure 1. We aimed to investigate the effect of a corrosive environment, specifically nitric acid vapor, on the water resistance properties of the conductive films based on gold/silver composites. The exposure to nitric acid vapor can simulate a corrosive environment and provide insights into the durability and stability of the conductive films under harsh conditions. By studying the changes in contact angle measurements after exposure to nitric acid vapor for different durations, we can assess the impact of the corrosive environment on the water resistance properties of the films. This information is valuable for understanding the performance and potential applications of the conductive paste in real-world conditions where exposure to moisture or corrosive substances may occur.

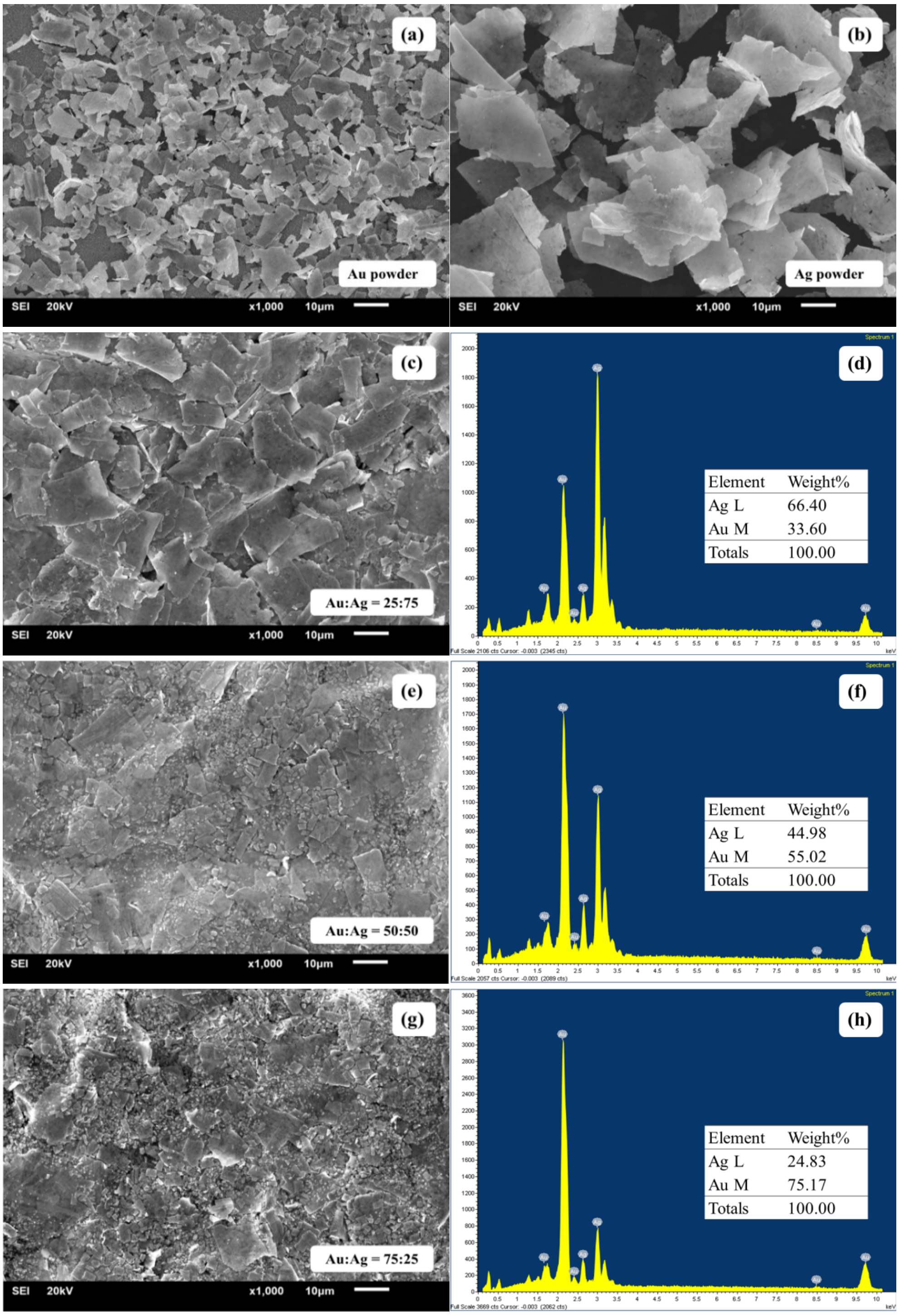

Figure 2. SEM images of gold powders (a), and silver powders (b), and conductive paste based on gold/silver composites prepared with different mass ratio of gold and silver including: 25:75 (c), 50:50 (e), and 75:25(g). EDS spectra of conductive paste with different mass ratio of gold and silver including: 25:75 (d), 50:50 (f), and 75:25(h).

3. Results and discussion

Figure 2 presents typical SEM images of gold and silver powders and conductive paste based on gold/silver composites. The gold and silver powders were prepared by milling gold and silver foils using ultrasonic wave-assisted vibrating liquid media. The analysis revealed that both gold and silver powders exhibited a micro-flake morphology, with an average lateral size of approximately 5 µm and 20 µm, respectively, which depicted in Figure 2(a) and Figure 2(b). Notably, gold powders displayed a smaller lateral size compared to silver powders, which can be attributed to gold being the most malleable of all metals. The conductive pastes depicted in Figure 2(c), Figure 2(e), and Figure 2(g) still preserves a flake morphology separation with both silver and gold flakes in contact. Additionally, an average lateral size of the metal composites was no significant melting or fusion of gold and silver into a new product. This finding implies that the conductive paste retained the distinctive characteristics of both gold and silver, maintaining their original sizes within the composite.

Figure 3(a) displays the FT-IR spectra of polyvinyl acetate, polyvinyl chloride, and resin. The spectra of polyvinyl acetate exhibited peaks corresponding to C–H stretching at approximately 2969 cm^{-1} and 2920 cm^{-1}, C=O stretching at 1728 cm^{-1}, C–H bending at 1431 cm^{-1} and 1369 cm^{-1}, C–O and C–C stretching at around 1227, 1120, 1018, and 949 cm^{-1} and CH_2 rocking at 794, 631, and 602 cm^{-1}. These results are indicative of the vibrational modes of the vinyl acetate molecule [32]. In the case of polyvinyl chloride, the FT-IR spectra displayed peaks associated with C–H stretching from CH–Cl at around 2960 cm^{-1}, C–H stretching from CH_2 at approximately 2900 cm^{-1}. Additionally, the spectrum revealed the presence of oxygenated structures within the polyvinyl chloride chain at around 1713 cm^{-1}. Other observed peaks included CH_2 wagging at approximately 1459 and 1426 cm^{-1}, CH_2 deformation at around 1332 cm^{-1}, C-C at around 1088 cm^{-1}, CH_2 rocking at around 957 cm^{-1}, and C–Cl stretching at approximately 691, 634, and 614 cm^{-1}. These peaks can be attributed to additives present in the polyvinyl chloride product [33]. The FT-IR spectra of the resin were acquired by combining the individual spectra of polyvinyl acetate and polyvinyl chloride. Importantly, no new peaks were observed in the combined spectrum, suggesting the absence of chemical interactions leading to the formation of new products. Similarly, Figure 3(b) showcases the FT-IR spectra of resin-silver (conductive paste based on silver) and resin-gold (conductive paste based on gold), which exhibited remarkable similarity to the FT-IR spectra of resin. This similarity implies the absence of chemical interactions among the composite components [34]. The slight changes in peak observed in the composites can be attributed to physical interactions between the resin and the metal [35].

In Figure 4, the resistance of the conductive paste based on gold/silver composites is depicted after exposure to nitric acid vapor for varying prolonged times. It was observed that the resistance of the conductive paste based on gold/silver composites showed a noticeable tendency to increase significantly after exposure to nitric acid vapor for varying prolonged times. However, the resistance of the conductive paste based solely on gold remained relatively unchanged. When comparing different ratios of gold and silver in the conductive paste, it was observed that the resistance increase after exposure to nitric acid vapor was more pronounced in the samples with higher silver content. In other words, a lower gold -to-silver ratio in the conductive paste resulted in a greater increase in resistance when exposed to nitric acid vapor. This result could be representative of a common oxidation of silver when exposed to air, moisture, or certain environmental conditions over time, leading to increased resistance and degradation of electrical conductivity.

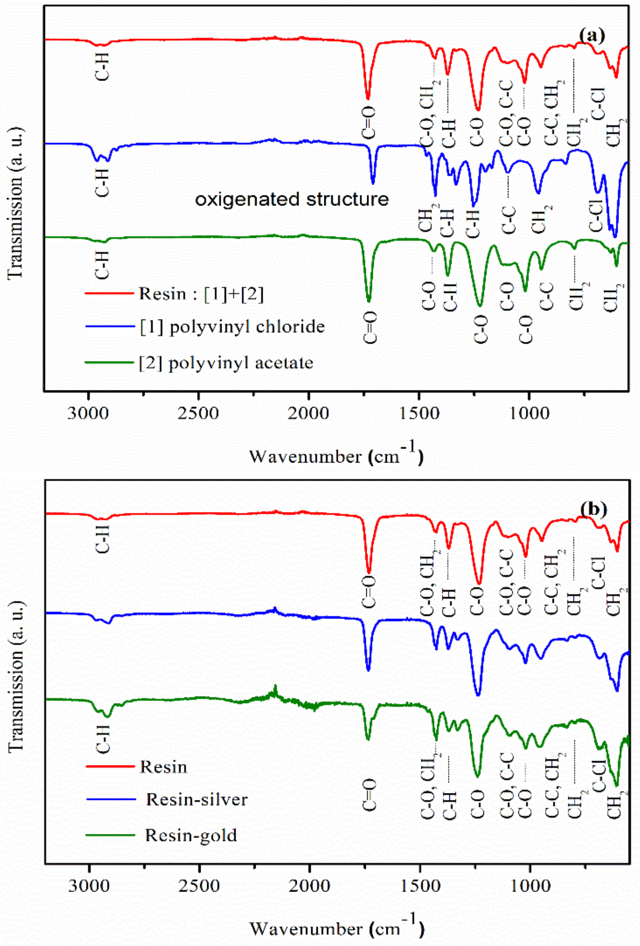

Figure 3. FT-IR spectra of polyvinyl acetate, polyvinyl chloride, and resin (a) and FT-IR spectra of resin-silver and resin-gold (b).

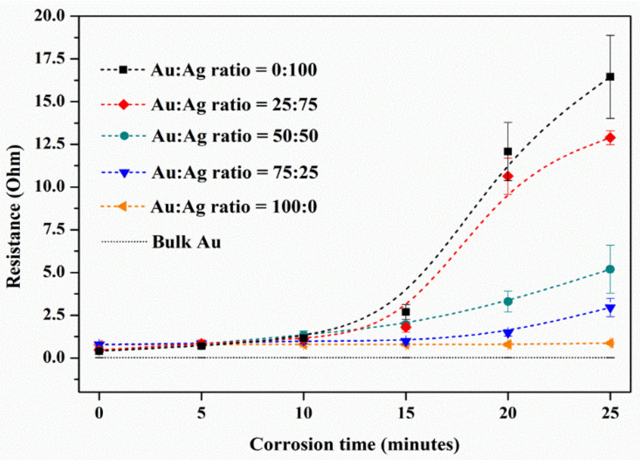

Figure 4. The resistance of the conductive paste based on gold/silver composites after exposure to nitric acid vapor for varying prolonged times.

The contact angle measurement was carried out to assess the water-resistant behavior of the conductive paste based on gold/silver composites. Figure 5 shows the results obtained from the measurements. The conductive films were exposed to nitric acid vapor for various durations ranging from 0 min to 25 min, and the contact angle was measured for a fixed duration of 120 s. In the absence of exposure to nitric acid vapor, the conductive paste based on gold/silver composites showed only slight changes in the contact angle over duration of 120 s. This indicates that the water-resistant behavior of the conductive paste remained relatively stable during this period. In present of exposure to nitric acid vapor, the contact angle of the conductive paste based on gold/silver composites with a mass ratio of gold and silver of 100:0 showed only slight changes. This suggests that the water-resistant behavior of this composition remained relatively unaffected by the exposure to nitric acid vapor. On the other hand, the conductive paste with a mass ratio of gold and silver of 0:100 exhibited drastic changes in the contact angle. This indicates a significant alteration in the water-resistant properties of the paste after exposure to nitric acid vapor, which contribute to the adhesive forces between the liquid and solid, likely underwent considerable alteration due to the exposure to nitric acid vapor. These results may in agreement to the creation of the polar components [36].

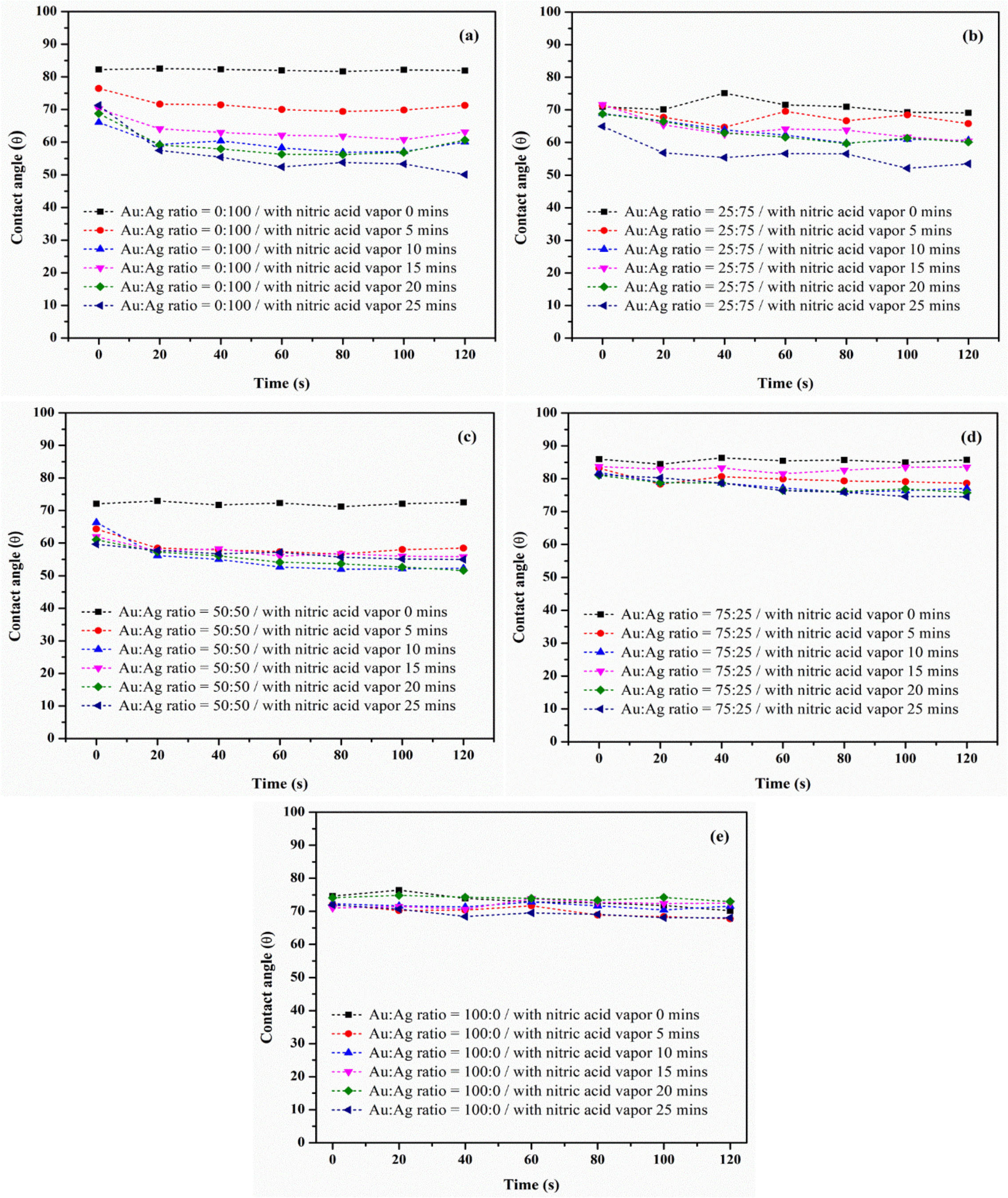

Figure 5. The contact angle of the conductive paste based on gold/silver composites after exposure to nitric acid vapor for varying prolonged times. Conductive paste based on gold/silver composites prepared with different mass ratio of gold and silver including: 0:100 (a), 25:75 (b), 50:50 (c), 75:25 (d), and 100:0 (e).

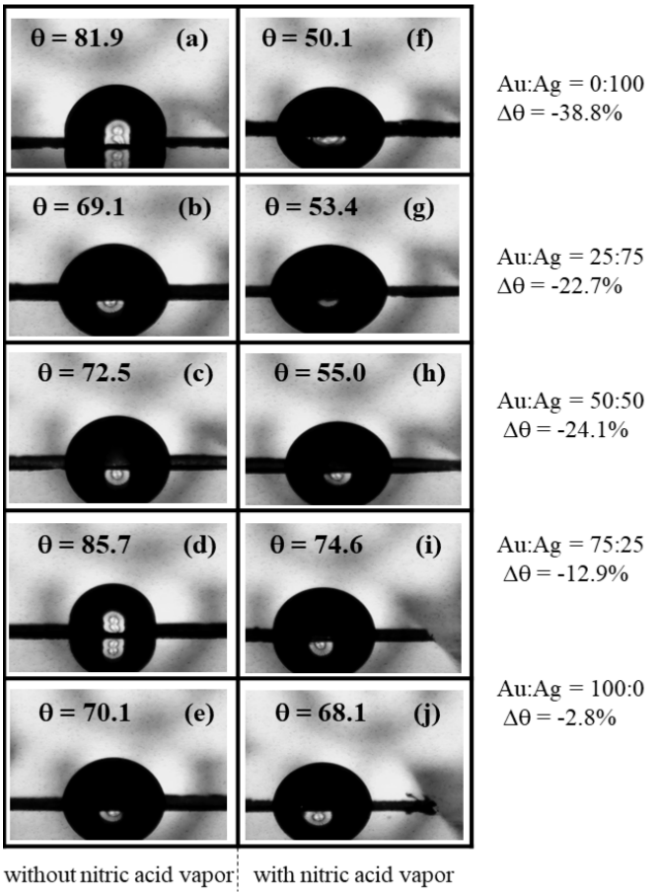

Figure 6. The contact angle of the conductive paste based on gold/silver composites under two conditions: in the absence of exposure to nitric acid vapor and in the presence of exposure to nitric acid vapor for a duration of 25 min.

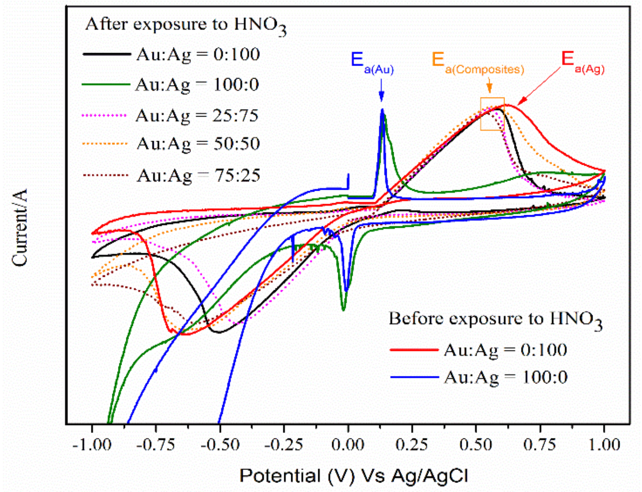

Figure 7. The cyclic voltammetry measurements of the conductive paste with different mass ratio of gold and silver. The measurements were observed under two conditions: before exposure to nitric acid vapor and after exposure to nitric acid vapor for duration of 25 minutes.

Figure 6 illustrates the contact angle of the conductive paste based on gold/silver composites under two conditions: in the absence of exposure to nitric acid vapor and in the presence of exposure to nitric acid vapor for a duration of 25 min. It seems that an alteration in contact angle decreased with an increase in the gold composition of the conductive paste. It suggests that a higher gold content in the composite has a positive effect on maintaining the water-resistant properties of the paste after exposure to nitric acid vapor. This trend suggests that the presence of gold in the composite plays a role in preserving the surface properties and preventing significant changes in the water-resistant behavior of the conductive paste when exposed to nitric acid vapor, which may be attributed to the specific properties of gold, such as its chemical stability and resistance to oxidation.

To gain a deeper understanding of the electrical behavior of the conductive pastes, a specific aspect that was explored is the redox characteristics of these pastes after exposure to nitric acid vapor. Figure 7 illustrates the cyclic voltammetry measurements of the conductive paste with different mass ratio of gold and silver. These conductive pastes were prepared and tested two conditions: (1) before exposure to nitric acid vapor and (2) after exposure to nitric acid vapor for duration of 25 min. When the conductive paste based on gold/silver composites with a mass ratio of gold and silver of 100:0 (gold paste) was subjected to cyclic voltammetry, an anodic peak potential (E_a) was observed at approximately 0.13V compared to a reference electrode. This peak represents a specific electrochemical process involving the gold component in the conductive paste. Anodic peaks in cyclic voltammetry typically correspond to oxidation reactions, where a species loses electrons. In the case of gold, common oxidation states include Au (neutral gold) to Au$^+$ or Au^{3+}. When gold paste that exposure to nitric acid vapor was subjected to cyclic voltammetry, an anodic peak potential was still observed at around 0.13V. This suggests that the electrochemical behavior of the gold paste did not significantly change after exposure to nitric acid vapor for 25 min. In case of the conductive paste with a mass ratio of gold and silver of 0:100 (silver paste), an anodic peak potential (E_a) was observed at approximately 0.64V compared to a reference electrode, indicated a specific electrochemical process involving the silver component in the conductive paste. A common oxidation states include Ag (neutral silver) to Ag$^+$. When silver paste exposed to nitric acid vapor was subjected to cyclic voltammetry, an anodic peak potential significantly changed at around 0.58 V. The shift in the anodic peak potential could be associated with the oxidation of silver or silver-containing species, likely influenced by the corrosive nature of nitric acid. Accordingly, the exposure to nitric acid vapor is likely causing changes on the surface of the silver paste. In case of conductive paste with a mass ratio of gold and silver of 25:75, 50:50, and 75:25 exposed to nitric acid vapor, an anodic peak potential was still observed at around 0.58 V which similar to silver paste. This suggests that the electrochemical process responsible for this peak is likely related to the silver component. Accordingly, the exposure to nitric acid vapor is likely causing changes on the surface of the silver paste.

4. Conclusions

Gold and silver powders were prepared through milling gold and silver foils using ultrasonic wave-assisted vibrating liquid media. The gold and silver powders exhibited the micro-flake morphology. The FT-IR spectra provided information about the vibrational modes and functional groups present in each material. The composites (i.e., resin-gold, resin-silver) exhibited similarities to the FT-IR spectra of the respective resins, indicating the absence of chemical interactions between the resin and the metal. Additionally, the resistance of the conductive paste based on gold/silver composites was examined after exposure to nitric acid vapor. It was observed that the resistance of the conductive paste increased significantly over prolonged exposure, particularly in samples with higher silver content. This result could be representative of a common oxidation of silver when exposed to corrosive environments over time, leading to increased resistance and degradation of electrical conductivity. The water-resistant property of the conductive paste was also evaluated through contact angle measurements. The presence of gold in the composites helped maintain its water-resistant property after exposure to nitric acid vapor. This suggested that the presence of gold in the composite plays a role in preserving the surface properties and preventing significant changes in the water-resistant behavior of the conductive paste when exposed to nitric acid vapor, which may be attributed to the specific properties of gold, such as its chemical stability and resistance to oxidation. Finally, the electrochemical behavior of the conductive pastes was studied using cyclic voltammetry. The conductive paste based on gold exhibited stable redox characteristics and resistance to changes in electrochemical behavior after exposure to nitric acid vapor. In contrast, the conductive paste based on silver showed a shift in redox characteristics, indicating the corrosive nature of the environment. These findings suggest that gold has advantageous properties in terms of stability, resistance to oxidation, and maintaining surface characteristics, making it a preferable component in conductive pastes for applications requiring resistance to corrosive environments.

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