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RESEARCH ARTICLE

Quantification of Corrosion on Cu Wire Bonding on Ag-Plated Lead Frame in HCl for Automotive Electronic Application

S.A. Rosli[1], **A. Jalar**[1,2]*, **M.A. Bakar**[1]

[1]Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[2]Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

ABSTRACT - Copper (Cu) wire bonding has been widely used in automotive electronics as an interconnection technology. However, Cu wire bonding faces long-term reliability challenges due to corrosion, particularly when exposed to harsh environments. While the corrosion behavior and mechanisms of bulk-sized Cu metal are well studied, the corrosion behavior of submicron-sized Cu wire bonding in miniaturized components remains unclear. This study investigates the corrosion susceptibility of Cu wire with a 1 mil diameter, bonded to an Ag-plated leadframe in a small-outline transistor (SOT-23) package, commonly used in automotive electronics. The Cu wire bonds were subjected to varying concentrations of hydrochloric acid (HCl), specifically 3 M, 5 M, and 7 M, for exposure durations of 6, 12, and 18 hours. The samples were characterized using a field emission scanning electron microscope to observe the microstructure, and ImageJ software was used to quantify the corrosion of the Cu wire bonds. The findings show that the Cu wire bonding is susceptible to corrosion when exposed to high concentrations of HCl. The corrosion of the microstructure became more severe with increasing HCl concentration and exposure time. The affected area of the Cu wire bonding was 21% after 6 hours of exposure to 3 M HCl, increasing to 100% after 18 hours of exposure to 7 M HCl. This study reveals that the corrosion behavior of Cu wire bonding is a combination of selective and pitting-like corrosion, resulting in localized surface degradation rather than uniform corrosion. These findings provide valuable insights into the corrosion behavior of 1 mil Cu wire bonding in SOT-23 packages under highly corrosive environments.

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1. INTRODUCTION

Electrical interconnection in microelectronic packages is one of the important parts of the microelectronic industry, as it ensures the functionality of the electronic devices. There are a few chip interconnects in microelectronic packaging, such as flip chip bonding, wire bonding, and tape automated bonding (TAB) [1, 2]. The microelectronic packaging industry still uses the wire bonding technique as it has been the most cost-effective and flexible interconnect technology [3, 4]. It serves as the method to connect the die (integrated circuit) and lead frame. The lead frame provides electrical connection and mechanical support for the integrated circuit within the electronic package. Various types of wire bonding materials have been employed, such as gold (Au), silver (Ag), Au-coated Ag, Ag coated with aluminium (Al), and copper (Cu) [5, 6]. Due to its exceptional advantages, Au wire has historically been the preferred material for wire bonding in integrated circuit (IC) packages, including single outline transistor (SOT) packages. Au wire has outstanding resistance to oxidation and corrosion, high ductility and electrical conductivity, enabling strong and flexible connections, low bonding requirement, good chemical stability, high reliability and processability [7, 8]. However, the increasing price of Au wire has become a significant concern for manufacturers, prompting consideration of Cu wire as a potential alternative [9, 10]. Compared to Au, Cu has several significant advantages for wire bonding applications. Cu wire offers superior electrical properties to Au and enhanced intermetallic reliability under high temperatures, making it particularly well-suited for automotive electronic applications [10]. Additionally, its lower material cost further enhances its appeal in the automotive electronics industry. However, Cu is easily oxidized when exposed to air due to its low resistance to corrosion [11].

As technology emerges, the trend toward miniaturization in electronics has led to the widespread adoption of the SOT-23 package in the automotive industry. The SOT-23 package finds application in various critical automotive components in automotive electronics, such as the electronic control unit (ECU), power management systems, sensor modules, and lighting control systems. As the SOT-23 is usually used in automotive, it is exposed to moisture, high temperature, and high-pressure conditions, which can lead to accelerated corrosion activity [12]. In addition, after the wire bonding process, the semiconductor chip will be sealed through the encapsulation process to prevent it from moisture or any damage to the wire bond. Epoxy moulding compound (EMC) is widely used in semiconductor packaging because of its low cost and ease of handling. Still, it contains halogen elements and ions and readily absorbs moisture due to the hydrophilic nature of EMC [11]. The SOT package for automotive electronics uses Cu wire bonding. This gives rise to doubt about the long-term reliability of Cu wire bonding for the SOT-23 package in terms of corrosion since corrosion is a primary threat

***CORRESPONDING AUTHOR | A. Jalar** | ✉ azmn@ukm.edu.my

to electronic devices' structural integrity and performance [13, 14]. Despite the technological advancements in electronic packaging, the industry continues to face challenges related to corrosion [15]. The corrosion of Cu wire bonding within semiconductor packages has the potential to result in package failure, consequently impacting the overall reliability and lifespan of these packages [16]. Studies show that most package failures are caused by problems in wire bonding [4]. Even though Cu corrosion has been widely studied in different contexts [17, 18], there is a lack of information on how corrosion behaves in small-scale electronic components. Generally, corrosion studies in different contexts are done with bulk Cu ingots, and the results are not always applicable to the miniature size of wire bonding, approximately ~1 mils used in electronic devices [19, 20]. These Cu wire bond submicron sizes, encompassing ball bonding, and wedge bonding techniques possess unique geometries and surface characteristics compared to bulk Cu. These unique geometries have the potential to influence corrosion behavior significantly.

The miniaturization of electronic components requires a better understanding of corrosion in the application of wire bonding. This study aims to bridge the gap of bulk-miniature size issue by assessing the actual Cu wire bonding in the SOT-23 package for automotive electronics on corrosion susceptibility and its corrosion behavior when subjected to different concentrations of hydrochloric acid (HCl) and exposure time. HCl has been chosen as the corrosion medium to study the corrosion behavior of Cu wire bonding. HCL has been widely used in other research studies on corrosion. Ran Lei et al. used HCl as a medium of corrosion to study the potential inhibitory efficacy of sunflower (*Helianthus annuus*.) stalk extract (HASE) on Al corrosion [21]. Other than that, Hojat Jafari et al. also choose HCl as an environment to initiate corrosion on the surface of carbon steel [22]. HCl is also known as one of the strong acids that can provide a highly aggressive environment that accelerates copper corrosion processes compared to other types of acid [23]. In this research, HCl was chosen as the corrosion medium to imitate the condition of the electronic packaging. Usually, the wire bond will be encapsulated in an Epoxy Molding Compound (EMC) to protect the wire from the external environment. Halogen elements such as chloride and sulfides in EMC can lead to a corrosive environment [24]. In contrast to conventional electrochemical testing methods, this study aims to observe corrosion using real electronic components, the SOT-23 package. This study will characterize the susceptibility of Cu wire bonding to corrosion in the HCl environment by assessing the surface morphology of the Cu wire bonding using field emission scanning electron microscopy (FESEM). In addition, ImageJ software will be used for quantitative analysis to determine the remaining area of the Cu wire bond after exposure to a corrosive environment.

2. METHODOLOGY

2.1 Sample Preparation

This study used the SOT-23 package as a sample, a common transistor package used in automotive electronic devices. The preparation of the SOT-23 begins with cutting a silicon (Si) wafer to create a precise and minor piece called a die. The die was meticulously attached to a lead frame, a structural component that serves as the foundational support for the subsequent stages. The lead frame used in this study is a Cu Ag-plated lead frame. After the die was securely attached to the Ag-plated lead frame, the wire bonding process was initiated to establish crucial electrical connections. Cu wire with a diameter of approximately 1 mil, or 24 µm ± 1 µm, was used for this wire bonding process. The wire bonding process started with forming the free air ball created at the end of the Cu wire using electronic flame-off (EFO). The Cu wire was then attached to the Cu bond pad to form the first ball bond. Then, the wire was pulled to the other side of the lead frame, which created a wire loop and finished by forming a wedge bond formation. A lead frame strip consists of more than ten pieces of SOT-23, as shown in Figure 1(a). Because the Cu wire is too small to be seen with the naked eye, Figure 1(b) shows the condition of the Cu wire on SOT-23, where the ball bond is located on the bond pad and the wedge bond at the Cu lead frame. Figure 2 shows a side view schematic of the sample of Cu wire bond on a Cu lead frame after the wire bonding process. Nine small pieces of SOT-23 package samples were carefully cut from the leadframe strip using small scissors before being tested for corrosion.

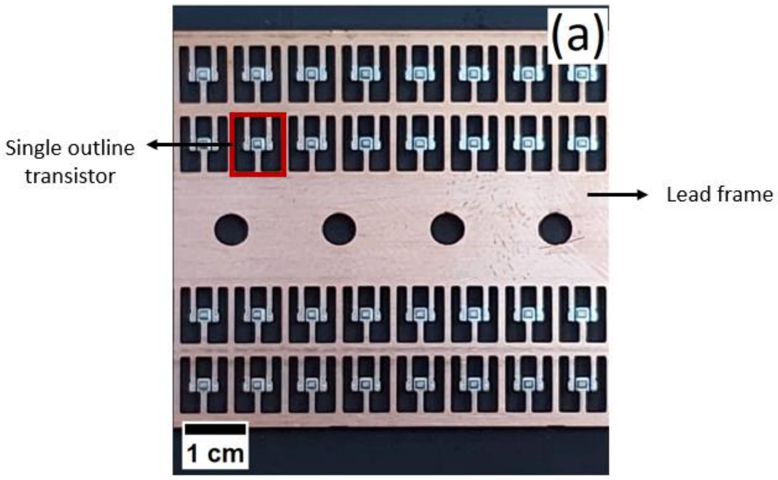


Figure 1. Single outline transistor (SOT-23) (a) strip of SOT-23;

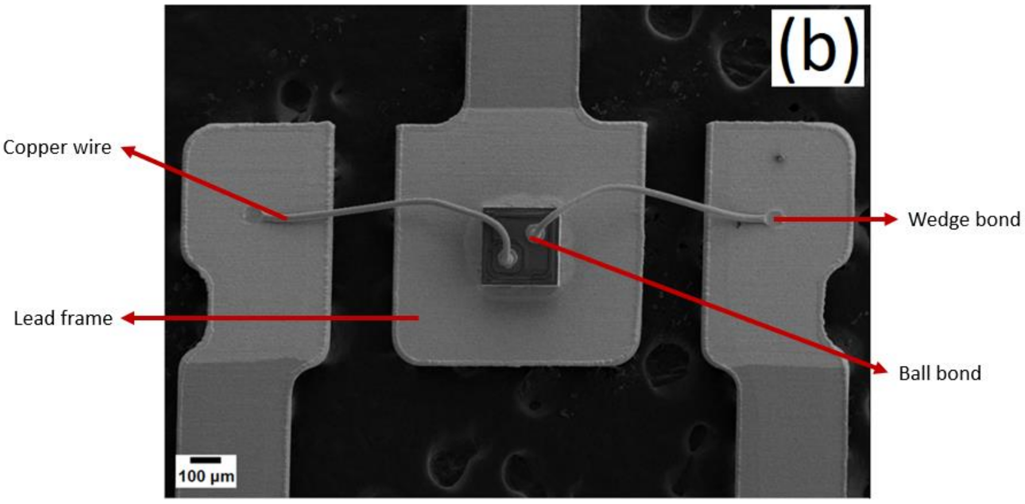


Figure 1. (cont.) (b) top view of FESEM image for SOT-23

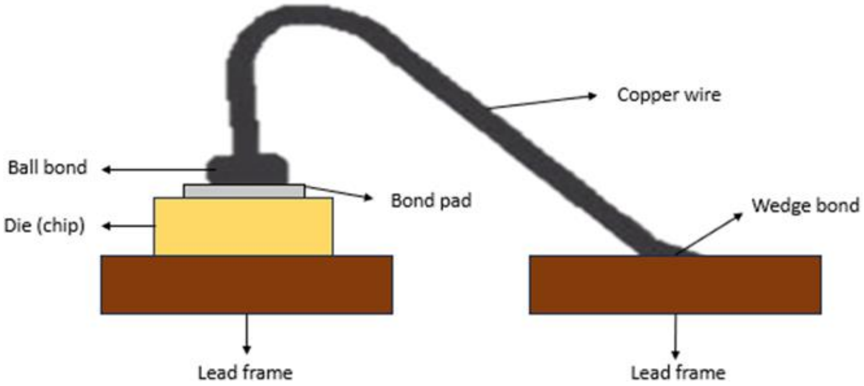


Figure 2. Schematic of the side view of SOT-23 that consists of Cu wire bond on the lead frame

2.2 Corrosion Testing

The SOT-23 package that consists of Cu wire bonding on an Ag-plated leadframe sample was subjected to an immersion test. The immersion test involved HCl acid as a medium to induce corrosion on the Cu wire. The HCl (37%, AR, Chemiz) was diluted using distilled water into three types of concentration, i.e., 3 M, 5 M, and 7 M. The experimental procedure of the immersion test involves immersing the nine samples in 10 ml hydrochloric acid placed in a glass beaker at room temperature. Each sample was immersed in HCl in 3 M, 5 M, and 7 M with a duration of 6h, 12h, and 18h for each concentration type. After the exposure time was completed, the sample was removed from the glass beaker using forceps and carefully rinsed with distilled water before surface morphology analysis. The samples were immediately characterized using field emission scanning electron microscopy (FESEM) to observe the Cu wire bonding microstructure. This study selects the Cu wire loop as an area of interest to assess corrosion behavior. Three different spots of the Cu wire bond loop were analyzed in detail, including area and wire diameter. Energy-dispersive X-ray (EDX) analysis was used to characterize mapping the elemental composition of the selected area of Cu wire bonding after the corrosion test. Quantitative analysis was performed on FESEM images to obtain the remaining area and the percentage of the affected area using the software ImageJ. The affected area of the Cu wire bonding was analyzed in terms of concentration types and corrosion test exposure times.

2.3 ImageJ Analysis

Image analysis was performed using ImageJ software on the obtained FESEM images to quantify the extent of corrosion on the copper wire. Initially, the scale of the FESEM images was calibrated by drawing a straight line across the scale bar present in each image (Figure 3). Subsequently, image thresholding was applied to isolate the affected area from the unaffected regions (Figure 4). The affected area was then manually selected, and its area was measured using ImageJ's built-in measurement tools. The calculated area data was tabulated as shown in Figure 5.

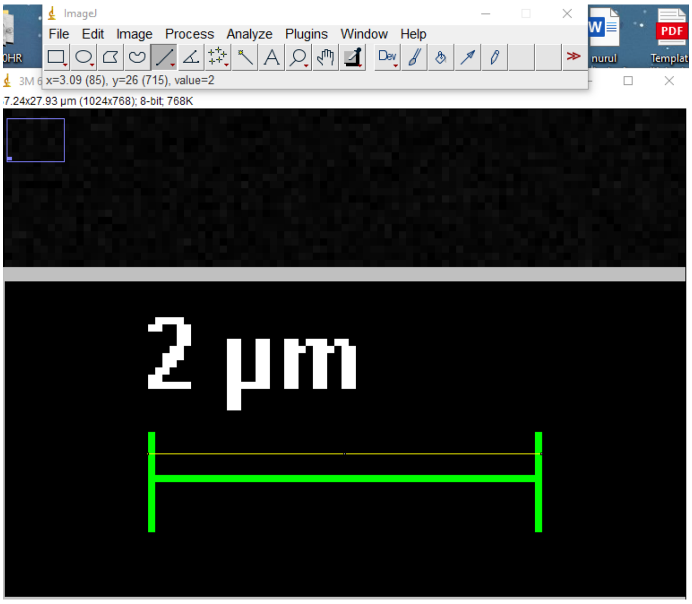


Figure 3. Set the scale on the FESEM image

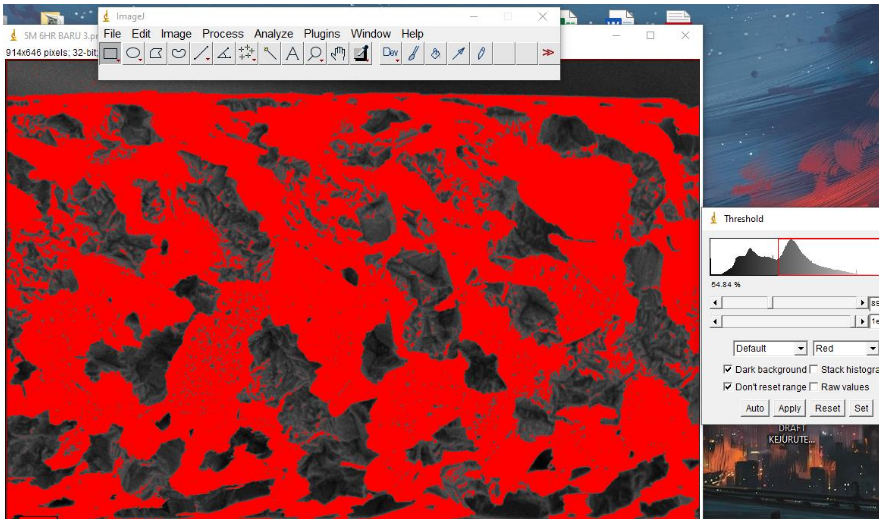
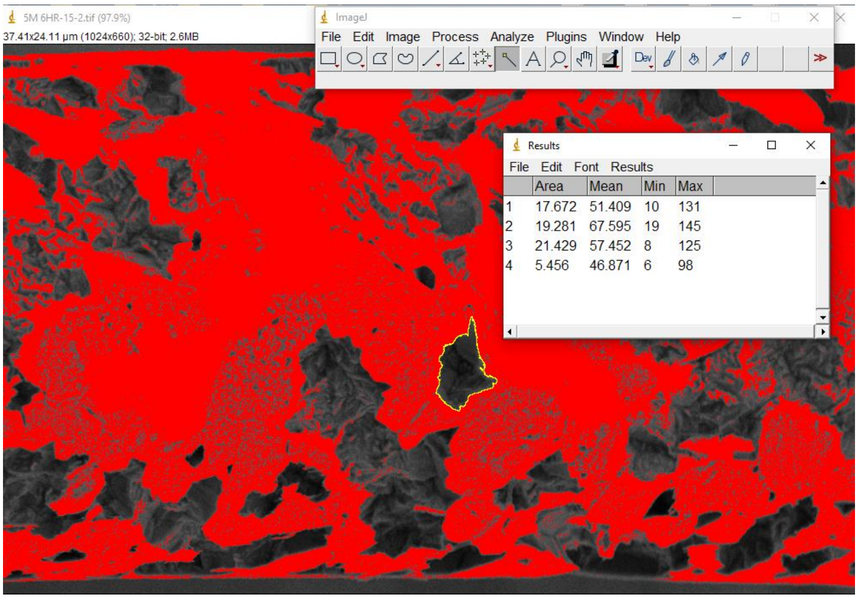


Figure 4. Adjust the image threshold to set the binary image using ImageJ



	Area	Mean	Min	Max
1	17.672	51.409	10	131
2	19.281	67.595	19	145
3	21.429	57.452	8	125
4	5.456	46.871	6	98

Figure 5. Select the area of interest and measure

3. RESULTS AND DISCUSSION

3.1 Microstructure Analysis

Characterizing the surface morphology of Cu wire bonds after exposure to HCl is essential to comprehending the corrosion behavior. Morphology analysis has been done using FESEM with a magnification of $3000 \times$ on the three different spots area within the area of interest (middle section) of the Cu wire bond, as shown in the white box, inset in Figure 6(a). Figure 6(a) represents the controlled sample of Cu wire bonding, which is in perfect condition before the corrosion test. Figure 6(b) shows the spotless surface of the Cu wire bonding for the controlled sample unit, which is flawless and smooth without any surface degradation or imperfection.

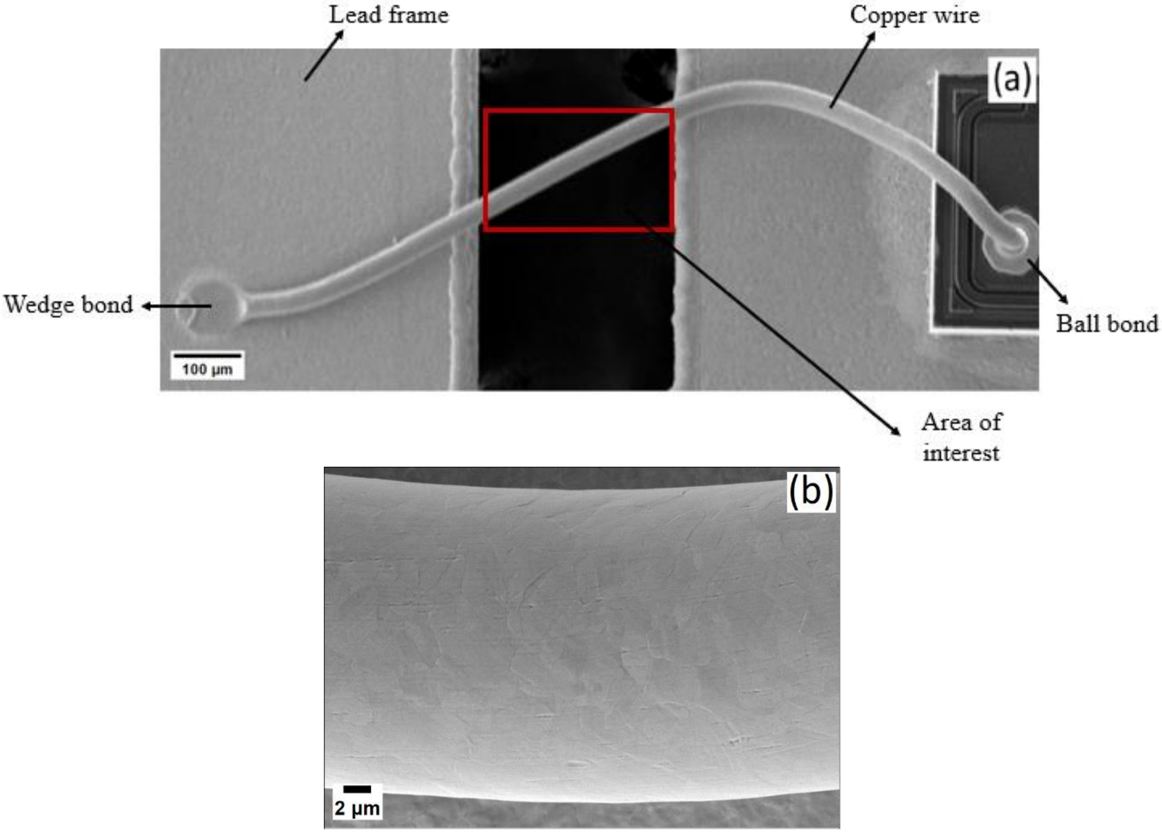


Figure 6. Top view of FESEM image Cu wire bonding controlled sample on an Ag-plated lead frame (a) area of interest in the middle of the wire (b) surface condition of Cu wire bonding sample before corrosion test.

Generally, corrosion and structure degradation may occur when the Cu is exposed to an acidic environment [25], [26]. Figures 7, 8, and 9 visually demonstrate the microstructure of 24 µm of Cu wire bonding after exposure to different concentrations of HCl at room temperature. For sample 3 M, as shown in Figure 7(a), after being exposed to HCl for 6h, the corrosion begins to attack the Cu wire as the surface roughens slightly. The affected area becomes more significant as the structure degradation of the Cu surface becomes visible when the sample is subjected to a longer time of 12h in Figure 7(b) and 18h in Figure 7(c). This shows that the actual small size of Cu wire bonding in the SOT-23 package with a diameter of 24 µm is strong and able to withstand the lower HCl concentration. In addition, longer exposure time has a greater impact on the degradation of Cu wire bonding surface.

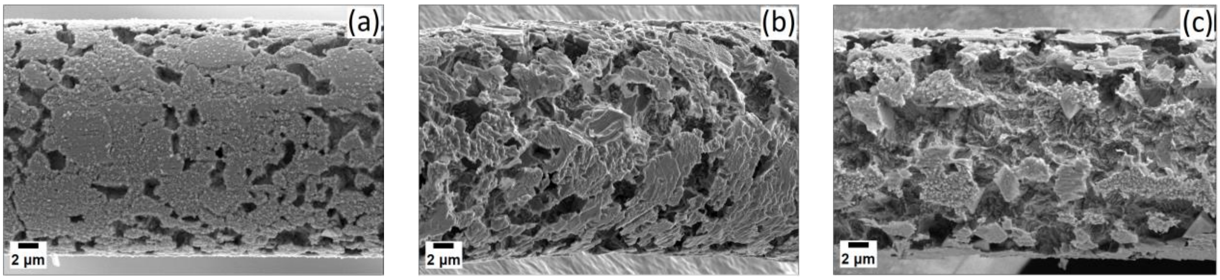


Figure 7. Area of interest (Cu wire) after being exposed to 3M HCl environment under FESEM (a) 6 hours; (b) 12 hours (c) 18 hours

As the concentration of HCl increases to 5 M in Figure 8, the degradation of the microstructure of the wire becomes more noticeable, and the surface of the wire slowly degrades over time. Similar observations were found in Figure 9 when the samples were subjected to a higher concentration of 7 M HCl; fewer corrosion attacks were observed for wires immersed for 6h compared to 12h. Increasing the immersion time makes the microstructure of the Cu wire become more severe, and the affected area becomes bigger, respectively. A significant reduction of diameter wire from 24 µm was observed on Cu wire bonding immersed in 7 M HCl for 18h. Notably, with increasing immersion time and concentration levels, the corrosion on the Cu wire becomes more pronounced. This shows that the Cu wire bonding is susceptible to corrosion when subjected to high HCl concentration. The observation on the Cu wire bonding microstructure in this study is in line with Yoo et al., reported that as the concentration of HCl increased, the surface morphology change resulted in a reduction in wire diameter [11].

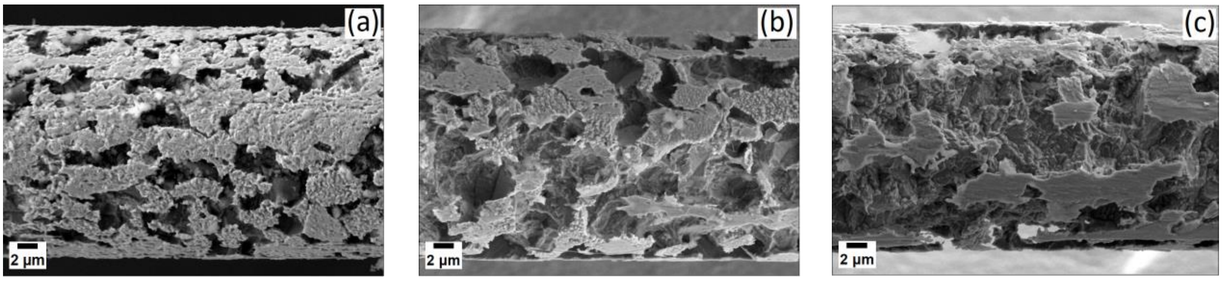


Figure 8. Area of interest (Cu wire) after being exposed to 5M HCl environment under FESEM (a) 6 hours; (b) 12 hours; (c) 18 hours

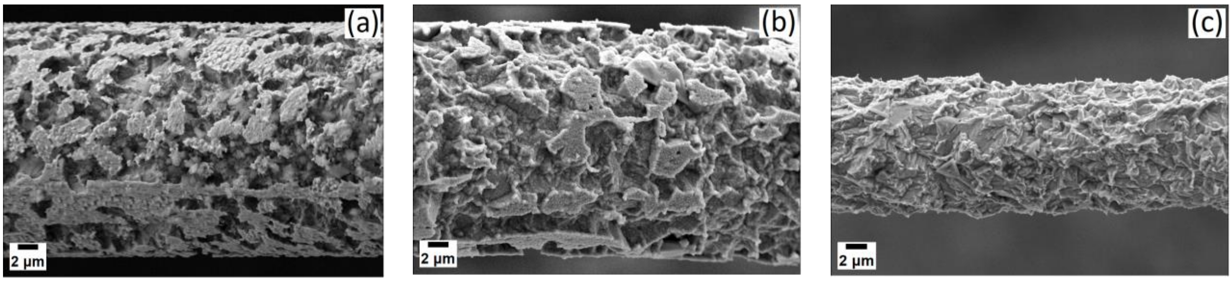


Figure 9. Area of interest (Cu wire) after being exposed to 7M HCl environment under FESEM (a) 6 hours (b) 12 hours (c) 18 hours

When Cu is immersed in hydrochloric acid (HCl), a strong acid that dissociates into chloride ions (Cl^-) and hydrogen ions (H^+) in an aqueous solution, the passivation layer may undergo disruption. This reaction involves a cathodic and anodic reaction. At the anode, copper oxidizes and releases an electron:

$$Cu(s) \rightarrow Cu^{2+} + 2e^-$$

Simultaneously, hydrogen ions are reduced at the cathode to form hydrogen gas.

$$2H^+ + 2e^- \rightarrow H_2(g)$$

The formation of soluble copper chloride ($CuCl_2$) occur as a subsequent reaction between the formed copper ion (Cu^{2+}) and Cl^- in the solution.

$$Cu^{2+}(aq) + 2Cl^-(aq) \rightarrow CuCl_2$$

Overall equation when Cu immersed in HCl formed a by-product $CuCl_2$ and hydrogen gas.

$$Cu(s) + 2HCl(aq) \rightarrow CuCl_2(aq) + H_2(g)$$

Cu is known to develop a protective passivation layer when exposed to oxygen, which shields the metal from corrosion [27]. This passivation layer can be disrupted by the presence of Cl^-, leading to localized corrosion such as pitting. This disruption, however, doesn't involve the selective removal of an element as in actual selective corrosion but rather the breakdown of the passivation layer at random spots on the Cu wire surface. Chloride and hydrogen ions randomly interact with the Cu surface upon immersion in HCl until the passivation layer breaks, exposing the underlying Cu metal. These weakened regions become susceptible to corrosion, leading to the observed formation of pits distributed in localized areas. Ashok Kumar et al. reported that in their studies, the formation of pitting in the localized area was observed when the sample was subjected to Cl^- and fluoride ion (F^-) environment [28]. This phenomenon, known as localized corrosion, explains why the wire diameter might not change initially. This shows that the corrosion behavior of the Cu wire bonding in this work is associated with a combination of selective corrosion and pitting-like corrosion. The selective corrosion occurs on the selected area of the Cu wire bonding surface and is not uniform throughout the Cu wire bonding surface. The pitting-like corrosion observed in this work was shown by the penetration of the corrosion into the Cu wire bonding on the selected area. These can be seen with the prolonged exposure to the HCl environment; the corrosion attacked and penetrated deeper into the Cu wire bonding from its surface, as shown in the previous figure. The prolonged corrosion activity eventually resulted in a change in diameter, as observed in the case of Cu wire immersed in 7 M HCl for 18h. Higher concentrations of HCl of 7 M broke the passivation layer, accelerating the corrosion process by penetrating deeper into the Cu wire bonding surface. This activity was parallel to the other area of the Cu wire bonding. Therefore, the diameter of the Cu wire bonding subjected to 7 M HCl for 18h has shown a reduction of its diameter as compared to the other samples in this work. In keeping with previous studies, some other researchers have also reported that Cu corrodes when exposed to a chloride environment [11], [16]. The surface morphology changed as the concentration increased, causing the formation of corrosion products and partial dissolution.

Energy-dispersive X-ray spectroscopy (EDX) analysis was performed to determine the elemental composition of the Cu wire and ensure that there is no other metal than copper. The obtained EDX spectrum in Figure 10 revealed the presence of Cu, carbon (C) and oxygen (O) elements. Figure 10 shows the EDX result of Cu wire immersed in 6h in 3 different concentrations: Figure 10(b) immersed in 3 M HCl, Figure 10(c) immersed in 5 M HCl, Figure 10(d) immersed in 7 M HCl and Figure 10(a) as a control sample. Cu elements were detected in all figures in Figure 10 to prove that it is Cu wire. It is assumed that element O was detected from the passivation layer of Cu, as reported in previous studies, and that the existing oxygen element was due to the passivation layer of Cu [29]. For element carbon, since copper is not a carbon-based material, there may be contamination in the sample during sample handling and preparation. Other than that, samples are mounted on carbon tape for analysis, and it may introduce carbon contamination.

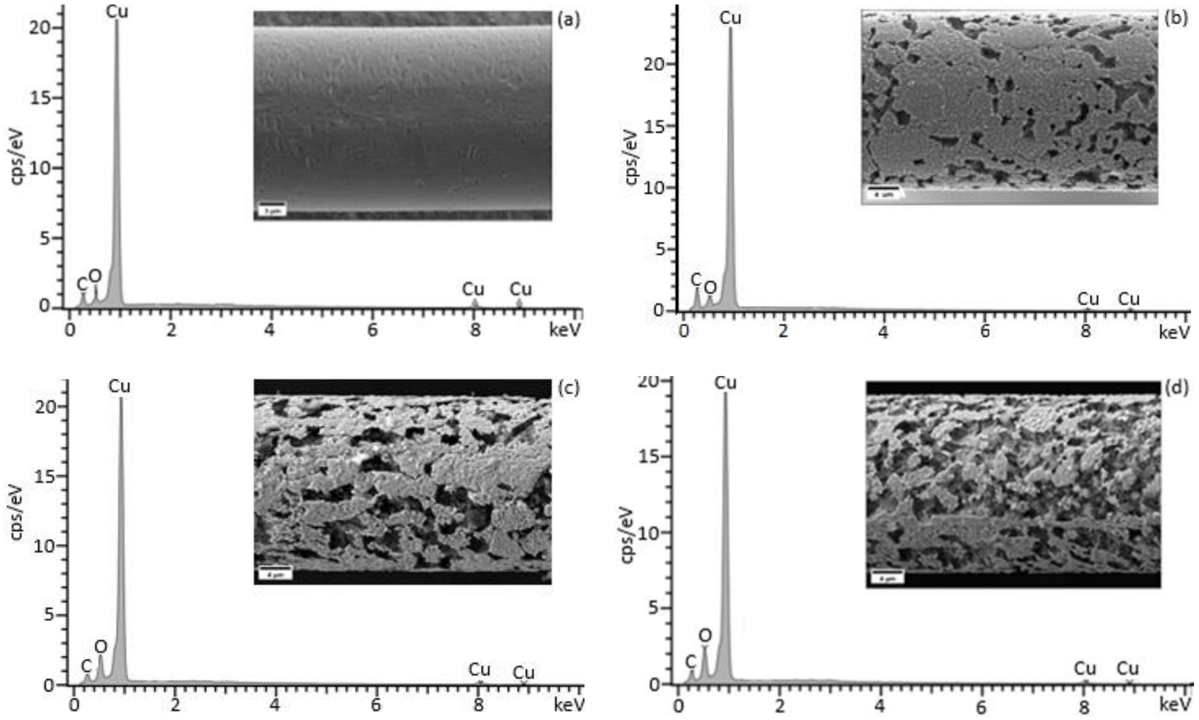


Figure 10. The results of EDX analysis after 6 hours of immersion time with different concentrations (a) control sample; (b) 3 M HCl; (c) 5 M HCl; (d) 7 M HCl

3.2 Effect of Corrosion on The Remaining Area of Cu Wire Bonding

Apart from the qualitative analysis, as shown in the figure above, this paper also quantifies the remaining area of the Cu wire bonding. From the Image J analysis, we noticed that the total area of the controlled sample was 855 µm^2 and significantly reduced after 6h exposure time to 677 µm^2 after being subjected to 3M HCl, 568 µm^2 for 5 M HCl, and 406 µm^2 for 7 M HCl as shown in Figure 8. A similar decreasing amount of remaining area has been observed for 12h exposure time when subjected to different types of HCl concentration. The remaining area has reduced to 302 µm^2, 288 µm^{2,} and 163 µm^2 for HCl concentrations of 3 M, 5 M, and 7 M, respectively. The change in the remaining area of Cu wire bonding becomes more severe after 18h. The remaining Cu wire bonding surface area was 291 µm^2 for 3 M HCl and 252 µm^2 for 5 M HCl. As the corrosion has consumed the Cu wire's surface, the remaining area for the sample of 7 M HCl for 18h yields no results. In Figure 11, we can see that the graph of the remaining area value of Cu wire bonding decreased as the concentration of HCl increased. Similarly, when the exposure time is prolonged, the remaining area of the Cu wire bonding is significantly decreased, as illustrated in Figure 12. According to Figure 11 and Figure 12, the findings show that the higher concentration of HCl contributed to more severe surface degradation of Cu wire bonding.

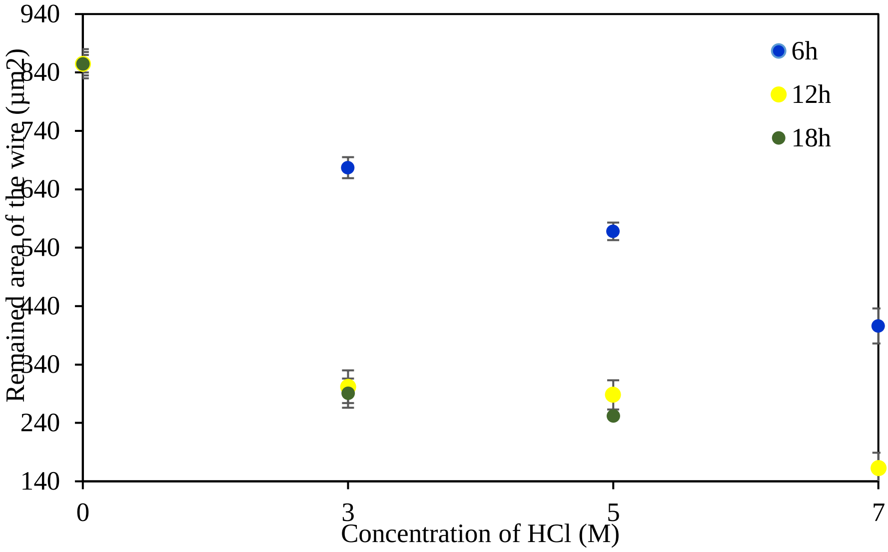


Figure 11. The remaining area of Cu wire bonding is after being subjected to different HCl concentrations

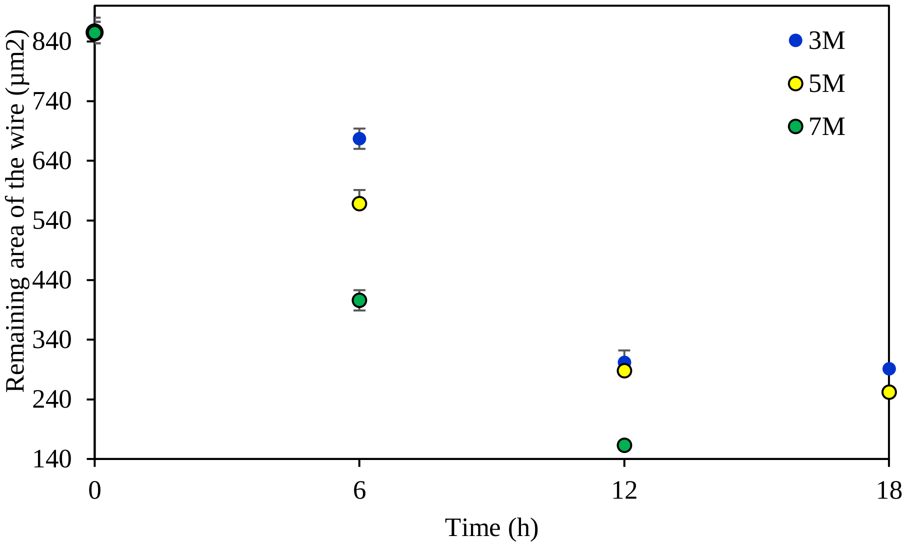


Figure 12. The remaining area of Cu wire bonding is after being subjected to different exposure times

Further analysis has been carried out to quantify the corrosion activity by assessing the percentage of the affected area of the Cu wire bonding. Table 1 shows that more than 50% of Cu wire bonding was affected when subjected to 7 M HCl for 6h, whereas lower affected areas were shown for sample 3 M, 21% and 34%, with similar exposure time, respectively. On the other hand, Cu wire bonding samples that were immersed for 12h showed a higher affected area than 6h samples. The affected area for 12h were 65% for 3 M, 66% for 5 M, and 81% for 7 M. This shows that the corrosion severely attacked the Cu wire bonding surface when the exposure time was prolonged. Similar findings were shown for 18h exposure time. As the concentration increases from 3 M to 5 M and 7 M, the percentage of the affected area becomes more significant, from 66% to 71% and 100%. Higher concentrations contribute to more severe corrosion activity.

The high HCl concentration leads to increased HCl ions within the environment, enhancing the acid ion to attack the Cu wire bond in line with the report by Hamidah et al. [29]. In this work, the percentage value of the affected area on the Cu surface can indicate the degree of corrosion attack on the Cu wire bonding. The remaining area of the Cu wire decreased, implying the percentage value of the affected area by the corrosion attack increased.

Table 1. The percentage of the affected area of the Cu wire in different concentrations and times

Concentration of HCl (M)	Percentage of the surface affected area (%)		
	6h	12h	18h
3	21	65	66
5	34	66	71
7	53	81	100

This study utilized the micro size of Cu wire bonding with a diameter of 24 µm of SOT-23 package. Therefore, the surface area of the Cu wire bonding size was relatively small to observe using the naked eye compared to a typical bulk Cu sample, which might influence the corrosion behavior. Kosec et al. reported that a larger surface area provides more sites for corrosion initiation and activity [30]. The EDX analysis in Figure 10 revealed the presence of some residual oxygen, indicating that the Cu oxide passivation layer has partially disrupted, thus contributing to the selective and pitting-like corrosion behavior. It also aligns with the possibility of generalized pitting-like corrosion observed in the FESEM images, as shown in Figures 7, 8, and 9. Table 1 shows a clear trend of increasing surface affected area percentage with higher HCl concentration and longer exposure time—the findings in this work aligned with the established knowledge of corrosion. Despite prolonged exposure time, the increased concentration of acidic ions is the significant contributing factor, which accelerates the corrosion activity of the Cu wire bonding in the SOT-23 package.

4. CONCLUSIONS

This paper has successfully assessed the corrosion behavior of 1 mils Cu wire bonding on an Ag-plated lead frame in the SOT-23 package for automotive electronics subjected to different concentrations of HCl environment. This work shows that the small size of Cu wire bonding can withstand corrosion in a low concentration of HCl. The corrosion activity becomes more severe as the Cu wire bonding is subjected to a high concentration of HCl. The prolonged exposure time of up to 18h also contributes to the severity of the Cu wire bonding corrosion activity. Among all the samples, the Cu wire bonding surface was 100% affected when subjected to 7 M HCl for 18h, and the Cu wire showed a significant reduction in diameter. This study shows that the 1 mils Cu wire bonding in the SOT-23 package subjected to HCl combines selective corrosion and pitting-like behavior as the surface of Cu wire bonding degrades unevenly throughout the Cu wire bonding area. This study provides some valuable insight into the corrosion behavior of 1 mil Cu wire bonding used in the SOT-23 package for automotive electronics.

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