The reliability study on electrochemical migration evaluations for common substrates in power electronics

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2023 24th International Conference on Electronic Packaging Technology (ICEPT) | 979-8-3503-3881-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICEPT59018.2023.10491991

Abstract—**The miniaturized electronic devices are driving the development of higher density and integration of smaller components, which leads to reliability issues for electronic devices in harsh environments such as high temperature and high voltage. Electrochemical migration (ECM) is an important phenomenon related to the failure of electronic devices, causing short-circuit failures between closed metal surfaces and significantly reducing the reliability of electronic products. Moreover, the complexity of the materials used in modern circuit boards, the increased number of component pins and the reduced spacing of multilayer boards have all increased the risk of failure from electrochemical migration, making it an unavoidable failure threat in the reliability of electronic packaging. Recently, silicon nitride (Si_3N_4) ceramics have received wide attentions due to their excellent mechanical properties, such as high bending strength and high fracture toughness. The Si_3N_4 substrate is not only responsible for electrical connections and mechanical support, but reliability is also important. However, the effect of Si_3N_4 ceramic substrate on the reliability of electrochemical migration is rarely studied.**

In this paper, we use the water drop (WD) test to investigate the effect of four commonly used substrate material types (aluminum nitride, alumina, silicon nitride, PCB) and bias voltages on electrochemical migration experiments in electronic products. The WD test was chosen due to the fact that results on the effect of conditions such as electrode spacing, bias voltage, ion type and concentration in the liquid on electrochemical migration can be obtained in a short time. During electrochemical migration, samples were recorded in situ under an ultra-deep field microscope (MPI TS150) for video of the entire WD process. The mean time to failure was determined based on the first sharp increase in current and the dendritic bridges observed under the optical microscope. In addition, the morphology of the dendrites and elemental analysis of the post-experimental samples were carried out by scanning electron microscopy (SEM), energy spectroscopy (EDS) and XPS, while the statistical electrochemical migration failure times were monitored in real time.

Keywords—Electrochemical migration; The water drop test; Dendrite microstructure; Electrochemical migration mechanism

I. INTRODUCTION

As wide band gap (WBG) semiconductors are developed in power electronics modules, interconnection becomes critical for devices with SiC or GaN power chips and integrated circuits. Packaging materials and processes are promising for high-value electronic applications such as hybrid vehicles, aerospace and oil exploration [1]. Since power chips need to withstand harsh conditions such as high-power density and high temperature and pressure, this brings new challenges to packaging materials. Brazing materials can cause damage to delicate power electronics during high-temperature reflow, and the intermetallic layer generated between the brazing material and the substrate material can form defects at high temperatures, so several new electronic interconnect materials have been developed. Among them, Ag-TLP nanosintering and conductive adhesives (ECA) have excellent temperature stability, excellent thermal and electrical conductivity due to the presence of silver particles, organic resins and some dispersants. They can also be sintered at lower sintering temperatures and have considerable ability to be used at high temperatures, and are currently widely studied as power electronic interconnect packaging materials [2,3].

However, reliability and lifetime are key issues for electronic devices. Corrosion is also an important factor affecting the service life of electronic products under harsh conditions such as high density, high pressure and high temperature [4]. Electrochemical migration (ECM) is a corrosion phenomenon that is influenced by bias pressure, electrode distance, and other factors [5]. The process occurs when two closely spaced oppositely biased electrodes are connected by a continuous electrolyte layer (water droplet or electrolyte layer). The anode electrode part of the metal dissolution occurs to produce metal ions into the medium, then migrate to the cathode under the impact of the electric field, electrochemical deposition occurs to generate a conductive dendritic structure, which eventually leads to the short-circuit phenomenon of the two electrodes [6].

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Compared with these ECM-related test methods, WDT test experiments are simple and easy to conduct, short experimental cycle, and are conducted at room temperature [7].

Extensive studies have been conducted on phenomena related to electrochemical migration: mechanism of ECM, material factors (addition of alloying elements), the type of applied bias, thickness of the absorbing electrolyte, etc [8,9]. Yoon JW et al. [10] investigated the electrochemical migration phenomenon after sintering silver layers on silicon-based material chip boards, and observed the microstructure and composition of dendritic structures by varying the sintering time and temperature, and concluded that longer time and higher sintering temperature made them more resistant to electrochemical migration. Yi Pan's group [11] has done a lot of work on the electrochemical migration of circuit boards with different surface treatments. It was found that relative humidity has an important influence on the electrochemical migration process of electronic components. Compared with copper-clad boards, printed circuit boards treated with electroless nickel-gold plating have higher sensitivity to electrochemical migration, and the short-circuit phenomenon is more pronounced as the humidity increases. This is mainly because the gold plating layer is extremely thin, with a large number of microporous surfaces, electrolyte adsorption to form a liquid film on the specimen surface, a corrosion coupling between Au and the middle layer Ni and the bottom layer Cu, which actually further accelerates the corrosion process of the substrate, thereby promoting the electrochemical migration process. However, the current studies are focused on improving the process methods and process parameters in the manufacturing process, and only a few studies focus on the effect on the circuit board substrate materials.

In this study, the effects of four substrate material types (aluminum nitride, alumina, silicon nitride, and PCB) commonly used in electronics and bias voltage on electrochemical migration experiments are investigated using water drop tests. The whole WDT process was observed in situ by ultra-deep field microscopy. The microscopic morphology and elements of the dendrites were analyzed by scanning electron microscopy (SEM), energy spectrometry (EDS), and XPS, while the statistical electrochemical migration failure time was monitored in real time.

II. Experimental

A. Synthesis of Ag-based conductive adhesives

A self-produced Ag-based conductive adhesive (ECA) was used. a self-produced Ag-based conductive adhesive (ECA) was used. The detailed steps of the Ag-ECAs preparation process are as follows: First, a certain amount of Ag microflakes (≤ 10 μm) and coupling agent were added to ethanol as the solution part A. Subsequently, solution A was sonicated and stirred to obtain a homogeneous solution; The coupling agent served to modify the filler surface. Next, the epoxy resin (E44), as the polymer matrix, was slowly added to the obtained the solution part A and stirred continuously for 30 min. Finally, some amount of hardener (epoxy resin: hardener = 2:1) was added to the above mixture. More details of the preparation can be found in our previous work [12].

Aluminum nitride (AlN), silicon nitride (Si_3N_4), alumina (Al_2O_3), and PCB substrates were used in this study. Fig. 1 presents the microscopic morphology of the substrate material. The size of the substrate was 10 mm×10 mm ×1mm. The sample preparation process for ECM testing was as follows: Ag-ECA paste was directly printed on the substrate by screen printing with a thickness of ~80 μm. The low-temperature sintered ECA paste-parallel electrodes have an exposed area of 3 × 8 mm and a pitch of 0.5 mm, allowing for uniform electrical bias distribution. The prepared Ag-ECA twin electrodes were preheated at 70 °C for 30 min and then heat cured at 130 °C for 1 h.

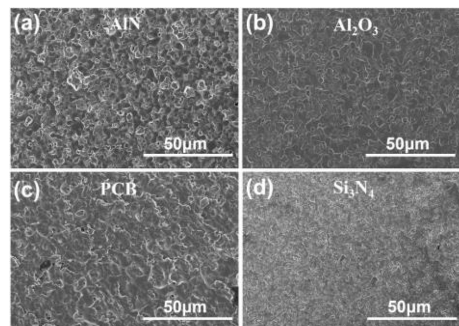

Fig. 1. The SEM image of the substrate material. (a) AlN; (b) Al_2O_3; (C) PCB; (d) Si_3N_4.

B. Electrochemical migration test (ECM)

A water drop test (WDT) method was performed on the twin electrodes at room temperature in order to analyze the ECM behavior of Ag-ECA electrode materials on different substrates. During the WDT, a bias voltage was applied between the two electrodes using a digital source meter (containing a picoammeter and various Keithley Model 2636B instruments) and the current was measured with a resolution of 0.1 fA. At the same time, on-site video recording of the entire WDT process under an ultra-deep field microscope (MPI TS150). Prior to applying the voltage, 15 ~ 20 μl of deionized water was dropped into the space between the two electrodes with a pipette, and a voltage was applied to the probe at the two electrodes (3 V, 5 V). The mean time to failure (TTF) was obtained based on the observed sharp increase in the first current and the arrival of the dendrite at the anode. ECM-induced TTF can be defined as the short-circuit failure time. All ECM measurements were repeated at least six times.

III. Results and Discussion

A. Short-circuit failure time of different substrates during ECM

To evaluate the impact of different substrate materials on the electrochemical migration behavior, water droplet experiments were performed on Ag-ECA electrodes. Fig. 2(a) shows the measured current-time curves of electrode Ag-ECA at different substrate materials and different voltages for ECM testing. As illustrated in Fig. 2a, the current measured between the two electrodes increased abruptly for each sample after the dendrites were grown to the anode. The minimum dendrite growth time from the cathode to the anode of the PCB substrate is 48.8 s at an applied voltage of 3 V. The maximum short-circuit failure time of Si_3N_4 substrate is 66s, which is comparable to that of the Al_2O_3 substrate (62.6s). The short-circuit time decreases sharply with increasing voltage for all samples. For example, as the voltage increases from 3V to 5V, the AlN substrate shorting time decreased from 52 s to 29.9 s.

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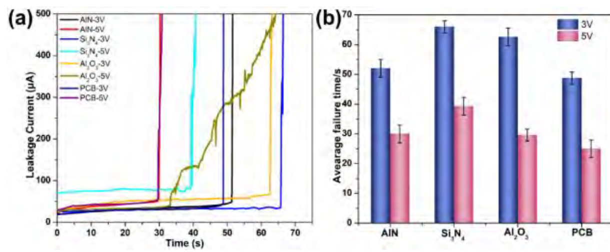

Fig. 2. (a) The current-time curves of different substrate materials under different bias voltages; (b) Average short-circuit time of different substrate samples at 3V, 5V.

To facilitate the observation of the dendrite growth process for each substrate, Fig. 3 shows the ECM process measured for each substrate at a bias voltage of 5V. (The PCB substrate could not be recorded due to the darker color at the bottom, but the overall ECM is similar to that of the AlN substrate). As shown in Fig. 3, after applying bias voltage, the anode slowly dissolved surface changed, and after a certain time, a small amount of dendritic structure appeared at the edge of the sample cathode.

As the experiment proceeded, the dendrites grew toward the anode while the number gradually became larger. When the growing dendrite structure touches the edge of the anode, there will be a big "jump" in the current-time curve. This means that a short circuit has occurred there. It can be seen that the ECM process for all samples is divided into three phases: the incubation phase, in which the anode is dissolved and the ions migrate to the cathode without the appearance of dendrites; the growth phase, where the dendrites appear at the edge of the negative electrode and gradually grow toward the positive electrode. Meanwhile, the number of dendrites increases. In the failure phase, the dendrites grow from the cathode to the anode and a short circuit occurs. The main difference between the different substrate materials was the prolongation of these three stages, which ultimately affects the short-circuit time. For example, the Si_3N_4 substrate significantly increases the incubation period from 8s to 12.5s compared to the AlN substrate.

The different ECM failure times of the substrates may be related to the variation in condensation strength caused by the different surface roughness and thermal diffusivity of the substrates [13]. The short-circuit failure time decreases with increasing voltage for different substrate electrodes. There are two reasons for this. On the one hand, the higher the voltage, the faster the anode dissolves and the faster the ions migrate; Ag^+ from the anode can reach the cathode and deposit quickly. In addition, the higher the voltage, the faster the electrochemical reaction and the more bubbles are generated; the strong agitation of bubbles enhances the ion migration and drives Ag^+ to the cathode in a short time [14].

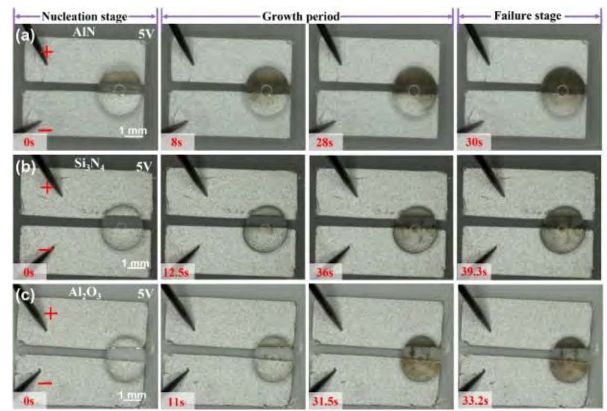

Fig.3. Electrochemical migration process of (a) AlN substrate, (b) Si_3N_4 substrate and (c)Al_2O_3 at 5V.

B. Microstructure and elemental analysis of dendrite structure

Fig. 4 shows SEM images of dendritic materials after ECM test with different substrate materials at 3V. There is little difference in the macroscopic structure of each sample. All dendrites are basically composed of clusters and clear dendritic fractal dendrite structures. The overall shape of dendritic structures in the experiment is very similar to the "fractal" structure, and the branch shape is a replication and iteration of the trunk shape [15]. In addition, dendritic dendrites are covered with many granular products. Among all the dendrites, the dendrite structure in the middle is the largest, and some of the dendrites are clustered.

There are several dendrites in the cathode electrode that fail to establish complete connections with the anode. It is inferred that after the intermediate dendrites contact the anode, the growth rate of other dendrites slows down and only grows to the middle of the electrode until the end of the experiment. Furthermore, there were scattered crystals in the electrode gap. The reason was that a large number of bubbles appeared from the cathode electrode stirred the liquid beads during the experiment, which caused the dendritic structure to break and split, and the resulting fine crystal dendritic was scattered everywhere in the electrode gap.

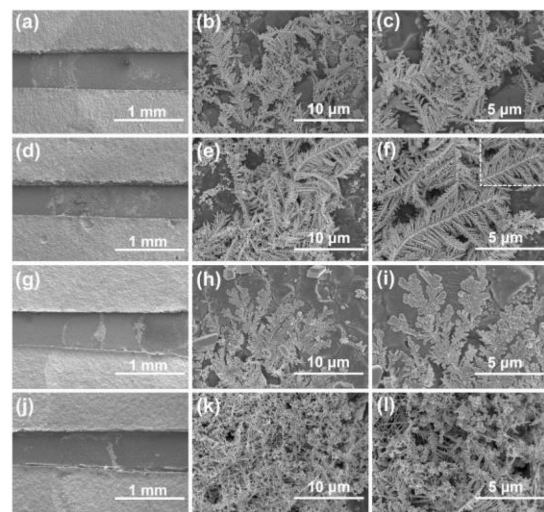

Fig.4. The SEM images of dendrites of different substrate materials after ECM test at 3V. (a, b, c) AlN; (d, e, f) Si_3N_4; (g, h, i) Al_2O_3; (j, k, l) PCB.

In terms of dendrite diameter, dendritic dendrites are relatively robust when the bias pressure is low. However,

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when the bias is higher, the dendrites show short and small morphology, and more corrosion products are distributed around the dendrites (Fig.5a, b). This is mainly due to the low bias voltage, the anode dissolution forms fewer metal ions, resulting in the cathode reduction of dendrites slowly. At higher bias voltage, the anodic reaction is accelerated, ion migration is expedited, dendrite nucleation and growth are significantly enhanced at the cathode edge, exhibiting a slender morphology.

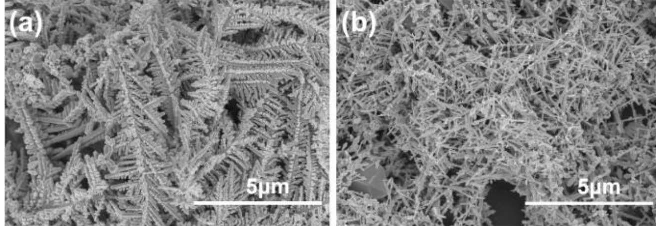

Fig. 5 SEM morphologies of dendrites generated on Si_3N_4 substrate at different bias voltages. (a) 3V; (b) 5V.

Fig. 6 and 7 demonstrate the EDS analysis results of the whole surface of the experimental sample and the dendrites, the EDS analysis results of different substrate materials are the same. The dendrites are mainly composed of Ag, and oxygen is distributed throughout the sample surface, which is inferred to come from metal oxides or hydroxides.

In order to investigate the specific composition of the dendrites, XPS were carried out on the dendrites generated after ECM testing on Si_3N_4 substrate with a 3 V bias voltage. From the full range of XPS survey spectrum of dendrites, it can be seen that the dendrites are mainly composed of Ag, O and C (Fig. 8a). The presence of C can be attributed to carbon conductive tape and contaminants. In Fig. 8(b, d), the two main peaks near 368.2 eV (Ag 3d5/2) and 374.1 eV (Ag 3d3/2) can be attributed to the Ag0 metallic state. The existence of Ag_2O was confirmed by Auger spectrum of Ag [16,17]. At the same time, the high-resolution spectra of O1s also presents broad and asymmetrical peak (Fig. 8c). The presence of oxygen is more complicated. This proved that the Ag dendrites are slightly oxidized.

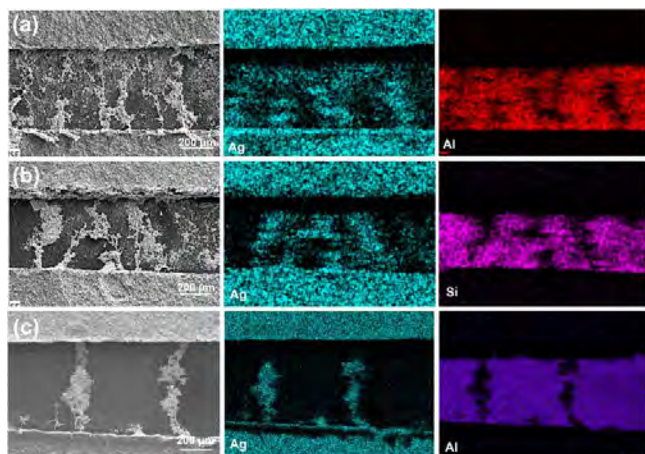

Fig. 6. The SEM and EDS analysis of dendritic products produced on various substrate materials after ECM. (a) AlN; (b) Si_3N_4; (c) Al_2O_3.

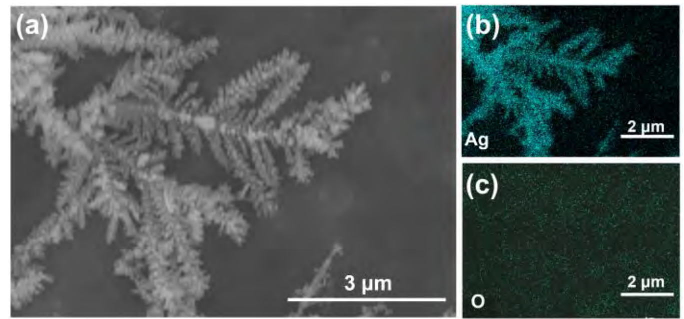

Fig. 7. The EDS of dendrites product. (a) Ag element; (b) O element.

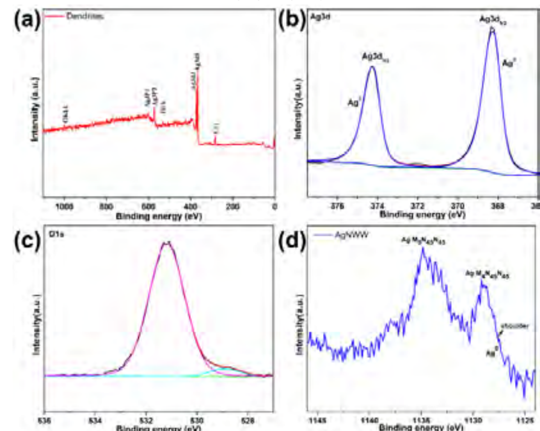

Fig. 8. The XPS wide scan spectra of dendrites (a); (b, c) Corresponding Ag3d, O1s high-resolution XPS spectra of dendrites for Ag-ECA; (d) Ag MNN Auger spectrum.

C. Mechanism analysis of electrochemical migration

The reaction mechanism of ECM cathode and anode is the same in different substrate materials. The anode process is the dissolution of Ag in Ag-ECA. The cathode process is mainly hydrogen evolution and oxygen reduction. Driven by an electric field, Ag^+ migrates towards the cathode, while hydroxide moves in the opposite direction. Ag^+ reacts with OH- to form Ag(OH) instability, and the unstable AgOH decomposes into Ag_2O, which is reduced to Ag on the cathode, and finally promotes dendrite gestation and growth [18]. Due to the different surface roughness and thermal diffusivity of Si_3N_4 substrate, AlN substrate, Al_2O_3 substrate and PCB substrate, the condensation strength of water droplets on the surface will be different. In addition, the higher the hydrophobicity of the substrate surface, the less easy to form liquid film on the substrate surface, which can improve the electrochemical migration sensitivity to a certain extent. As a result, the failure time in the ECM process is prolonged.

IV. Conclusion

1) Different substrates have little effect on the phenomenon of electrochemical migration, but have a significant impact on the failure time of the samples. Compared to other substrates, Si_3N_4 substrates have the best resistance to electrochemical migration. Si_3N_4 has 26.1% better resistance to electrochemical migration than PCB substrates in terms of failure time. The short-circuit time of all samples decreases sharply with increasing voltage.

2) The experimental phenomenon and mechanisms of electrochemical migration are similar for different substrates: The metal dendrites grow from the cathode to the anode until sample failure, and the overall structure of the dendrites

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resembles a fractal structure with clusters and dendrites. The main elemental composition of the dendrites is Ag. A higher bias voltage results in thinner dendrites.

3) The study of the tolerance and failure mechanisms of electrochemical migration of different substrate materials has implications for the reliability of electronic products. In the future, we will investigate the effect of alloying of Ag on the resistance to electrochemical migration [19] and the resistance to sulfation of Ag [20].

ACKNOWLEDGMENT

This work was financially supported by National Natural Science Foundation of China (No. 52203371, and 52271021). The authors thank Analysis & Testing Center at Beijing Institute of Technology for the SEM/EDS and XPS works done in Experimental Center of Advanced Materials at Beijing Institute of Technology.

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