Influence of interfacial interaction between various metal substrates and epoxies on bonding reliability under high temperature

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Abstract
The shift from gel encapsulation to epoxy encapsulation has been driven by the need to reduce the size of power modules. However, the dissimilar bond between the encapsulation epoxy and substrate is a potential weak point. Previous studies have primarily focused on the impact of epoxy materials on package reliability. In this study, we investigate the influence of interfacial interactions between three metal substrates (copper, Ag-plated copper, nickel-plated copper) and epoxy on the reliability of epoxy encapsulation under high temperatures. Two types of epoxy (bisphenol A and cycloaliphatic) were used to encapsulate metal substrates. Encapsulated packages were subjected to a high-temperature storage test (HST) at 200°C for 1000 hours, and changes in bonding strength were measured. We then analyzed the fracture surface and bonding interface at the nanoscale. Our results indicate that substrate material significantly impacts the reliability of epoxy encapsulation. After HST, we found that the catalytic effect of metals caused the epoxy in contact with the metal substrate to decompose. The decomposition was most significant for the epoxy in contact with Ag, followed by copper, which resulted in a significant drop in bonding strength. In contrast, epoxy in contact with nickel showed little decomposition and only a slight change in bonding strength. These findings will greatly benefit power module design.

Key words
Epoxy encapsulation, Epoxy degradation, High temperature storage, Reliability.

I. Introduction
The conventional power module was encapsulated by pouring silicone gel onto the substrate inside a case. Recently, the miniaturization trend made the encapsulation technique under transformation. Epoxy encapsulation, which eliminates the outer case and forms an integrated module by molding, attracted attention.

Epoxy encapsulation produces many dissimilar bonding interfaces. These interfaces are regarded as weak points, and many researchers investigated them to avoid bonding failure and improve reliability. Many studies proposed the thermal stress between the substrate and epoxy as the main reason for the bond failure [1]. In our previous study [2], we found that besides the thermal stress, the decomposition of the epoxy contacted with the copper substrate influences the bonding strength greatly. Our results indicate that the interfacial interaction is also an important factor.

Therefore, in this paper, we investigated the reliability of the bonding between the two types of encapsulated epoxies and three different substrates under a high temperature storage test (HST). The thermal aging was performed at 200 ℃ lasting for 1000 h. Our study aims to reveal the influence of interfacial interaction on the bonding strength for different combinations of metal substrates and epoxies.

II. Experimental
A. Materials

To compare the influence of different substrate materials on the reliability, we used three different substrates, including a C1020 oxygen-free copper substrate, a 2.0 μm Ag plated C1020 oxygen-free copper substrate (layer composition: Cu, 0.8 μm Ni, 0.2 μm Pd, 2.0 μm Ag), and a 3.5 μm Ni plated C1020 oxygen-free copper substrate (layer composition: Cu, 3.5 μm Ni). Fig. 1(a) shows the images of a C1020 oxygen-free copper substrate. The other two substrates have the same

structure. It shows that the substrate has a square shape with a dimension of 35 mm × 35 mm × 2 mm. We only performed ultrasonic ethanol cleaning for the substrate before encapsulation.

For the epoxy, we used two different kinds of epoxies, including a bisphenol-A type epoxy and a cycloaliphatic type epoxy. The same anhydride hardener was used for these two epoxies. Fig. 2 shows the molecular structure of the epoxies and hardener. To reduce the difference in the coefficient of thermal expansion between the metal substrate and epoxy, we added 71.5 wt% silica filler with a diameter ranging from 10 μm to 30 μm to the epoxy. In addition, 0.2 wt% carbon black was also added to make the epoxy possible for laser decapsulation.

The substrates were encapsulated with epoxy by a commercialized compression molding machine (YPM1180, TOWA). After demolding, the encapsulated substrates were put in an oven at 100 ℃ for 2 hours and 150 ℃ for 2 hours to cure the epoxy. Then, we separated the four packages from the encapsulated substrate along the dicing line shown in Fig. 3(a). A separated package is shown in Fig. 3(b); it has a dimension of 12.5 mm × 12.5 mm × 3.3 mm.

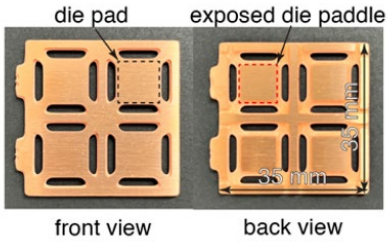

Fig. 1. An image of a substrate.

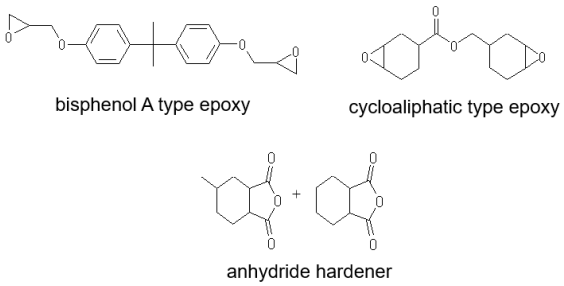

Fig. 2. Molecular structure of the epoxies and hardener.

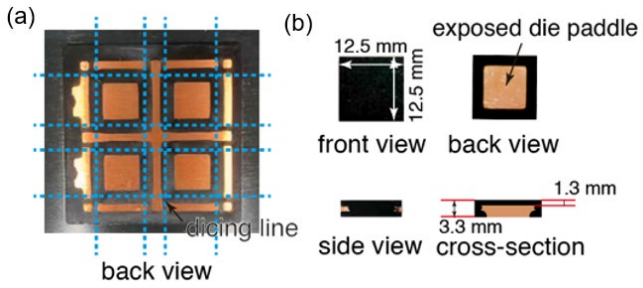

Fig. 3. (a) The dicing line for the encapsulated substrate; (b) Dimension of an encapsulated package.

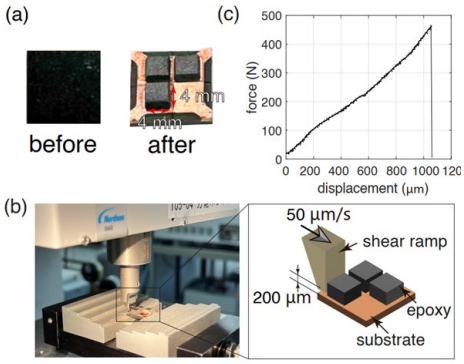

Fig. 4. (a) Images of the package before and after the decapsulation; (b) Image and illustration of the setups for the shear test; (c) An example of the displacement-force curve during the shear test.

B. Reliability test

After curing, high temperature storage test was performed (HST). The encapsulated packages were placed in a high-temperature oven at 200 ℃ for 0 h, 240 h, 500 h, and 1000 h to test the reliability of the package in high temperature. Here, 0 h means the package was not put into the oven.

C. Characterizations

After the reliability test, the bonding strength between the substrate and epoxy was evaluated. As shown in Fig. 4(a), we first used a laser decapsulation system to remove some epoxy and form a 4 mm × 4 mm cubic island shape on the substrate. Then, the bonding strength was measured by a shear tester (Dage 4000, Nordson). Fig. 4(b) shows the bonding strength measurement setups. Fig. 4(c) shows an example of a force-displacement curve. For each treatment condition, six islands were measured to calculate the average bonding strength.

The fracture surface of the substrate side was observed with an SEM (JSM-F100, JEOL). The encapsulation epoxy side was characterized by an ATR-FTIR. The spectrums were taken at a resolution of 4 cm^{-1} and 64 times. In addition, XPS depth profiling of the epoxy fracture surface was performed to investigate the possible diffusion of metals into the epoxy.

III. Results

A. Bonding strength results

The bonding strength for different substrates and epoxies is shown in Fig. 5. For the copper substrate, the bonding strength reduced after HST for both epoxies, but the bisphenol A reduced faster. The bonding strength for bisphenol A reduced to zero after 500 h HST. For the Ag-plated copper substrate, the bonding strength reduced extremely fast. Only after 240 h the bonding strength for both epoxies were zero or almost zero. On the other hand, although the Ni-plated copper substrate's initial bonding strength was relatively lower than the copper and Ag-plated copper, its bonding strength almost did not change even after 1000 h HST.

B. Fractures surface of the substrate side

To find the possible reason for the bonding strength change, the fracture surfaces of the substrate side after 0 h and 500 h were observed. Fig. 6 shows the fracture surfaces of the substrate side for the bisphenol A type epoxy. Fig. 6(a) shows the copper substrate before HST (0 h). The surface is flat with some machining marks. Fig. 6(b) shows that many oxidized copper bumps formed on the surface after 500 h HST, indicating that the copper substrate was oxidized. Fig. 6(c) shows that bumps formed by the Ag-plating were observed before HST. However, as shown in Fig. 6(d), many nano cubic structures were formed on the surface after HST. By EDS, these nano cubic structures were identified as Cu_2O. It shows that the copper atoms can diffuse through the plated NiPdAg layer. Besides, some residual epoxy was observed. Fig. 6(e) shows the fracture surface of the Ni-plated surface before HST. Bumps formed by the Ni-plating were observed. After 500 h HST, as shown in Fig. 6(f), the surface was not changed obviously. Unlike Fig.6(d), no nano cubic structures were observed.

The fracture surfaces of the substrate side for the cycloaliphatic type epoxy are shown in Fig. 7. Fig. 7(a) shows the copper substrate before HST. Like the bisphenol A type epoxy, the surface is flat with some machining marks. However, unlike the bisphenol A type, in Fig. 7(b), no copper oxide bumps were found. The machining marks are still observed. In addition, some residual epoxy was observed. Fig. 7(c) shows that bumps formed by the Ag-plating were observed before HST. After 500 h HST, unlike the bisphenol type epoxy, although the nano cubic structures on the Ag-plated surface are observed, the number is limited. Some residual epoxy was also observed. As shown in Figs. 7(e) and (f), the surface structures of the Ni-plated substrate do not change too much after 500 h HST, similar to the bisphenol A type epoxy.

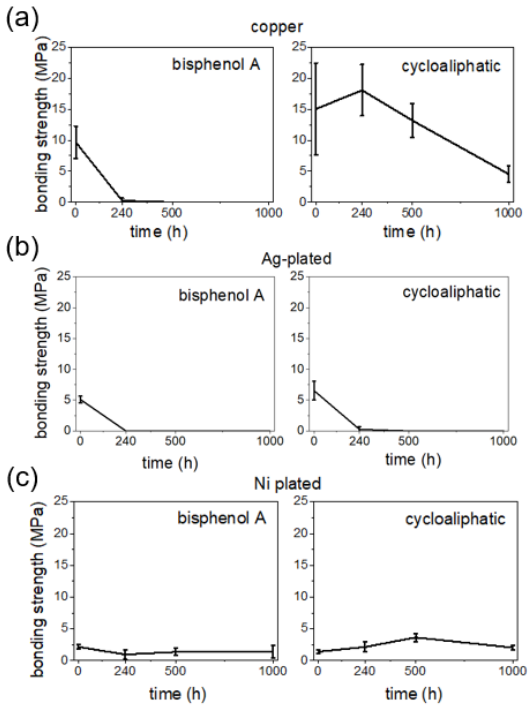

Fig. 5. The bonding strength results after HST for (a) copper substrate; (b) Ag-plated copper substrate; (c) Ni-plated copper substrate.

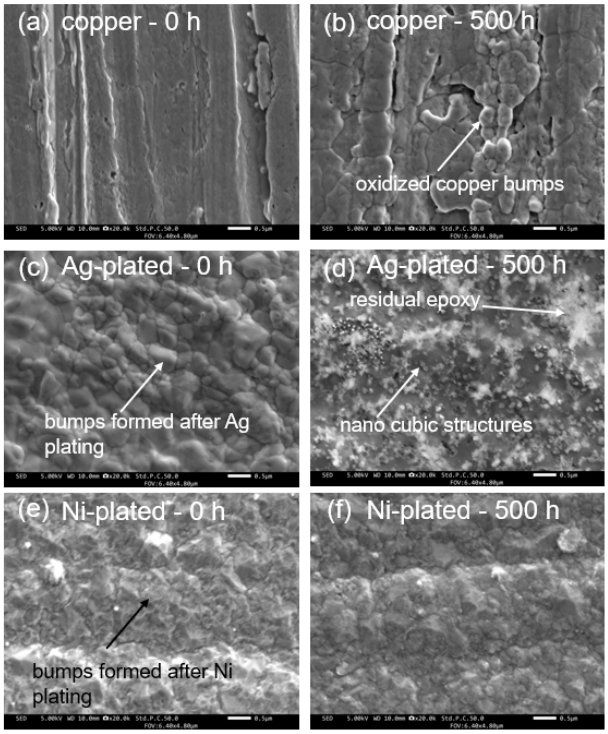

Fig. 6. The fracture surface of the substrate side for the bisphenol A type epoxy after 0 and 500 h HST for (a) copper substrate; (b) Ag-plated copper substrate; (c) Ni-plated copper substrate.

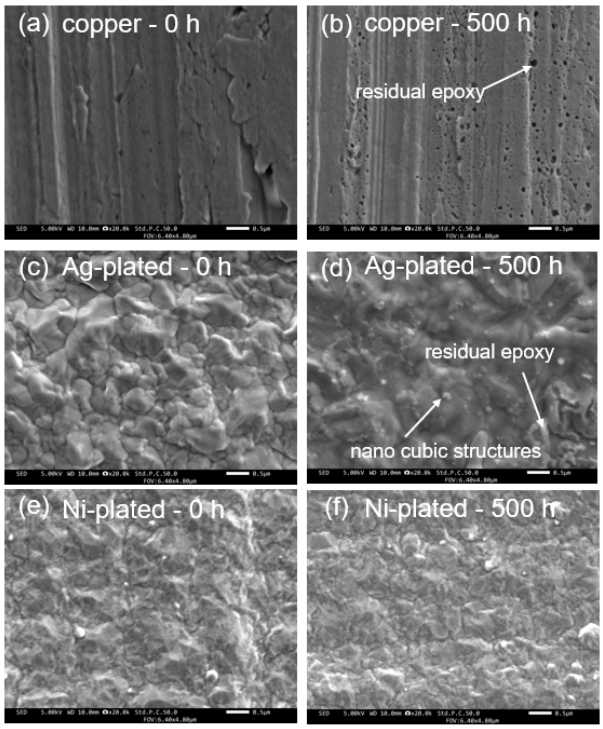

Fig. 7. The fracture surface of the substrate side for the cycloaliphatic type epoxy after 0 and 500 h HST for (a) copper substrate; (b) Ag-plated copper substrate; (c) Ni-plated copper substrate.

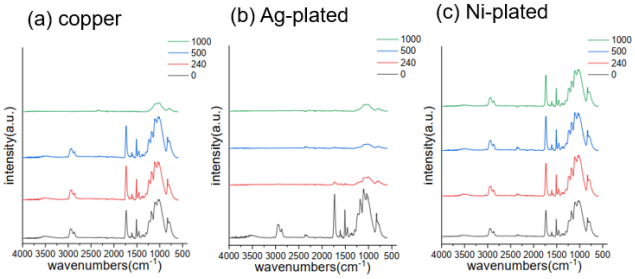

Fig. 8. The ATR-FTIR results for fracture surface of the bisphenol A type epoxy for (a) copper substrate; (b) Ag-plated copper substrate; (c) Ni-plated copper substrate.

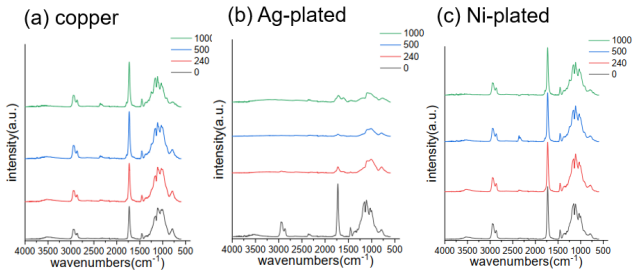

Fig. 9. The ATR-FTIR results for fracture surface of the cycloaliphatic type epoxy for (a) copper substrate; (b) Ag-plated copper substrate; (c) Ni-plated copper substrate.

C. Fracture surface of the epoxy side

The fracture surfaces of the epoxy side for both epoxies were analyzed by ATR-FTIR. Fig. 8 shows the ATR-FTIR results of the epoxy side for the bisphenol A type epoxy. The peak at 1100 cm^{-1} related to Si-O in silica filler, the peak at 1500 cm^{-1} related to the aromatic ring, the peak at 1732 cm^{-1} related to ester were observed.

As shown in Fig. 8(a), for the copper substrate, the peak at 1732 cm^{-1} increased after 240 h and decreased after 500 h, indicating that the bisphenol epoxy was oxidized first and then decomposed. The decomposition of epoxy was obvious after 1000 h HST, as the peak intensity reduced to almost zero. As shown in Fig. 8(b), for the Ag-plated substrate, only after 240 h, the peak intensity reduced to almost zero, indicating that the bisphenol A type epoxy was very easy to decompose when it bonds with Ag. In Fig. 8(c), no obvious epoxy decomposition was observed for the Ni-plated substrate. The peak at 1732 cm^{-1} increased until 500 h and slightly reduced after 1000 h, indicating limited epoxy decomposition.

Regarding the cycloaliphatic type epoxy, as shown in Fig. 9(a). No obvious epoxy decomposition after 1000 h was observed for the copper substrate, unlike the bisphenol A type epoxy. The peak at 1732 cm^{-1} increased until 500 h and slightly reduced after 1000 h, indicating limited epoxy decomposition. Since the cycloaliphatic type epoxy does not contain aromatic rings, no peak around 1500 cm^{-1} was observed. As shown in Fig. 9(b), the cycloaliphatic type epoxy has the same trend for the Ag-plated substrate as that for the bisphenol A type epoxy. The peak intensity reduced to almost zero after 240 h, indicating that the cycloaliphatic type epoxy was also very easy to decompose when it bonds with Ag. In Fig. 9(c), no obvious epoxy decomposition was observed for the Ni-plated substrate. The peak at 1732 cm^{-1} increased until 1000 h. No obvious decreasing trend was observed.

Previous studies indicate that the metal ions can diffuse into the epoxy and cause epoxy decomposition [3]. Here, the diffusion of the metal ions was evaluated by XPS depth profiling.

Figs. 10 (a) and (b) show the atomic percentage results for the fracture surface of the bisphenol A type epoxy. It shows that before HST, no copper atom diffused into epoxy. After 1000 h HST, large amounts of copper atoms diffused into the epoxy. For the Ag-plated substrate, as shown in Figs. 10(c) and (d), before HST, neither Cu or Ag diffused into epoxy. However, after 1000 h HST, both Cu and Ag diffused into the epoxy. Although copper was underneath the Ag plating layer, copper atoms diffused through the Ag plating layer and

into the epoxy. More copper atoms were detected inside the epoxy than Ag atoms. For the Ni-plated substrate, no Cu and Ni atoms were detected before and after HST. The high Ni percentage at 0 nm for the Ni-plated substrate after 1000 h is highly possible from the surficial contaminations, as no nickel was detected inside the epoxy.

Figs. 11 (a) and (b) show the atomic percentage results for the fracture surface of the cycloaliphatic type epoxy. Unlike the bisphenol A type epoxy, almost no Cu atoms diffused into the epoxy. For the Ag-plated substrate, as shown in Figs. 11(c) and (d), before HST, neither Cu or Ag diffused into epoxy. However, after 1000 h HST, both Cu and Ag diffused into the epoxy, but the percentage of diffused atoms was less than that of the bisphenol A type epoxy. Similar to the bisphenol A type epoxy, no Cu and Ni atoms were detected before and after HST for the Ni-plated substrate.

D.Discussions

We first want to discuss the reason for the bonding strength change after HST. After encapsulation, the bonding is supposed to relate to the surface structures of the substrate and epoxy contacting the substrate. Change happened on the surface structures and the epoxy contacting the substrate would influence the bonding strength.

For the copper substrate with the bisphenol A type epoxy, as shown in SEM images Figs. 6(a, b), the copper surface structures were changed greatly after HST. We suppose that this kind of surface structure change would break the formed bond between the substrate and epoxy, which results in strength reduction. This explains why the bonding strength for the bisphenol A type epoxy reduced to zero after 500 h HST. On the other hand, for the cycloaliphatic type epoxy, as shown in SEM images Figs. 7(a, b), the surface structure changed minorly, which can keep the formed bond between the substrate and epoxy. Thus, the bonding strength changes little for the cycloaliphatic type epoxy.

Besides the structures of the copper substrate, the epoxy is also changed. As shown by the ATR-FTIR results in Fig. 8(a), the bisphenol A type epoxy decomposed severely after 1000 h HST. The decomposition should result from the copper-catalyzed thermal decomposition. As shown in Figs. 10 (a,b), copper atoms largely diffused into the bisphenol A type epoxy, making the copper-catalyzed decomposition easier to happen [3]. In comparison, for the cycloaliphatic type epoxy, copper diffusion is limited, as shown by Figs. 11 (a,b), causing limited epoxy decomposition, as shown by Fig. 9(a).

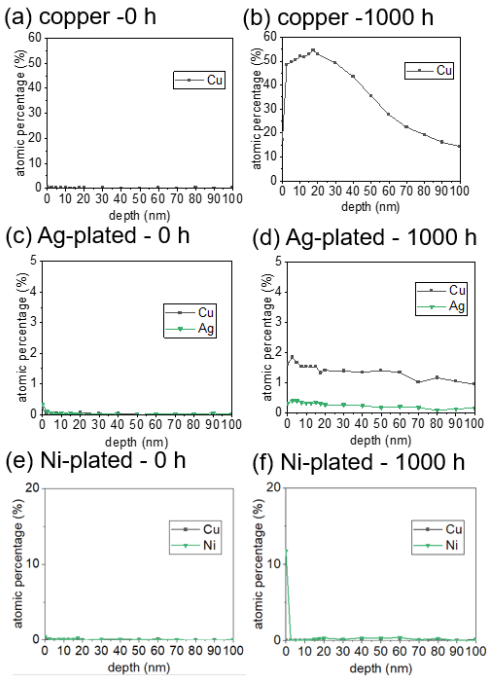

Fig. 10. The metal atomic percentage results for fracture surface of the bisphenol A type epoxy for (a) copper substrate; (b) Ag-plated copper substrate; (c) Ni-plated copper substrate.

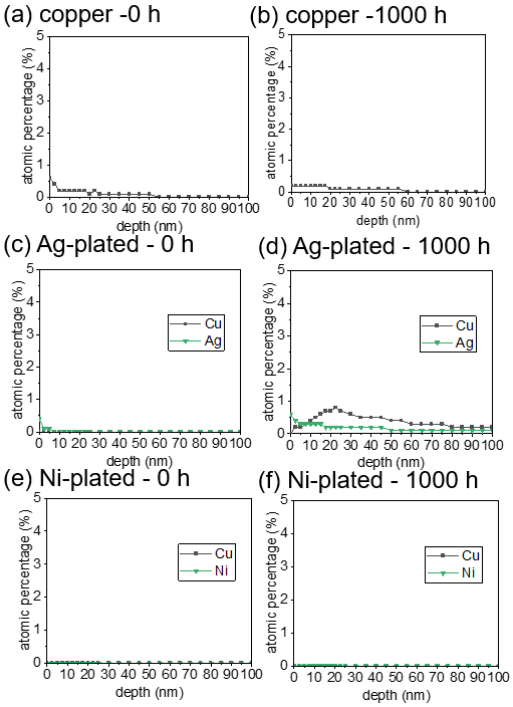

Fig. 11. The metal atomic percentage results for fracture surface of the cycloaliphatic type epoxy for (a) copper substrate; (b) Ag-plated copper substrate; (c) Ni-plated copper substrate.

Both surface structure change and epoxy decomposition influence the final bonding strength. For the copper substrate with the bisphenol A type epoxy, since the bonding strength dropped to zero after 500 h HST, the influence of the surface structure should be dominant. For the copper substrate with the cycloaliphatic type epoxy, both structure change and epoxy decomposition are limited. Therefore, the bonding strength is still kept after 1000 h HST.

For the Ag-plated substrate, the surface structure change happened, as shown in Figs. 6(c,d) and Figs. 7(c,d). Copper diffused through the Ag-plating, forming nanostructures on the surface. In addition, epoxy decomposition is also observed, as shown in Fig. 8(b) and Fig. 9(b). For the Ag-plated substrate, both epoxies decomposed severely after 240 h. Such severe decomposition is supposed to result from the catalyzed decomposition caused by both copper [3] and silver [4]. Compared to the copper substrate, it seems that Ag atom has a larger decomposition promotion effect. Such severe epoxy decomposition should be the main reason for the bonding strength reduction. At the same time, nanostructures were formed, which also deteriorated the bonding strength.

For the Ni-plated substate, neither the surface structure nor the epoxy decomposition was observed for both epoxies. Also, diffusion of Ni and Cu was also not observed. This should explain why the bonding strength did not drop after 1000 h HST.

We discussed the reasons for the surface structure change. The surface structure change is caused by oxidation, which is related to the metal types and the oxygen amount. Among the metals we used, copper is the easiest to be oxidized, while nickel is the most difficult to be oxidized. In addition, the oxygen amount should be decided by the epoxy density. Previous studies [5] have shown that epoxy with less density is easier for oxygen to pass. According to the datasheet for the epoxy provider, with the same weight, the cycloaliphatic type epoxy used in this study has 1.5 times the epoxide group than that of the bisphenol A type, which means that the 3D network of the cycloaliphatic type epoxy formed after curing is 1.5 times denser than that of the bisphenol A type. The bisphenol A type epoxy is easier for oxygen to reach the encapsulated substrate. The large surface change shown in Fig. 6(b) should result from the easiness of copper oxidation and enough oxygen, while the unchanged surface in Fig. 7(b) should result from less oxygen.

We also discuss metal diffusion. We supposed that the diffusion should relate to the metal type and the density of the epoxy. With the results of this study, it is difficult to provide experimental evidence for the reasons behind the diffusion difference between metals, but we supposed that different metal diffusion comes from the different activation energies for diffusion [6]. As for the epoxy, the diffusion is supposed to relate to the epoxy density. Less-density epoxy has more space, resulting in a larger diffusion. This explains well the diffusion results, which shows that the bisphenol A type epoxy has more diffusion than the cycloaliphatic type epoxy.

IV. Conclusion

This paper investigated the reliability of the bonding between the two epoxies (bisphenol A type and cycloaliphatic type) with three metal substrates (Cu, Ag-plated, Ni-plated) for HST. The metal surface structure change caused by oxidation and the metal-catalyzed epoxy decomposition greatly influenced the bonding strength after HST. Metal surface has the most change for the Cu/bisphenol A epoxy due to the easy oxidation of copper and the less density of the bisphenol A (less density makes the oxygen easier to reach the substrate). In addition, the epoxy bonded with Ag-plated copper substrate is easiest to suffer decomposition, followed by the copper substrate. The Ni-plated substrate almost did not cause decomposition.

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