NICKEL PLATED COPPER HEAT SPREADER SURFACE CHARACTERISTICS

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ABSTRACT
Nickel plated copper heat spreader acts as a medium to dissipate heat from silicon die towards heat-sink. Electroless nickel plating requires catalytic activation before the nickel can be deposited onto copper. Different catalytic activation techniques such as galvanic initiation and thin nickel-copper electrodeposition have diverse impact on the thermal performance of the heat spreader. Surface roughness of heat spreader was studied using Infinite Focus Microscope. High temperature storage test was also run to investigate intermetallic diffusion between the nickel and copper layers. This study found out that nickel-copper layer grew after high temperature storage condition. Furthermore, heat spreader with thin nickel-copper electrodeposition also gave a smoother surface.

INTRODUCTION
Thermal management plays a very important role in semiconductor packaging technique. Heat has to dissipate at a higher rate to maintain the chip performance for high power package. For flip-chip technology, heat can be dissipated from the die back to ambient environment through heat spreader. Copper has been chosen as the material for heat spreader in flip-chip ball grid array package, due to its high thermal conductivity. A layer of nickel is plated onto the copper for the reason to improve wear resistance and prevent oxidation of copper. In addition, nickel is also a more refractory element with higher melting point than copper [1-5].

Electroless nickel plating technique refers to a chemical coating process that is being used to deposit nickel onto copper. This technique operates without electricity and provides a very uniform thickness over the most complicated shapes. Therefore, it overcomes the major problem of non-uniform plating thickness that resulted from variation in current density caused by the geometry of the plated body and its relationship to the plating anode. The irregular surface of heat spreader causes thermal interface material difficult to attach on it and causes air voids trapped between them. Air voids create hot-spot inside the package and block the heat from dissipating into the environment [6-9].

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Electroless nickel deposits are generally semi-bright, but this will vary depending on bath composition and surface finish of the base material. Phosphorous content in the electroless nickel-phosphorous layer can range between 0 to over 13 percent and in general can be classified as low (1-5 wt % P), medium (5-8 wt % P), and high (9 wt % P and more) phosphorous layer. Microcrystalline or amorphous structures will vary depending on the phosphorous content in the alloy. Low-phosphorous concentration nickel has a higher melting point, better solderability properties and also more resistant to alkaline attack. High-phosphorous concentration nickel is nonmagnetic material and more resistant to acid attack. Medium-phosphorous concentration nickel has excellent wear resistance and is normally used as plating material when no specific requirement is needed [10].

The initial nickel deposit is itself catalytic to the chemical reduction process, with the deposition of nickel continuing until the operator terminates the process. Provided a chemically clean surface, metals that are spontaneously deposited with nickel when immersed in an electroless nickel plating solution, are nickel, cobalt, iron, aluminum (usually processed through a zincate treatment prior to plating to enhance adhesion), zinc, titanium, beryllium, and palladium. Metals such as lead, cadmium, antimony, and bismuth are catalytic poisons and incapable of direct electroless nickel deposition. These metals can be electroless nickel deposited by first applying a copper or nickel electrodeposit. Plastics, ceramics, silver, copper, and copper alloys require catalytic activation such as galvanic initiation or a thin nickel electrodeposit (strike). Some typical activation procedures for surface treatment of metals include the application of momentary cathodic current, the application of palladium film, and the immersion of the part in reducer solution such as dimethylamineborane (DMAB) [11-13].

Two types of nickel plated copper were used as heat spreader in assembling flip-chip ball grid array package. However, a significant difference in performance was noticed between these two types of package after assembly process. After both heat spreaders had been cross sectioned, one of the heat spreaders was found out to have an addition of thin layer between electroless nickel deposit layer and copper layer. Generally, this thin layer is a catalyst layer that manufacturer applies to initiate electroless nickel plating process. This is because copper does not have a catalytic action for the oxidation of hypophosphite. Therefore, the difference of the thermal performance between both heat spreaders is due to the thin layer.

**EXPERIMENTAL METHOD**

Two types of heat spreader were used in this study. Both heat spreaders having size of 30 mm × 30 mm with 0.7 mm thickness in the middle of the heat spreaders. Both heat spreaders are plated with a thin layer of nickel. The intrinsic properties of the heat spreader are assumed to be the same but different in plating process. Heat spreaders which contains catalyst layer and without catalyst layer are respectively

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named as heat spreader A and heat spreader B. Both heat spreaders were cross sectioned to display the entire layer inside the heat spreader. Elements contained inside both heat spreaders were characterized using Philips XL 30 E-SEM (Scanning Electron Microscope) equipped with an Oxford Instruments Inca X-sight Energy Dispersive X-Ray (EDX) system. After elements of thin layers had been identified, thin layer formed by catalyst treatment process were characterized by Siemens D5000 X-Ray Diffractometer (XRD) to identify the compound at the catalyst layer.

High temperature storage (HTS) test for heat spreaders was performed at 150°C for 24, 48, 96, 168 hrs in Despatch LAC HTS Oven. Accelerated ageing at high temperature is used to promote Ni-Cu intermetallic growth. Two series of HTS test were run on different study purposes. In the first test, full piece of heat spreaders were baked under different time condition in order to see the thickness changing between each layer after diffusion. A single heat spreader was cut into five parts in the second test after which all the parts with the same initial catalyst layer thickness were baked under different time ranges to see the growing of catalyst layer. Cross sections were prepared in the normal metallographic manner by Buehler Ecomet 3, without smearing the thin metals and ensuring that the deformation layer due to polishing was minimized. Specimens were mounted in a low heat evolution epoxy to reduce the risk of heat-induced stress damage to the samples. After potting and curing, samples were wet-grinded with 180, 400, 800 and 2000 grit size papers and then polished with 9μm, 3μm diamond suspension on silk cloths. Lastly, samples were final polished by 0.05μm colloidal silica suspension on polyurethane cloth. Optical imaging was performed with Olympus BH3-MJL microscope to measure the thickness of each layer.

Finally, both heat spreaders’ surface roughness were measured by Alicona Infinite Focus Microscope (IFM) to study the effect of deposited catalyst layer towards surface roughness of electroless nickel plating. The IFM was performed on a scanning area of 500 μm × 500 μm and the height scanned is 40 μm. Average roughness ($R_a$) and Root-Mean-Square roughness ($R_q$) which are commonly used as a surface finish roughness parameter were gathered over the entire measured array. For each sample, the results are presented in the 3D view of processed heat spreader surface and section analysis showing topography of each sample.

RESULTS AND DISCUSSION

Identification of the nickel deposited layers
From the SEM image (Figure 1(a)), it is apparent that three layers of materials existed in the composition. The EDX spectra of each of these layers were shown in Figure 1(b) to 1(d). Figure 1(b) shows the copper content was the only element that has been found and its high intensity level suggested this copper layer came from the heat spreader. Platinum has also been found in the spectrum (Figure 7) because it was used as a coating material for better SEM image capturing, while the carbon content came from the potting material. Both platinum and carbon also appeared on
other spectra and can be ignored with the same reasons.

Nickel and phosphorous were shown in electroless nickel plating layer in Figure 1(c). The cathodic reactions of electroless nickel plating can be written as:

\[
\begin{align*}
H_2PO_2^- + 2H^+ + e^- & \rightarrow P + 2H_2O \quad (1) \\
2H^+ + 2e^- & \rightarrow H_2 \quad (2) \\
Ni^{2+} + 2e^- & \rightarrow Ni \quad (3)
\end{align*}
\]

According to the above expressions, hypophosphite reduces to atomic phosphorous, hydrogen ions turn into hydrogen gas and nickel ions become atomic nickel during the cathodic reactions. Both the atomic phosphorous and the atomic nickel deposite on the base surface forming nickel-phosphorous (Ni-P) alloy. Figure 1(d) shows that nickel and copper are the deposited elements at this layer. The thin layer of Ni-Cu alloy whose thickness is less than 1 µm produced by the direct current plating from a sulphate type bath (using an aqueous citrate electrolyte containing Ni and Cu sulfates) and the alloy composition can be varied by changing the deposition current density. The cathodic reactions for nickel-copper deposition can be written as:

\[
\begin{align*}
Ni^{2+} + 2e^- & \rightarrow Ni \quad (4) \\
Cu^{2+} + 2e^- & \rightarrow Cu \quad (5)
\end{align*}
\]

Figure 1: Image and EDX spectra of heat spreader A. (a) SEM image of heat spreader A after cross-sectioned; (b) EDX spectrum of copper layer; (c) EDX spectrum of electroless nickel plating layer; (d) EDX spectrum of Ni-Cu electrodeposition layer.
In the cathodic reactions, nickel and copper ions in sulphate solution change into atomic nickel and copper. Both the atomic copper and the atomic nickel were deposited on the substrate's surface forming the nickel copper thin layer.

Figure 2 shows the EDX spectra for heat spreader B and only two layers of materials were found inside heat spreader B. The elements which found inside the spectra for electroless nickel plating layer and copper layer are similar to the heat spreader A spectra. Manufacturer uses the application of momentum cathodic current to electroplate some nickel on the surface and cut off the electricity when deposited nickel is sufficient to catalyse the electroless nickel plating process. Therefore, the electrodeposited nickel-copper layer did not form between copper and nickel layers.

Figure 3: XRD spectrum of Ni-Cu electrodeposition layer for heat spreader A.
According to the study, two intermetallic compounds appeared in the Ni-Cu systems which are Cu$_{0.81}$Ni$_{0.19}$ and Cu$_{3.8}$Ni. XRD was used to identify the formation of intermetallic compound. The spectrum was edited with computer interface software DIFFRAC and EVA as shown in Figure 3 between the ranges of 40° and 80°. Figure 3 shows the XRD pattern of the copper and nickel metals while Ni-Cu bimetallic particles did not exist. Pure copper showed the characteristic reflections at 43.3°, 50.4° and 74.2° related to the (111), (220) and (220) planes. Similarly, pure Ni metal showed characteristic reflections at 44.4°, 51.8° and 76.4° corresponding to the (111), (200) and (220) planes. This concluded that nickel-copper electrodeposition did not form any intermetallic compound.

**Effect of high temperature storage towards intermetallic diffusion**

Figure 4 shows the Ni-Cu deposition layer for heat spreader A was growing under HTS condition. Meanwhile, Figure 5 shows the nickel layer was getting thinner under HTS condition. From an atomic perspective, diffusion is simply the stepwise migration of atom from one lattice site to another. These atomic motions occur in two different ways, namely vacancy diffusion and interstitial diffusion. The vacancy diffusion involves the interchange of an atom from a normal lattice position to an adjacent vacant lattice site or vacancy. The interstitial diffusion involves atoms that migrate from an interstitial position to a neighbouring one that is empty. Both, copper and nickel, have a face centred cubic lattice structure with almost identical lattice constants of $a_{Cu}=0.361$ nm and $a_{Ni}=0.352$ nm and its lattice mismatch is approximately 2.5%. Hence, the diffusion happened at Ni-Cu deposition layer was vacancy diffusion rather than interstitial atomic movement.

![Graph](image)

**Figure 4: Heat spreader A nickel-copper thickness with different time conditions**

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Comparing the two graphs in Figure 4 and Figure 5, the growth of the electrodeposition layer was at higher rate than the thinning of electroless layer. This showed that the diffusion of electrodeposition layer occurred towards two directions, i.e. towards the nickel-phosphorous and copper layer. The magnitude of the diffusion coefficient $D$ is indicative of the rate at which atoms diffuse. The equation of diffusion coefficient is written as follow:

$$D = D_0 \exp \left(-\frac{Q_d}{RT}\right) \text{[m}^2/\text{s]}$$  \hspace{1cm} (6)

where $D_0$ = temperature-independent pre exponential [m$^2$/s], $Q_d$ = the activation energy for diffusion [J/mol], $R$ = the gas constant, 8.31J/molK and $T$ = absolute temperature in Kelvin. The Ni-Cu metal diffusion rate is very low which can be attributed to its lower temperature-independent pre-exponential ($D_0 = 2.7 \times 10^{-5}$) and higher activation energy ($Q_d = 256$) if compared with other metals.

Figure 6 shows the electroless nickel plating layer thickness under different time conditions. Under HTS condition, heat spreader B did not show any formation of diffusion layer. Hence, deposited atoms arranged nicely onto the surface of copper during electroless nickel plating deposition process. There was lack of vacancy for copper atom particles to diffuse into the electroless nickel plating layer.

As a result, electroless nickel plating layer provides a stronger wear resistance and highly anti-corrosion material for today’s industry. However, for the Ni-Cu electrodeposition layer in heat spreader A, nickel and copper atoms create some vacancies during deposition onto the copper surface. This makes copper and nickel atoms are much easier to diffuse inside the Ni-Cu electrodeposition layer.
Effect of deposited catalyst layer towards surface roughness

The topographies of the heat spreader A and B were further analyzed using IFM (Figure 7). Roughness analysis using the IFM software quantitatively showed the average $R_a$ of heat spreader A and B, which were 0.3074 $\mu$m and 0.5800 $\mu$m respectively. On the other hand, the mean $R_q$ of the heat spreader A and B was 0.3889 $\mu$m and 0.7260 $\mu$m respectively. The result in Figure 8 shows that the heat spreader A with Ni-Cu electrodeposition had a much smoother topography than the heat spreader B without electrodeposition. The smoother surface of heat spreader A was due to the deposition of Ni-Cu which has smoothened up the copper surface earlier. A rougher surface caused difficulty for solid thermal interface material to fill up the cavity of the heat spreader and the effectiveness of heat dissipation was reduced.
CONCLUSION

The thermal properties of the Ni-Cu electrodeposition layer were studied and compared. Both galvanic initiation and thin nickel-copper electrodeposition catalytic activation techniques were identified by EDX and XRD. This study shows that after HTS condition, diffusion took place between the Ni-Cu electrodeposition layer and neighbouring layers. Surface roughness of the heat spreader was vastly improved by this Ni-Cu electrodeposition technique. In a nutshell, the Ni-Cu electrodeposition technique offers a much improved thermal performances of the heat spreader.

REFERENCES

[7]. S W.P. Chen, S.G. Lu, and H.L.W. Chan, (2003); Influence of electroless


