Evaluation of New Substrate Surface Finish: Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG)

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Abstract

In this paper, we studied the wire bonding ability and the solder joint reliability for Electrolytic Ni/Au and ENEPIG. For studying wire bonding ability, 4N wire with 20um in diameter was used. Pull strength of Au wire and failure mode after each pull test were both the criteria of wire bonding. After wire pull test, the pull strength and failure mode of Electrolytic Ni/Au and ENEPIG were similar. Therefore, it could be supposed the wire bonding ability of ENEPIG is similar with Electrolytic Ni/Au. For solder joint reliability, different types of solder joint test were conducted- conventional ball shear test, cold-ball pull test. High speed ball shear test was also applied to simulate high strain rate loading, similar as drop test. Failure mode and micro analysis were carried out by the analytical tools, including Scanning Electron Microscope (SEM) and Energy Dispersive Spectrometer (EDX).

In addition, samples were performed thermal process, like multi reflow (as-soldering, 3x, 6x) and solid aging (duration: 250, 500, 1000 hours at 150^0C). Interfacial reaction of two type surface finish with solder ball, Sn96.5Ag3Cu0.5 (SAC305), were observed by SEM for different thermal process. Cross section image and morphology image were observed to study IMC appearance. And EDX was also used to confirm the IMC phase

From the ball shear test results, it was no obvious difference after multi reflow times and different solid aging duration for Electrolytic Ni/Au and ENEPIG. The failure mode of Electrolytic Ni/Au and ENEPIG were both broken at solder. Cold-ball pull test showed Electrolytic Ni/Au and ENEPIG have similarly failure mode distribution after multi reflow process and solid aging process. In the high speed ball shear test, the behavior of broken interface was quite different between Electrolytic Ni/Au and ENEPIG. For as-soldering samples, the broken interface of Electrolytic Ni/Au usually happened at intermetallic compound (IMC) phase, but the ENEPIG usually happened at solder phase. Besides, samples are tested with different test speed to observed the transition point of failure mode that from ductile to brittle. The results showed the transition point of Electrolytic Ni/Au was prior to ENEPIG. On the other hand, the high speed shear test results of ENEPIG after performing solid aging showed lower IMC-broken percentage than Electrolytic Ni/Au. It could be deduced that ENEPIG has better solder joint quality.

Introduction

In electronic package industries, various substrate surface finish have been developed and studied, such as immersion Sn, Organic Solderability Preservatives (OSP), Electrolytic Ni/Au and electroless Ni/ immersion Au (ENIG), etc. Each surface finish shows different advantage and is used in different product application. For example, OSP own low substrate price, simple process and environment friendly. ENIG has good wettability due to Au layer and component size miniaturizable. From the application point of view, generally speaking, ENIG is used in flip chip product, but Electrolytic Ni/Au is used in wire bonding product. However, as the semiconductor technology advancing, the component size is gradual miniaturizing inevitably, so either busless design or electroless plating process should be used to meet the requirement of high routing density. Between these two solutions, electroless plating process has another advantage- lower cost. In electroless plating process, ENIG is popular in the industries, but it easily causes weak wire bonding performance and solder joint problems. Weak wire bonding performance resulted from too thin Au layer thickness- it causes small process window of wire bonding. On the other hand, solder joint problems result from black pad issue. Black pad is due to nickel oxide happening. Because immersion is a substitution reaction, which means Au atom replaces Ni atom during Au layer plating, resulted in porous structure formed at the surface of Ni layer. Therefore, galvanic corrosion occurs between the interface of Au layer and Ni layer. Once black pad happening, brittle failure show up easily along with the interface of solder ball and substrate surface finish. Therefore, a new surface finish- E'less nickel E'less Palladium immersion Gold (ENEPIG) is developed to overcome weak wire bonding performance and solder joint problems by introducing a Pd layer between Ni and Au layer. Ni layer plays a role in diffusion barrier layer, which prevents inter-diffusion between Cu and solder ball. Au layer could prevent underneath layer oxidation and improve wetting ability when soldering. And Pd layer plays a part of protecting layer. It could prevent "black pad" failure resulted from Au atoms replacing Ni atom during Au layer plating and improve wire bonding ability- enlarge process window of bonding wire.

In this paper, we studied the wire bonding ability and the solder joint reliability for Electrolytic Ni/Au and ENEPIG.

EXPERIMENT

The test vehicle in this study was PBGA, which was with two types of surface finish on wire bonding place and ball placement place: electrolytic Ni/Au (Ni: 5um; Au: 0.5um) and ENEPIG (Ni: 5um; Pd: 0.2um; Au: 0.1um). Bonding wire diameter was 1mil, and wire alloy was 99.99%Au. The solder ball composition used in this study was Sn96.5-Ag3-Cu0.5 (SAC305), which diameter is 0.6 mm.

Wire Bonding Ability

For two surface finishes, 60 wire were pull and measured pull strength. Failure mode was also inspected. By the value pull strength and failure mode distribution, bonding window could be define, so that the bonding ability of two surface finish could be seen.

Solder Joint Reliability

Specimens were subjected into IR reflow oven (peak temperature was set at 245^{0}C). Besides 1x reflow (so called as-soldering for solder ball attaching on substrate), the specimens underwent 3x and 6x reflow times. The as-soldering specimens were also subjected into solid aging at 150 ^{0}C for 250, 500 and 1000 hours.

In order to study solder joint reliability after multi reflow and solid aging, three test method were conducted: conventional ball shear test, cold-ball pull test and high speed ball shear test. Ball shear test was performed using DAGE-2400 and the shear rate was set at 500 um/sec.. For the ball pull test, the DAGE-2400 was also used and the pull rate was set at 5000 um/sec. High speed ball shear test was conducted using DAGE-HS4000, shown in Fig.1. [1] The test speed was set at four different shear rates, 100 mm/sec, 500 mm/sec, 1k mm/sec and 2k mm/sec. All of ball shear, pull and high speed ball shear test results were comprised of 40 measurements. After each test, failure modes were inspected. Different types of failure mode were defined. For conventional ball shear test and cold-ball pull test, failure modes were divided into two types: solder residue and IMC-broken. For high speed ball shear test, failure modes were divided into three types: solder residue, IMC<50% and IMC>50%, shown in Fig.4. The specimens undergoing multi reflow and solid aging were observed and analyzed by Scanning Electron Microscopy (SEM), including cross-section and morphology to study interfacial reactions.

RESULTS AND DISCUSSION

The wire pull test results are shown in table1. From this table, it was observed electrolytic Ni/Au showed similar pull strength as ENEPIG. The predominant failure mode was neck-broken for two surface finishes. That is electrolytic Ni/Au shows similar wire bonding ability as ENEPIG.

FIGURE 1. High speed Ball Shear Tester

Fig.2 showed the conventional ball shear test results of two surface finishes after multi reflow. Only solder-residue failure mode was observed. The cold-ball pull test results were shown in Fig.3. The observed failure mode were divided into 100% solder-residue (so-called ductile mode) and IMC-broken (so-called brittle mode), as shown in Fig.4.

The failure mode distribution of Electrolytic Ni/Au and ENEPIG was similarly. It means Electrolytic Ni/Au has similar solder joint reliability as ENEPIG after multi reflow. However, ENEPIG showed better solder joint reliability than Electrolytic Ni/Au after solid aging. The failure mode distribution was shown in Fig.5. As reflow times increasing, IMC-broken percentages increased. Generally speaking, when specimen was subjected to thermal process, like reflow and solid aging, the IMC thickness would be increasing. Since IMC layer tends to be brittle, IMC-broken probability should be increasing and solder joint strength should be decreasing after thermal process. However, ENEPIG showed better solder joint reliability than Electrolytic Ni/Au after solid aging.

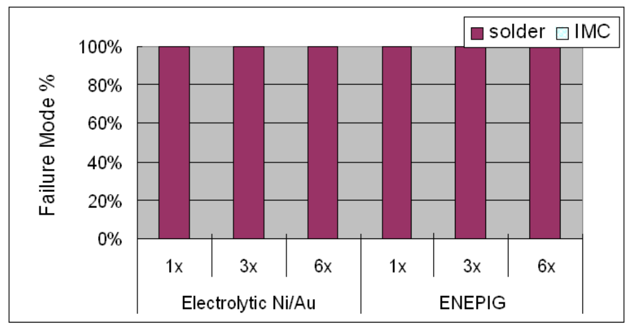

FIGURE 2. Failure mode distribution of shear test with various reflow times

In terms of weak joint selection ability, cold-ball pull test seems to be better than conventional ball shear test. Two factors were concerned [2-5]: First, the interface seems to be weaker in tension than in shear. It is because that pull test applied a pure tensile load at the solder ball pas interface, but in shear test, solder ball gained a combination force of shear and tensile loads resulting in difficulty identifying weak joint. Second, the failure in shear direction should be affected by solder mask, but in pull direction should not.

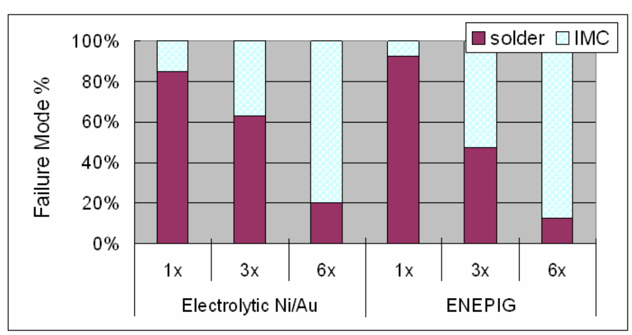

FIGURE 3. Failure mode distribution of cold-pull test with various reflow times

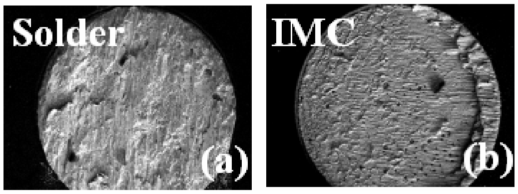

FIGURE 4. Failure modes of cold-pull test

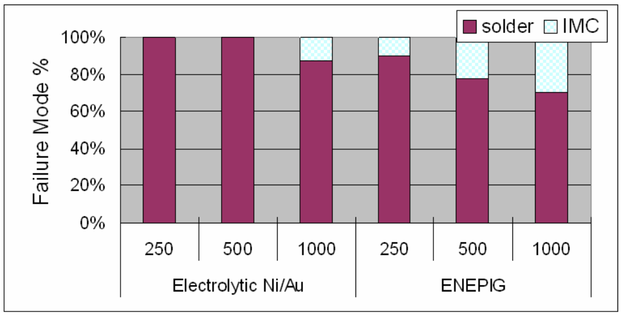

FIGURE 5. Failure mode distribution of cold-pull test with various aging time

Generally speaking, conventional ball shear test and cold-ball pull test are popular and be a easy method to identify solder joint quality. However, both of they are not suitable to simulate the real situation, like drop, due to the limit of test speed, typically less than a few mm per second. Recently, high-speed ball shear test method is developed. The test speed could reach maximum 4 m/sec. When loading is rapid, solder need to accommodate high strain rate. If bulk solder could not afford this high strain rate, the loading would affect solder joint. Under these conditions, the solder joint interfaces could be the weakest and appear IMC-broken.[6] It is easy to characterize failure mode and make IMC-broken occur by using higher test speed. Therefore, high-speed ball shear test was conducted in this study to identify solder joint quality.

The observed failure mode were divided into three types: 100% solder-residue, IMC<50% (IMC coverage area on pad is smaller than 50%) and IMC>50% (IMC coverage area on pad is bigger than 50%). Representative imagines were shown in Fig.6. The failure mode distribution of high speed shear test with various test speed was shown in Fig.7. It was observed that the brittle failure mode percentage increased with increasing shear rate for both surface finishes. At test speed 1k mm/sec, the IMC-broken percentage of Electrolytic Ni/Au is up to 23%, while ENEPIG is only about 10%. When test speed rose to 2k mm/sec, the IMC-broken percentage of Electrolytic Ni/Au is up to 50%, while ENEPIG is only about 10%. If we set the transition speed [6] of failure mode from ductile to brittle happens at 50% IMC-broken percentage. Therefore, the speed of electrolytic Ni/Au is about 2000 mm/sec, but ENEPIG need higher test speed to make IMC-broken percentage reach 50%. It could be deduced that ENEPIG has better solder joint quality.

Fig.8 and Fig.9 shows the failure mode distribution of high speed shear test for two surface finishes after multi reflow times. As previous say, higher test speed is easy to make IMC-broken happen. So, specimens with 2k mm/sec test speed showed higher IMC-broken than that with 100 mm/sec for each reflow times. From the failure mode distribution, the IMC-broken percentage increased when reflow times increased. This might be related to IMC growth. Besides, Electrolytic Ni/Au and ENEPIG showed similar trend in failure mode distribution after multi reflow. In the other hand, Electrolytic Ni/Au and ENEPIG has similar solder joint reliability.

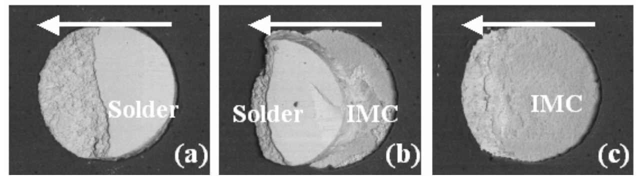

FIGURE 6. High speed ball shear test failure modes: (a) 100% Solder-residue, (b) IMC<50%, (c) IMC>50%

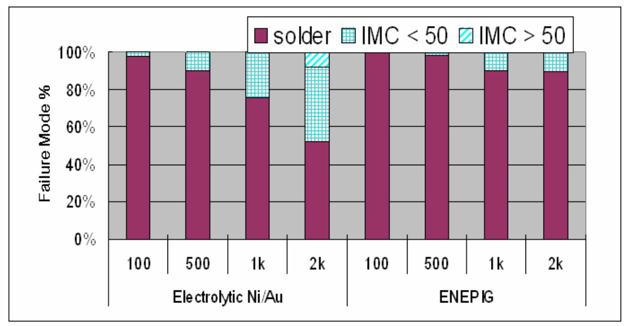

FIGURE 7. Failure mode distribution of high speed ball shear test with various test speed

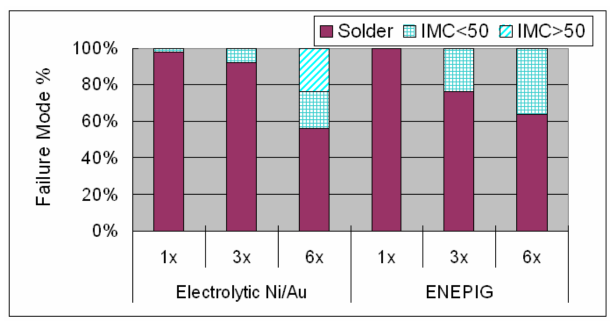

FIGURE 8. Failure mode distribution of high speed ball shear test with various reflow times (shear rate 100mm/sec)

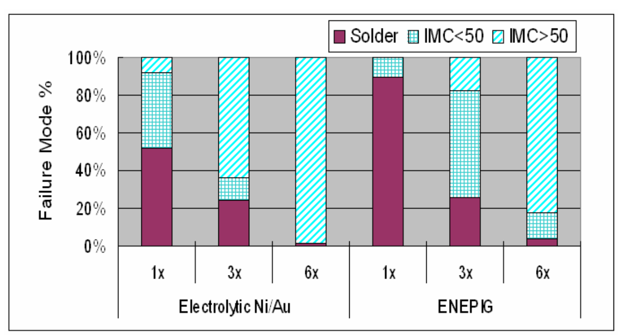

FIGURE 9. Failure mode distribution of high speed ball shear test with various reflow times (shear rate 2000mm/sec)

The failure mode distribution after solid aging were shown in Fig.10 and Fig.11. After solid aging for 250, 500 and 1000 hours , the IMC-broken percentage increased obviously compared with as-soldering results shown in Fig.5 at identical test speed. It was shown ENEPIG has lower IMC-broken percentage than Electrolytic Ni/Au for each test speed. Compared with the failure mode distribution of multi reflow and solid aging, two factors were concerned. First, for test speed with 2k mm/sec, surface finish with Electrolytic Ni/Au showed high IMC-broken percentage for both solid aging and multi reflow, but for surface finish with ENEPIG, specimens after solid aging process showed lower IMC-broken percentage than that after multi reflow process even for aging 1000hrs. Second, for test speed with 100 mm/sec, surface finish with Electrolytic Ni/Au after multi reflow showed lower IMC-broken percentage than after solid aging, but for surface finish with ENEPIG, specimens after solid aging showed lower IMC-broken percentage than that after multi reflow process even for aging 1000hrs. These differences might be due to different interfacial reaction.

Many factors would affect interfacial reaction, like solder ball composition, pad surface finish, and thermal process. Different solder ball composition and pad surface finish would form different IMC phase. Thermal process would affect IMC growth and formation.

These differences would result in different solder joint strength and reliability. In this study, solder ball SAC305 was used for two surface finishs- Electrolytic Ni/Au and ENEPIG, and the IMC growth after multi reflow times and solid aging would be observed.

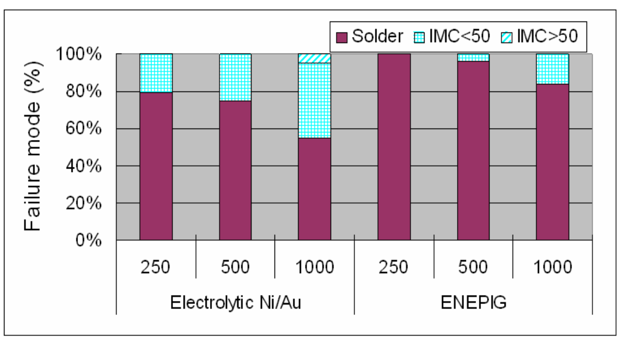

FIGURE 10. Failure mode distribution of high speed ball shear test with various aging time. (Shear rate: 100mm/sec)

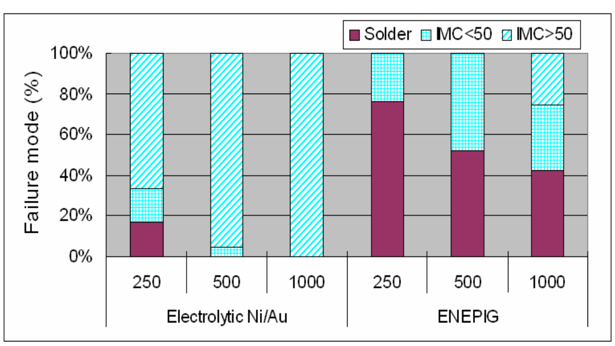

FIGURE 11. Failure mode distribution of high speed ball shear test with various aging time. (Shear rate: 2000mm/sec)

Cross-section imagine of Electrolytic Ni/Au and ENEPIG after multi reflow times were shown in Fig.12. Specimens after solid aging was represented in Fig.13. From the EDS analytic results, the IMC phas were $(Cu_x, Ni_{1-x})_6Sn_5$ and Ni-P layer. For specimens after multi reflow process, it was observed that IMC thickness increased and $(Cu_x, Ni_{1-x})_6Sn_5$ became bigger as reflow times increasing. The IMC of specimens with Electrolytic Ni/Au surface finish appeared to be scallop-shape, but that with ENEPIG appeared to be column-shape. For specimens after solid aging process, it was also observed that IMC thickness increased and $(Cu_x, Ni_{1-x})_6Sn_5$ became bigger as solid aging time increasing. But the IMC thickness of ENEPIG was smaller than Electrolytic Ni/Au. The IMC of specimens with Electrolytic Ni/Au and ENEPIG surface finish appeared to be scallop-shape. Compared with interfacial reaction of specimens with Electrolytic Ni/Au after multi reflow and solid aging, specimens after solid aging showed higher IMC thickness than that after multi reflow. It might be the reason for specimens after solid aging showed higher IMC-broken percentage. Compared with interfacial reaction of specimens with ENEPIG after multi reflow and solid aging, the IMC of specimens after multi reflow showed column-shape, but that after solid aging showed scallop-shape. Different IMC shape might be the reason for different solder joint reliability discussed before. What would be the reason for different interfacial reaction for ENEPIG?

It might be related to different thermal process temperature. For multi reflow process, solder ball would be melt during reflow (Peak temperature: 245℃), therefore, Pd and Au atom diffuses into solder immediately and easily. But for solid aging process, the temperature is set at 150℃ so that solder would not be melt. It is hard for Pd and Au atoms diffusing into solder ball. So, specimens after solid aging showed better solder joint reliability than that after multi reflow.

Table1. Wire pull strength results

Surface finish	Diameter	Pull strength (g)		
		Max	Min	Avg.
Electrolytic Ni/Au	25 um	7.2	5.8	6.6
ENEPIG	25 um	7.5	5.9	6.8

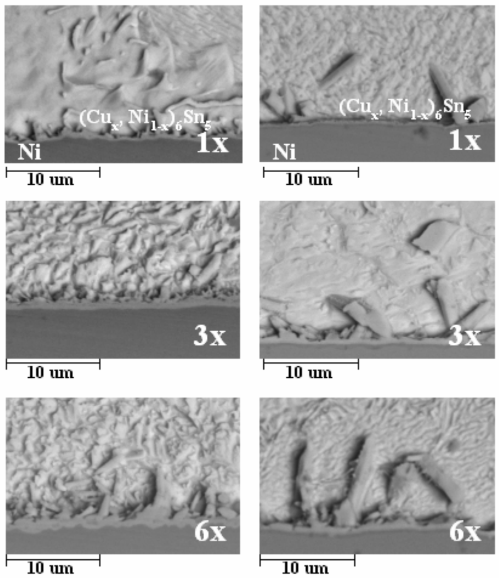

FIGURE 12. Interfacial reaction of Electrolytic Ni/Au (left) and ENEPIG (right) with various reflow times

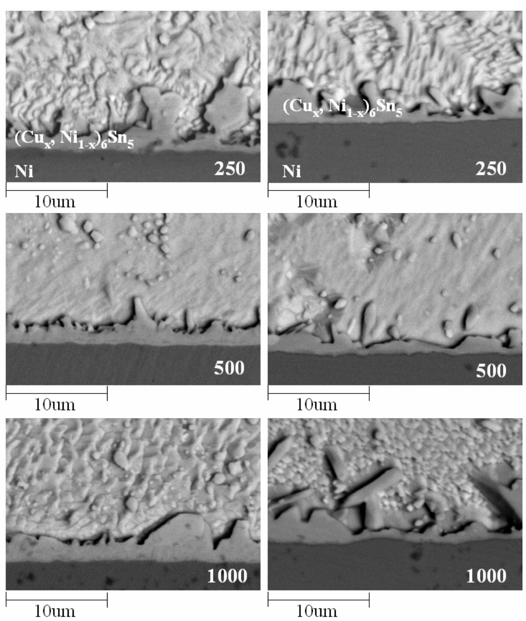

FIGURE 13. Interfacial reaction of Electrolytic Ni/Au (left) and ENEPIG (right) with various aging times

Conclusions

In this study, wire bonding ability and solder joint reliability of two surface- Electrolytic Ni/Au and ENEPIG were investigated. The conclusions could be ascribed as follow:

- By the results of wire pull strength, specimens with Electrolytic Ni/Au showed similar wire bonding ability as that with ENEPIG.
- The transition speed that failure mode transfers from ductile to brittle of electrolytic Ni/Au is about 2000 mm/sec, but ENEPIG need higher test speed to make IMC-broken percentage reach 50%. It could be deduced that ENEPIG has better solder joint quality.
- For multi reflow process, the failure mode distribution of specimens with Electrolytic Ni/Au showed similar trend as that with ENEPIG. For solid aging process, specimens with Electrolytic Ni/Au showed higher IMC-broken percentage than that with ENEPIG.
- After multi reflow process, the IMC of specimens with Electrolytic Ni/Au appeared to be scallop-shape and that with ENEPIG appeared to be column-shape. After solid aging process, the IMC of specimens with Electrolytic Ni/Au and ENEPIG both appeared to be scallop-shape. Specimens with ENEPIG after solid aging showed better solder joint reliability than that after multi reflow.

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