

Evaluation of Electroless Nickel Electroless Palladium (ENEP) finish as a replacement for Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) for Gold Wirebonding and SAC305 Solderability

Jaspreet Gandhi, Shijian Luo, Tom Jiang

Micron Technology Inc

8000 S. Federal Way

Boise ID 83707-0006

Ph: 208-363-3673, Fax: 208-368-2256, E-mail: jgandhi@micron.com

Abstract

In this paper, we compared the wirebonding and solder joint reliability of Electroless Nickel Electroless Palladium (ENEP) and Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) under bump metallurgy (UBM) on Aluminum bond pads formed by redistribution layer (RDL) process. Since the immersion gold bath operates at a higher temperature and the final layer is extremely thin, the risk of corrosion to the underlying pad due to galvanic potential difference and discoloration due to pin holes is always a concern. In that aspect removing the immersion gold layer from the UBM and reducing the finish to ENEP only can mitigate this issue. Both Chip on board (COB) and Flip Chip packages were prepared and side by side comparison is shown for each finish's interaction with gold wire and 96.5%Tin-3%Silver-0.5%Copper (SAC 305) solder. Mechanical (wire pull, ball shear) and high temperature storage testing was performed to determine the reliability of each finish over time. Micro structural study over high temperature aging was also performed using scanning electron microscopy (SEM/EDS) and Transmission electron microscopy (TEM). The intermetallic compound (IMC) formation is very well in agreement with the literature. Overall, results show that ENEP finish has a high potential to replace ENEPIG finish.

Keywords: Lead Free solder, electroless nickel electroless palladium immersion gold, wirebonding, ENEPIG, ENIG, Black pad

1.0 Introduction

The concept of a redistribution layer (RDL) is very common in the DRAM industry as it allows routing the bond pads to new locations for better interconnection between chip and substrate, ease of wirebonding, high pitch flip chip attach or 3D stacking. There might be some performance tradeoffs due to additional resistance of the traces, but all these are considered in the design phase and generally routing requirements from customers take the precedence. RDL is a key enabling technology and strong emphasis should be laid on the reliability. In the RDL process, the device undergoes an additional metallization step. In the present study Aluminum is deposited and patterned into a new bond pad layer. Electroless Nickel Electroless Palladium (ENEP) plated directly on non-RDL Cu pads can be used with conventional wire bonding tools and methods while offering long-term reliability [1]. ENEP plating technology was adapted to RDL Aluminum bond pads with an additional flash of immersion gold (IG) layer

on top of metal stack. ENEPIG finish has the widest latitude for a variety of applications and is perceived to provide better solder wet ability and same wirebonding quality as ENEP [2]. The Palladium (Pd) layer (~0.10-0.5um thick) preserves the solderability of the underlying Ni layer by limiting oxidation at reflow temperatures and breaking the galvanic contact between nickel and gold. On the flip side, the thin gold layer (~0.04um) is extremely porous [3], leading to bond pad discoloration and pitting corrosion over time. In order to mitigate this issue, a study was performed to verify if removing the immersion gold layer from the UBM would have any adverse effect on wirebondability and solder joint reliability. No wirebonding problems were foreseen as bonding on ENEP is an established process championed by Micron 5 years ago. ENEPIG and ENEP UBM finishes were compared in a standard wire bonded chip on board (COB) using 0.8 mil 4N gold wire and solder based flip chip package using 96.5%Tin-3%Silver-

0.5% Copper (SAC 305) solder. Mechanical tests (wire pull and ball shear) and high temperature storage tests were performed to determine the reliability of each finish over time. Study of the growth of intermetallic phases over high temperature aging was also performed using scanning electron microscopy (SEM/EDS) and transmission electron microscopy (TEM).

2.0 Experimental

2.1 Materials and Process

Short loop wafers (no active circuitry) were used in this study. Blanket Tetra Ethoxy Ortho Silicate (TEOS) wafers were coated, photo patterned with polyimide dielectric to create native bond pad openings. A Titanium/Aluminum/Titanium layer was deposited and patterned using photolithography and dry etched to form the redistribution layer. Finally, polyimide is applied and patterned to create openings that become the new pad also called as outer layer bond pad (OLB), Figure 1a. Titanium was removed from the OLB by dry etch exposing the fresh Aluminum. The wafers were then electroless plated, Figure 1b. The electroless plating DOE was comprised of three splits as listed in Table 1.

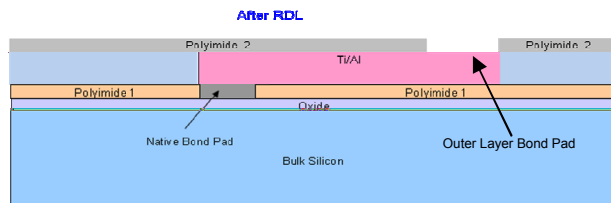


Figure 1a: Outer Layer Bond Pad post RDL

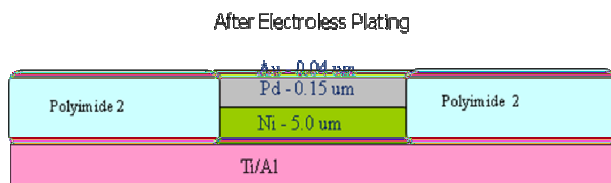


Figure 1b: UBM stack post electroless plating on OLB

Table 1: ENEPIG (Control) vs ENEP Split DOE

Process	Ni (um)	Pd (um)	Au (um)
Control	5	0.15	0.04
ENEP-A	5	0.3	n/a
ENEP-B	5	0.3	n/a

A and B refer to different Electroless Palladium chemistry suppliers. The process sequence for electroless plating included two zincating cycles prior to ENEPIG (control) or ENEP deposition. Electroless Palladium bath immersion time was adjusted to obtain 0.15 and 0.30 um thickness. The bond pad size was

approximately 80 X 60 um. Wafers after plating were split and sent for wirebonding and solder ball attach respectively for COB and Flip Chip packaging. Some of the COB dies post wirebonding were submitted for wire pull and ball shear tests as well as intermetallic studies over time. Few dies were also subjected to 85% relative humidity (RH) and 60 deg C accelerated aging to observe the effect of temperature and humidity on the bond pad aesthetics and wire pull strength. Remaining dies were sent through full package flow for assembly completion. The Flip chip wafers were stencil printed with 220 um SAC305 solder paste and sent through 1X reflow at peak temperature of 245C. The wafers were diced and few dies were submitted for ball shear test and intermetallic studies. Rest went through flip chip attach to substrate, underfilled, encapsulation and other backend process for assembly completion.

2.1 Test Methods

Wire pull and ball shear before and after high temperature aging (high temperature storage at 175C) was performed on both wirebonded and solder ball bumped (ball shear only) die. Dage 4000 was used for measurements using a 250g Ball Shear Cartridge. The test speed was 100 um/s, max test load 250 g, land speed 200 um/s, shear height 3.0 um, and overtravel 100 um. 10 dies (40 wires per die) were used as the sample size for wire pull test and 10 dies (40 balls per die) were used as the sample size for ball shear test. In order to observe the interaction of wirebonded gold balls and SAC solder ball with underlying UBM, samples were submitted for intermetallic growth study at time 0 (as it is) and after HTS at 175C for 1000 hrs. Full COB and Flip chip packages post assembly complete were also submitted for Moisture Sensitivity Testing (MST) Levels 2-4 and TC-B 1000 cycles.

3.0 Results and Discussion

3.1 COB package

Figure 2 shows the wire pull data between 3 splits before and after temperature humidity accelerated aging. No significant difference was observed and all parts showed M1 failure (Neck Break) – wire breaks directly above the ball bond. The ball shear data before and after HTS at 175C is shown in Figure 3. All parts showed M2 failure (ball shear). In this mode, the tool “shears” through the gold ball, leaving 25% or more of the gold ball (below the shear plane) intact and undisturbed. Mode 2 is the preferred mode, which suggests the strongest and most desirable bond. No statistical significant difference was observed. All values were higher than the established specification of 15.5g individual/ 20g average.

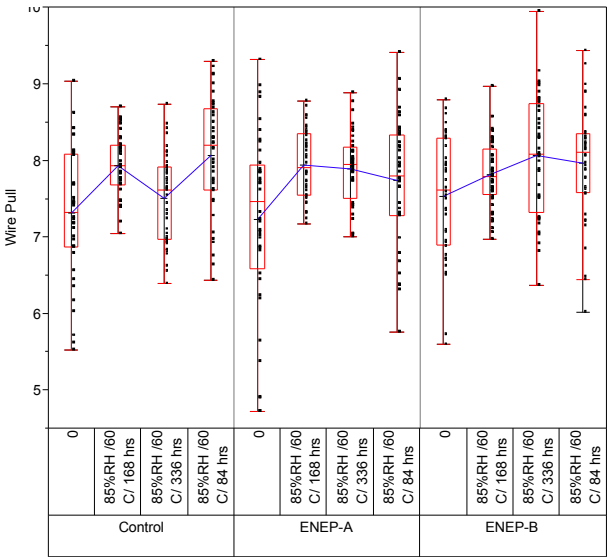


Figure 2: Wire pull data before and after accelerated aging

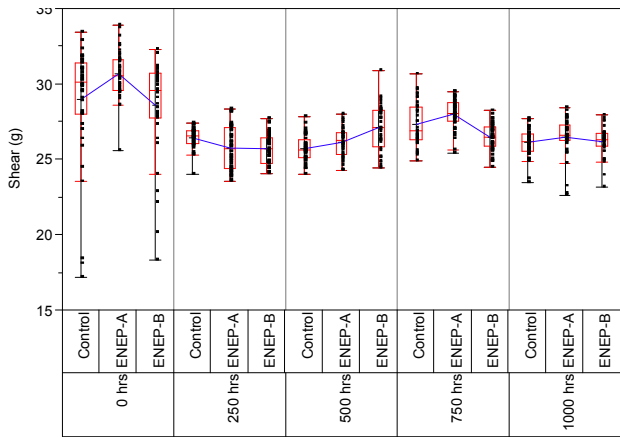
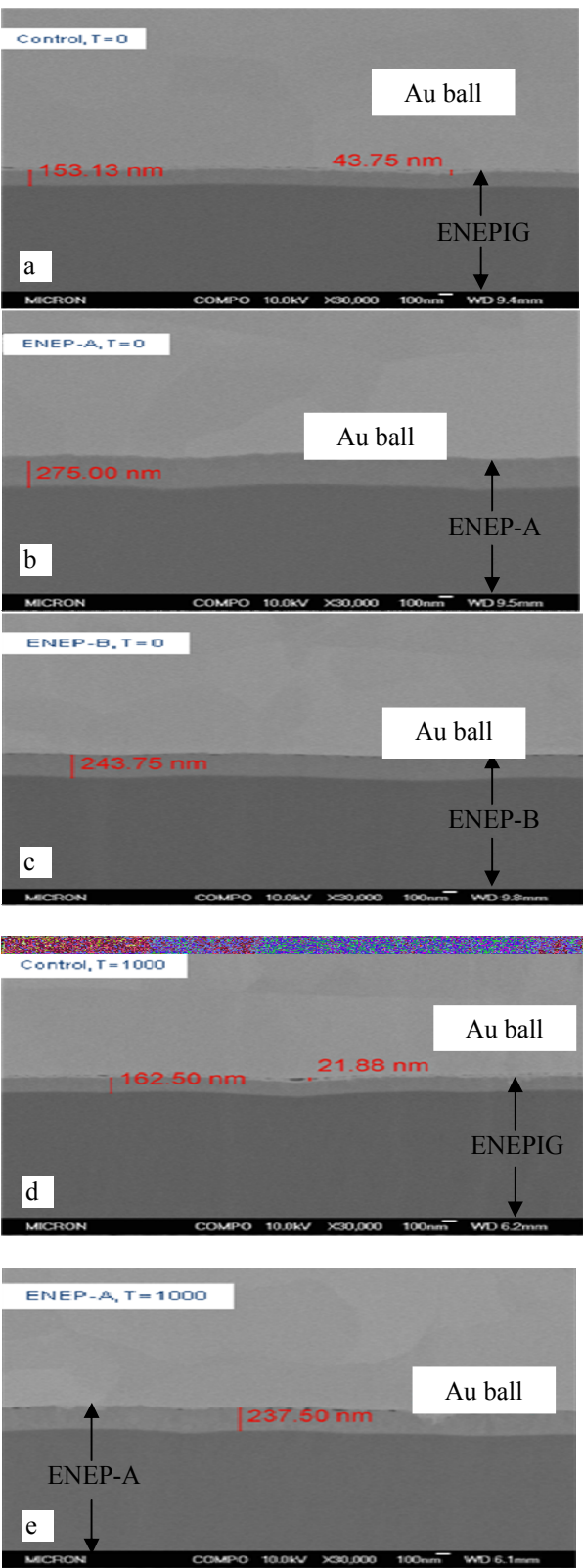


Figure 3: Gold ball shear before and after high temperature storage @ 175C

Figure 4a-4c and 4d-4e show the cross-sections of the splits at time 0 and 1000 hrs HTS at 175C. The gold layer can still be seen after 1000 hrs HTS in case of control sample. It is clear that solid state diffusion between immersion gold layer and wire bonded gold ball is very slow. For ENEP-A and ENEP-B no change in Pd thickness was observed over time



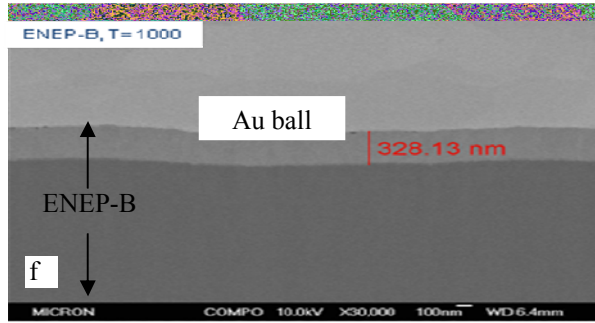


Figure 4: Cross-section showing interaction between Au ball before and after 1000 hrs HTS at 175C. (a/d) ENEPIG, (b/e) ENEP-A, (c/f) ENEP-B

According to Au-Pd phase diagram [1], new phases are formed between 400C-500C. This result verifies that no IMC is formed at 175C between Au and Pd and the bonding is expected to be metallic [4]. Table 2 shows various properties of Au and Pd and how they satisfy the Hume Rothery rules [5]. The atomic radii difference is less than 15%, electronegativity difference is negligible, both have the same FCC crystal structure and a metal of lower valence (Au) tends to dissolve more of a metal of higher valence (Pd) than vice versa. We speculate that Au-Pd metallic bond may form a substitutional solid solution at higher temperature due to higher Pd diffusion but post 175C HTS we did not detect any Pd presence in Au ball or Au presence in Pd layer

Table 2: Atomic and physical properties of Au & Pd [4]

Properties	Au	Pd
Atomic radii (nm)	0.144	0.137
Electronegativity (Pauling Scale)	2.4	2.2
Valency	1	(2)
Crystal Structure	FCC	FCC

All samples post assembly complete passed MST L2-L4 and TC-B 1000 cycles. Product yield did not show any differences between the 3 finishes. However, an important aesthetic difference was observed post accelerated high temp and humidity exposure. Figure 5a-5f show the bond pad surface at time 0 and after 336 hrs exposure at 85% relative humidity and 60 deg C temperature. The ENEPIG control sample showed discoloration and pitting as compared to ENEP-A and ENEP-B. Since thin immersion gold coatings are porous to begin with [3], high temperature and humidity in the chamber may have caused localized corrosion in the pores causing pitting and non-uniformity exposing Pd surface underneath. However the discoloration did not seem to impact the wire-bonding performance as seen in Figure 2.

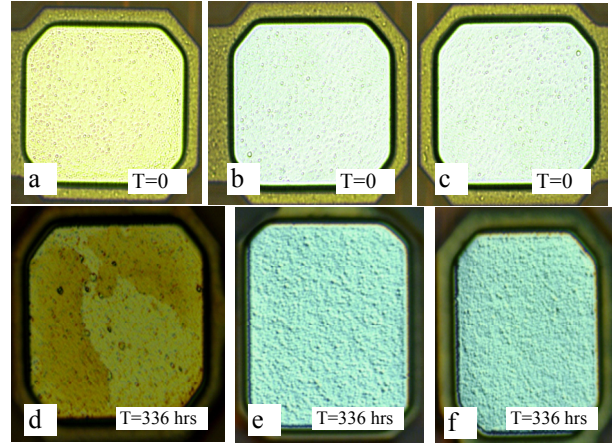


Figure 5: Bond pad condition at time 0 and post 336 hrs at 85%RH/60C. (a/d) ENEPIG Control, (b/e) ENEP-A, (c/f) ENEP-B

3.2 Flip Chip Package

Figure 6 shows the ball shear data at time 0 and different HTS intervals

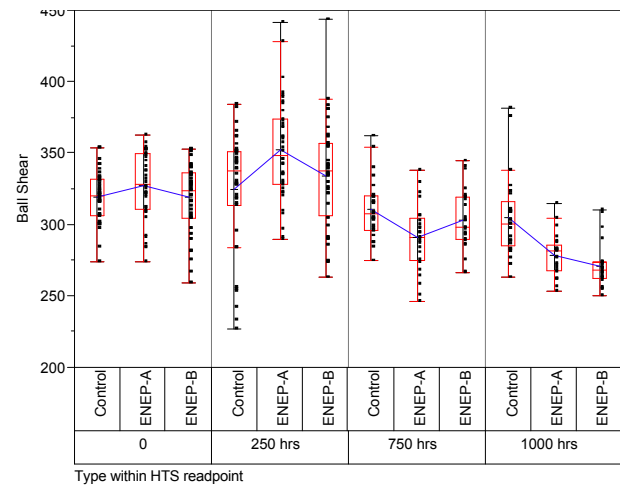


Figure 6: Solder Ball Shear before and after high temperature storage at 175C

Time 0 and 250 hrs showed Mode 1 (Ball Shear) failure whereas 750 hrs and 1000 hrs showed Mode 3 (Ball Lift) failure. The initial increase in ball shear from time 0 to 250 hrs aging can be related to IMC growth as certain IMC thickness is required to ensure a reliable joint as well as impart strength. However increased aging time leads to a continual increase in IMC thickness which makes the joint brittle, resulting in decreasing ball shear values at 750 hrs and longer leading to Mode 3 fail. Nevertheless, all 3 splits passed the minimum ball shear requirement of 200 gms at different aging intervals. Figure 7a-7c and 7d-7f show the SEM images post cross-sections for three splits at time 0 and 1000hrs HTS respectively.

IMC growth is evident and ENEP-A and ENEP-B tend to show higher IMC growth than control sample. This can be attributed to the thicker 0.30 μm Pd thickness layer in ENEP-A and B as compared to the thinner 0.15 μm layer in ENEPIG control sample. This is discussed further in the Pd-Sn section

3.3 Intermetallic Formation

Au-Sn Intermetallic

Due to high solubility of gold in molten solder and diffusivity of $10^{-5} \text{ cm}^2/\text{sec}$, gold atoms can diffuse a distance of 100 μm in 5 sec and reach the top surface of the solder cap [7]. This explains the instant disappearance of 0.04 μm gold in the ENEPIG sample post reflow as no gold signal was observed near the interface during EDS

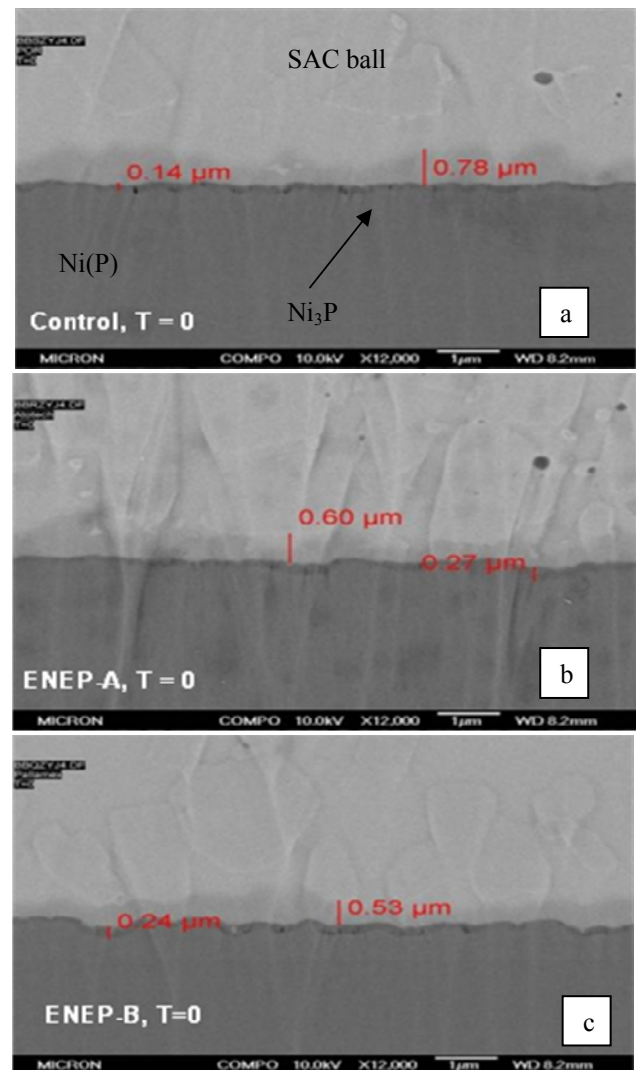
Pd-Sn intermetallic

After Au dissolves, interaction of Pd with solder leads to formation of PdSn_4 [8-9]. Rohm and Hass published studies on various Pd thicknesses and found that thin Pd 0.05-0.1 μm layers show best results for ball shear and ball pull [10]. Thicker films, 0.2 μm -0.3 μm lead to thick weak IMC and lower pull and shear force. In our case ball shear data after 1X reflow did not show significant difference between thin Pd (0.15 μm) and thick Pd (0.30 μm) but over time in HTS, shear value decreased for thicker Pd. Greater Pd thickness tends to form the more brittle PdSn_4 phase near the interface during solid state aging. Another data point (not shown) was collected where all three finishes were subjected to multiple reflows. Pd was not found near the interface during multiple reflows but it was found during solid state aging. This can be explained by the thermodynamic and kinetic considerations where Pd diffusion occurs at a rapid pace in molten solder but is much slower in solid state restricted by bulk lattice, surface and grain boundary. A thin Pd film in contact with molten solder would dissolve very quickly and allow the solder/Ni reaction to take place. But a slightly thicker Pd may lead to Pd-Sn compound formation, which could become a diffusion barrier in the subsequent reflow and pose a hindrance to solder-Ni interaction [11].

Ni(P)-Sn intermetallic

The hypophosphite based electroless Ni plating solution leads to amorphous Ni(P) deposits. During soldering action, Ni diffuses into the solder from the amorphous Ni(P) concentrating phosphorous (P) in the form of Ni_3P compound. Figures 7a-7f show the continuous dark Ni_3P layer clearly. The growth of the Ni_3P is diffusion-controlled with an activation energy of 0.33 eV/atom. It is a conservative reaction, in which the Ni_3P consumes nearly all the P in the amorphous

Ni(P) and very little P goes into the solder. Ni_3P -solder layer is brittle and is further aggravated by Kirkendall voids due to Ni diffusion to participate in Ni-Sn intermetallic [7, 11]. Right above the continuous Ni_3P layer, two distinct IMC layers are visible. Figure 8a-8d show the representative EDS elemental weight percentages for ENEP-B split at 250 hrs and 1000 hrs HTS respectively. At 250 hrs, the bottom IMC is Ni rich with 23.8 %Ni and 76.2%Sn (Ni_3Sn_4) while the top IMC layer is copper rich with 26.1% Cu and 73.9%Sn (Cu_6Sn_5). The IMC thickness increased with HTS aging. At 1000 hrs, a ternary intermetallic ($\text{Ni,Cu}_3\text{Sn}_4$) is observed. Formation of a ternary intermetallic is due to substitutional solid solution between Cu and Ni. These two elements are completely soluble in one another at all proportions. The atomic radii for Cu and Ni is 0.128 and 0.125 nm respectively, both have FCC crystal structure and their electro negativities are 1.9 and 1.8 [5, 12].



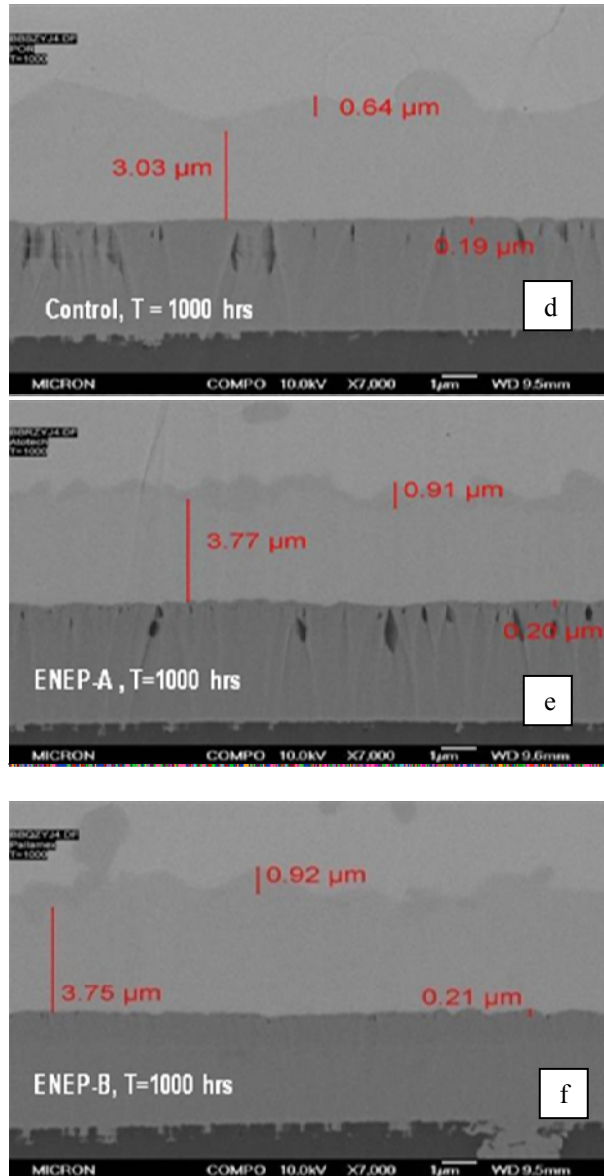


Figure 7: X-section and SEM of solder/UBM finish before and after 1000 hrs HTS@ 175C a) control, T=0 b) ENEP-A, T=0 c) ENEP-B, T = 0 d) control, T=1000 hrs e) ENEP-A, T=1000 hrs f) ENEP-B, T =1000 hrs

Literature also supports [7, 13-17] that for SAC solders, complex ternary intermetallic compounds are formed; $(\text{Cu},\text{Ni})_6\text{Sn}_5$ or $(\text{Ni},\text{Cu})_3\text{Sn}_4$ and $(\text{Cu},\text{Ni})_6\text{Sn}_5$. The top layer is initially Cu_6Sn_5 substituting some of its Cu with Ni, while the bottom is initially Ni_3Sn_4 , substituting some of its Ni with Cu. With the presence of Cu in the SnAgCu solder, the formation of Ni_3Sn_4 is initially suppressed and $(\text{Cu}, \text{Ni})_6\text{Sn}_5$ is formed. Over time and with annealing, the $(\text{Cu},\text{Ni})_6\text{Sn}_5$ phase gradually transforms into $(\text{Ni},\text{Cu})_3\text{Sn}_4$ phase. We however did not observe ternary phases at 250 hrs. To

further confirm the presence of ternary IMC, the same set of samples (ENEP-B 250 hrs and 1000 hrs) were submitted for TEM elemental mapping. Figure 9a and 9b show the TEM micrographs for ENEP-B at 250 hrs and 1000 hrs respectively. Cu signal is very vague in the bottom IMC and it appears that some copper might be present. It was not quantified however.

Ag-Sn intermetallic

Since no Ag was detected in the interfacial IMC layer, it is assumed that Ag was not directly involved in the interfacial reactions but formed Ag_3Sn globules in the bulk of the solder [11].

Overall no difference was observed in the IMC structures for control, ENEP-A and ENEP-B. Packages post assembly complete also passed MST L2-L4 and TC-B 1000 cycles.

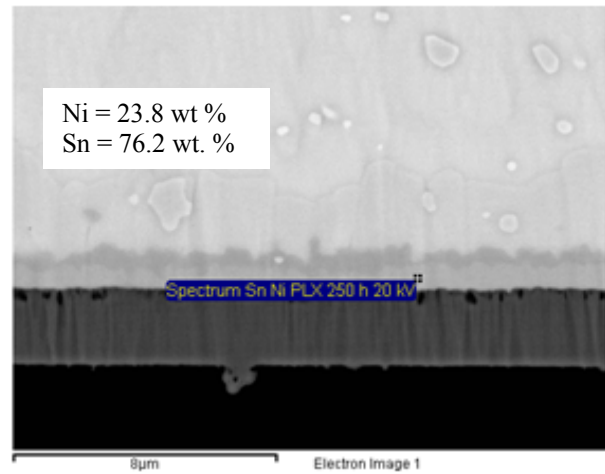


Figure 8a: EDS elemental percentage for ENEP-B after 250 hrs HTS @ 175C

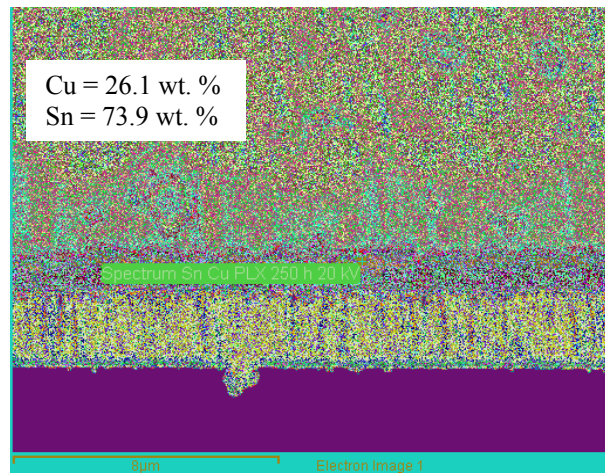


Figure 8b: EDS elemental percentage for ENEP-B after 250 hrs HTS @ 175C

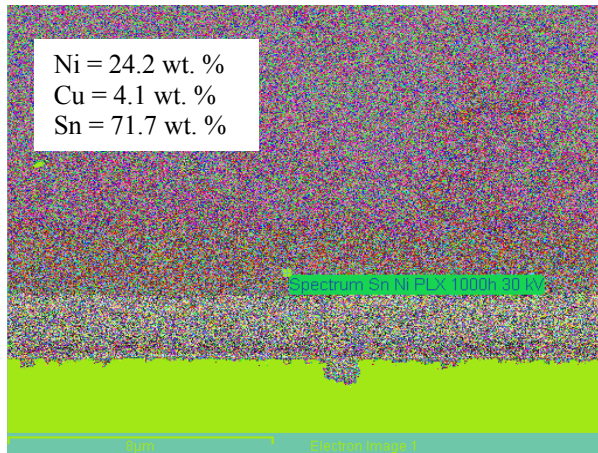


Figure 8c: EDS elemental percentage for ENEP-B after 1000 hrs HTS @ 175C

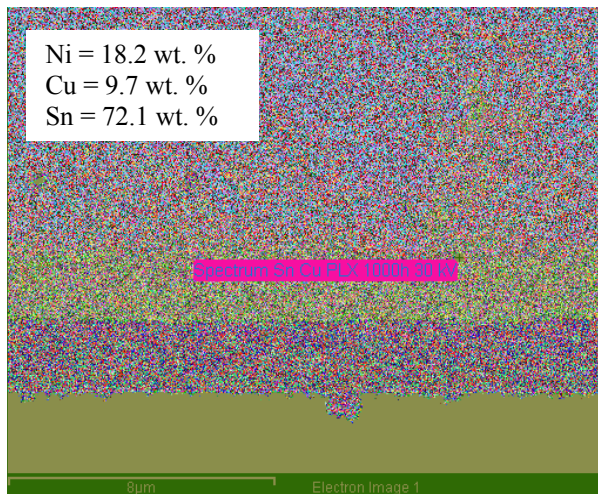


Figure 8d: EDS elemental percentage for ENEP-B after 1000 hrs HTS @ 175C

Conclusions

- ENEP only plating is a feasible option for both wirebonding and flip chip packaging
- There is no discernible difference between Pd chemistries from supplier A or B.
- Pd thickness of 0.30 um may be optimal for wire bond application as it is a metallic bond
- For solder ball attach, Pd thickness should be restricted to 0.15-0.20um only. Thicker Pd can lead to formation of brittle IMC near the interface during solid state aging resulting in reduced ball shear strength.

Acknowledgement

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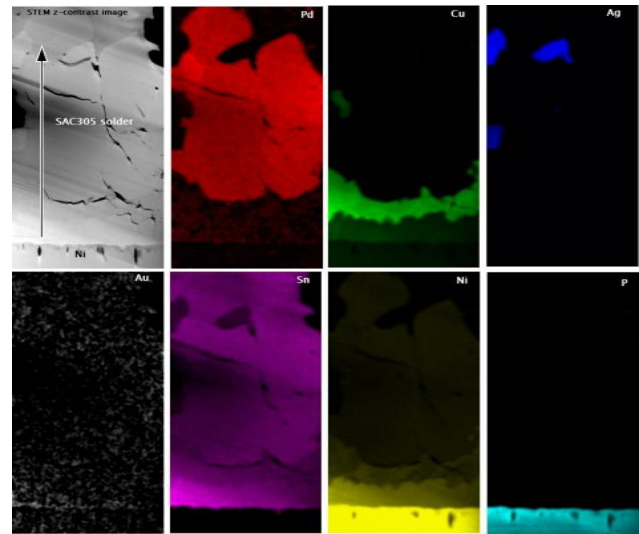


Figure 9a: TEM elemental mapping for ENEP-B after 250 hrs HTS @ 175C

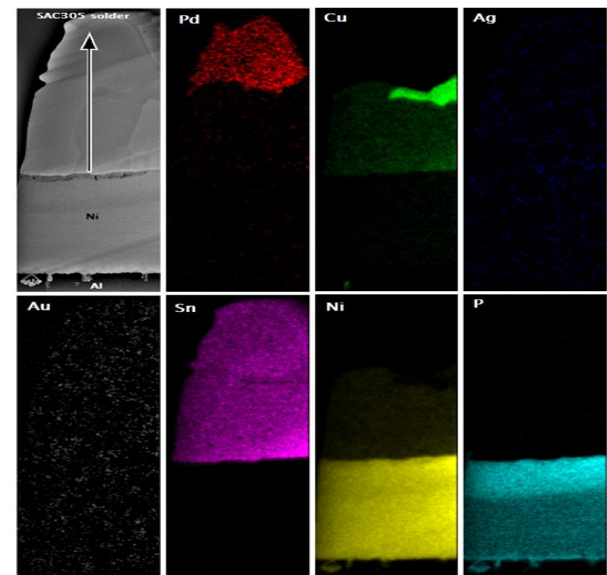


Figure 9b: TEM elemental mapping for ENEP-B after 1000 hrs HTS @ 175C

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